



Energy Research Partnership
Technology Report

BIO-ENERGY TECHNOLOGIES REVIEW

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The Energy Research Partnership

The Energy Research Partnership is a high-level forum bringing together key stakeholders and funders of energy research, development, demonstration and deployment in Government, industry and academia, plus other interested bodies, to identify and work together towards shared goals.

The Partnership has been designed to give strategic direction to UK energy innovation, seeking to influence the development of new technologies and enabling timely, focussed investments to be made. It does this by (i) influencing members in their respective individual roles and capacities and (ii) communicating views more widely to other stakeholders and decision makers as appropriate. ERP's remit covers the whole energy system, including supply (nuclear, fossil fuels, renewables), infrastructure, and the demand side (built environment, energy efficiency, transport).

ERP is co-chaired by Professor David Mackay, Chief Scientific Advisor at the Department of Energy and Climate Change and Nick Winser, Executive Director at National Grid. A small in-house team provides independent and rigorous analysis to underpin ERP's work.

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The Energy Research Partnership Technology Reports

The ERP Technology Reports provide an overarching insight into the Research, Development and Demonstration (RD&D) challenges for key low-carbon technologies. Using the expertise of the ERP membership and wider stakeholder engagement, each report identifies the innovation challenges that face a particular technology, the state-of-the-art in addressing these challenges and the organisational landscape (both funding and RDD&D) active in the area. The work identifies critical gaps in innovation activities that will prevent key low-carbon technologies from reaching their full potential and makes recommendations for investors and Government to address these gaps.

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The views are not the official point of view of any organisation or individual and do not constitute government policy.

This report provides a summary of high level findings from the review. The main report is available at www.energyresearchpartnership.org.uk

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Contents

Executive Summary and Recommendations	5
Glossary and Abbreviations	14
1 Introduction.....	21
1.1 Background	21
1.2 Review Aim, Objectives and Scope	22
1.3 Review Process and Methodology	24
1.4 Structure of the Review	24
2 Introduction to Bio-energy	26
2.1 Introduction.....	26
2.2 Current Use of Biomass.....	29
2.3 Why the Increase in Activity in Bio-energy and Where is the Agenda Going?	31
2.4 State of the Bio-energy Agenda: Summary	34
3 Sustainable Bio-energy in the 2050 Energy System	34
3.1 Introduction.....	35
3.2 Meta-Analysis of the Role of Bio-energy in 2050 Energy Scenarios.....	35
3.3 Uncertainties Impacting the Extent of Bio-energy use in UK Scenarios	36
3.4 Summary	39
4 Biomass Feedstock Production: Potentials and Research Areas.....	40
4.1 Introduction.....	40
4.2 Biomass Resource Assessments	40
4.3 Feedstock Research, Development, Demonstration and Deployment	47
4.4 Summary and Recommendations	60
5 Bio-energy Logistics, Process Conversion Technologies and End Uses: Research, Development, Demonstration and Deployment.....	62
5.1 Background	62
5.2 Feedstock Logistics: Field to Process Conversion	63
5.3 Process Conversion and End Use	68
5.4 Whole System Analysis and Cross Cutting Issues	92
5.5 Best Use of Biomass: Analysis Framework and Performance Metrics	98
5.6 Summary and Recommendations	99
6 International and UK Bio-energy Policy, Research Activity and Innovation Landscape	99
6.1 Introduction.....	102
6.2 International Bio-energy Research Activity and Innovation Landscape	102
6.3 UK Bio-energy Technology RDD&D Capacity, Bio-energy Policy and Innovation Landscape.....	107
6.4 Summary and Recommendations	121
7 Summary of Conclusions and Recommendations.....	125
7.1 Overarching Issues.....	125
7.2 Framing Issues and State of the Bio-energy Agenda	125
7.3 Sustainable Bio-energy in the 2050 Energy System.....	126
7.4 Biomass Feedstock Production and Areas of Research.....	126
7.5 Bio-energy Logistics, Process Conversion Technologies and End Uses: Research, Development, Demonstration and Deployment	128
7.6 UK and International Bio-energy Policy, Research Activity and Innovation Landscape.....	130
References.....	134
Appendices.....	A1

Bio-energy Technologies Review: Executive Summary and Recommendations

Key Messages

There is substantial potential for the UK to develop a reliable, sustainable and economic supply of biomass and to encourage a multiplicity of uses for bio-energy. The potential importance of the role of bio-energy in the UK 2050 energy system and its significant contribution to attaining the 2050 goal of 80% reduction in greenhouse gas emissions, cost effectively, has only recently been fully realised. The extent of bio-energy's role would be increased by improvements in end-use technologies and in methods of supplying biomass, by taking advantage of good new ideas and, especially, by the support given to the deployment of bio-energy through development of the bio-energy supply chain. In addition, the sustainability of the wider economy may be enhanced by developing better understanding of the options for optimising land use. All of these issues are considered in this Review, which has been undertaken by the ERP in order to identify the opportunities and address the challenges to further development of bio-energy technologies by 2050. The Review, undertaken between May 2010 and January 2011, has involved structured interviews with 70 key people involved in bio-energy, both in the UK and internationally, and makes recommendations about UK bio-energy in 3 areas:

1. UK support for bio-energy

Substantial benefits would flow from a co-ordinated bio-energy strategy involving all relevant government departments and executive agencies. This should be facilitated by the Department of Energy and Climate Change which should be recognised as the Department responsible for leading the development and implementation of the strategy. The strategy should set long-term targets, make explicit the roles of domestic and imported supplies of bio-energy, and develop plans for utilisation of resources both within and outside government, including winning support from all relevant stakeholders. This review has also found that the government departments responsible for bio-energy policy would benefit from having deeper understanding of the specifics of bio-energy technologies. It is proposed that government should improve its capability in and access to expertise in bio-energy in order to develop more robust plans for the long-term¹.

2. UK research on bio-energy technologies

A number of existing areas of scientific research will underpin the successful development and deployment of bio-energy technologies, especially plant science, applied agronomy and conversion technologies. Continued support for research in a number of such areas is recommended as well as exploration of the potential in several prospective new ones which could become important by 2050, including:

- Growth of algae for energy as part of a broader study of these plants
- Bio-energy with CO₂ capture and storage
- "Drop-in" bio-fuels that could be substituted for conventional liquid fuels
- Development of large scale bio-refineries.

Each of these should be subject to ongoing assessment to confirm they have the potential for large-scale application with substantial reduction in specific greenhouse gas emissions at competitive cost.

3. Deployment of bio-energy

There is need for better information on land use, and improved understanding of how to optimise the use of available land to produce food, fibre and energy in a sustainable and cost effective manner. It is also recommended that more work should be done with other countries through collaborative research programmes, which would allow the UK to benefit from advances elsewhere. The UK should also use its scientific and technical knowledge to assist other countries, including helping them understand their potential to supply part of the UK's bio-energy needs, including detailed assessment of the likely costs and sustainability. This would also assist bio-energy development globally. Development of improved methods of harvesting and transport suitable for use on marginal land, and of programmes of education for farmers about sustainable practices are also necessary. The

¹ The ERP is aware that an initiative has recently been started by the relevant Government departments to address this as a part of the DECC led cross-departmental Bio-energy Strategy refresh.



EU's policy on genetically modified organisms should be reconsidered as many plant scientists believe this is inhibiting work in areas of great opportunity. It is essential that UK policy addresses concerns about financial risk along the whole bio-energy chain; without this there may not be sufficient incentive for farmers to dedicate land for biomass supply, or for users to deploy innovations in bio-energy, or to implement more sustainable practices.

The initial findings of the Review have been fed into Government since October 2010 and therefore some of the recommendations are in hand.

Introduction

Bio-energy is the production of energy from recently living biological materials (which are referred to as biomass). Use of bio-energy can provide benefits in terms of reduction in greenhouse gas emissions and as a means of lessening society's dependence on fossil fuels.

Biomass for energy can be used to provide heat, power and fuel for transport. There are many types of biomass (including purpose grown crops, plant residues and waste materials, see Table S1) and many types of process that could be used to produce fuel from biomass (see Table S2). Growing biomass for energy can be an attractive crop for farmers but, in some cases, this would use land that might otherwise be used to grow food for humans or animals or provide material for other markets such as fibre. Biomass may be used to generate bio-energy either in the form that it is harvested (such as by combustion in a boiler) or after conversion into bio-fuels designed for particular applications, such as liquid fuels for cars or aeroplanes. These and other issues, explored below, make consideration of the supply and use of bio-energy much more complicated than is the case for conventional fuels - especially where the sustainable biomass resource is limited. As a result it is difficult to gain a clear picture of the best options for future development of bio-energy. However, in view of the important benefits that widespread use of bio-energy could deliver, it is important to consider whether the understanding, planning and development of bio-energy in the UK could be improved.

In recognition of this, the ERP has undertaken a review of bio-energy technologies, in order to describe the opportunities and identify the challenges to further development of bio-energy technologies by 2050. This review provides the basis for understanding the role that research and development could play in addressing the opportunities and overcoming the challenges. Successful development of bio-energy technologies would need to be followed by UK-focused demonstration as a key step before full-scale deployment could be expected.

A broad range of disciplines is involved in bio-energy; the supply chains are complex; many different players are already involved in researching and developing bio-energy applications. For these reasons, a global assessment of the state of development of the technology has been undertaken across all stages of the supply chain. This review has looked for key gaps in the UK capacity for bio-energy research, development and demonstration (RDD&D) as well as in deployment of bio-energy. It has also sought out the structural barriers that may reduce the effectiveness of UK policy in this area.

How has this review been undertaken?

This review has involved structured interviews with 70 key individuals concerned with the development and deployment of bio-energy, both in the UK and internationally. In addition, an international survey of bio-energy work has been carried out, as well as an assessment of UK capacity for bio-energy research and development. The project has been conducted by the ERP Analysis Team with input from ERP's Bio-energy Technologies Steering Group. Additional input was also sought from a number of outside organisations. The main report is available at www.energyresearchpartnership.org.uk

Introduction to bio-energy

Use of bio-energy reduces greenhouse gas emissions by utilising biomass to displace fossil fuels used in heating, power generation or transport. Because the growth of plants draws down carbon from the atmosphere, the eventual combustion of the biomass to produce energy releases more or less the same amount of carbon, making the process theoretically neutral in its effect on the concentration of carbon in the atmosphere. The production of biomass - planting, harvesting and conversion or the utilisation of waste - does have a carbon penalty, which for bio-energy to be beneficial, should be smaller than the fuel that it is substituting.



By using plants as feedstock to produce fuel, the UK would gain an alternative supply of energy that could reduce dependence on fossil fuels, much of which is and in the future will increasingly be imported. This is particularly important for sectors where there are few alternatives, such as road transport and, especially, aircraft. At the same time, growth of edible plants for fuel could divert them from food supply, something which is thought to have contributed to recent spikes in the prices of agricultural commodities. There are also concerns about the impact of widespread growth of single crops on biodiversity and also about the effects of intensified agriculture on water supplies. Coupled with these factors, there is also uncertainty about bio-energy's precise contribution to tackling climate change (not all forms of bio-energy are as beneficial as the best ones) and about the sustainability of some bio-energy approaches. These problems and uncertainties have, to some extent, inhibited the deployment of bio-energy.

What has been learnt about the potential for wider use of bio-energy in the UK?

It is confirmed by this review that bio-energy could make a significant contribution to the UK's 2050 energy system² in a cost effective manner³. It would also make an integral contribution to the goal of 80% reduction in greenhouse gas emissions by 2050 but the extent and focus of the contribution is subject to considerable uncertainty due to the range of options and the inherent competition for biomass supplies with other uses, the complexity of some bio-energy supply chains, and the very fragmented nature of innovation in bio-energy technologies. Development of a bio-energy supply chain would enable the UK to meet some of the country's anticipated demand for biomass from domestic sources; the rest would have to come from imported supplies. This underlines the importance of developing our own expertise and engagement and cooperation with other countries in order to ensure that supplies will be available in the future that meet the UK's needs.

In order that UK users have confidence in the reliability of supplies of biomass and bio-fuels, it is essential that an efficient domestic system is developed for production of these fuels, at a scale substantially greater than has so far happened. In order to improve the competitiveness of bio-energy in the UK, new science and technology can be brought to bear, as this has potential for increasing the supply and reducing the cost of bio-energy; UK has leading expertise in several important aspects of this science and technology. For example, amongst others, in the areas of fundamental plant science, micro and macro-algae, fermentation, pyrolysis, we also have industrial capacity for some thermo-chemical routes and bio-chemical routes.

Table S1: Some types of plants used to produce biomass for energy

Sugar cane
Sugar beet
Maize
Rape
Sunflower
Willow
Miscanthus
Poplar
Forestry

Table S2: Some methods of processing and converting biomass to bio-fuels

Biomass may be processed in a number of ways to produce intermediate products (that require further treatment), or final fuels, or both. These processes include:

Drying	Anaerobic digestion
Dedicated combustion	Fermentation
Co-firing	Hydrolysis
Gasification	Methanation
Pyrolysis	Esterification

Opportunities for improving the supply chain

At the start of the chain of supply and use, more systematic procedures are needed for optimising land use between the production of food, of materials and of bio-energy. In this way the expansion of UK capability for bio-

² Recent modelling undertaken by the UK Energy Research Centre MARKAL, the Energy Technologies Institute Energy System Model Environment (ESME) and the DECC 2050 Pathways Calculator suggest a contribution of over 10%.

³ The ETI ESME suggests that the non-deployment of bio-energy technologies has an annualised opportunity cost of the order of £10's of billions.

energy can take place without risk of serious impact on the national food supply. Bio-energy also provides a route to make productive use of waste materials from various sources, including municipal solid waste.

The type of plants and biomass to be grown will be influenced by the end-use of the bio-energy (e.g. whether in heating, power generation, or transport) which determines the degree of processing needed (examples are given in Table S2). Power generation can use biomass straight from the field with relatively little treatment; based on present technologies the most attractive approach is co-firing with fossil fuels although power plants fuelled purely with biomass are also being developed. The use of biomass in space heating, such as for domestic use, is likely to be best used in large installations due to the requirements for handling and storage of the fuel. However this means that the application will be constrained by the acceptability of local district heating schemes, which are not widely used in the UK, or in local combined heat and power systems (CHP) that may need more highly processed bio-fuels. The type of bio-fuel which has probably received the most publicity is that used in transport; for this purpose a liquid fuel is likely to be required, especially one that could be “dropped-in”, i.e. without needing modifications to the vehicle (some options are shown in Table S3). One country, Brazil, has made major changes in its vehicle fuelling system by nationwide supply of ethanol derived from sugarcane. The UK has a different climate and does not have the same availability of land so alternative approaches are being developed although the potential may be more limited than in Brazil. At the same time, several competing methods of fuelling light duty vehicles are also being developed (e.g. electric, compressed natural gas, hydrogen vehicles, etc.), some of which could also achieve the goal of reducing greenhouse gas emissions, so the future demand for bio-fuels is the subject of much debate. In contrast for aircraft and long haul road freight, which also use a substantial amount of hydrocarbon fuels worldwide, there are no alternatives currently in prospect for major reduction in greenhouse gas emissions which suggests the use of bio-fuels in aviation and road freight may take priority over light duty road transport. Relatively little consideration has been given to marine uses of bio-fuel, which also warrant attention. A means of prioritising the use of bio-fuel is needed, as is development of a consensus on how the results should be implemented.

Table S3: Examples of the range of bio-fuels considered for transport uses

Blended with conventional fuels and/or requiring vehicle modification	Substituted for existing fuels without vehicle modification
Ethanol (to legislated percentages)	Syndiesel
Bio-diesel (to legislated percentages)	Upgraded pyrolysis oil
DiMethylEther	Synthetic petrol
Butanol	
Methanol	
Bio-methane	
Hydrogen	

A number of obstacles to the wider use of bio-energy in the UK have been identified through this work including the following:

- In relation to production of biomass, there may be competition for use of land between production of food, fibre and biomass for energy - particularly for presently utilised biomass though less so for future dedicated bio-energy biomass which can be grown on non-arable land. Also, the optimum forms of biomass that should be grown in any particular location are not yet clear.
- As regards transport of biomass, the sheer volume of matter to be moved raises issues about which systems would be acceptable for large-scale transport; the advantages of the pre-treatment of the biomass to reduce bulk are not clear.
- International trading of bio-fuels is inhibited by lack of agreed standards.
- The economics of the stationary production of heat and power. In the case of the utilisation of biomass for stationary production of heat and / or power, some options are already relatively well developed so

this technology could be deployed on a wider scale once the economics justify investment in production and use of the fuel and a reliable supply is available to the end-user.

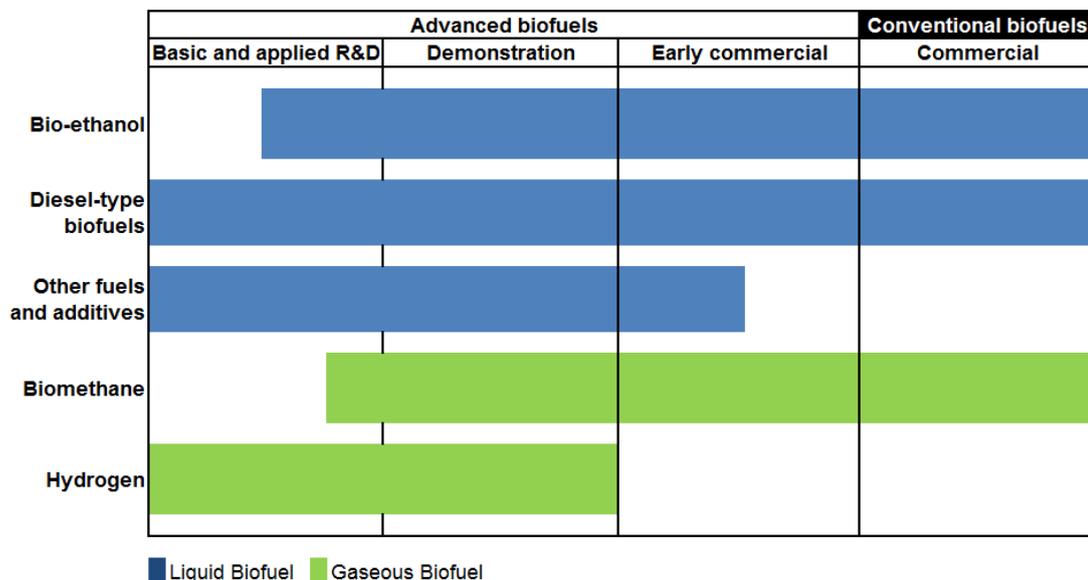
- The conversion of biomass into transport bio-fuels is the subject of significant debate. Issues include identifying and agreeing on which are the most important sectors to address, understanding the infrastructure requirements and whether the optimal fuel would be one that is blended into conventional fuels or whether it would be one that has to be handled and used separately from existing fuels. In addition there may be a need for vehicle makers to develop and deploy vehicle power-trains adapted for bio-fuels. There is also a lack of appreciation of the role of bio-fuels for marine uses. The state of development of the various transport bio-fuels varies considerably, as shown in the figure below.

In view of the great potential benefits of bio-energy, the range of challenges to deployment must be addressed. This can best be done by a clear and focussed national strategy that has broad stakeholder support.

The state of development of technologies for producing transport bio-fuels (adapted from Bauen et al⁴)

Commercial bio-fuels include: bio-ethanol which is produced from sugar and starch crops; bio-diesel which is produced by the transesterification of oily crops; and biomethane production from biogas generated by anaerobic digestion. It is noteworthy that these bio-fuels are only commercially viable due to regulation and policies.

Those technologies that are at the basic and applied R&D to early commercial are termed advanced bio-fuels.



What needs to be done?

There are key areas which would benefit from global RDD&D. These include aspects of the production, supply, conversion and use of bio-energy:

- Improved understanding of the factors which will influence demand for bio-energy; this would highlight the areas of greatest uncertainty so that account could be taken of them in scenario planning; this would also help to identify the least-cost actions that could have greatest effect in stimulating the use of bio-energy.
- Improve the understanding of how the production and costs of biomass development varies with location and conditions, so as to optimise the planning of supply. This needs to be done on relatively large-scale (>1ha) plots to generate representative data. Plant science should be deployed to enhance the production of current and dedicated energy crops and improve the economics and sustainability of this part of the process. In this vein, the EU's policy on genetically modified organisms should be reconsidered as many plant scientists believe this is inhibiting work in areas of great opportunity.

⁴ Bauen, A., Berndes, G., Junginger, M., Londo, M., and Vuille, F. **2009**, Bio-energy - a sustainable and reliable energy source. A review of status and prospects., IEA Bioenergy: ExCo: 2009:06.



- Related to the above, the sensitivity of the economic viability of bio-energy to transport costs makes the need for assessment of spatial issues, logistics and value chain impact vital to the optimising of the use of bio-energy in the energy system.
- A range of feedstocks should be examined for biomass production in the UK and worldwide; this should prioritise the optimisation and the development of new applications for conventional crops as well as investigation of the value of unconventional biomass such as from algae, and development of better ways of using waste streams, especially cellulosic residues.
- Current technology is being used to produce heat and power from biomass at present. Further improvements in this technology will be possible but the rate at which the end-user makes these changes is likely to be determined by the economics of the process and the reliability of biomass supply. Specific action on these aspects of the supply is needed to encourage the wider deployment of bio-energy. In addition there are various novel approaches which would benefit from further development in order to demonstrate their commercial potential (such as biomass combined heat and power systems and novel power generation technologies such as large-scale gasification).
- The many options for advanced transport bio-fuels each have their own advantages and disadvantages which suggests that the range of possibilities will only be reduced once these products are closer to the market. A better understanding of how the fuels will integrate into the fuel supply system should help to distinguish the features of each bio-fuel option in terms of blending with conventional fuels, handling, distribution and end-use, especially the compatibility with the existing and future vehicle fleet. “Drop-in” fuels may be developed as substitutes for existing fuels but there is a need for a suitable policy and accounting framework that recognises these types of fuels. There are many options for conversion of biomass into bio-fuels and many of the processes are proprietary which suggests that work is required by a cross-industry body to illuminate society’s understanding of the relative merits of the various options. Transport fuel is an internationally traded commodity so the UK should engage in international forums to ensure future fuel developments conform to international market needs and so that international transport fuel specifications reflect the opportunities for bio-fuels.
- Bio-energy supply systems are inherently more complex than the systems for supply and use of conventional fuels. Understanding the options is important but this must be done on the basis of the whole system; such analysis must take account of changes in land use consequent upon rising demand for bio-fuels, including the competition with growth of crops for food and other uses; the analysis must also take account of the balance of greenhouse gas emissions since the more processing that takes place, the smaller may be the reduction in CO₂ emissions; in addition it is very important to consider the sustainability of each bio-energy option and to be able to demonstrate that the claimed benefits can be achieved. One means of presenting such information is through the use of Life-Cycle Analysis (LCA); this needs to be done in a transparent, standardised and unbiased manner if the results are to be accepted by society at large; international cooperation on development of LCAs for bio-energy is essential.
- Several new opportunities have been identified in recent years which could have long-term potential for improving the prospects for bio-energy; because of their novelty they are mostly too risky for private sector activity, except perhaps as a watching brief. These opportunities include:
 - Large-scale bio-refineries, which would make a variety of energy and non-energy products from the biomass⁵
 - Bio-energy production with CO₂ capture and storage (BECCS) which offers the possibility of increasing the draw-down of carbon from the atmosphere (i.e. “negative emissions”)
 - Engineering of the waste from production of biomass as “biochar”, something which could be used to sequester carbon in the soil rather than releasing it to the atmosphere.
 - Recognising that the several technologies being addressed are at different stages of development there is a need for a flexible process for ongoing understanding and evaluation of options, in order that the best uses of biomass can be identified on a sound and rational basis.

Improvements in UK policy and plans for bio-energy

Although there is growing consensus about the important contribution that bio-energy could make towards achieving the UK’s renewable energy targets, the development of policy and planning for bio-energy is hindered

⁵ The ERP is aware that, as a part of the European Industrial Bio-energy initiative, the Centre for Process Innovation and the National Non Food Crop Centre is seeking to submit a proposal to develop a pilot large scale biorefinery in the UK.

by the complexity of the issues. Unlike conventional fuels, there are many potential sources of biomass, each with their own costs, logistics and regional features, which means that national planning cannot easily develop a detailed picture of the future supply of biomass; this problem is exacerbated by the many options available for processing and distribution of bio-fuels, especially in transport applications, so that decisions about the future of bio-energy in some sectors will have to be taken in circumstances of considerable uncertainty.

These problems are reflected in the difficulty that potential users have in deciding on future use of bio-energy since the availability of supplies and the cost of them will be very much subject to government policy. With such uncertainty, identifying and selecting the most appropriate targets for RDD&D is especially difficult, not least because of the number of bodies in government and in executive agencies with responsibility for some aspect of bio-energy policy or implementation (for example, see Table S4).

Table S4: Some of the UK public and public/private bodies involved with bio-energy

Government Departments

Department of Energy and Climate Change
 Department for Transport
 Department for Environment, Food and Rural Affairs
 Department for Business Innovation and Skills
 Department for International Development
 Foreign and Commonwealth Office
 HM Treasury

Executive Agencies and others

5 Research Councils
 Technology Strategy Board
 Carbon Trust
 Energy Technologies Institute
 Forestry Commission
 UK Energy Research Centre
 Environment Agency
 Devolved Administrations
 Regional Environment Agencies

It is recommended that the following would be appropriate actions for the UK Government to improve the capacity and reliability of bio-energy supply chains and end-uses in the UK:

- Provide a clear vision of the role that bio-energy is expected to play in the UK.
- Implement this vision by developing an up-to-date national policy and strategy for bio-energy.
- In recognition of the many government departments and executive agencies involved in bio-energy, identify and/or clarify the roles and responsibilities of those implementing each aspect of bio-energy policy.
- Gain industrial and institutional support for such a policy, which would be greatly aided if a framework could be developed that enhanced financial security along the supply chain.
- All of these steps are contingent upon government having sufficient understanding of the interaction and trade-offs between the different aspects of bio-energy. Developing such understanding would be facilitated by access to suitable expertise in all aspects; this could be achieved by increasing the level of specialist knowledge available to the appropriate government departments⁶.
- Because of the complexity of the issues and the multiplicity of players in bio-energy, it is more than usually important that there is clear leadership of policy development and implementation of bio-energy policy. It is suggested that this can be best achieved by giving one Department the leadership in bio-energy with commitment from related departments to implement the policies in their areas of accountability.

A number of areas of bio-energy technology have been identified that are prospective and which could become important by 2050; taking account of UK areas of expertise, these would be suitable for long-term, directed research funding:

- Improvement of bio-energy crops, through use of fundamental plant science and applied agronomy.
- Development of liquid fuels that could be used as direct substitutes for conventional fuels ("drop-in" fuels).
- Exploration of the potential of algae as a competitive source of bio-fuels, including a consideration as to whether other applications of algae could help establish algae production in the early stages.

⁶ The ERP is aware that an initiative has recently been started by the relevant Government departments to address this as a part of the DECC led cross-departmental Bio-energy Strategy refresh.

- Examination of the potential for Bio-energy with CO₂ Capture and Storage as a “negative emissions” technology.
- Identification of key gaps that could be overcome in order to strengthen the bio-refinery concept.

In these and other respects, there is need for co-ordination of research planning in government departments, in the Research Councils and with the private sector, so that key aspects are not missed and to avoid unnecessary duplication. The development of a unified, open source database of UK bio-energy capacity and of bio-energy projects would very much help this coordination. The Research Councils should be encouraged to build on the work of BBSRC Sustainable Bio-energy Centre (BSBEC) and SUPERGEN Bio-energy I and II and the emphasis given to the application and market-related aspects of proposals for directed-funding research. It is also suggested that the Research Councils should consider further encouragement for multi-disciplinary research in bio-energy, and that key elements of bio-energy research should be concentrated at particular establishments with significant funding for an extended period, such as 5 years (with strategic review half way through). If the UK were to collaborate with international leaders in bio-energy, such as Brazil, USA and certain European Countries - subject to the appropriate ‘fit’ - this would allow all parties to make best use of existing resources. If the UK expects to import a significant fraction of its bio-energy needs, collaboration with potential supply countries should also be encouraged to enhance the development of sustainable exports suited to UK needs.

Recommendations

This review makes recommendations about UK bio-energy in 3 areas:

- Management of the UK support for bio-energy
- Focus of UK research on bio-energy technologies
- Support for development and deployment of bio-energy

Management of the UK support for bio-energy.

This review has identified that substantial benefits would flow from a co-ordinated bio-energy strategy involving all government departments and executive agencies concerned with the subject. This should be facilitated by the Department of Energy and Climate Change which should be recognised as the department responsible for leading the development and implementation of the strategy. There is insufficient information available to develop a comprehensive 2050 strategy based on what we know now. For example, there is a need to better understand the impact of soil organic carbon and value chain issues to avoid locking bio-energy into parts of the energy system which may not be economic or sustainable in the long term. However, there is sufficient information to develop an informed strategy that can be improved with time. The strategy should set long-term targets, make explicit the roles of domestic and imported supplies of bio-energy, and develop plans for utilisation of resources both within and outside government including winning support from the relevant stakeholders. This review has found that there is a significant gap in the government departments responsible for bio-energy policy in that they are insufficiently staffed with people having the necessary understanding of the specifics of bio-energy technologies. This is all the more salient when consideration is made of the potential substantial contribution that bio-energy can make to the UK 2050 energy system and the economic benefits of doing so. It is proposed that government should improve its capability in and access to expertise in bio-energy in order to develop more robust plans for the long-term⁷.

Focus of UK research on bio-energy technologies.

It is strongly recommended that there should be continued support for research in a number of existing areas that will underpin the successful development and deployment of bio-energy, such as plant science, applied agronomy and conversion technologies, with exploratory work in a number of new areas including use of algae for energy, bio-energy with CO₂ capture and storage, investigation of the potential for liquid “drop-in” bio-fuels that could be substituted for conventional fuels, and investigation of the opportunities for development of large scale bio-refineries.

⁷ The ERP is aware that an initiative has recently been started by the relevant Government departments to address this as a part of the DECC led cross-departmental Bio-energy Strategy refresh.



Each of these should be subject to ongoing assessment to confirm they have the potential for large-scale application and substantial reduction in specific greenhouse gas emissions at competitive cost.

Support for development and deployment of bio-energy.

This review has identified the need for better global information on land use, and understanding of how to optimise the use of available land to produce food, fibre and energy in a sustainable and cost-effective manner. It is also recommended that more work should be done with other countries through collaborative research programmes, which would allow the UK to benefit from advances elsewhere. The UK should also use its scientific and technical knowledge to assist other countries, including helping them understand their potential to supply part of the UK's bio-energy needs, and detailed assessment of the likely costs and sustainability. Development of improved methods of harvesting and transport suitable for use on marginal land, and of programmes of education for farmers about sustainable practices are also necessary. It is essential that UK policy addresses concerns about financial risk along the whole bio-energy chain; without this there may not be sufficient incentive for producers to dedicate land for biomass supply, or to make use of innovations in bio-energy, or to implement more sustainable practices.

Glossary and Abbreviations

1 st generation biofuels	1 st generation bio-fuels include mature technologies for the production of bio-ethanol from sugar and starch crops, biodiesel and renewable diesel from oil crops and animal fats, and bio-methane from the anaerobic digestion of wet biomass.
2 nd generation biofuels	2 nd generation biofuels are novel biofuels or biofuels based on novel feedstocks. They generally use biochemical and thermochemical routes that are at the demonstration stage, and convert lignocellulosic biomass (i.e. fibrous biomass such as straw, wood, and grass) to biofuels (e.g ethanol, butanol, syndiesel).
3 rd generation biofuels	3 rd generation biofuels generally include advanced biofuels production routes which are at the early stage of research and development or are significantly further from commercialisation (e.g. biofuels from algae, hydrogen from biomass).
Agricultural residues	Agricultural residues include arable crop residues (such as straw, stem, stalk, leaves, husk, shell, peel, etc.), forest litter, grass and animal manures, slurries and bedding (e.g. poultry litter). Anaerobic digestion Decomposition of biological wastes by micro-organisms, usually under wet conditions, in the absence of air (oxygen), to produce biogas.
Agronomy	The study of crops and the soils in which they grow, which aims to develop methods that will improve the use of soil and increase the production of food and fibre crops. Research is conducted in crop rotation, irrigation and drainage, plant breeding, soil classification, soil fertility, weed control, and other areas
Animal residues	Agricultural by-products originating from livestock operations. It includes among others solid excreta of animals.
Ash	Residue obtained from the combustion of a fuel.
Bagasse	Fibre left over after the juice has been squeezed out of sugar-cane stalks. It is commonly used as a source of heat supply in the production of bioethanol.
Bark	The outermost sheath of tree trunks, branches, and roots of woody plants. It overlays the wood and consists of inner bark (living tissue) and outer bark (dead tissue). Bark is usually a by-product (residue) from conventional wood processing.
BBSRC	Biology and biological sciences research council
BIG/CC	Biomass integrated gasification and combined cycle.
Bio-butanol	Alcohol with a 4 carbon structure and the molecular formula C ₄ H ₉ OH produced from biomass. Biobutanol can easily be added to conventional petrol and can be blended up to higher concentrations than bioethanol for use in standard vehicle engines. Biobutanol can also be used as a blended additive to diesel fuel to reduce soot emissions.
Bio-diesel	Biodiesel refers to a diesel-type fuel produced by transesterification of vegetable oils or animal fats. Biodiesel can be blended (with some restrictions on the level of blending) with conventional diesel for use in unmodified diesel-engine vehicles. Its full name is FAME (Fatty Acid Methyl Ester) biodiesel.
Bio-economy	All economic activity derived from the application of our understanding of mechanisms and processes, at the genetic and molecular level, to any industrial process
Bio-energy	Renewable energy produced from the conversion of organic matter. Organic matter may either be used directly as a fuel or processed into liquids and gases.
Bio-ethanol	Alcohol with a 2 carbon structure and the molecular formula C ₂ H ₅ OH, produced from biomass. Bioethanol can be blended with conventional gasoline or diesel for use in petroleum-engine vehicles.
Bio-fuel	Fuel produced directly or indirectly from biomass. The term biofuel applies to any solid, liquid, or gaseous fuel produced from organic (once-living) matter. The word biofuel covers a wide range of products, some of which are commercially available today, and some of which are still in the research and development phase.
Biogas	A combustible gas derived from decomposing biological waste under anaerobic conditions. Biogas normally consists of 50-60% methane, 25-50% carbon dioxide, and other possible elements such as nitrogen, hydrogen or oxygen. See also Landfill Gas.
Biomass	Organic matter available on a renewable basis. Biomass includes forest and mill residues, agricultural crops and wastes, wood and wood wastes, animal wastes, livestock operation residues, aquatic plants, fast-growing trees and plants, and municipal and industrial wastes.
Biomass energy	See Bio-energy above.
Biomass feed system	Electromechanical system (e.g. conveyors, pumps) to feed the biomass feedstock into the boiler of a biomass-based plant.
Bio-methanol	Simplest possible alcohol with the molecular formula CH ₃ OH. Biomethanol can be blended into gasoline, but the substance is more volatile than bioethanol.
Bio-oil	A carbon-rich liquid produced by pyrolysis of plant material, which can be used to produce chemicals and fuels
Bio-reactor	A bioreactor is a vessel in which a biochemical process occurs.
Bio-refinery	Any facility that produces a variety of products, such as fuels, heat, power and chemicals, from bio-based materials
Biochar	Biochar is charcoal created by pyrolysis of biomass.
BIS	Department for Business Innovation and Skills
Bio-SNG	Bio Synthetic Natural Gas is syngas (produced from gasification of biomass) that has been

	upgraded to meet the quality standard of natural gas. Bio-SNG is often called simply SNG.
Black liquor	Black liquor is a by-product of the kraft process during the production of paper pulp. It is an aqueous solution of lignin residues, hemicelluloses, and the inorganic chemicals used in the process.
Briquette	Densified solid biofuel in the shape of cubiform or cylindrical units, produced by compressing biomass. The raw material for briquettes can be biomass of various origins (e.g. woody, herbaceous, fruit). Biofuel briquettes are usually manufactured in a piston press. The total moisture content of the biofuel briquette is usually less than 15 % of mass.
BTL	Biomass-to-liquid is a (multi-step) process to produce liquid biofuels from biomass. The first step is gasification, while the second step may, for example, be Fischer Tropsch.
By-product	Bulk density Mass of a portion of a solid fuel divided by the volume of the container which is filled by that portion under specific conditions. A by-product, or co-product, is a substance, other than the principal product, generated as a consequence of producing the main product. For example, a by-product of biodiesel production is glycerine. Every bio-energy conversion chain generates co-products. These may add substantial economic value to the overall process. Examples include animal feed, food additives, specialty chemicals, charcoal, and fertilisers.
Calorific Value (Q)	Amount of heat released during the complete combustion of a given amount of a combustible. Capacity The maximum power that a machine or system can produce or carry safely. The maximum instantaneous output of a resource under specified conditions. The capacity of energy generating equipment is generally expressed in kilowatts (for devices) or megawatts (for plants).
Capital cost	The total investment needed to complete a project and bring it to a commercially operable status. The cost of construction of a new plant. The expenditures for the purchase or acquisition of existing facilities.
Catalyst	A catalyst is a substance that increases the rate of a chemical reaction, without being consumed or produced by the reaction. Enzymes are catalysts for many biochemical reactions.
Cellulose	Polysaccharide (long chain of simple sugar molecules) with the formula $(C_6H_{10}O_5)_n$. Cellulose is the fibrous substance which is contained in leaves, stems, and stalks of plants and trees. It is the most abundant organic compound on earth and can be used to produce biofuels.
Cellulosic ethanol	Cellulosic ethanol is ethanol fuel produced from lignocellulosic material such as wood. Cellulosic ethanol is chemically identical to ethanol from other sources, such as corn or sugar, and is available in a great diversity of biomass including waste from urban, agricultural, and forestry sources.
Char	The remains of solid biomass that has been incompletely combusted, such as charcoal resulting from wood that is incompletely burned.
Charcoal	Solid residue derived from carbonisation distillation, pyrolysis, and torrefaction of fuelwood.
Chips	Woody material cut into short, thin wafers. Chips are used as a raw material for pulping and fibreboard or as biomass fuel.
Circulating fluidised bed (CFB)	A type of furnace in which the emission of sulphur compounds is lowered by the addition of crushed limestone in the fluidised bed thus obviating the need for much of the expensive stack gas clean-up equipment. The particles are collected and recirculated, after passing through a conventional bed, and cooled by boiler internals.
Combined Heat and Power (CHP)	See cogeneration below.
CO ₂	Carbon dioxide.
Cogeneration	The simultaneous production of electricity and useful thermal energy from a common fuel source. Surplus heat from an electric generating plant can be used for industrial processes, or space and water heating purposes (topping cycle).
Combined cycle	Two or more energy generation processes in series or in parallel, configured to optimise the energy output of the system.
Combined Cycle Power Plant	The combination of a Brayton-Joule Cycle (gas turbine) and a Rankine Cycle (steam turbine) in an electric generation plant. The waste heat from the gas turbine provides the heat energy required for the steam cycle. This is also called combined cycle gas turbine.
Combustion (of biomass)	The transformation of biomass fuel into heat, chemicals, and gases through chemical combination of hydrogen and carbon in the fuel with oxygen.
Compressed Natural Gas (CNG)	CNG is made by compressing natural gas to less than 1% of its volume at standard atmospheric pressure. It is used in traditional gasoline internal combustion engine cars that have been converted into bi-fuel vehicles (gasoline/CNG).
Co-product	See By-product.
CT	The Carbon Trust
DECC	Department for Energy and Climate Change
Density	Ratio of mass to volume. It must always be stated whether the density refers to the density of individual particles or to the bulk density of the material and whether the mass of water in

	the material is included.
Defra	Department for Environment, Food and Rural Affairs
DfID	Department for International Development
DfT	Department for Transport
Dimethyl ether (DME)	Liquid biofuel with the molecular formula CH_3OCH_3 . DME is produced by the dehydration of methanol and can be used as a fuel in diesel engines, petrol engines, and gas turbines. It works particularly well in diesel engines due to its high cetane number.
District heating	District heating is a system for distributing heat generated in a centralised location for residential and commercial heating requirements, such as space and water heating. Digester An airtight vessel or enclosure in which bacteria decompose biomass in wet conditions to produce biogas.
Discount rate	A rate used to convert future costs or benefits to their present value.
Dry basis	Condition in which the solid biofuel is free from moisture.
Dry matter	Material after removal of moisture under specific conditions.
Dry matter content	Fraction of dry matter in the total material on mass basis.
E85	Mix of 85% ethanol and 15% petrol. E85 is a common bioethanol blend used in flex-fuel vehicles. Other blends exist such as E5 and E100. The number always refers to the percentage of ethanol blended in the petrol.
EC	European Commission
Effluent	The liquid or gas discharged from a process or chemical reactor, usually containing residues from that process.
EJ	Exajoules ($1\text{EJ} = 10^{18}\text{J}$). See also Joule.
Emissions	Waste substances released into the air or water. See also Effluent.
Energy crops	Crops grown specifically for their fuel value. These include food crops such as corn and sugar-cane, and non-food crops such as poplar trees and switchgrass.
Energy density	Ratio of net energy content and bulk volume.
Engine	A device that converts the energy of a fuel into mechanical power. The combination of an engine and an alternator converts heat from combustion (e.g. of biomass) into power.
Enzyme	A protein or protein-based molecule that speeds up chemical reactions occurring in living things. Enzymes act as catalysts for a single reaction, converting a specific set of reactants into specific products.
ETI	Energy Technologies Institute
Ethyl-tertio-butyl-ether (ETBE)	Organic compound with the formula $\text{C}_6\text{H}_{14}\text{O}$. ETBE is commonly used as an oxygenate gasoline additive in the production of gasoline from crude oil.
EU	European Union.
Externality	A cost or benefit not accounted for in the price of goods or services. Often 'externality' refers to the cost of pollution and other environmental impacts.
FAME	Biodiesel Fatty Acid Methyl Ester Biodiesel. See Biodiesel.
Feed System	See Biomass Feed System.
Feed-in tariff	Subsidy mechanism by which the regional or national electricity companies are obligated to buy the electricity generated from renewable resources by decentralised producers at fixed prices (the feed-in tariffs) set by the government, The higher price helps overcome the cost disadvantages of renewable energy sources.
Feedstock	A feedstock is any biomass resource destined for conversion to energy or biofuel. For example, corn is a feedstock for ethanol production, soybean oil may be a feedstock for biodiesel and cellulosic biomass has the potential to be a significant feedstock source for biofuels.
Fermentation	Conversion of carbon-containing compounds by micro-organisms for production of fuels and chemicals such as alcohols, acids or energy-rich gases. It is a biochemical reaction that breaks down complex organic molecules (such as carbohydrates) into simpler materials (such as ethanol, carbon dioxide, and water). Bacteria or yeasts can ferment sugars to bioethanol
Firewood	Cut and split oven-ready fuelwood used in household wood burning appliances such as stoves, fireplaces and central heating systems. Firewood usually has a uniform length, typically in the range 150 mm to 500 mm.
Fischer Tropsch (FT) Process	Catalysed chemical reaction in which syngas from gasification is converted into a liquid biofuel of various kinds.
Flex-fuel vehicle (FFV)	Vehicles that can use either biofuels and/or petroleum interchangeably.
Fluidised-bed combustion (FBC)	Fluidised-bed combustion is a technology that improves the chemical reactions and heat transfer of boilers in power plants, and hence its overall efficiency, as compared to traditional fixed-beds. FBC plants are more flexible than conventional plants because they can be fired on coal and biomass, among other fuels. FBC also reduces the amount of sulphur emitted in the form of SO_x emissions.
Fly ash	Small ash particles carried in suspension in combustion products.
Forest residues	Material not harvested or removed from logging sites in commercial hardwood and softwood

	stands as well as material resulting from forest management operations such as pre-commercial thinning and removal of dead and dying trees.
Fossil fuel	Solid, liquid, or gaseous fuels formed in the ground after millions of years by chemical and physical changes in plant and animal residues under high temperature and pressure. Oil, natural gas, and coal are fossil fuels.
Fuel cell	A device that converts the energy of a fuel directly to electricity and heat, without combustion. Fuel gas See Producer Gas.
Fuel handling system	A system for unloading biomass feedstock from vans or trucks, transporting the feedstock to a storage location (e.g., pile, silo), and conveying it from storage to the boiler or other energy conversion equipment.
Fuelwood	Wood fuel where the original composition of the wood is preserved.
Furnace	An enclosed chamber or container used to burn biomass in a controlled manner to produce heat for space or process heating.
Gas turbine	A turbine that converts the energy of hot compressed gases (produced by burning fuel in compressed air) into mechanical power. Often fired by natural gas or fuel oil.
Gasification	A thermochemical process at elevated temperature and reducing conditions to convert a solid fuel to a gaseous form (CO, H ₂ , CH ₄ , etc.), with char, water, and condensibles as minor products.
Gasifier	A device for converting solid fuel into gaseous fuel.
Gha	Gigahectares (1Gha = 10 ⁹ ha).
GHG Greenhouse gas.	Gases that trap the heat of the sun in the Earth's atmosphere, producing the greenhouse effect. The two major greenhouse gases are water vapour and carbon dioxide. Other greenhouse gases include methane, ozone, chlorofluorocarbons, and nitrous oxide.
GJ	Gigajoule (1GJ = 10 ⁹ J).
GJ _e	Gigajoule electrical.
GJ _{th}	Gigajoule thermal.
GM	Genetic Modification
GMO	Genetically Modified Organism.
Green diesel	See Syndiesel.
Greenhouse effect	The effect of certain gases in the Earth's atmosphere in trapping heat from the sun.
Grid	An electric utility company's system for distributing power.
GW	Gigawatt. A measure of electrical power equal to one billion watts (1,000,000 kW). A large coal or nuclear power station typically has a capacity of about 1 GW.
Heating value	Amount of heat released during the complete combustion of a given amount of a combustible. See Higher Heating Value and Lower Heating Value for more details.
Hectare (Ha)	Common metric unit of area, equal to 2.47 acres. 1 hectare equals 10,000 square meters. 100 hectares = 1 square kilometre. Abbreviated as ha.
Herbaceous biomass	Biomass from plants that has a non-woody stem and which dies back at the end of the growing season.
Higher heating value (HHV)	Amount of heat released during the complete combustion of a given amount of a combustible (initially at 25°C) and the cooling of the combustion products back to 25°C. Thus, the HHV includes the latent heat of vaporisation of the water contained in the combustion products.
Hydrocarbon	Any chemical compound containing hydrogen, oxygen, and carbon.
Hydrogen	Simplest molecule conceivable, with a molecular formula of H ₂ . Gaseous fuel that can be produced from fossil fuels, biomass and electricity.
Hydrogenation	Process which typically constitutes the addition of pairs of hydrogen atoms to a molecule. Biodiesel manufactured from the hydrogenation of vegetable oil and animal fat can be blended in any proportion with petroleum-based diesel.
Hydrolysis	Hydrolysis is a chemical reaction that releases sugars, which are normally linked together in complex chains. In bioethanol production, hydrolysis reactions are used to break down the cellulose and hemicellulose in the biomass.
Hydroprocessing	This is a high temperature and pressure catalytic chemical reaction, where a molecule of hydrogen is added over a carbon-carbon single bond, causing the bond to break. It can be used to produce synthetic biofuels/diesel
Hydrotreated Biodiesel	See Renewable Diesel.
IEA	International Energy Agency.
Incinerator	Any device used to burn solid or liquid residues or wastes as a method of disposal. In some incinerators, provisions are made for recovering the heat produced.
Indirect Land Use Change (iLUC)	Indirect Land Use Change is that which occurs outside the production boundary of a feedstock, but which is caused by a change in the level of output of that feedstock.
Indirect liquefaction	Conversion of biomass to a liquid fuel through a synthesis gas intermediate step.
IPCC	Intergovernmental Panel on Climate Change.
Jatropha	Jatropha curcas is a non-edible evergreen shrub found in Asia, Africa and the West Indies.

	Its seeds contain a high proportion of oil which can be used for making biodiesel.
Joule	Metric unit of energy, equivalent to the work done by a force of one Newton applied over a distance of one metre ($= 1 \text{ kg.m}^2/\text{s}^2$). One joule (J) = 0.239 calories (1 calorie = 4.187 J).
kW	Kilowatt. A measure of electrical power equal to 1,000 watts. 1 kW = 3.413 Btu/hr = 1.341 horsepower. See also Watt.
kWh	Kilowatt hour. A measure of energy equivalent to the expenditure of one kilowatt for one hour. For example, 1 kWh will light a 100-watt light bulb for 10 hours. 1 kWh = 3.413 Btu.
kW _e	Kilowatt electrical. See also kW.
kW _{th}	Kilowatt thermal. See also kW.
Landfill gas	Biogas generated by decomposition of organic material at landfill disposal sites. Landfill gas is approximately 50% methane. See also Biogas.
Lifecycle Assessment (LCA)	Investigation and valuation of the environmental impacts of a given product or service caused or necessitated by its existence. The term 'lifecycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product's existence.
Lower Heating Value (LHV)	Amount of heat released during the complete combustion of a given amount of a combustible (initially at 25°C) and the cooling of the combustion products down to 150°C. Thus, the LHV excludes the latent heat of vaporisation of the water contained in the combustion products.
Lignin	Structural constituent of wood and (to a lesser extent) other plant tissues, which encrusts the cell walls and cements the cells together.
Litres	Metric unit of volume, where one litre (l) = 1000 cm ³
LNG	Liquefied natural gas.
Log wood	Cut fuelwood, with most of the material having a length of 500 mm and more.
LPG	Liquefied Petroleum Gas.
Land Use Change (LUC)	Land Use Change is that which occurs inside the production boundary of a feedstock, and which is caused by a change in the level of output of that feedstock.
Methane	Methane is a combustible chemical compound with the molecular formula CH ₄ . It is the principal component of natural gas.
MOGD	Methanol to olefins, gasoline and diesel, a catalysed conversion process that uses methanol to produce petrol or diesel
Miscanthus	Miscanthus or elephant grass, is a genus of about 15 species of perennial grasses native to subtropical and tropical regions of Africa and southern Asia. The rapid growth, low mineral content and high biomass yield of Miscanthus makes it a favoured choice as a bioethanol feedstock.
MJ	Megajoule (1MJ = 10 ⁶ J). See also Joule.
Moisture content	The quantity of water contained in a material (e.g. wood) on a volumetric or mass basis.
Monoculture	The cultivation of a single species crop.
MSW	Municipal Solid Waste
MTBE	Methyl tert-butyl ether. MTBE is used as an oxygenate additive to raise the octane number of gasoline.
MW	Megawatt. A measure of electrical power equal to one million watts (1,000 kW). See also Watt.
MW _e	Megawatt electrical.
MW _{th}	Megawatt thermal.
N ₂	Nitrogen.
N ₂ O	Nitrous oxide or laughing gas. Powerful greenhouse gas that can be emitted from soils with intensive (nitrogen) fertilisation.
NERC	Natural Environment Research Council
NGO	Non-governmental organisation
Nitrogen Oxides (NO _x)	Nitrogen oxides are a product of photochemical reactions of nitric oxide in ambient air, and are one type of emission produced from fuel combustion.
O ₂	Oxygen.
Octane number	Measure of the resistance of gasoline and other fuels to detonation (engine knocking) in spark ignition internal combustion engines. The octane rating of a fuel is indicated on the pump. The higher the number, the slower the fuel burns. Bioethanol typically adds two to three octane numbers when blended with ordinary petroleum, making it a cost-effective octane-enhancer.
Organic compounds	Chemical compounds based on carbon chains or rings and also containing hydrogen, with or without oxygen, nitrogen, and other elements.
Organic matter	Matter that comes from a once-living organism.
Organic Rankine Cycle (ORC)	A Rankine Cycle is a closed circuit steam cycle to convert heat into mechanical energy in an engine. An organic Rankine Cycle uses an organic fluid with a high molecular mass instead of steam, allowing heat recovery from low temperature sources such as industrial waste heat, geothermal heat, solar ponds, etc.

Particulate	A small, discrete mass of solid or liquid matter that remains individually dispersed in gas or liquid emissions. Particulates take the form of aerosol, dust, fume, mist, smoke, or spray. Each of these forms has different properties.
Pellet	Densified biofuel made from pulverised biomass with or without pressing aids usually with a cylindrical form, random length typically 5 to 30 mm, and broken ends. The raw material for biofuel pellets can be woody biomass, herbaceous biomass, fruit biomass, or biomass blends and mixtures. They are usually manufactured using a die. The total moisture content of biofuel pellets is usually less than 10% of mass.
Photosynthesis	Process by which chlorophyll-containing cells in green plants convert incident light to chemical energy, capturing carbon dioxide in the form of carbohydrates.
Pilot scale	The size of a system between the small laboratory model size (bench scale) and a full-size system.
Process heat	Heat used in an industrial process rather than for space heating or other housekeeping purposes.
Producer gas	The mixture of gases produced by the gasification of organic material such as biomass at relatively low temperatures (700-1000°C). Producer gas is composed of carbon monoxide (CO), hydrogen (H), carbon dioxide (CO ₂), Nitrogen (N ₂) and typically a range of hydrocarbons such as methane (CH ₄). Producer gas can be burned as a fuel gas in a boiler for heat or in an internal combustion gas engine for electricity generation or combined heat and power (CHP). It can also be upgraded to Syngas for the production of biofuels.
Pyrolysis	The thermal decomposition of biomass at high temperatures (greater than 400°F, or 200°C) in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, carbon monoxide and carbon dioxide) with proportions determined by operating temperature, pressure, oxygen content, and other conditions.
Renewable diesel	Hydrotreated biodiesel produced by the hydrogenation of vegetable oils or animal fats. Its fuel characteristics are similar to fossil diesel.
Reforming	Chemical process used in the petrochemical industry to improve the octane rating of hydrocarbons, but is also a useful source of other chemical compounds such as aromatic compounds and hydrogen. Steam reforming of natural gas or syngas sometimes referred to as steam methane reforming (SMR) is the most common method of producing commercial bulk hydrogen. At high temperatures (700 – 1100°C) and in the presence of a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide and hydrogen. $CH_4 + H_2O \rightarrow CO + 3 H_2$ Additional hydrogen can be recovered by a lower-temperature gas-shift reaction with the carbon monoxide produced. $CO + H_2O \rightarrow CO_2 + H_2$.
Refuse-derived fuel (RDF)	Fuel prepared from municipal solid waste. Non-combustible materials such as rocks, glass, and metals are removed, and the remaining combustible portion of the solid waste is chopped or shredded. RDF facilities process typically between 100 and 3,000 tonnes of MSW per day.
RDD&D	Research, development demonstration and deployment
Residues	By-product of agricultural cultivation (e.g. bagasse), farming activities (e.g. manure) or forestry industry (tree thinnings).
RME	Rape methyl ester. Esterified rape-oil commonly used as biodiesel.
RTFO	Renewable transport fuels obligation
Sawdust	Fine particles created when sawing wood.
Short rotation crop	Woody biomass grown as a raw material and/or for its fuel value in short rotation forestry.
Sludge	Sludge is formed in the aeration basin during biological waste water treatment or biological treatment process and separated by sedimentation. Sludges can be converted into biogas via anaerobic digestion.
SNG Synthetic natural gas.	Gas mixture that contains varying amounts of carbon monoxide and hydrogen generated by the gasification of a carbon-containing fuel to a gaseous product with a heating value.
Solid biofuel	Solid fuels (e.g. pellets, wood charcoal) produced directly or indirectly from biomass. Steam turbine A device for converting energy of high-pressure steam (produced in a boiler) into mechanical power which can then be used to generate electricity.
Stirling engine	Closed-cycle regenerative heat engine with a gaseous working fluid. The working fluid, the gas which pushes on the piston, is permanently contained within the engine's system.
Sustainability	The balancing of environmental, social and economic factors in order to meet the need of present generations without compromising the need of the future
Switchgrass	Perennial energy crop. Switchgrass is native to the USA and known for its hardiness and rapid growth. It is often cited as a potentially abundant 2 nd generation feedstock for ethanol.
Syndiesel	Synthetic diesel produced through Fischer Tropsch synthesis from lignocellulosic biomass (e.g., wood). Its fuel characteristics are similar to fossil diesel.
Syngas	Syngas (from the contraction of synthesis gas) is a mixture of mainly carbon monoxide (CO) and hydrogen (H ₂), which is the product of high temperature steam or oxygen gasification of organic material such as biomass. Following clean-up to remove any impurities such as



	tars, syngas can be used to produce organic molecules such as synthetic natural gas (mainly CH ₄) or liquid biofuels such as synthetic diesel (via Fischer Tropsch synthesis).
Synthesis gas	See Syngas.
Synthetic Diesel	See Syndiesel.
Torrefaction	Mild pre-treatment of biomass at a temperature between 200-300°C. During torrefaction of the biomass, its properties are changed to obtain a better fuel quality for combustion and gasification applications.
Transesterification	Process of exchanging the alkoxy group of an ester compound with another alcohol. Biodiesel is typically manufactured from vegetable oils or animal fats by catalytically reacting these with methanol or ethanol via transesterification.
Tri-generation	Tri-generation is the simultaneous production of mechanical power (often converted to electricity), heat and cooling from a single heat source such as fuel.
TSB	Technology Strategy Board
Turbine	A machine for converting the heat energy in steam or high temperature gas into mechanical energy. In a turbine, a high velocity flow of steam or gas passes through successive rows of radial blades fastened to a central shaft.
UKERC	UK Energy Research Centre
VOC	Volatile organic compounds are air pollutants found, for example, in engine exhaust.
Watt	The common base unit of power in the metric system. One watt equals one joule per second, or the power developed in a circuit by a current of one ampere flowing through a potential difference of one volt. 1 Watt = 3.413 Btu/hr. See also Kilowatt.
Wood chips	Chipped woody biomass in the form of pieces with a defined particle size produced by mechanical treatment with sharp tools such as knives. Wood chips have a sub-rectangular shape with a typical length 5-50 mm and a low thickness compared to other dimensions.
Wood fuel	All types of biofuels derived directly or indirectly from trees and shrubs grown on forest and non-forest lands, from silvicultural activities (thinning, pruning, etc.), and from industrial activities (harvesting, logging or primary and secondary forest industries).
Woody biomass	Biomass from trees, bushes and shrubs.
Yeast	Yeast is any of various single-cell fungi capable of fermenting carbohydrates. Bioethanol is produced by fermenting sugars with yeast.

Definitions from IEA (2009a) and The Royal Society (2008).



1 Introduction

1.1 Background

There is substantial potential for the UK to develop a reliable, sustainable and economic supply of biomass and to encourage a multiplicity of uses for bio-energy. The potential importance of the role of bio-energy in the UK 2050 energy system and its significant contribution to attaining the 2050 goal of 80% reduction in greenhouse gas (GHG) emissions, cost effectively, has only recently been fully realised. The extent of bio-energy's role could be increased by improvements in end-use technologies and in methods of supplying biomass, by taking advantage of good new ideas and, especially, by the support given to the deployment of bio-energy through development of the bio-energy supply chain. In addition, the sustainability of the wider economy may be enhanced by developing better understanding of the options for optimising land use. These issues are considered in this Review, which has been undertaken by the ERP in order to identify the opportunities and address the challenges to further development of bio-energy technologies by 2050. The Review has involved structured interviews with 70 key people involved in bio-energy, both in the UK and internationally, and makes recommendations about UK bio-energy in a number of areas.

Bio-energy was initially seen as a triple win of reconciling the GHG mitigation agenda by virtue of its low carbon credentials, the energy security agenda by reducing energy systems dependence on imported petroleum and international development opportunities by stimulating stagnant agricultural commodity prices. Consequently, bio-energy was whole heartedly embraced by policy makers across the world in the mid 2000's. However, a number of key issues have curbed this enthusiasm. Firstly, the 2007/08 food price spike which was attributed by some to bio-energy mandates and policies; secondly the publication of the Searchinger et al (2008) and Fargione et al (2008) papers which questioned the impact of Indirect Land Use Change (iLUC) on bio-fuels GHG balances; and finally the broadening of further sustainability contraventions by biomass for bio-energy production to water, biodiversity and social issues. However, food prices recovered to more sustainable levels in 2009 despite the continued increase in the use of bio-energy and the causes of such fluctuations attributed to a broader suite of factors; iLUC was shown to be an issue of substantial complexity which was overly simplified in initial claims of the impact of the iLUC on GHG balances, poorly captured in existing modelling frameworks and the impact of iLUC from bio-fuels is also seen to be a fraction of that caused by LUC for food production; and the understanding of the fact that biomass can be produced in a sustainable or an unsustainable manner. Furthermore, there is the realisation that there is a deficiency of comprehensive datasets, lack of agreement on measurement methodology and highly contextual nature of the impacts of many sustainability issues has made the accusations aimed at bio-energy unbalanced and flawed. Nonetheless, the focus of advocacy groups on bio-energy issues and the continued asymmetry of coverage of the debate has polarised experts, confused the general public and has made policy makers, particularly those where NGO's have been most effective, extremely nervous when addressing bio-energy policy.

Bio-energy policy development is further complicated by the fact that the role and extent that bio-energy will play in the UK and international low carbon energy system is highly uncertain. This may attributed to the following issues:

- the complexity and international extent of bio-energy supply chains makes the assessment of sustainable biomass potential difficult;
- the intricate nature of bio-energy pathways and the adaptability of bio-energy to produce a wide variety of energy carriers / intermediaries for heat, power and transport; and
- the highly fragmented nature of bio-energy innovation and uncertain rate of technological development in terms of greenhouse gas profile, resource use, energy conversion efficiency and the economics of bio-energy systems makes them extremely difficult to integrate into whole systems, cost optimisation scenario modelling.

The aggregated impact of these factors is that a comprehensive understanding of the entire bio-energy sector, along and across value chains, is problematic. This results in information asymmetries which in turn makes it extremely difficult to design effective policy which will facilitate sustainable biomass production at scale and economically efficient bio-energy technological development for optimum penetration into the future energy system.



This Review of bio-energy has sought to assess these issues across the bio-energy value chain with a view to making recommendations relevant to the development of bio-energy in the UK and global 2050 low carbon energy system.

1.2 Review Aim, Objectives and Scope

1.2.1 Review aim and objectives

The ERP bio-energy technologies review ***describes the opportunities and challenges to further development of bio-energy technologies in the 2050 energy system in order to identify the role that UK Research, Development, Demonstration and Deployment (RDD&D) should play in the sector.***

This was translated into the following objectives / outputs:

- Identify bio-energy's role and extent of penetration within the UK and International energy system in 2050 and assess the uncertainties and assumptions upon which these projections are based.
- Assess global and UK biomass potential projections and identify areas of uncertainty within these projections. Identify key areas of feedstock research, implications on future feedstock production / use and their state of development.
- Review the technologies that are in development along the bio-energy value chain with a view to identifying key technical challenges including the potential roles and benefits of novel technologies;
- Review international bio-energy RDD&D activity.
- Map UK RDD&D bio-energy capacity with a view to recommending areas where domestic capacity should be strengthened, areas which should be avoided and where opportunities exist for international collaboration.
- Review the UK bio-energy policy development framework and innovation landscape with a view to making recommendations as to how it could be improved.
- And, make recommendations for the development of a UK strategic bio-energy action plan to 2050.

Within these objectives were highlighted the following:

- No-regrets options and potential decision points as to where lock-in into an undesirable future may take place.
- And, areas that bio-energy may be used as efficiently as possible in the applications where alternative decarbonisation options may be unavailable or very expensive.

The Review is literature based which has been augmented by interviews with a number of specialists on aspects of bio-energy development. To this end, it is a snap-shot of the state that the bio-energy agenda as per the state of the recent literature. Within this born in mind - the following is relevant:

- The literature database tends to represent developments in the previous 18 months and so the review represents the state of development to early 2010. There are advances that are being made in some areas such as BECCS, biochar, torrefaction, proprietary process conversion processes *etc.* which are not in the public domain and so the material accessible to this review may not represent perspectives of the actual state of those technologies to early 2010.
- And, the rate at which technologies and perspectives within the bio-energy agenda are developing will mean that some aspects in this review, particularly those related to technology development, will have changed.

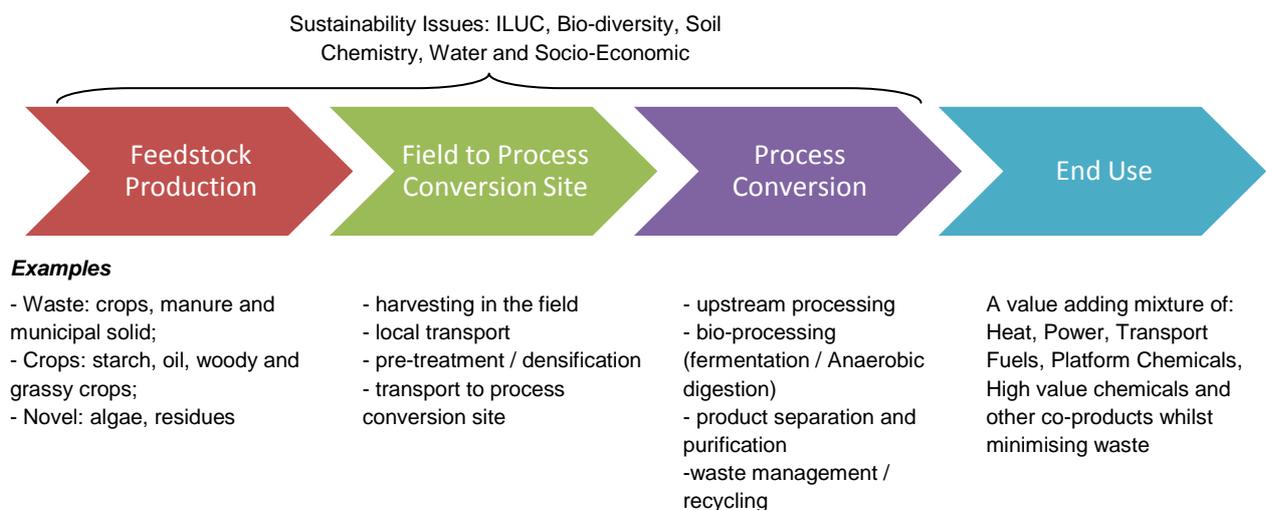
Though it was intended that the interviewees would assist in updating the literature based material, this could not be consistently carried out for all aspects of the review. Therefore, the report seeks to highlight the present state of the literature base and thinking in the period June 2010 to March 2011 as well as sign-post where further material may be found should researchers wish to gain more recent perspectives.

Finally, it is worth emphasising that the volume of material dedicated to each aspect of bio-energy does not in any way infer prioritisation of that particular dimension of bio-energy in the energy mix rather it represents the extent of technological development activity taking place in that area.

1.2.2 Review scope, breakdown of bio-energy value chain and definitions

Due to the broad range of disciplines and complexity of bio-energy supply chains the review has sought to undertake a high level global assessment of the state of technological development across feedstock production, logistics (from field to process conversion site), process conversion and end use in order that a comprehensive set of recommendations may be made - as per figure 1.1. It also describes capacity gaps in areas of bio-energy RDD&D from a UK perspective and the structural barriers that are inhibiting the effective development of a coherent UK bio-energy policy and technological development within the UK innovation chain.

Figure 1.1: Proposed break-down of the bio-energy value chain for the ERP Bio-energy Technologies Review.



Definitions

The following definitions were used for the review:

Biomass material of biological origin excluding material embedded in geological formations and transformed to fossil⁸:

- Typically including all organic matter that derives from photosynthetic conversion of solar energy
- but excluding peat resources.

Bio-energy encompasses electricity, heat or transport fuels derived from renewable (non fossil) biological sources⁹:

- typically the combustion of fresh or processed (solid, liquefied or gasified) biomass
- or, potentially, electricity generation through redox reactions in microbial fuel cells

Bio-energy research addresses⁴:

- the production and processing of biomass derived from agriculture or arboriculture, human/animal and plant waste,
- microbial biomass and microbial processing of biomass
- assessment of the sustainability impacts of the various bio-energy chains - social, environmental and economic

In this review bio-energy refers to all forms of biomass to energy and bio-fuels relate specifically to the liquid medium which tends to be used for transport.

⁸ FAO 2004 Unified Bio-energy Terminology

⁹ Review of Bio-energy Research (2006) - A Report for BBSRC Strategy Board



1.3 Review Process and Methodology

This review has involved structured and informal interviews with 70 key individuals concerned with the development and deployment of bio-energy, both in the UK and internationally (see Appendix 1 for the names of the individuals and organisations involved). In addition, an international survey of bio-energy work has been carried out, as well as an assessment of UK capacity for bio-energy research and development. The project has been conducted by the ERP Analysis Team with input from ERP's Bio-energy Technologies Steering Group. Additional input was also sought from a number of outside organisations.

The Bio-energy Technologies steering group was chaired by Dr Graeme Sweeney (Executive Vice President CO₂, Shell International). The remainder of the steering group was made up of:

Dr Rebecca Heaton	Shell Research Ltd
Dr Robert Sorrell	BP
Dr Robert Trezona	The Carbon Trust
David Pickering	National Grid
Charles Carey	Scottish and Southern Energy
Dr Susan Weatherstone	E.ON
Duncan Eggar	BBSRC

Contributions were also made by Professor Robert Lee (Shell Research Ltd) and Steven Vallender (National Grid) during the early stages of the review. The steering group sought to ensure that the material in the Review represented the most recent thinking in the UK bio-energy agenda in line with that stated in section 1.2.1; any errors are the fault of the author.

The initial findings of the Review have been fed into Government since October 2010 and therefore some of the recommendations are in hand.

1.4 Structure of the Review

Two documents have been produced for the ERP Bio-energy Technologies Review. The Executive Summary and Recommendations report, produced in late June 2011, is a high level set of statements targeted at policy makers, private sector executives and senior bio-energy stakeholders. This main report is a catalogue of evidence that validates the key findings made in the Executive Summary and Recommendations report and is targeted at technically orientated staff. A box at the start of sections 4 to 6 lists the evidence in respective sections which supports the recommendations made in the high level summary report.

The detailed review is structured in the following way:

Section 2: Frames the key issues of bio-energy sector in the context of how it relates to other components of the future energy system including the nature of biomass as a renewable low carbon energy source, the highly heterogeneous nature of bio-energy pathways and the present state of bio-energy use in the current global energy system and UK. The section also explains the revolution in bio-technology that has reinvigorated the potential for advances in bio-energy technological development which in turn has lead policy makers to heavily subsidise the sector. Here a case for caution as to the extrapolation of present trends in bio-energy development is made. Finally, an over view of the key enabling issues that need to be addressed to develop a fully functioning bio-energy market / sector is made; the complexity of which cannot be underestimated. Key issues in the bio-energy debate are also touched upon where relevant in these areas.

Section 3: Describes a meta-analysis of role of bio-energy in UK and global energy system in 2050 in order to assess likely demand for bio-energy. The uncertainties that impact on the role that bio-energy will play in the electricity, heat and transport sector are highlighted along with the difficulties of modelling the role of bio-energy in the future energy system.

Section 4: Provides an overview of global biomass feedstock potential, uncertainties and the research / data gaps in projections of potential in 2050 for individual biomass streams. The key areas of bio-energy feedstock research are also reviewed which include: producing sustainable feedstocks; maximising presently used and future feedstocks and broadening the feedstocks that may be utilised in bio-energy systems including algae, ligno-cellulosic residues and waste.



Section 5: Gives an overview of feedstock logistics issues (from field to process conversion site), RDD&D and the need for standards. The issues, opportunities and barriers to the development of an international trade in bio-energy are touched upon.

The main part of the section describes the bio-energy routes and conversion technologies for the production of heat and power as well as transport intermediaries. An overview description of the technologies is made as well as the RDD&D issues that need to be addressed. End uses across all sectors but with a focus on transport fuel intermediaries are also reviewed in terms of fungible and non-fungible fuels.

Cross-cutting issues are also described. These include: life cycle analysis and UNFCCC accounting concerns, spatial issues and value chain modelling, the bio-refineries concept, the use of bio-energy as a carbon negative process technology, the role of genetic modification in bio-energy technology development and the present trend towards the merging of technology streams for bio-energy technology development.

Finally, the issue of the best use of biomass is discussed.

Section 6: Here, the international bio-energy policy and RDD&D landscape is summarised based on a survey undertaken for this study by the BIS Science and Innovation Network. A review is also made of UK bio-energy capacity with a view to identifying which areas in the bio-energy value chain and with whom the UK should collaborate. The section goes on to describe concerns with UK bio-energy policy development including the innovation landscape with a view to making recommendations as to how the UK can improve bio-energy strategy development and deployment.

Section 7: This section provides a summary of all the conclusions and recommendations made in the review.

There are also two separate supporting documents which are also available on the ERP website - these include:

- Appendices 1 - 8 which provides detailed information relevant to sections of the main report; and
- Annex to Appendix 7 - An NNFC document assessing the UK Capabilities in Advanced Bio-fuels. This material feeds into the UK bio-energy capability review in Section 6 and was undertaken with Dr Claire Smith of the National Non-Food Crops Centre as a part of a wider review of UK capabilities in bio-energy for this project.

2 Introduction to Bio-energy

2.1 Introduction

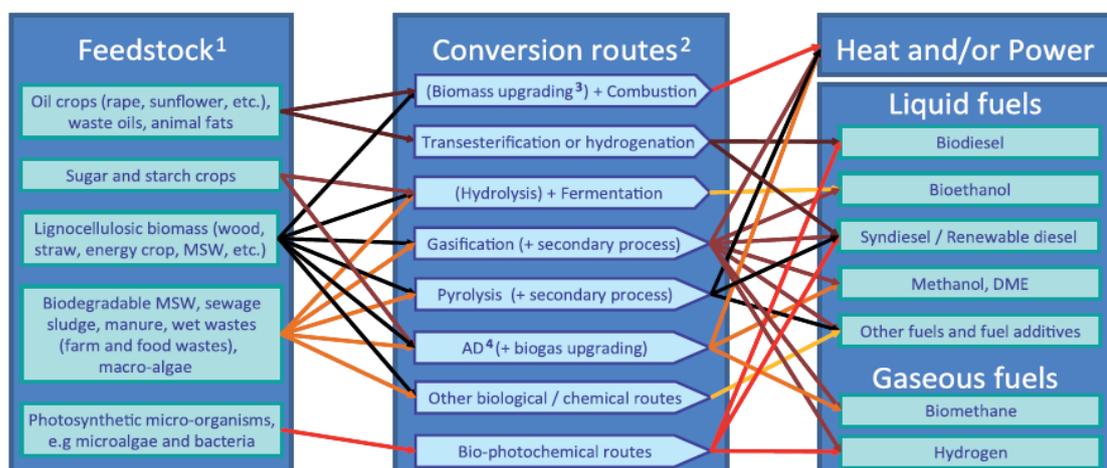
Bio-energy is a unique and highly adaptable renewable energy source - it can be used for heat and power production and liquid fuel for transport - and it already makes up a substantial proportion of the global primary energy consumption. Bio-energy chains and products are also highly complex and heterogeneous with a range of disciplines contributing to the development of the sector ranging from biotechnology, agronomy through to chemical engineering. This section seeks to frame the bio-energy agenda as well as contextualise the reason for the resurgence in interest in bio-energy technologies and where the agenda is likely to be heading.

2.1.1 Biomass as a renewable resource

Biomass differs from conventional renewable energy sources in a number of ways (IEA, 2009a). Key differences include:

- Biomass feedstock and bio-energy products may be stored and transported relatively easily. This contrasts with renewables such as wind and solar that produce intermittent electrical energy which needs to be utilised immediately.
- Biomass, as an energy resource, has a cost involved in the production of feedstock as well capital investment costs for the conversion process. Though wastes and residues tend to be cheaper the cost of the biomass feedstock is typically around 50 - 90 % of the production cost of bio-energy. This, as well as the relatively low energy density of biomass, makes the economics of bio-energy fundamentally different from other renewable options, which utilise a free resource (e.g. wind, solar) as spatial relationships between feedstock production, process conversion and distribution sites become important.
- The process conversion routes for bio-energy from feedstock production to end use are highly complex. Biomass may be converted to a number of intermediate chemical biomaterials and energy compounds. The energy carriers come in many states: solid (wood chips, bales *etc.*), gaseous (biogas, syngas, hydrogen *etc.*) and liquid (bio-oil, biodiesel, bio-ethanol *etc.*) which can be used for a number of applications. The complexity of bio-energy routes is shown in figure 2.1, below.

Figure 2.1: Schematic view of the wide variety of bio-energy routes (E4Tech, 2009 after IEA, 2009a).



¹ Parts of each feedstock, e.g. crop residues, could also be used in other routes

² Each route also gives co-products

³ Biomass upgrading includes any one of the densification processes (pelletisation, pyrolysis, torrefaction, etc.)

⁴ AD = Anaerobic Digestion

- The variety of feedstocks and forms of energy carrier, at present levels of technological understanding, tends to require the development of specific technologies to be developed for each type of feedstock and energy carrier. Again, wind and solar energy technologies have a relatively limited number of conversion technologies.

2.1.2 Biomass as a low carbon energy resource

The premise upon which biomass low carbon credentials rests is based on the assumption that carbon emitted through biomass conversion is re-sequestered by plants growing on the land from which the feedstock is removed. The actual emissions produced by converting biomass per unit of energy produced when displacing fossil fuels may actually be greater than that produced by the reference fossil fuel. A recent body of literature has emerged which has questioned the carbon balance of biomass when utilised in bio-energy value chains. The three key concerns raised by the literature which question the low carbon profile of biomass include the use of forest stocks as a feedstock, accounting issues within the UNFCCC GHG National Inventories Reporting system and the need to include carbon emitted from land conversion, direct or indirect, on which biomass is grown. The latter two points relate to the fact that the land used for biomass production, the establishment, processing and conversion of biomass into an alternative energy carrier has a GHG footprint and may take place in jurisdictions which have different accounting requirements under the UNFCCC. These are dealt with in this review as life cycle and sustainability issues and are addressed in sections 5.4.1 and 4.3.2, respectively. Here the issue that is dealt with is whether the actual biomass that undergoes conversion in a bio-energy value chain can be considered low carbon.

Manomet (2010) and Bird et al. (2010) highlight the fact that using the carbon debt¹⁰ concept the payback of carbon sequestered by tree growth from long standing forest wood¹¹ utilised in bio-energy takes tens of years to payback. Bird et al (2010) work actually states substantially longer (>200 years) due to the inclusion of soil organic carbon (SOC) loss from LUC). The work therefore highlights the danger of assuming that the conversion of any living biomass can be assumed to be carbon neutral due to the fact that the carbon was only recently sequestered. Habitats such as forests act as carbon stocks which take a substantial period of time to accrue but can be released instantaneously when combusted in a bio-energy value chain. The assumption of low carbon profile for this type of biomass is questionable - though dependent on boundary conditions (e.g. O'Laughland, 2010). Where the biomass used is specifically grown on land with low soil carbon and no existing vegetation for consumption in a bio-energy value chain e.g. dedicated energy crops then biomass can be assumed to be carbon neutral as the carbon was sequestered by those plants on a piece of land specifically to be combusted for bio-energy; this also complies with Searchinger's (2009) need for biomass to be *additional*.

This body of literature emphasises the following:

- the need for the preservation of high carbon stock habitats / biomes. Indeed the avoidance of high carbon stocked habitats as a source of biomass is imperative not only to avoid violation of the low carbon profile but also within the larger sustainability debate - section 4.3.2; and
- that the automatic assumption that biomass combustion in bio-energy value chains is immediately balanced - especially for biomass which takes a substantial period of time to mature - does not always hold (though this is dependent on boundary issues (Garthorne-Hardy, In Prep)).

This review, assumes that biomass utilised in bio-energy value chains is low carbon due to the fact that the biomass potential literature (e.g. Hoogwilk et al., 2003) - covered in section 4.3.1 - does not cite the utilisation of forest stock as a resource and only refers to the following components of woody biomass:

- forest wood flow (i.e. the management of existing forest stock and harvesting of woody biomass to place into the bio-energy value chain which then re-grows and is re-harvested and is therefore low carbon). Though Bird et al. (2010) still state that there is still some loss of carbon sink due to the fact that a proportion of forest deadfall becomes recalcitrant and is therefore sequestered. However, the size of this carbon store is small and the resolution of biomass potential projections is insufficiently detailed to account for this component; as such one could state that these woody biomass flows in the projections account for this.

¹⁰ The carbon debt concept is based on the premise that for some bio-energy value chains the initial GHG emissions produced when cultivating (including that emitted from the soil due to LUC), harvesting, transporting and converting biomass into energy emits more GHG than the fossil fuel source that bio-energy was substituting. This carbon debt is paid back over time as the biomass re-grows (in the case of forest) and / or the savings made from subsequent harvesting of biomass (where initially large emissions have taken place due to LUC).

¹¹ This is to be distinguished from quick growing forest plantations that are currently used in the pulp and paper industry.

- And, energy crops i.e. land is acquired for the specific purpose of growing biomass for bio-energy. The boundary issues in this case is simple for both woody and grass energy crops. What is grown and used in the bio-energy value chain sequestered the carbon for that purpose and is therefore low carbon.

The biomass potential literature also expressly avoids high carbon stock lands e.g. Dornburg et al., 2008.

Further details of the intricacies that surround biomass as a low carbon source of energy and the differences between carbon emissions from biomass and fossil fuels, carbon sinks and biomass production impact on CO₂ emissions can be found in <http://www.ieabioenergy-task38.org/publications/fag/>.

2.1.3 The heterogeneous nature of biomass and bio-energy value chains

Biomass and bio-energy is highly heterogeneous, in terms of feedstock types and conversion technology, that it is extremely difficult to apply generalisations across the sector. For example, feedstock energy density can vary from 150 to 370 GJ/ha/yr for short-term poplar and long term sugar beet, respectively (table 2.1). In the case of conversion technologies for heat generation, with combined heat and power the efficiency is up to 90% whereas for anaerobic digestion to electricity the efficiency is approximately 15% (table 2.2). These variations are also manifest in the GHG savings and energy balance relative to reference fuels. For example, rapeseed via esterification to biodiesel saves 52.9% relative to low sulphur diesel and has an energy balance of 0.437 and residues to electricity via gasification saves 95.7% and has an energy balance of 0.133 relative to grid pool electricity (table 2.3). Finally, the costs for producing the different energy vectors also varies as displayed in table 2.4.

Table 2.1: Energy Density and yields per hectare of a variety of biomass feedstocks (after Faaij, 2006)¹²

Feedstock	Yield ranges (odt/ha/yr)	Net Energy Yield (GJ/ha/yr)	Production Costs (Euro/GJ)
Rape - Longer Term	4 (seed) 4.5 (straw)	180 (total)	12
Sugar Beet - Short Term	14	250	12
Sugar Beet - Long Term	20	370	8
SRC - Willow - Short Term	10	180	3 - 6
SRC - Willow - Long Term	15	280	< 2
Poplar - Short Term	9	150	3 - 4
Poplar - Long Term	13	250	< 2
Miscanthus - Short Term	10	180	3 - 6
Miscanthus - Long Term	20	350	~2

Notes.

odt - Oven Dried Tonne

Energy density of feedstocks can vary depending upon their moisture content for example bone dry wood has an energy density of 18 GJ/odt whereas air dried wood has 15 GJ (Net CV). This is replicated to a greater extent for more water rich sources of biomass such as manure, for example, poultry manure has a wet energy density of 6.9 GJ/t and a dry content of 14 GJ/odt (UK Biomass Strategy, 2007) - food and kitchen waste 3.3 GJ/t.

Table 2.2: Energy efficiency metrics for primary conversion technologies. The figures shown represent the efficiency of the conversion process (fuel to vector) in isolation from the rest of the supply-chain (Faaij (2006), after UKERC, 2010a)¹².

Technology	Vector	Typical capacity	Net efficiency (LHV basis)
Combustion	Heat	1-5 MWth	70-90%
	CHP	0.1-1 MWe	60-90% (overall)
	CHP	1-10 MWe	80-100% (overall)
Co-combustion	Electricity	20-100 MWe	20-40%
	Electricity	5-20 MWe	30-40%
Gasification	Heat	50-250 kWh _{th}	80-90%
	CHP	0.1-1 MWe	15-30% (electrical)
	Electricity	30-100 MWe	40-50% (electrical)
Pyrolysis	Bio-oil	0.1-0.5MWe	60-70%
Anaerobic digestion	Electricity	0.1-0.5MWe	10-15%
	Ethanol		40-45%
	LC Ethanol		50-60%
Extraction and Esterification	RME		88%

CHP: Combined Heat and Power; RME: Rape Methyl Ester; LC: Lignocellulosic

¹² These datasets are from multiple sources the direct comparability of which should not be assumed.

Table 2.3: Mid-range estimates for lifecycle GHG emissions per unit energy provision and energy ratios for selected bio-energy chains (Elsayed et al (2003) after UKERC, 2010a)¹².

Feedstock	Technology	Vector	GHG Saving relative to reference [1]	Energy Balance GJin/GJout ⁻¹
Rapeseed	Esterification	Biodiesel	52.9%	0.437
Grain	Fermentation	Ethanol	64.2%	0.464
Ligno-cellulosic crop	Hydrolysis / fermentation	Ethanol	84.0%	-0.028
Residues	Combustion	Electricity	86.4%	0.309
Residues	Pyrolysis	Electricity	91.4%	0.284
Residues	Gasification	Electricity	95.7%	0.133

[1] The reference energy service pathways used were: low sulphur diesel, petrol, oil; combustion for heat and grid pool electricity where appropriate. The assumed technological scale is 25 MWe for electricity generation, 50 kWth for heat generation and 40,000 t. yr⁻¹ for bio-fuel production; wherein residual lignin from Ligno-cellulosic crop to ethanol via hydrolysis and fermentation is combusted for power generation. The negative energy ratio for the conversion Ligno-cellulosic crops to ethanol via hydrolysis and fermentation arises because energy credits are allocated to residual lignin combustion for electricity generation. In the absence of this allocation the ratio shifts to +0.249

Table 2.4: Typical costs of bio-energy¹².

Biomass Energy Source	Cost per unit	Source
Biomass Power	US\$ 0.05 - 0.12 kWh	
Biomass Heat	US\$ 0.01 - 0.06 kWh	
Bio-fuels Ethanol - Sugar Cane Feedstock	US\$ 0.3 - 0.5 Litre	REN 21 Renewables 2010
Bio-fuels Ethanol - Corn Feedstock	US\$ 0.6 - 0.8 Litre	Global Status Report
Biodiesel	US\$ 0.4 - 0.8 Litre	

Table 2.5: Biome Land Carbon Stocks¹².

Land Type	Carbon Stocks (tC/ha)	Source
Forestry (IPCC High - Low)	404 to 151	
Grassland (IPCC High - Low)	241 to 145	
Croplands	81	
Wetlands	679	

Finally, it is worth considering the impact of the establishment of crops for bio-energy on land and the impact that this has on SOC release on bio-energy value chain carbon balances. This has become increasingly salient, particularly when virgin land is cleared to grow food that has been displaced by the production of bio-energy feedstocks - so call Indirect Land Use Change (iLUC). Such is the intensity of the indirect land use change debate and its impact on carbon payback times for bio-energy products it is worth emphasising that this figure is highly sensitive to the type of land that any feedstock is displacing indirectly as displayed in table 2.5, above. The extent of SOC released is also highly dependent on the method of cultivation for example no till techniques result in lower soil organic carbon oxidation.

The net result of this degree of heterogeneity is that it is important when describing bio-energy chains that a precise definition of the land upon which the feedstock was grown, method of harvesting, conversion process and energy source is made as well as the reference fuel. The rate of development of technologies and processes in bio-energy chains is such that a date for when the Life Cycle Assessment (LCA) was undertaken is also important. Finally, the influence of LCA methodology can impact of metrics (section 5.4.1) and these methodological issues need to be explicitly stated so as to maintain transparency in calculations (UKERC, 2008).

2.2 Current Use of Biomass

2.2.1 Bio-energy use global context

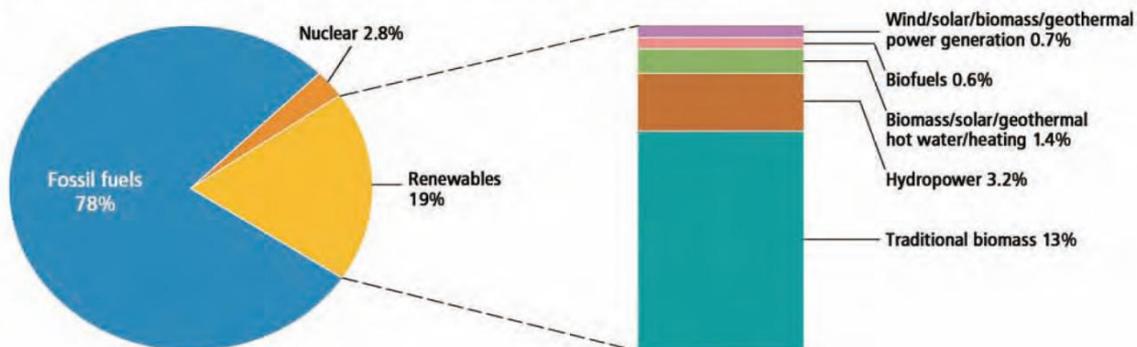
The global proportion of final energy consumption made up of biomass in 2009 was just over 14%; this was composed of the following:

- Traditional biomass uses are estimated to have made up 13% of final energy consumption (see section 3). The driver for this is the 2.6 billion of the global population that are reliant on wood, straw, charcoal or dung to cook their daily meals. Though hard to assess, it is suggested that slowly trends are changing and there is an increasing proportion of households that cook and light their homes with biogas (~160 M households) and a growing number of small scale industries are obtaining process heat and motive power from small scale digesters (REN21, 2009 and UNEP, 2009).

- The bio-energy related technologies that are the focus of this study made up <1.2% of final energy; this is composed of:
 - Globally, there exists some 270 GWth of heat generation capacity from biomass (excluding single dwelling domestic heating). There has been substantial development of biomass heating capacity, particularly in Europe where heating demand is large, resulting in an increase in the use of solid biomass such as wood pellets on scales ranging from buildings to community scale combined heat and power plants (CHP) and for centralised district heating systems (REN21, 2010).
 - Globally, an estimated 54 GW of biomass power generation capacity was in place by the end of 2009; this comprised just over 1% of total global electrical capacity. This capacity is distributed over 50 nation states with an increasing number of European states having a significant proportion of their electricity being generated by biomass e.g. Finland has 20%. Rapidly emerging economies such as China and India are also developing this sector.
 - Bio-fuels made up 0.6% of final energy consumption. This was generated by 64 billion litres of bioethanol and 12 billion litres of biodiesel, an increase of 16% from 2008, and comprised ~3% of total transport energy. Though mandates for blending bio-fuels into vehicle fuels have been enacted in at least 41 states / provinces and 24 countries - 90% of the bio-fuels market is made up of the US, Brazil and EU27. This sector is forecast for rapid growth in the next 10 years such that at present trajectories bio-fuels will make up 12% of global transport energy by 2020 (Mabee et al., 2009 and US EIA, 2009).

These trends are displayed in Figure 2.2, below.

Figure 2.2: Proportion of biomass in the renewable energy share as a function of global final energy consumption (after REN21 (2010)).



2.2.2 Bio-energy use in the UK

In 2009, it was estimated that the UK consumption of energy totalled 8,905 PJ. Of this renewable sources contributed 288 PJ (3.2 %) with bio-energy making up 80.7% (232 PJ or 2.6%); of this around 80% is considered to have been domestically sourced (UKERC, 2010a). A breakdown of the UK renewable energy and the role of biomass is shown in figure 2.3, below.

Figure 2.3: Contribution of biomass to UK renewable final energy consumption in 2009 (DUKES, 2010).

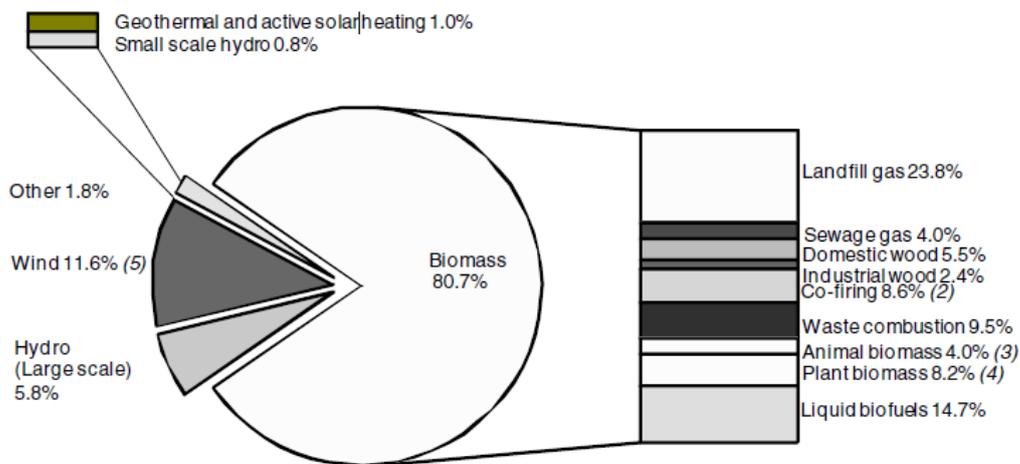


Table 2.6: Total fuel consumption by final users in 2009 (%) - primary input basis (DUKES, 2010).

	Coal	Petroleum	Gas	Primary Electricity	Biomass	Total
Industry	23	14	49	11	3	100
Transport	1	95	1	1	2	100
Domestic	17	6	65	9	3	100
Others	24	5	53	14	4	100
All Users	15	34	41	8	3	100

As per table 2.6, the role of biomass as a function of fuel consumption by final users breaks down to 2% in transport, 3% in each of industry and domestic users and 4% in others.

The break down for UK bio-energy generation capacity may be summarised as follows:

- UK renewable heat production in 2006 was 21 PJ mainly from domestic wood fuel combustion. This is a drop since 1996 from 37.7 PJ of which 21 PJ alone was produced by wood combustion by industrial applications; though the reason for the fall may be attributable to data resolution issues (Perry, 2010).
- As of August 2009, the biomass power generating capacity accredited by Ofgem was 380 MW for dedicated facilities with a further 2,210 MW of planned capacity from announcements by plant developers. In March 2008, 723 MW of co-firing was accredited by Ofgem (2009) - though, for operational or economic reasons, these plants may not have actually co-fired ; and
- In 2009-10, the Renewable Transport Fuel Obligation resulted in the consumption of 430 and 1,068 M litres of bioethanol and biodiesel, respectively - which made up 3.33% of total UK transport fuel (RFA, 2010). The RFTO was introduced in 2008 with a target of 5% by energy in 2010/11 and then subsequently revised to 5% by volume by 2013/14. According to the European Biodiesel Board (2009) and European Bioethanol Fuel Association (2009) the UK installed refinery capacity for biodiesel and ethanol stands at 228 M litres and 820 M litres, respectively. As imported feedstock is classified as imported bio-fuel irrespective of the fact that it was refined in the UK accounts for the fact that ~90% of bio-fuels were classified as imported in the first year of the RFTO.

2.3 Why the Increase in Activity in Bio-energy and Where is the Agenda Going?

Bio-energy technologies for the generation of all energy vectors have been in existence for more than a century. So why the sudden increase in interest in bio-energy technologies and the decision by policy makers to heavily subsidise the sector? This section seeks to address this issue as well as where the bio-energy agenda is likely to be going and what is needed to attain a scalable and liquid market in bio-energy. It provides a strategic context for the report.



With regards the first issue, the renewed interest in bio-energy for the heat and power industry and the bio-fuels for transport were very different. In the case of the former, the primary driver has been the introduction of financial incentives / penalties to drive investment into the renewable energy industry, with biomass being one of a range of options being developed. The advantage of biomass was that sources were already available, investment in new plant required for low co-firing percentages were comparatively low, and biomass co-firing could contribute to base load generation rather than being an intermittent source. With biomass perceived to have a long term future in the generation mix this sector is now looking at working with feedstock producers to improve biomass quality for heat and power.

In the case of bio-fuels for transport the ability to develop novel techniques has been assisted by a revolution in life sciences biology and its scale up to industrial biotechnology. The ability in the 1980's to modify simple life forms to produce medicines, seeds and a few chemicals evolved in the 1990's to the ability to undertake rapid gene sequencing which allowed the entire genetic code of viruses, bacteria and even humans to be realised. During this period came the discovery that all complex organisms start as pluripotent cells *i.e.* cells can be 'rebooted' to unspecialise from their differentiated state and even reprogrammed. Recently, there have been developments which allow the writing of genetic code from scratch - *i.e.* strands of DNA can be brought together to programme cells to do specific things. In effect the ability to manipulate unicellular organisms to become programmable bioreactors had been realised. These discoveries, in conjunction with standardised cheap cellular components and the tumbling cost of sequencing, are scalable and therefore may be industrialised due to the fact that the gene code builds its own hardware. This has therefore taken biotechnology from a speciality area of interest which was confined to the pharmaceuticals industry into agriculture, chemicals, bio-defence and energy; whereby agricultural feedstocks can be used rather than petroleum-based ones to produce chemicals, plastics and fuels (McKinsey & Co. (2009) and Ragauskas et al. (2006)).

These developments have substantial commercial implications. Revenues from industrial biotechnology were estimated to be US\$ 170 B in 2008 and are forecast to grow to US\$ 450 B in 2020. After a number of false starts it is thought that the industrial biotechnology revolution is here to stay due to the ability to scale up from lab to larger scale facilities; this has attracted greater interest and investment from industry and governments (Economist dated 3rd July 2010).

The substantial advances in industrial biotechnology are likely to impact every aspect of the global economy from improving agricultural methods (increasing yields with reduced inputs, reducing land area to allow ecosystems to expand); fuel production where by organisms can be programmed to produce useful hydrocarbons; nanotechnology whereby micro-structures will be able to assemble themselves automatically; and health in the form of gene therapy and regenerative medicine. The role of biotechnology in agriculture is already substantial with over 59%, 27%, 18% and 13% of global plantings for soy beans, corn, cotton and carrots, respectively in 2005 being genetically modified (McKinsey & Co., 2009).

These recent advances in industrial biotechnology have applications to bio-energy production across the value chain from producing sustainable feedstock at scale which can be more easily utilised through to process conversion to produce fuels and intermediaries that can be dropped into existing infrastructure. This has resulted in the re-emergence of enthusiasm for the potential of bio-energy technologies to make a substantial contribution to the energy system in 2050.

Additional drivers for the bio-energy agenda are the spectre of increased fossil fuel prices and environmental concerns. The prolific demand for energy, as emerging economies develop and geopolitically induced supply side restrictions become all too frequent, are resulting in widely fluctuating fossil fuel prices (e.g. Brent Crude in July 2008 in the high US\$ 140's bbl to low US\$ 40's bbl in September 2008 and then back to over US\$ 110 bbl in the early to mid 2011). The proposition of sustained US\$ 200 bbl oil no longer seems so far-fetched making energy security an ever greater concern. If scarcity of supply does not increase prices then environmental legislation which gives a price for carbon eventually will. Diversification of energy sources via bio-energy is seen as attractive as it addresses environmental concerns and is seen as a way to reinvigorate agricultural and rural economies. The fact that Brazil produces 14% of its energy from sugarcane on 0.4% of its land and has become the first tropical global agricultural powerhouse (see Appendix A.3.3) is a demonstration of what can be done. Furthermore, the whole sale shift from the fossil economy to the so called bio-economy is seen as a way of meeting the 21st century's grand challenges of the sustainable management of natural resources, sustainable production, improved public health, mitigating climate change, integrating and balancing social developments and global sustainable development (EU, 2011).



Onto the issue as to where the bio-energy technology agenda is going. With regards to heat and power applications of bio-energy technologies the processes are well established and the main requirement is for technological improvements for scale up, efficiency, reliability, market penetration of bio-energy generated energy services as well as adapting systems to take poorer quality feedstocks as demand increases.

In the case of liquid bio-energy markets - bio-fuels - though the present focus is on ethanol it is extremely unlikely that this will be the main focus to 2050¹³. Ethanol is lower in energy content (21.28 MJ/l) compared to petrol (32.95 MJ/l), is hydrophilic and therefore corrosive requiring engine and infrastructure modifications even in low blends. The ideal new generation of bio-fuels will be hydrocarbon based - molecules chemically more similar to those already powering existing transport vectors *i.e.* 'drop-in' fuels. Subject to the economics of the conversion processes being viable, the advantage of going down this route is that it immediately increases the size of the potential market, reduces the refining requirement that even existing petroleum based hydrocarbons require and could potentially be retrofitted to existing ethanol plants (Economist dated 30th October 2010).

Finally, in order for these strategic objectives to be achieved at scale there is the need for the development of a scalable bio-energy market. The ability to attain this is predicated on a number of factors which need to converge and be mutually supporting; these are summarised in table 2.7, below. The ability to align all factors and the agendas of actors will be highly complex as all issues are fundamental but the relative degree of importance is likely to vary.

Table 2.7: A number of elements need to fall into place for a global scale, liquid bio-energy sector and market to develop (adapted from Accenture, 2007, 2008 and 2009).

Feedstock. The ability to produce sufficient volumes of biomass economically and sustainably (*i.e.* maintaining ecosystem services and biodiversity) without adversely impacting on other agricultural markets and the biomaterials industry underpins the potential scale and role of bio-energy.

Regulation. The ability to generate regulation and policy to promote liquid and transparent markets, where bio-energy products can be moved to the markets with the highest prices.

Producers. The need to have the confidence that the, present policy led market for bio-energy, will be maintained for the foreseeable future in order to develop long term research programmes in technologies to optimise the economics, sustainability and broad utility of biomass feedstocks and end uses.

Consumers. Environmental benefits must be clear for consumers and business-to-business demand to support the growth of bio-energy.

Power Generators. One of the most economically efficient use of bio-energy is co-firing. Where sustainable sources of biomass are obtainable these should be encouraged. Furthermore, the development of negative emissions by the use of Bio-energy with Carbon Capture and Storage should be considered as it may prove to be more economic to sequester via bio-energy power generation than mitigating in other sectors.

Heat Service Providers. Where heat services are advantageously provided by bio-energy systems optimum penetration of bio-energy technologies for heat needs to be encouraged.

International Oil Companies (IOCs) / National Oil Companies (NOCs) - Distribution. There are growing pains integrating bio-fuels into the current fuels value chain, and NOCs are moving beyond distribution.

Original Equipment Manufacturers. OEMs are introducing flexible-fuel vehicles (FFVs). In addition, most cars currently on the road can take up to 10 % of ethanol (in gasoline cars) and 5 to 10 percent of biodiesel (in diesel cars), but warranties continue to vary by vehicle manufacturer and country.

How will OEMs manage the introduction of drop-in fuels into the transport sector?

Infrastructure. Infrastructure to facilitate operational scale and trade is critical if an efficient market is to develop.

Financial Markets. Paper markets (exchanges where contracts, including futures and options, are traded freely without the need for physical delivery) are still immature, and risk management for producers as well as blenders/consumers of bio-fuels is a significant challenge as a result.

Technology. The bio-energy industry needs to evolve into a truly global and efficient industry before competing technologies start to challenge conventional fossil fuel and competitive renewable sources; the extent to which it plays in the future energy mix will be dependent on the relative developments for other renewable sources.

¹³ Ethanol and bio-diesel's dominance has been a function of the fact that they were an immediately available way to reduce GHG emissions in the transport sector and that in low blends they can be utilised in the present transport fuel infrastructure.



2.4 State of the Bio-energy Agenda: Summary

Bio-energy is a unique renewable energy resource with complex and highly heterogeneous value chains. The low carbon profile of the conversion of biomass is generally accepted but should not be assumed particularly where the biomass utilised has a long maturation period. Indeed the avoidance of the utilisation of unmanaged high carbon stocked habitats as a source of biomass feedstock is imperative not only to avoid compromising its low carbon credentials but also within the larger sustainability debate.

Globally bio-energy provides about 14 % of global primary energy consumption most of which is for traditional uses (13 %). The bio-energy technologies reviewed in this report represent ~1 % of all primary energy consumption. With regards the role of bio-energy in the UK energy mix, though the consistency of statistical material is questionable, especially for heat, it represents a substantial proportion (~80%) of all UK renewable energy consumption which stood at 3.2% of total energy consumption in 2009. Of all renewables it also has the potential to grow most rapidly.

The rapid development of bio-energy in the heat and power sector has been as a result of the introduction of incentives to encourage renewables and the availability of biomass as a base load generation source. In the case of bio-fuels for transport and the development of novel techniques has been greatly assisted by the recent revolution in life sciences and industrial biotechnology. This has re-invigorated the potential for advances in bio-energy technology, at all stages of the bio-energy value chain, to be made which could allow bio-energy to make a tangible contribution to the future global energy system. This has resulted in policy makers heavily subsidising the sector. However, extrapolation of present R&D activities is dangerous as the strategic objective will be the production of a renewable fuel which behaves and can be handled in the same way as the fossil fuel that it substitutes in the future energy system of 2050.

The likely sustained high price for fossil fuels, its impact on energy security and the potential for cost reductions to be made in bio-energy make the option of doing nothing untenable. The knowledge and experience to deliver stable policy to supply sustainable feedstocks at scale and support technological learning curves is available as demonstrated by Brazil where sugarcane provides 15% of its energy on 0.4% of its land.

Finally, the realisation of scale and liquid bio-energy markets will need the concurrent establishment of a wide range of factors - ranging from feedstock development, technology development, financial markets and infrastructure development - the complexity of which should not be underestimated.

3 Sustainable Bio-energy in the 2050 Energy System

3.1 Introduction

From section 2, it can be seen that bio-energy is a highly adaptable renewable energy resource. Here, the demand side projected degree of bio-energy penetration in the international and UK energy system for a variety of energy models and scenarios is reviewed. This seeks to address two issues. Firstly, assessing whether there is any consensus as to the demand for / extent that bio-energy will play in the future energy system; and secondly what uncertainties exist that lead to differing levels of utilisation in different end use sectors. The work is indicative rather than exhaustive and builds on the scenarios meta-analysis work in Energy Innovation Milestones 2050 (ERP, 2010).

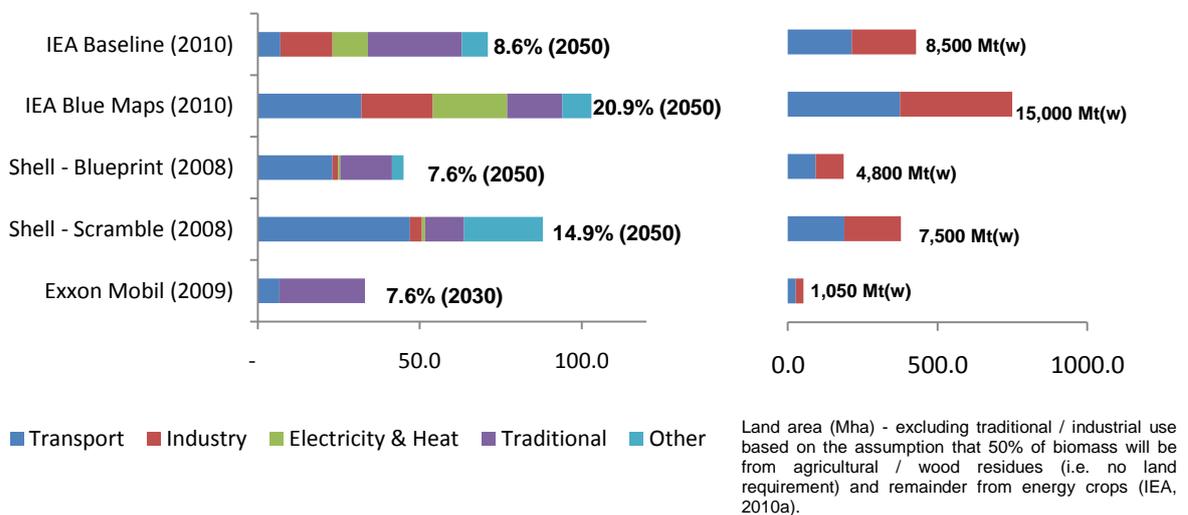
As a caveat to each section, it is worth noting that the material for this review is based on the recent literature base and will therefore likely to be representative of developments to early 2010. Furthermore, this section does not deal with the role of bio-energy mandates, policies and regulation in bio-energy development; this is dealt with in section 6.

3.2 Meta-Analysis of the Role of Bio-energy in 2050 Energy Scenarios

3.2.1 Global energy scenarios

In terms of total global primary energy demand there are a range of views on how bio-energy will develop in the 2050 energy system. The scenarios vary between about 7.6% (46 EJ of 754 EJ) in the Shell Blueprints Scenario (2008) to 20.9% (140 EJ of 670 EJ) in the IEA Blue Maps (2010a) work - see figure 3.1, below.

Figure 3.1: Final biomass demand for global biomass scenarios broken down by end use type, estimated upper and lower bound areas of land required to grow biomass (in Mha) and logistical requirement for wet mass (figures in brackets in left hand graph indicates year and proportion of primary energy supply that is from biomass).



Opinions vary as to the proportion that will be for transport, in the form of liquid bio-fuels, or used for heat and electricity generation. In the IEA Blue Maps scenario co-firing biomass with coal increases to 2020 and by 2050 13% of electricity is generated in dedicated bio-energy plants with CCS including those operating with combined heat and power (CHP). Conversely, in the Shell Scramble and Blueprints (2008) and Exxon (2009) (for 2030) scenarios have a limited role for biomass in electricity generation - both suggesting that a substantial proportion is used for traditional purposes (between ~12 and 25 EJ).

In the Shell Scramble scenario bio-fuels grow rapidly from unchecked competition and the drive for new energy supplies, helped by a strong agricultural lobby. This results in first and second generation bio-fuels, in roughly equal proportions, making up approximately 25% (43 EJ) of transport energy demand with the remainder being made up of fossil fuel resources and minor amounts for gaseous hydrocarbons and negligible amounts of

electrification. In the more coordinated Blueprint scenario overall transport energy demand would reduce, with global agreements leading to electric and hydrogen based technologies being accelerated therefore reducing the demand for bio-fuels. In contrast to the Shell scenarios the IEA baseline (BAU) scenario sees less use of biomass in the energy system than the co-ordinated response as represented in the Blue Maps work.

Using the same assumptions as the IEA (2010a)¹⁴, and removing the component used for traditional biomass, the range of land requirements, depending on yields is 26 Mha to 750 Mha which equates to 0.5 to 15.2% of presently used agricultural land (~4.93 Bha). This equates to 1,000 to 15,000 M tonnes (wet weight) of biomass having to be transported to processing plants; the logistical effort of this cannot be underestimated when it is considered that global coal production in 2009 was approximately 8,000 M tonnes (BP, 2010). Furthermore, coal tends to be sourced from a discrete number of point sources to a number of end users via a dedicated logistics supply chain whereas biomass logistics will involve dispersed supply sources and distributed end users. Biomass logistics will therefore be more complex; logistical issues are dealt with in Section 5.2.

3.2.2 UK energy scenarios

In the UK scenarios there is similar variation and lack of consensus as to the role of bio-energy in the energy system. Some scenarios anticipate bio-energy supplying over 10% of primary energy (UKERC MARKAL Low Carbon Core 80, DECC 2050 Pathways and ETI ESME) with ESME suggesting that the annualised opportunity cost of not deploying bio-energy could run into £10's of billions. Others have a limited role. The degree of penetration of bio-energy in the MARKAL models is highly dependent on the assumptions around the relative long term costs of the technologies. In the UKERC MARKAL Low Carbon Core 80 projection biomass is used principally for transport (83%) with the remainder going into electricity production. Of the 0.73 EJ that goes into transport 33% is imported and the remainder domestically produced. Further studies using MARKAL have improved the resolution of bio-energy chains (Jablonski et al., 2010) and modelled accelerated technological development (Clarke et al., 2009). In these scenarios bio-energy penetration displays substantial improvement to baseline cases. In some cases the role of bio-energy is dynamic, peaking in a single sector prior to 2050 and then falling away again, as bio-energy is diverted to an alternative end use sector (mostly heat in the case of TSEC MARKAL).

In the expert based forecasting methods, such as the DECC 2050 Pathways work, the main role of bio-energy is seen as being in co-fired electricity production with CCS i.e. the assumption is that CCS will be reliable and economic and able to be applied to co-firing. A key conclusion is that sustainable bio-energy is a vital part of the low carbon energy system, though the availability of sustainable bio-energy is highly uncertain. It is suggested that 10% (~2.4 Mha) of UK land will be dedicated to bio-energy producing the equivalent of 7.2 M tonnes of dry woody biomass. The impact on domestic food production was not fully considered.

The TSEC-BIOSYS and RELU BIOMASS projects undertook assessments of the potential for meeting the 20% renewable energy directive and 10% transport requirement. Based on spatial analysis to produce Miscanthus and short rotation coppice (SRC - willow and poplar) the work suggested that to meet the former would require 350,000 Ha without significantly impacting on food production or valuable habitats (Lovett et al., 2009). To meet both would require up to 1 Mha and would be much more demanding. The main finding was that different species of bio-energy crops would be employed in different parts of the country in order to take advantage of the differing conditions to maximise yields and prevent damage to surrounding habitats by denuding water tables. Further work in this area was also undertaken by Aylott et al., 2010.

3.3 Uncertainties Impacting the Extent of Bio-energy use in UK Scenarios

A consistent theme for the global and UK scenarios is the divergent degree of penetration of bio-energy in the energy system as a whole and within each end use sector. This is due to a number of uncertainties both with regards the nature of the evolution of the future energy system and technological advances that are anticipated in bio-energy for each end use sector. The nature of these uncertainties are reviewed below.

¹⁴ that in 2050, 50% of biomass will be sourced from agricultural and forest residues (i.e. from existing biomass sources) and the other half from dedicated energy crops which require dedicated land to be cultivated.

3.3.1 Bio-energy in the electricity and heat generation sector

The role of bio-energy in the electricity and heat generation sector is subject to the following issues within the UK energy system:

- In many energy system models, though there is consensus as to the main electricity generation sources (nuclear, wind and fossil fuel with CCS), the role for other low carbon technologies, including biomass, are highly undeveloped (ERP, 2010). The degree of penetration tends to be small across a range of technologies with no patterns or dominance of any one low carbon technology (except wind and nuclear).
- With regards heat generation, the scenarios tend towards multiple technologies and away from a single dominant technology (gas central heating). Biomass Combined Heat and Power (CHP) and bio-methane play a varied role and generally many solutions suggest a change in the way that domestic, commercial and industrial properties receive heat services. In the case of the Committee on Climate Change Medium Abatement scenario, around 25% of total heat demand by industry will be supplied by biogas or biomass with domestic heat being provided by electric sources (CCC, 2010).
- The decentralisation of power generation through micro-generation (small CHP units serving dwellings, businesses and communications) is considered to be a key development which would assist in the penetration of bio-energy in the electricity and heat sector - negating the need to transport biomass long distances to centralised power generation units (Taylor, 2008). However distributed power has two barriers. Firstly, the economics is seen as a limiting factor requiring a need to reduce costs and secondly the need for local biomass supplies which can be stored - these issues result in uncertainty as to the degree of penetration in the 2050 UK energy system.

3.3.2 Bio-energy in the transport sector

Of all sectors the role of bio-fuels in the transport sector is the most uncertain - with global projections ranging from 6.7 to 47 EJ. The global nature of the transport industry makes the issues relevant to both the UK and global system.

Present global transport energy consumption ~94EJ is split into Light Duty Vehicles (LDV) over half (52 %), heavy duty vehicles (HD) just under a quarter (23%), rail at 3%, Marine at 10% and Aviation 11%. Based on IEA (2009b) projections, road transport is set to grow from 750 M LDVs to between 1.8 (Blue Maps) to 2.2 B (Baseline) in 2050. Trucks and shipping also grow substantially with aviation projected to have the fastest growth with a 4 fold increase in passenger kilometres by 2050.

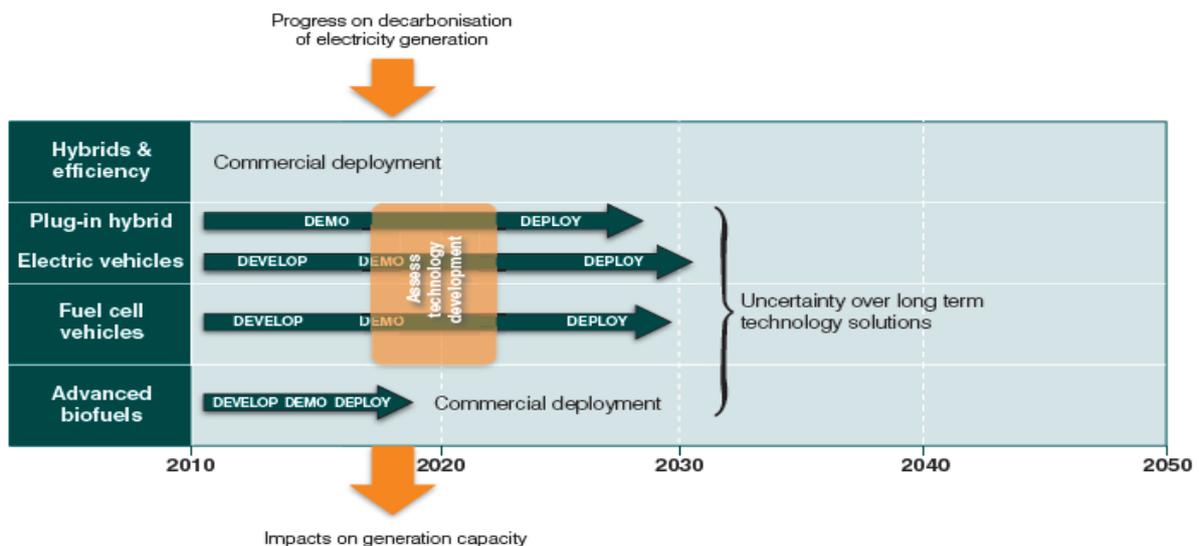
Studies suggest that emissions gains in conventional transport are generated from efficiency improvements and the use of hybrids up to 2020-25. After this period, though there is a good alignment of the portfolio of technologies that will make up the 2050 transport system, there is a divergence as to which will dominate. The technologies include: fuel efficiency, Plug-In Hybrid Electric Vehicles (PHEV), Electric Vehicles (EV), Fuel Cell and advanced bio-fuels - but the scale, relative contribution and timing of the different technologies is highly uncertain (AEA, 2009a). Some models have a high penetration for bio-fuels (for example the IPPR MARKAL-MACRO scenario has biodiesel powering 70% of cars) others see a greater role for Plug in Hybrids with bio-fuels as a low carbon bridging technology whilst PHEV are developed (UKERC Carbon Ambition). The IEA sees bio-fuels playing a fundamental role across all transport modes making up 27% of road transport (electrified transport makes up 11%), 30% for aviation and marine shipping; with a segregation of high quality bio-fuels for heavy duty vehicles (HD) and aviation and low quality and cost bio-fuels for the marine sector. The degree of penetration for aviation, based on the ability to provide sustainable bio-fuels, ranges from 10% to 60% in assessments undertaken by the Committee on Climate Change and E4Tech, respectively (CCC, 2009). The technology options for road transport are displayed in figure 3.2.

The lack of consensus of technology dominance in the road transport sector is due to uncertainty in technology limitations and economics which may be summarised as follows:

- Will a battery technology ceiling favour a bio-fuels future or will advanced bio-fuels not emerge as an economically viable alternative to electric vehicles? Will battery technology be able to fulfil the requirements of HD vehicles, shipping and aviation sectors - if not then will there be a long term niche role for bio-fuels in the transport sector?

- What are the volumes of sustainable bio-fuels that can be supplied for the transport sector? Will there be sufficient supplies to support a large proportion of transport or will there be only sufficient supplies for niche roles?
- Will hydrogen / fuel cell technology development accelerate sufficiently in time to make a substantial impact on the transport system?
- What is the role of infrastructure development as a determinant of the dominant energy source? How will bio-fuels and EVs penetrate the road transport system?
 - Bio-fuels are considered the most adaptable to the present petroleum based system. Nonetheless, scaling up bio-fuels still has substantial transaction costs, for example in the US, the EPA has set the ethanol blending wall to 10%. It is suggesting that E15 may be possible though only on vehicles purchased since 2001 - this will mean having separate pumps for different model vehicles. To attain greater proportions of bio-fuel in transport fuels (up to 85 to 100%) will require the shift of the transport fleet to Flexi Fuel Vehicles (FFVs) unless economically viable bio-based hydrocarbon drop-in fuels can be developed in a timely manner. On the supply side, according to the IEA to meet the 32 EJ bio-fuels component in 2050 will require the scale up for bioethanol and diesel refineries of the order of 7 one hundred million litre capacity plants per year between now and 2015 and over 30, 104 and 165 hundred and fifty million litre capacity plants per year between 2015-2020, 2021-2030 and 2031 to 2050, respectively.

Figure 3.2: Innovation Timeline for Road Transport Technologies - 2015 to 2020 is considered a timeframe when a better assessment of the relative role of different technologies can be made (ERP, 2010)



- The electrification of transport requires an enormous scale up of decarbonised electricity production, grid reinforcement (which in turn will probably require the development of a smart grid) and installation of recharging terminals as well as the turnover of the transport fleet from fossil fuelled vehicles to EVs and PHEVs.
- Recent literature questions whether the GHG LCA of advanced bio-fuels will be sufficiently sustainable to warrant its inclusion as a credible low carbon transport fuel vector and that it is best combusted in electricity generation capacity as a part of the EV infrastructure (Gibbons et al., 2009). However, this does not address how aviation, shipping and HD vehicles will be powered if battery technology is insufficiently well developed.

What is clear is that there is a need for international strategic coordination and ongoing review to realise the most efficient energy system for transport (ERP, 2010 and BCG, 2010).



3.3.3 Influence of modelling on bio-energy impact on 2050 energy system

A final uncertainty, which should be considered is the fact that the scenarios are subject to inherent bias and methodological flaws. These are considered below:

- The main strength of energy whole system cost optimisation models like MARKAL is in holistic analysis of the energy system, enabling analysis of issues such as resource competition, selection of entire energy chains and synergies between choices in different parts of the system. They are, however, highly challenged relation to their representation of bio-energy resources' variety, paths' multiplicity, infrastructure, uncertainties in technological advances / costs and demand markets (especially in the case of heat) as demonstrated by the marked differences in bio-energy penetration in the TSEC MARKAL scenario from the MARKAL Low Carbon trajectories (Jablonski et al., 2007 and 2010). See also Dunnett (2009 - Chapter 2) for the difficulty in modelling bio-energy.

Furthermore, such approaches tend not to be well adapted to encapsulate the impact of infrastructure developments tending to limit their focus on end use technology; this is particularly important with regards the trade off in the role of electrification and bio-fuels in the transport system.

- Quantitative scenarios based on expert opinion (e.g. MacKay Plan C work) tend to have a highly simplified representation of the energy system there is no system modelling or testing of viability of supply portfolio proposed (*i.e.* scenarios may not actually be viable). They are also based on judgement, which though transparent, tends to bias the technology pool to the areas that the panel are more familiar with.

3.4 Summary

The scenarios reviewed demonstrate multiple development opportunities for bio-energy. However, there is no consensus as to the scale (ranging from 46 to 140 EJ pa), timing or sector of the 2050 energy system that bio-energy will dominate. The reasons for the uncertainties are attributable to a number of factors which include:

- The economics of decentralised CHP systems, which would facilitate high levels of bio-energy penetration, are unattractive due to the established centralised generation systems in the electricity sector and for heat - take-up is limited by the difficulty in modifying the way in which domestic, commercial and industrial properties receive heat services.
- In the case of bio-fuels for transport, the enormous uncertainty lies in the degree of development of PHEV, EV, Fuel Cell and advanced bio-fuels (including 'drop-in' fuels) and their ability to address the needs across all transport modes or only in selected niches as well as the costs involved in modifying the transport fuel infrastructure; and
- Finally, the complexity and uncertainties of costs / performance of bio-energy pathways are extremely difficult to capture and model accurately in whole system cost-optimisation models. The key role that whole system scenario modelling plays in determining the role of energy policy and of energy RDD&D may therefore inadequately represent the role of bio-energy technologies.

With the extent of the role of bio-energy subject to such uncertainty, designing the appropriate policy incentives is highly problematic. Furthermore, it is worth emphasising that the need for globally compatible transport systems suggests that international co-ordination be undertaken in order that the most efficient evolution of transport technology be realised.

4 Biomass Feedstock Production: Potentials and Research Areas

Evidence presented here supports the following elements of the ERP Bio-energy Technologies Review Executive Summary and Recommendations:

- **UK R&D:**
 - Support ongoing research where UK is a leader: plant science.
 - Establishment of a database of feedstock yields for different biotic and abiotic conditions to enable better modelling of biomass potential and matching of feedstocks to appropriate conditions.
- **UK deployment issues:**
 - Improved understanding how biomass production costs vary with location and conditions.
 - Need for better information on land use and optimisation of land for food, feed and fibre.
 - Use UK knowledge to assist other countries in sustainable production.
 - Education of farmers on sustainable farming practices.
 - Re-consider EU GMO policy with the need for public engagement.

4.1 Introduction

In section 3, it can be seen that there is no consensus on likely global bio-energy demand; here bio-energy supply side issues are addressed. Feedstock production represents a vital component in the viability of bio-energy to make a substantial penetration in the 2050 energy system for the following reasons: Firstly, in terms of economics, feedstock production makes up between 50 to 90 % of bio-energy production costs (IEA, 2010b); secondly, it tends to be where the majority of GHG are expended in the value chain (especially where conversion processes are powered by non-fossil fuels sources); thirdly in environmental terms producing it sustainably is vital to ensuring that in substituting fossil fuels bio-energy does not create other environmental unintended consequences; and fourthly, global biomass potential sets an effective upper limit to the amount of bio-energy that may be produced and therefore its maximum role in the global energy system.

This section reviews the biomass potential literature with a view to highlighting the key uncertainties in, first global and then UK, projections to 2050 and the areas of work that need to be undertaken to reduce the variability in datasets. It also reviews the nature of the main feedstock research areas - producing feedstocks sustainably, increasing the yields of existing and future feedstocks and broadening the feedstocks that may be used in bio-energy production. Within each of these categories the following are assessed: the reasons for undertaking research in these areas, the barriers to development, implications of those barriers being overcome and presently recognised research gaps.

As a caveat to each section, it is worth noting that the material for this review is based on the recent literature base and will therefore likely to be representative of developments to early 2010. Furthermore, the volume of material dedicated to each aspect of bio-energy does not in any way infer prioritisation of that particular dimension of bio-energy in the energy mix rather it represents the extent of technological development activity taking place in that area.

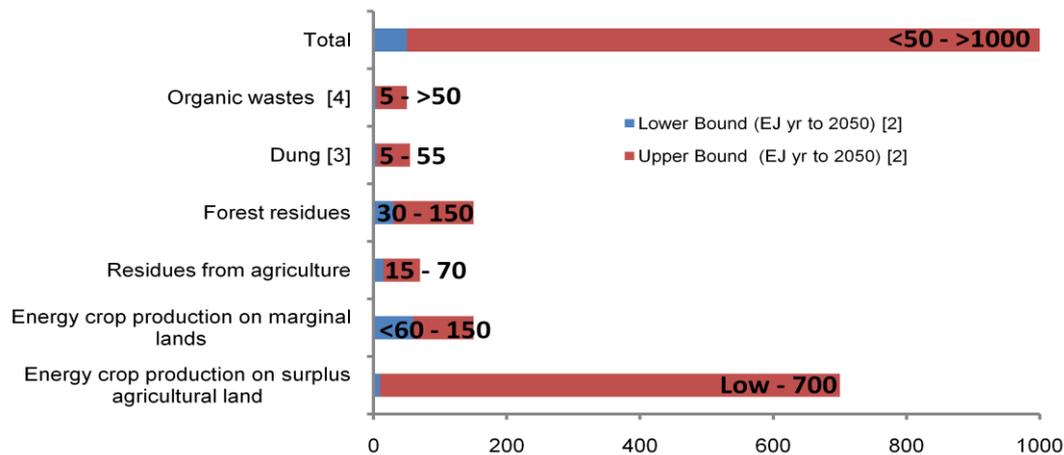
4.2 Biomass Resource Assessments

The limited scope of this review does not warrant extensive analysis of biomass assessments. However, though the importance of these projections on the potential penetration of bio-energy on the global energy system and the manner that they deal with the economics and sustainability of biomass makes an understanding of fundamental aspects worthwhile. To this end, Appendix 2 provides an edited version of Biomass Energy Europe (BEE): A Review and Harmonisation of Biomass Resource Assessments which highlights methodologies (such as resource focus, demand driven and integrated modelling assessments), key issues, problems and dimensions to global biomass assessment. UKERC (2010c) also provides a short overview of these issues. These are worth being aware of when reviewing biomass projections.

4.2.1 Biomass Projections to 2050

A large number of biomass resource base assessments have been made - those produced within the last decade suggest a potential across three orders of magnitude (Berndes et al., (2003); Smeets et al., (2007), Hoogwijk et al., (2005) and Dornburg et al., (2008)).

Figure 4.1: An overview of the global potential of bio-energy supply over the long-term for a number of categories and the main preconditions and assumptions determining these potentials (all figures are in EJ/yr)^[1]



[1] The overview is based on Berndes et al., (2003), Smeets et al., (2007) and Hoogwijk et al., (2005).

[2] A lower limit of zero implies that potential availability could be zero, e.g. if global agriculture is not modernised and additional land is needed to meet the world's food demand.

[3] Note that traditional use of dung as fuel should be discouraged. The dung potentials shown here mainly stem from intensive agriculture, which offers opportunities for fermentation and production of biogas.

[4] The energy supply of bio-materials ending up as waste can vary between 20-55 EJ (or 1,100 - 2,900 Mt dry matter) per year. This range excludes cascading and does not take into account the time delay between production of the material and 'release' as (organic) waste.

This is reflected in the IEA's most recent bio-energy report (IEA, 2009a - p81) which displays global biomass potential assessments over a range of <50 to >1,000 EJ pa - see Figure 4.1, above. It is worth noting that the upper bound projections of >1,000 EJ pa are probably unrealistic due to the fact they suggest the appropriation of a proportion of global net primary productivity that is unlikely to be tenable - see for example, Field et al. (1995), Vitousek et al. (1986) and Imhoff et al. (2006).

These projections fall within the anticipated demand side projections reviewed in section 3 (46 to 140 EJ pa).

4.2.2 Research Gaps in Biomass Projections, Ongoing Work and Recommendations for Further Work

The reason for the enormous spread in projected bio-energy potential is due to the uncertainties and sensitivities in the parameters used - these are reviewed here. Uncertainties and research gaps in the biomass potential calculations are broken down into methodological issues, general issues and then feedstock stream specific issues.

a. Methodological Issues

The database is subject to both methodological inconsistencies and several varied assumptions of key uncertain influencing factors such as:

- On the demand side: population growth and dietary changes; and
- On the supply side: productivity development in agriculture especially the extent of the modernisation of agriculture that can be achieved globally notably in developing countries where the greatest potential of biomass increase is projected (IEA, 2009a)¹⁵ but also attainable energy crop yields on reclaimed lands,

¹⁵ For example, current grain yields in Africa are around 1-3 tonnes per hectare whereas in Europe they are around 8 (FAOSTAT, 2010).



restrictions on land availability connected to biodiversity and nature conservation, roads and other infrastructure expansion.

This situation is compounded by the lack of transparency in model assumptions and calculation of energy potential from biomass streams which makes direct inter comparability between biomass projections difficult (Hoogwijk et al., 2003).

Definitions and boundary conditions for feedstocks / feedstock streams are highly varied from one study to the next. This is as a consequence of there being no single classification system for feedstocks in the case of the former and in the case of the latter the range of biomass materials included in each feedstock stream differs for each assessment. The impact of these two factors is that feedstocks are either grouped in different streams or excluded altogether depending on the scope of the assessment. This also makes direct comparison between studies problematic.

The extent of methodological variability, the heterogeneity of factors / assumptions and growing importance of bio-energy assessments for the formulation of policies to promote environmental, social and economically sustainable biomass development has led to initiatives to review and harmonise these assessments. The EU FP7 Research Programme is underwriting two projects to harmonise assessment methods and understand the reasons for the discrepancies: Biomass Energy Europe (BEE) (<http://www.eu-bee.org/>) and Classification of European Biomass Potential for Bio-energy Using Terrestrial and Earth Observations (CEUBIOM: www.ceubiom.org) - (after UKERC, 2010c).

b. General

For biomass potential studies as a whole, there is a lack of regional and national detail on land availability, infrastructure and material flows - particularly in less developed countries where the greatest increase in biomass potential is projected. This lack of data resolution and understanding makes the derivation of feedstock resource cost curves extremely difficult which in turn makes assessment of economic viability problematic.

The relatively low energy density of biomass feedstocks makes the economics of biomass highly sensitive to transport costs. This in turn makes the spatial relationship between feedstock producers and processing plant and the state of the transport infrastructure crucial. For example, in the UK the breakeven point for raw biomass (predominantly sugar beet) collection for the British Sugar Wissington Plant is approximately 50 km - suggesting that, for sugar beet to bio-energy, this is the level of data resolution that is needed to derive accurate cost curves.

The economics of biomass production will also be dependent on yields which in turn will be a function of environmental factors. Without a detailed knowledge of these issues the availability of biomass as an economically viable resource, to the extent the scenario derived projections display in figure 4.1, is uncertain. The following issues, raised by a representative of Oak Ridge National Laboratories ORNL (Grahame, pers coms), need to be addressed in this area include:

- Economic models that explicitly capture geographic variation and crop management and land use drivers at the appropriate scale;
- Environmental models that can easily be implemented and capture geographic variation and crops management features; and
- Economic and environmental linking at the appropriate scale.

It has been suggested that due to the highly variable nature of biomass cost curves, analysis at a regional, country and project level is needed. This is best facilitated by the development of case studies and that when considering economics there is a need to also assess opportunity costs, externalities and co-benefits of feedstock sources (IEA, 2011).

This lack of data resolution prevents accurate assessment of the potential impact of an expanding bio-energy sector and its interaction with other land uses, such as food production, biodiversity, soil and nature conservation, social issues, and carbon sequestration which as a result has been insufficiently analysed (Berndes et al., 2003). Though this is being redressed to some extent, for example, recent work by Dornburg et al., (2008) has attempted to better integrate environmental factors into biomass assessments there remains much work to be undertaken in this area to improve datasets. Finally, the impact of bio-energy production on agricultural commodity prices by integrating bio-energy production in existing markets is also an area for additional work (BEE, 2009).

c. Uncertainties within each feedstock stream.

Taking the categories from figure 4.1, the following uncertainties are relevant:

Energy crop production on surplus agricultural land and on marginal lands. The two forms of biomass identified for development on surplus agricultural land in the projections are:

- Conventional crops (which can be used for food and animal feed as well as bio-energy - e.g. maize, sugar-cane, rapeseed, oil palm, soybeans - these are technically exploitable at a commercial scale, the majority of which are commercially economic with subsidies and a few without); and
- ligno-cellulosic energy crops (e.g. poplar, willow, eucalyptus, miscanthus, switchgrass - which can be technically converted to bio-energy intermediaries but as yet process conversion plants are only at a development / demonstration scale).

According to analysis of projections by the IEA (2009a), the range of land surplus ranges from 0 to 4 Bha with most in the 1-2 Bha range. The releasing of such surplus land is a function of the modification of all aspects of intensive agricultural production systems. In the case of the utilisation of deforested or degraded / marginal land that is still suitable for biomass cultivation - on a global scale a maximum of 1.7 Bha has been identified. However, the supply could be low due to poor economics or the need for this land for food production (IEA, 2009a).

The sensitivities which impact potential in this feedstock stream are the availability of land, the ability for intensive agricultural production to be undertaken on a widespread basis and the obtaining of sustainable high yields once the demand for food, animal feed and fibre has been satisfied. The following uncertainties are relevant:

- Land projections are difficult to assess for two reasons. Firstly, making land available for energy crops is dependent on the ability for agricultural intensification for food production to become widespread which in turn is predicated on effective technological transfer and the ability for capital to be invested in under developed agricultural regions of the world. Secondly, global land databases are highly uncertain often displaying substantial variability between each category for example in MODIS and GLC databases for Agricultural Ecological Zone 5 the differences are over 100 Mha which is the size of the EU27 arable land take (Kline, 2010). With regards marginal and degraded lands the situation is compounded by the fact that there are no internationally developed definitions for these land types which is exacerbated by the general lack of understanding of competition with other land use functions (Hoojwijk et al., 2003).

Despite these issues, there is considered to be a substantial amount of surplus land in both OECD and developing nations - see for example World Bank (2011).

- The projections are highly sensitive to yield forecasts¹⁶ and the impacts of developing biomass on degraded / marginal land on yield. In the case of the projections in figure 4.1, average high yields are anticipated on agricultural lands to be 8-12 dry tonne ha/yr⁻¹ and lower productivity of 2 to 5 dry tonne ha/yr⁻¹ on degraded / marginal lands. Many studies have used commercial yield averages or ranges and then globalised the yield according to land availability which implicitly assumes that crops will be adaptable to a number of regions around the world. Yet the heterogeneous nature of abiotic factors makes this assumption potentially unrealistic, for example, work by Heaton et al (2004) displayed substantial variation in yields due to nitrogen, temperature and water availability. Recent work by Johnston et al (2009), who conducted an assessment of 20 bio-energy feedstock crops for 238 countries using the best available *regionally specific* data, found that their global results displayed previous yield projections overestimated bio-energy yields by 100% for many crops. Furthermore, yield data on marginal / degraded lands is based on a nascent and limited dataset (Taylor, pers comms). This highlights the need for geographically specific patterns of biomass production in different regions and land types to be developed and applied to biomass projections.

Uncertainties and developments in energy crops are dealt with later in section 4.3.3.

¹⁶ For example, in a scenario whereby bio-energy is projected to make up 104.4 EJ of global primary energy. Based on yields ranging from 75 GJ/Ha to 200 GJ/Ha, the global land requirement varies from 100 Mha to over 300 Mha - i.e. yield variations result in the utilisation of approximately between 6.6% - 20% of presently used arable land.



Residues from agriculture. These are residues associated with food production and processing such as cereals straw (primary) and rice husks (secondary residues). Biomass potential assessments calculate this stream using direct coefficients from conventional crops and therefore the availability of residues will be a function of agricultural output and the production system which in turn will be dependent on a number of environmental variables such as soil quality and climate. The following is relevant for this feedstock stream:

- The ability to assess the potential of this feedstock stream will be heavily dependent on projecting the farming practices and crop mix in the future. Furthermore, the removal of residues has an impact on the maintenance of soil quality and the degree to which fertiliser needs to be applied in the following rotation. This will have an impact on the energy and GHG balance of production and therefore the environmental credentials of bio-energy feedstock chains.
- The research needs of this feedstock stream are discussed in section 4.3.3.

Forest residues and other forest feedstocks

Forest residues are the residues left on a forest site after the logs have been removed, so tops, dead wood, leaves/needles and small branches. Harvesting this fraction is a relatively recent development, and yields are uncertain as well as being subject to sustainability constraints. Depending on soil type, some residue needs to be left on site to maintain soil carbon.

Conventional forest feedstocks are likely to become increasingly important as a bio-energy feedstock:

- Logs, round-wood and pulp wood: currently going into paper and board manufacture, may be diverted for use for energy production.
- Sawmill co-product: the off cuts from sawmills, currently chipped and sold to particle board manufacturers, could also be diverted for energy use.

In projections, sustainable energy potential from natural forest using sustainable forest management results in low potential values and the use of dedicated bio-energy plantations results in higher potentials (Berndes et al., 2003).

Uncertainties of biomass potential for bio-energy from these sectors are:

- From the forest sector, especially from plantations, arise due to the need for a relatively long term planning cycle compared to other streams because of the long rotations (7 to 30 years).
- Competition from other markets such as lumber, paper and particle board (MDF). The availability for bio-energy will be dependent on the global supply and demand trends for these sectors - see for example, Katila (2011).

Manure / Dung. The availability of dung, biomass from animal manure, is calculated by projecting the number of and type of different livestock. Each form of livestock is then assumed to produce a specific amount of dung the availability of which is dependent on its collection. In reviewed scenarios low projections are based on present global use and high end potentials on increases in livestock being significant.

- The uncertainties in projected livestock development are substantial. Past growth in the livestock sector has been a function of population growth, income growth (which results in greater meat consumption), urbanisation and technological development in livestock systems. Developments which will impact future production efficiency and therefore projected growth include breeding, nutrition and animal health as well as resource constraints of land, water and the availability of feed. How these factors evolve in the different regions and over time are highly variable (Thornton, 2010).
- The role of farming practices will impact on dung collection both in terms of the economics of collection and the fraction that may be required to be utilised as a component of soil management.

Organic Wastes. Wastes include the biomass from materials use such as waste wood and municipal solid waste (MSW). The waste streams from projections are based on different expectations of economic development, consumption and extent to which bio-materials are used (the greater use of which results in higher values).

- On top of the difficulties in assessing rates of development, consumption patterns and use of biomaterials the uncertainties in this stream lie in the degree to which recycling is taken up and the accessibility of different fractions of waste. These factors in turn will be dependent on relevant legislation such as the EU waste directive which sets an upper limit on the organic fraction that goes into landfill equivalent to a 35% reduction on a 1995 baseline by 2010 (NNFCC, 2011a).
- Waste is often an attractive feedstock due to the tipping / gate fees that are associated with them which, gives them, in theory, a negative value. Though there are some waste streams, such as separated waste wood which has a significant cost to users. The accessibility of this feedstock stream is discussed further in section 4.3.3 and the process conversion issues including negative public attitudes to waste incineration in section 5.3.2 (Table 5.3).

4.2.3 UK Biomass Potential

The issues that result in substantial global biomass variation are also relevant to the UK orientated studies (e.g. ADAS, 2009) which also demonstrate substantial variation. For example, projections for 2020 and 2030 vary by a factor of 10 (from <110 to >1,100 PJ) and 2 (from <400 to >1000 PJ), respectively - with contribution of waste and the perennial energy crops being especially variable. A key finding of the UKERC (2010c) review of UK biomass potentials - see figure 4.2, below - was the paucity in data sets for respective UK feedstock streams.

Recent studies to assess the availability and costs of the UK biomass resource relative to international resource base have been conducted by E4Tech (2009) and AEA (2011).

Spatial and regional distributions of domestically produced biomass based on land availability was the subject of work undertaken in TSEC-BIOSYS and RELU studies and can be reviewed in work undertaken by Aylott et al., 2010, Bauen et al., 2010 and Dunnett., 2009. These are summarised in figure 4.3, below.

Figure 4.2: Review of UK Bio-energy Resource Potential (modified after UKERC, 2010c).

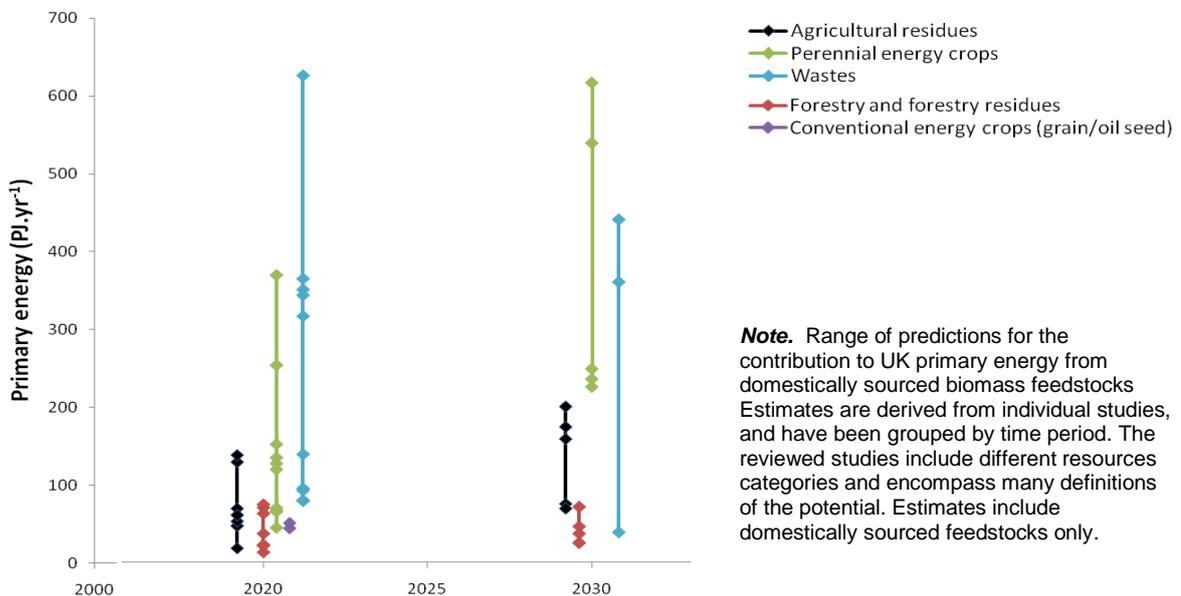
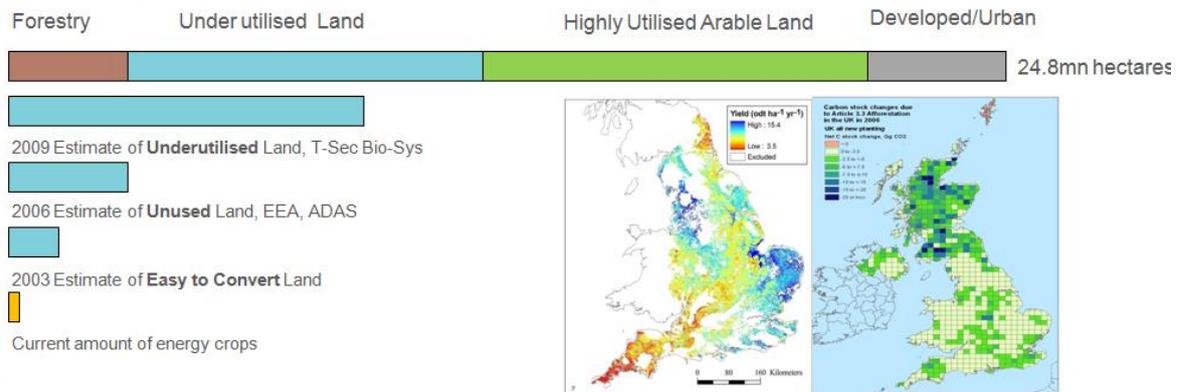


Figure 4.3: Summary of land availability for biomass production in the UK based on a number of recent studies (after ETI, 2011)



4.2.4 Implications of Biomass Projections

There are a number of issues that are raised by the biomass resource assessments - these include:

- The diversity and complexity of bio-energy feedstock streams makes the need for the drawing on a broad range of expertise when deriving projections from each stream to feed into total biomass potential e.g. fundamental agronomics, food commodity markets, waste legislation etc.;
- The integrated nature of food, feed, fibre and bio-energy issues means that policy impacts in any one aspect needs to be assessed for impact on biomass projections. For example, the 2013 EU CAP reform, the EU Pesticide Directive 2008, EU Waste Legislation 2008 *etc* will all impact on the ability for EU to produce biomass for bio-energy. The relationship between different policies on the availability of biomass needs to be better understood - especially by policy makers;
- The integrated nature of feedstock streams with large markets means that should ligno-cellulosic bio-energy technologies attain commercial economics and scale then there is likely to be impacts on pulp, paper and fibre markets in the same way that sugar-starch and oily crops have on food commodity markets. The volatility of markets on the economics of biomass streams will mean that projections will always be subject to a certain level of uncertainty.
- The enormous range of figures produced in biomass assessments, though well researched, highlights the substantial uncertainty in the parameters and datasets which will remain for the foreseeable future. This makes the need for a substantial amount of research to be conducted to reduce this uncertainty a priority. The projections, in their present state, are best used to assess trends / risks rather than as absolute figures.

Despite this uncertainty it is clear that biomass for bio-energy is available in amounts that would make a material impact on global energy supply in the future. Key areas for work to reduce uncertainty and improve quantitative assessments of biomass for bio-energy potential include:

- Developing regional cost curves by the development of a database of project, country and regional bio-energy case studies; and
- Developing a monitored catalogue of large scale (>1ha) feedstock performance in different environmental conditions. Generating this data would assist in the development of feedstocks that would be best matched to agricultural / environmental conditions globally (AEA, 2009a). This could then be loaded into modelling frameworks, which account for environmental heterogeneity, to allow more refined assessments of feedstock performance in regionally specific environmental conditions when extrapolating global biomass potentials (Johnstone et al. (2009)). This would be akin to presently available Global Oil Geo-databases.
- The regional variations in the biomass potential and energy consumption requirements (Smeets et al., 2007 - p91-92 and Hoogwijk et al., 2005 - p248) suggests that there will be regional surpluses and deficits. This therefore means that a substantial proportion of bio-energy commodities may be sourced within an international market and feedstock issues need to be considered within an international framework. This has already been born out with the RFA (2010) stating that over 18 nation states provide the feedstocks for the UK RFTO highlighting the fact that biomass production is of an international nature already.



4.3 Feedstock Research, Development, Demonstration and Deployment

In the interests of addressing the sustainability debate to which present feedstocks have been subjected, increasing the availability of biomass for bio-energy conversion and enhancing the economics of value chains - there are three main research areas of focus in feedstock production for bio-energy technologies; these include:

- Producing present and future feedstock streams sustainably;
- Getting more from existing conventional feedstocks, and
- Broadening the feedstock mix for bio-energy utilisation.

These are discussed in detail below in terms of the issues and gaps in the knowledge base.

4.3.1 Producing Present and Future Feedstocks Sustainably

The ability to produce feedstocks that are of net environmental benefit when utilised in bio-energy value chains is a substantial challenge and a key issue within the bio-energy arena.

a. Issues

- The most salient sustainability issues that are relevant to bio-energy feedstock production are: Indirect land use change (iLUC), Soil Quality / Biology, Food and Fuel, Biodiversity and Ecosystem Services, Water Use and Social Sustainability. These sustainability issues are characterised by the fact that their impacts are at many scales ranging from local to global, they are all extremely difficult to measure (iLUC is very difficult to quantify e.g. Kim et al 2011), there is a lack of consensus as to measurement methodology and existing baseline datasets are highly uncertain. Table 4.1, highlights the nature of the issues, challenges / areas of controversy and state of the debate for each issue. Greater detail of these issues is covered in Appendix 3.
- The inability to reconcile the sustainability debate is having a major impact on policy formulation - this is particularly relevant to nations of the EU¹⁷. This in turn is having an impact on confidence to invest in the bio-energy sector in the EU.

¹⁷ The EU who are presently undertaking a consultation on iLUC with a view to reporting to the European Parliament and Council, reviewing the impact of iLUC on GHG emissions and addressing ways to minimise that impact (article 19.6 of RED).

Table: 4.1: Summary of Sustainability Issues relevant to Feedstock Production. These sustainability issues are discussed greater detail in Appendix x.

Sustainability Issue	Challenges and Areas of Controversy	State of the Debate
<p>Land Use Change, Indirect Land Use Change and Soil Organic Carbon. Where bio-energy cropping occurs on land previously used for food, feed or fibre production, it displaces the previous production of food, feed or fibre. As demands for displaced production remain, it will be produced somewhere else, which might result in converting other land (releasing carbon emissions) to producing the respective amounts of food, feed, or fibre. These emissions from indirect land use changes (iLUC) are caused by the displacing bio-energy production and can, in the net balance, negate any positive effects of replacing fossil fuels (IEA, 2009a). For example, Searchinger et al. (2008) claimed that pay-back timeframes of 167 years for US corn ethanol and Fargone et al. (2008) 17 to 420 years for a variety of land types for corn ethanol.</p>	<p>The introduction of iLUC to the biomass production debate has called into question the climate change credentials of bio-energy feedstock streams. Despite the compelling nature of the impacts suggested by Searchinger and Fargone, the iLUC debate and its perceived impact on bio-energy value chains GHG balance remains controversial. On the one hand, the causes of land use change are highly complex (Lambin et al (2007) and on the other the fact is that the quantities of feedstocks diverted to bio-energy production cannot entirely be made up from yield increases on remaining land area allocated to food production.</p> <p>There have been attempts to model iLUC to derive so called 'iLUC factors' in order to internalise the emissions from indirect land cultivation.</p>	<p>The use of modelling, in particular, has been questioned due to the following factors:</p> <ul style="list-style-type: none"> • Models are not able to take into account the multiple factors in land use change decisions (Lambin et al., 2007) and the derivation of causality for any one crop is contentious (Woods et al., 2010a); • Globally, regionally and locally - detailed knowledge of land use is extremely poor (Young, 1994). It is suggested that the uncertainties in baseline data can be more significant than estimated biomass for bio-energy production land use impacts (Kline, 2010); and • The modelling projects undertaken so far have demonstrated substantial methodological variation making comparability extremely difficult (Woods et al., 2010), <p>More recent attempts have included causal descriptive approaches in a bid to make the derivation of emissions more transparent (E4Tech, 2010b). Even these acknowledge that there are substantial knowledge gaps in assumptions. The ability to improve iLUC calculation methodology and land use data sets remains a substantial gap in knowledge.</p>
<p>Soil Quality / Soil Biology. The total amount of carbon stored in global soil stock to a depth of 1 m - Soil Organic Carbon (SOC) - (1,500 Gt) is over twice as much as that in the atmosphere (720 Gt). Intensive tillage methods which turn the soil over result in the oxidation of this SOC. Furthermore, irresponsible agricultural practices are blamed for the large amount of land being degraded as a result of erosion, loss of fertility and desertification.</p>	<p>The cultivation of bio-energy crops on marginal or idle land have been shown to have the potential environmental benefit of improving management of land use with better soil restoration¹⁸, the creation of vegetation filters and possible reduction of wildfire risk. Many of the perennial and woody crops proposed for biomass dedicated for bio-energy production would actually involve no-till and no-till cover crops (i.e. the soil is not turned over but saplings are placed individually in the soil), limited fertiliser application and cropping regimes would greatly reduce the SOC loss and reduce GHG balance paybacks.</p>	<p>The introduction of sustainable agricultural practices which maintain soil health and increase yields are relevant to the maintenance of sustainable soils - see Food and Fuel section, below.</p>
<p>Food and Fuel. The 2007/08 food price spike which occurred as the US and EU bio-energy mandates were being fully implemented suggested that the divergence of food commodities to bio-energy were having an impact on food prices. The impact of bio-fuels was attributed to be from 3 to 75% of total food price inflation.</p> <p>Present production of bio-ethanol and bio-diesel continues to increase (18% between 2008-09) and yet food commodity</p>	<p>To this end, it is considered that other factors contributed to the 2007/08 food crisis; these include:</p> <ul style="list-style-type: none"> • Changing dietary habits in emerging economies resulting in the consumption of more meat and the diversion of large quantities of grain to animal feed; • Low stocks of grain due to production not keeping up with demand due to natural disasters and declines in yields in the previous decade; 	<p>There are still concerns as to whether the world is able to produce enough biomass to both feed itself and have a significant bio-energy sector. Despite the fact that food commodity prices have fallen they are still 20% higher than they were before the 2007/08 crisis.</p> <p>The underlying issue is whether sustainable agricultural practices can be introduced to increase yields, limit land expansion and maintain the ecological health of soils and water</p>

¹⁸ Bio-energy crop production can improve the soil structure, SOC, water retention capacity, reduce the impact of erosion through wind and water and the fertility of degraded lands (IEA, 2010b).

<p>prices have fallen.</p>	<ul style="list-style-type: none"> • High oil prices which increased agricultural inputs along the agricultural chain from fertilisers, fuel for mechanised establishment and harvesting to transport; • Devaluation of the US dollar; and • Domestic policy responses by grain exporting nations which reduced liquidity in the market for nations dependent on imports. 	<p>systems in order to feed an additional 2-3 Bn global population in 2050. It is considered that policies to address other drivers such as population growth, dietary preference, protected areas and forest policy will have a significant impact on the availability of land for both food and fuel (Smith et al., 2010). The realisation of ligno-cellulosic feedstocks will avoid many of the Food and Fuel debate issues.</p>
<p>Biodiversity and Ecosystems. Expanding land for agricultural food commodities and bio-energy feedstocks may result in the losses of ecosystem and biodiversity services soils and loss of carbon sinks. Even replacing the land with plantations for forest growth, as proposed in many of the biomass assessments typically do not have the same biodiversity and carbon storage benefits as primary land (particularly forest land). Reduced biodiversity is also considered to impact on ecosystem resilience - the ability for ecosystems to resist environmental pressures. Though the relationship is not clearly understood it is thought that lower biodiversity leads to increased likelihood of abrupt shifts in ecosystem states (Gunderson et al., 2007). Biodiversity loss also has an impact on the availability of the gene pool upon which future biomass / pharmaceuticals may be enhanced / developed.</p>	<p>The important role that biodiversity plays in stabilising ecosystems, and the importance of ecosystem function in the role of agriculture and the biosphere as a whole, makes the protection of bio-diverse regions and the avoidance of LUC there vital (even for subsequent plantation development). This, however, leads to the need to intensify agricultural practices on those lands that have been converted which has historically resulted in the demise of biodiversity - jeopardising the resilience of those existing agricultural ecosystems. This suggests that there is a need for revision of present intensive agricultural systems to accommodate ecosystem issues (Conway, 1997). The difficulty in measuring biodiversity and ecosystem services exacerbates the situation as the ability to collect data which is of a transferable nature and assess status is problematic.</p>	<p>Policy measures which incorporate a component of biodiversity protection (e.g. Reduced Emissions from Deforestation and Degradation and Pro-active investments in Natural Capital (Tropical Canopy Programme, 2009)) are considered vital to maintain units of land which optimise carbon sequestration and ecosystem services. The ability to implement these policies is somewhat problematic due to a lack of governance in those parts of the world where these ecosystems predominate (CIFOR, 2009). Established certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and Bonne Sucre include measurement of some aspects of biodiversity.</p>
<p>Water Use. Agriculture utilises 70% of all freshwater consumed by humans (In Developing nations it is 82% and in Developed nations it is 30% (WBCSD, 2005)). Many of areas of crop production are now maintaining food production through unsustainable extractions of water from rivers and groundwater. In China ground water extraction exceeds replenishment by 25% and in NW India it is 56% (FAO, AQUASTAT 2009). There is a concern that the growth of biomass for bio-energy supply chains will place additional pressure on freshwater resources. The issue is likely to be of pressing concern with the impact of climate change on water availability (IPCC, 2007 and Smakhtin, 2004).</p>	<p>The key challenges with regards water is the fact that:</p> <ul style="list-style-type: none"> • There is no widely accepted method of measuring water impact or metrics; • Globally, regionally and locally detailed knowledge of water availability is extremely poor; and • Knowledge of water needs at a local and regional level, for feedstock type and along bio-energy pathways is poor. 	<p>The role of water in bio-energy chains is highly complex and has largely been overlooked in the bio-energy debate (UNEP, 2010). There is a need to implement mitigation systems for bio-energy chains as well as conduct further research on the water requirements and impacts of different bio-energy pathways.</p>
<p>Social Sustainability. The development of biomass supply chains of the magnitude required to support some of the scenarios in figure 4.1 suggests the need for the establishment of a robust global agricultural sector supporting both food production and biomass for bio-energy supply; the section below suggests that with careful policy this will be possible. If so then it would also provide a socio-economic benefit in that a significant opportunity to promote rural diversification development in developing nations may result.</p>	<p>The ability to ensure wealth distribution in the benefits of the development of a robust bio-energy market are extremely difficult as decades of failed international development programmes will testify. Furthermore, measurement of the social performance of projects is often a highly subjective issue and can take time to assess.</p>	<p>Tools and methodologies to meet the new demands with the awareness of the social and economic impacts are evolving and will need to develop and be collected as the market continues to evolve (GBEP, 2011). Established certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) and Bonne Sucre include measurement of some social factors.</p>



Table 4.2, below summarises the research gaps within individual aspects of the biomass sustainability agenda. Underlying these issues are the following overarching points:

- There is a need to develop consistent methodological procedures for each sustainability issue to facilitate comparable accounting and monitoring procedures and based on this provide assessments of feedstock production techniques which optimise environmental, social and economic value (The Royal Society, 2008).
- The essential need for reliable information on land-cover, use, productivity, soil qualities, stocks, fluxes, environmental services as well as develop new approaches and collaborations required to understand the complexity of the challenges with such broad scope (Kline, 2010).
- There is an increasing consensus that there is a need to grow both our food and energy crops for future generations on the land which is presently cultivated by the development of sustainable intensification farming practices and integrated land management practices¹⁹, rather than increasing arable and pasture land take (The Royal Society, 2009 and Godfrey et al., 2010).

Within this framework, the international nature of the sustainability agenda highlights the need for the UK to be engaged / aware of developments globally to facilitate understanding of their application to UK bio-energy targets.

Table 4.2: Summary of knowledge gaps in the sustainability agenda.

Indirect Land Use Change (ILUC)
<ul style="list-style-type: none"> • There is a need to develop internationally agreed best practice, transparency in modelling frameworks for ILUC and the role of co-products. At present there is no agreed framework for ILUC modelling and methodological inconsistencies are having high order impacts on results (Woods et al., 2010b). This will result in confusion for policy formulation in the US and EU and be perceived as a trade barrier for bio-energy exporting nations. • There is a need to gain a better understanding of land use globally. Data quality may be improved if there is better data resolution and capacity to match satellite data with ground truthing surveys (Brown et al., 2005); this would facilitate a better understanding of LUC causality. • The definition of 'alternative' lands (such as idle, marginal, and degraded land) and 'alternative' feedstocks (wastes, by-products and residues), their contribution to reducing indirect effects for biomass production and the incentive framework to motivate biomass activity on these lands and use of alternative feedstocks needs to be assessed.
Food and Fuel
<ul style="list-style-type: none"> • The potential contribution of improvements in yield and productivity of both energy and conventional agricultural crops to decreasing indirect effects and reducing the potential for conflicts between food and fuel (AEA, 2009a). The ability for yields to be increased under abiotic stresses is also required (The Royal Society, 2008). • Assessing the potential for developing countries with underused land to establish biomass production industries serving local, national and export markets. The ability to develop logistical capacity, fulfil social and environmental sustainability criteria and economic requirements. • Monitoring the potential harm to poor and vulnerable people in developing countries arising as a result of higher prices for food on international markets, and from localised effects on access to land and working conditions of marginalised people resulting from domestic development of bio-energy industries in the developing world (AEA, 2009a). • The intimate relationship between food security and bio-energy is demonstrated by the use of traditional biomass to cook in less developed nations. In section 2, it is estimated by the IEA that traditional biomass makes up over 40 EJ of final energy consumption. The management of the biomass that is accessible for the sector of society that depends on traditional biomass and how they substitute cooking fuel without exacerbating environmental sustainability (i.e. moving to more GHG intensive fuels) and there disadvantaged state is an area that is under-researched and requires focus.
Biodiversity and Eco-systems / Soil Quality and Biology / Water and Social Sustainability
<ul style="list-style-type: none"> • Understanding the direct effects of bio-energy crops on natural resources (soil and water), biodiversity (role of invasive species) and ecosystems. The availability of a monitored catalogue of feedstocks to generate this data would assist in the generation of feedstocks that would be best matched to agricultural / environmental conditions globally (AEA, 2009a). • There is a lack of information and decision support tools to predict the impact of the removal of residue as a function of soil type (US DOE, 2010a).

As things stand in the bio-energy sustainability debate - the lack of consensus as to the methodology that should be used to measure impacts, the extent that impacts can be wholly attributable to bio-energy feedstocks, uncertainty in datasets and the comparability of tradeoffs (*i.e.* how does one reconcile trade off between excess water use and GHG savings) is fundamental to the present discourse. It has led to a polarised debate in which the potentially negative aspects of bio-fuels have been most widely reported. This in turn has made policy formulation extremely difficult and therefore impacts on market confidence. This is best exemplified by publication of the ILUC paper by Searchinger et al., (2008) in Science which, in the UK, prompted the Gallagher Review (2008) that in turn resulted in the deferring of the RFTO targets by over half from the 5.75% by energy to ~3% by volume by 2010/11.

¹⁹ According to Lal (2009) revised global land management could sequester between 2 to 3 GtC pa.



However, the agenda has moved on substantially since 2008 and there are signs that the balance of the debate is being redressed as is evidenced by the fact that:

- Though many of the early biomass assessments have been criticised for their very simplistic assessments of environmental constraint. Recent work by, for example, Dornburg et al., (2008) have attempted to factor in environmental constraints, and suggests that a realistic projection based on the world growing food needs will be of the order 220 to 500 EJ pa; this is in line with IEA (2009a) recent assessments and with the revisionist thinking with regards the potential of sustainable bio-fuels production in conjunction with food needs within environmental constraints (Tillman et al., 2009).
- The GHG emissions from LUC caused by bio-energy feedstocks are only a fraction of all GHG produced by global LUC (which account for 16 to 20% of net global GHG emissions) suggesting that LUC needs to be managed across a larger agenda. There are indications that the sustainability agenda, which has been ruthlessly applied to bio-energy feedstocks, has already broadened into the food commodity arena. This is demonstrated by the situation with oil palm which was initially limited to issues surrounding biodiesel production but also recently consumed food producers and retail outlets which utilise palm products such as Danone, E.Leclerc and Aldi (The Economist dated 26th June 2010). The broader role of GHG emissions from agricultural is also undergoing greater scrutiny - see for example Worldwatch (2009), as well as the need to manage emissions derived from land use as whole e.g. Wise et al. (2010).
- The need to address the sustainability issues has led to the development of chain of custody and supply chain management systems (IPIECA, 2010 and Dam et al., 2010) and a number of initiatives to provide assurance of the sustainability of bio-energy feedstocks²⁰ at a global and regional level. These have sought to address a number of issues such food security (e.g. Bio-energy and Food Security Criteria and Indicators by the FAO), promote best practice when assessing GHG emissions in environmental, social and economic principles (e.g. Global Bio-energy Partnership), voluntary stakeholder groups to establish third party certification schemes for sustainability standards (e.g. Roundtable on Sustainable Bio-fuels). At a regional level, the EU has introduced sustainability criteria which have to be adhered to comply with the Renewable Energy Directive and in the US the Environmental Protection Agency has mandated GHG savings that renewable fuels have to comply. These are, at present, perceived to be credible and demonstrate a proactive response to the mitigation of sustainability impacts unprecedented in any other food or energy sector.

Taken in **this** context, it is suggested that the sustainability agenda, particularly with regards iLUC / LUC is diverting attention from understanding the opportunities that exist to how to integrate / intensify agriculture and use land more effectively. Though the definition of alternative land is poor there is sufficient confidence as to where the areas of marginal and idle land are (World Bank 2011). Sustainable practices to enhance carbon sequestration, water recycling and improve bio-diversity on degraded / marginal and idle lands are also sufficiently robust. Practices to avoid enhancing emissions from LUC are known (e.g. avoiding high carbon (above and below) ground carbon lands, increasing yield intensity per unit area of land utilised and the use of efficient production systems which optimises the production of co-products). Therefore an effort should be made to focus on using land as efficiently as possible (across all agricultural commodities) and start implementing best practice agricultural processes to produce biomass sustainably (Faaij, pers coms). In order to enhance knowledge in these areas best practice data should be collected to feed into land use and biomass projections. Only then will the state of knowledge as to the feasibility of producing the biomass sustainability to met global demand will be validated (e.g. Dornborg et al., 2008 and Wirsenius et al., 2010)²¹. It is worth stating that the role of a broad range of policy decisions in agriculture, forestry, energy and conservation sectors rather than just bio-energy in achieving this cannot be underestimated. Furthermore, policies addressing other drivers such as population growth, dietary preference, protected areas and forest policy will have significant impacts on the availability of land for food and fuel are also important (Smith et al., 2010).

²⁰ Though the ability to develop metrics that are relevant and easy to measure for feedstock producers - still remains problematic (Graheme, pers comms).

²¹ The work by Wirsenius, Azae and Berndes (2010) suggests that there is opportunity for the food system to operate at lower land use from 5.4 Bha in a BUA scenario in 2030 to a possible 4.4 Bha - suggesting that there will be sufficient land available for both biomass for food and energy.



In summary, the impact of large-scale energy crop production on environmental and socio-economic aspects can be both positive and negative, and are highly dependent on the specific situation and location of projects. There is the need on the one hand to reconcile the fact that the bio-energy industry needs to rapidly expand to attain economies of scale (which would be more attractive to investors) and the fact that having stringent sustainability criteria will negate the ability to produce sufficient compliant feedstock to attain these economies. On the other is the fact that insufficiently robust criteria may result in the potentially large one off GHG release from soil carbon stocks from LUC. The scientific knowledge to reconcile these issues is available to develop stable policy. Policy makers also need to recognise that the issues are interconnected and that policy measures to deal with sustainability need to be both complementary and stable; feedstock auditors and producers take time to adapt to new criteria and the administrative burden. The ability to optimise geo-political frameworks in order to realise the benefits of increased sustainable biomass production on the scale for bio-energy to have a material impact on global energy systems in the context of these tensions will be challenging. However, they should proceed within a collaborative framework of international standard development in order to collect reliable information to enhance the understanding of manner in which biomass is grown across all end uses - food, feed, fibre and energy.

4.3.2 Getting more from existing bio-energy feedstocks

Research into dedicated bio-energy feedstocks are based on the assumption that the scaling and economics of heat and power systems and ligno-cellulosic conversion technology for transport bio-fuels will be realised at a commercial scale in the near term (5 to 10 years - IEA, 2011). In the interim, in the interests of fulfilling the sustainability agenda and attaining favourable economic bio-energy yields a focus of the research effort is based on attaining more from present feedstocks (also termed 1G+).

The most widely used feedstocks for the production of heat and electricity from biomass, at present, are forest feedstocks and agricultural residues and various organic wastes.

Conventional sugar, grain, and vegetable oil crops are used for liquid bio-fuels production for transport (IEA, 2008). In 2008, around 90% of ethanol is produced by sugar cane and corn (approximately 45% each) and the remainder was produced by wheat (7%) and sugar beet (2%). Biodiesel feedstock is approximately 85% rapeseed, 10% soy and the remainder coconut and palm oil (Accenture, 2008).

With Brazilian based sugar cane ethanol being the only bio-fuel that is performing competitively (economically and sustainably) it is likely that this source of feedstock will remain for the foreseeable future - dependent on the rate of development of drop-in fuels. The role and prominence of other feedstock streams is less certain.

a. Issues:

- Attaining of higher yields from presently used feedstocks and closure of the yield gap is probably one of the quickest ways of enhancing feedstock production. Higher yields have been realised in US corn by the ability to utilise hybrid genetics and biotechnology which have driven a five-fold increase since 1940. In the case of closing the yield gap, 2005 corn yields in the US stood at 9.35 t/ha (149 bushels/acre) whereas in India and Sub-Saharan Africa the yields stood at 1.95 t/ha (31 bushels/acre) and 1.56 t/ha (25 bushels/acre), respectively. The technologies and better agronomic practices that have realised increased yields in the US can be applied to other continents and crops - this is a function of technology transfer and international development (see also Appendix 3.3 on Brazilian agriculture).
- The mechanisms by which feedstocks may be enhanced are outlined in table 4.3, below.

Table 4.3: Mechanisms by which gaining more from existing feedstocks might be achieved (E4Tech, 2007a).

-
- Increase energy outputs of plants:
 - Plants to produce greater quantities of useful compounds; and
 - Developing crops with more rapid growing cycles.
 - Develop plants with harvestable components (molecular farming²²):
 - Screening of crops with potentially useful, harvestable components;
 - Identification of crops that can be easily transformed (genetically) to produce desirable components such as, for Ligno-cellulosic crops, improving ratios of cellulose to lignin content; and
 - Development of crops from which components can be easily removed in the field or after they have been harvested.
 - Reduce inputs and carbon intensity per unit feedstock
 - Development of plants that require fewer inputs (fertiliser, water and pesticides) and management;
 - Development of low ash crops; and
 - Minimising effects of land use change on carbon intensity of biomass.
 - Increasing the biotic and abiotic range over which bio-energy crops can be grown:
 - Increasing the stability of a chosen crop over a wider geographical range; and
 - Development of regionally adapted crops.
 - Increase accessibility of useful plant components (chemical and energy):
 - Manipulating plants so that cell walls can be more easily deconstructed facilitating easier accessibility of valuable components; and
 - Making plants produce enzymes that will hydrolyse their own cells or assist the release of useful compounds.
-

b. Potential areas for research

- The mechanisms in table 4.3 may also be applied to enhance some future feedstocks such as oil crops and ligno-cellulosic feedstock's in order to deliver sustainable yield optimisation, reduce land footprint and GHG profile. As the establishment of these crops are still relatively small (in terms of land area) they are not considered to be fully commercialised and are discussed in section 4.3.3, broadening the feedstock mix - below.
- There is an enormous amount of work taking place and given the UK's substantial world renowned capacity²³ pioneering advances would be possible in this area albeit with the appropriate funding and level of integration with industry. With 50 to 90% of costs bio-energy being in feedstock production it is an important capacity to maintain and the need to collaborate internationally is vital due to the ongoing work taking place in the US and Brazil - see Section 6.
- However the opportunities in table 4.3 need to be considered together to ensure feedstock optimisation. It is especially important to consider the entire bio-energy process chain as work in feedstock research has implications on the economics, sustainability, reliability, reduction in carbon intensity, potential modification of agricultural routines and ease of process conversion across a range of technology chains. This highlights a recurring aspect of bio-energy issues - the need for integrated whole systems thinking both along and across the chains.

4.3.3 Broadening the feedstock mix

The extent to which presently used bio-energy feedstocks have been subjected to sustainability issues and the desire to increase biomass potential has resulted in the research drive to broaden the feedstock available to produce bio-energy. These include the use of dedicated ligno-cellulosic energy crops, oil crops, algae, ligno-cellulosic residue components of plants (corn stover, wheat straw and forest residues) and waste; these are considered in turn below.

Ligno-cellulosic energy crops

The future energy crops that presently have the greatest research focus include:

- Perennial herbaceous ligno-cellulosic crops such as miscanthus, switch grass, high sugar grasses and energy cane;
- annual herbaceous ligno-cellulosic crops such as Sorghum; and
- woody ligno-cellulosic crops such as hybrid poplar, willow and eucalyptus.

²² Molecular Farming is the use of genetically engineered crops to produce compounds with therapeutic value.

²³ The UK has a number of internationally renowned capacity in plant sciences and agronomics - see Section 6.3.1.



For more details on miscanthus and willow see NNFFC 2010a and b.

a. Issues

- These crops are being grown commercially for power and heat applications, but their use is still not widespread, and the extent of deployment of these feedstocks is highly variable. For example (after E4Tech, 2011a):
 - Woody Crops deployment ranges from 7 - 10 Mha in China (estimate of wood fuel plantations) to 2,500 ha in Demark (in the UK there are 5,500 ha); and
 - Grassy energy crops ranges from 18,700 in Finland (Canary Grass) to 300 ha of Miscanthus in Germany (In the UK 13,500 ha of Miscanthus has been established).
- Within the UK, ligno-cellulosic crops of interest are willow and popular short rotation coppice (SRC), miscanthus, reed canary grass and switch grass (Panoutsou et al., 2010).
- The focus of the bio-energy industry, particularly in the area of bio-fuels, has been the process conversion improvement rather than feedstock optimisation (IEA, 2008). Within the feedstock optimisation sector there is no consensus as to where to focus work (IEA, 2010b and E4Tech, 2007a).
- Perennial energy crops have had relatively little effort dedicated to increasing yields which has led to the postulation that, though harder to manipulate, substantial improvements may be made analogous to those for food crops. However, with the relatively nascent state of new energy crop research, the application of many of the new energy crops on a commercial and global scale is fraught with uncertainty which may result in the overestimation of viable yields and their sustainability credentials.
- Large scale field trials of energy crops of the order of 2,500 ha (~6,000 acres) need to be undertaken to ascertain²⁴:
 - If commercial yields are achievable;
 - data on commercial production costs can be measured; and
 - environmental sustainability criteria can be measured and tested in terms of: soil carbon / erosion, GHG emissions, water quality and consumption and wildlife and biodiversity.

In reality plot sizes tend to vary according to that which researchers are assessing (Gwyn, pers comms). Research plots for discrimination of genetic types or agricultural treatments, which is stage where research in future energy crops are, tend to be of the order of <1 to 2 ha (and some as small as 4 m²) with the largest being no more than 5 to 10 ha in the UK (Karp, pers comms) which makes assessment of commercial yields, costs and sustainability issues problematic. This in turn makes the reliability of feeding yields from these studies into resource potential projections subject to uncertainty. It is noteworthy studies for assessments of biodiversity and water yields (in the UK RELU study) were substantial ranging from 4 to 2000 ha in size suggesting that large scale studies are available for research projects.

- Also notable is the US government funded Sungrant initiative www.sungrant.org established for the purposes of researching and developing sustainable and environmentally-friendly bio-based energy alternatives. There are extensive crop trials of a wide range of energy crop species across the US. The aim of the trials is to understand relative yields of different energy crops. The scale of the sites is large, 17 hectares per entry, and 4 replicates mean 66 hectares at each site, which should give excellent data for statistical purposes, as well as understanding mechanisation issues.
- The relationship between warm season grasses and short rotation woody coppices on the soil requires further work in terms of impact on SOC sequestration, GHG emissions, nutrient water pollution (nitrogen and potassium) and wind erosion as well as the impact on the environment (Blanco-Canqui, 2010)²⁵.
- Recent work by the IEA (2010b) also suggested that little research on indigenous Ligno-cellulosic crops has been undertaken in Asia or Africa. Therefore there is a risk that potentially invasive species may be introduced to these regions should bio-energy demand in these regions become significant. Experiences in South Africa and other countries show that non-native species can become a severe threat for local biodiversity.

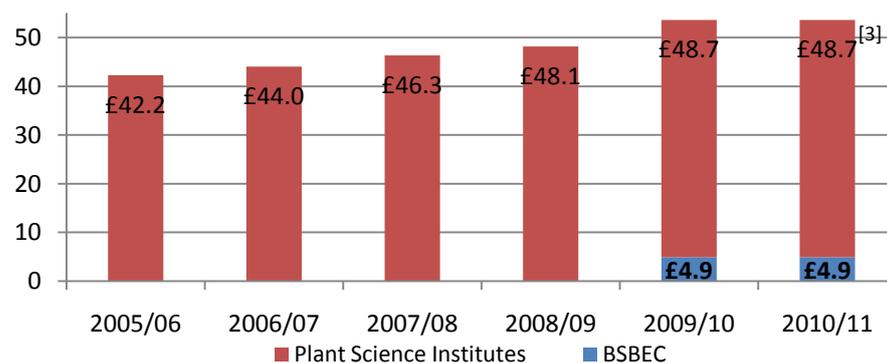
²⁴ These can be extremely expensive, for example, in the US farmers charge \$450 per acre per year for crop trials. For a 6,000 acre trial, that's \$2.7 M on just leasing the land before starting to incur costs for conducting the trials (Robin Grahame, pers coms).

²⁵ Though it is known that in well managed regimes these crops can be of a net positive benefit (Blanco-Canqui, 2010).

b Potential areas for research

- UK capacity for large scale plant breeding is impacted by the EU stance on genetically modified (GM)²⁶ crops (moratorium on biotech GM) where many feel greatest (novel) opportunities lie - see also section 5.4.5 for more details on the potential role of GM. Despite the moratorium, it has been recommended that species diversity and genetic resources should be captured as potential new feedstocks and crop development for year round supply of feedstock to feed into the supply chain (The Royal Society, 2008).
- It is vital that the UK maintain its global position in plant science and agronomy as, not only within a well coordinated biomass programme, does it facilitate the optimisation of feedstock potential but there is also substantial scope for plant research to assist in climate change mitigation land use practices. Though the nominal funding for centres has been maintained the number of plant scientists at plant science institutes has reduced (various interviews)²⁷. Figure 4.4 displays the UK BBSRC funding for plant science institutes in the UK which continues to grow peaking at £53.6 M in 2009/10. The impact of the 2010 Comprehensive Spending Review budget cuts on the publically funded plant sciences is not known though the establishment of the BBSRC Sustainable Bio-energy Centre (BSBEC) in 2009 for 5 years with industry (funding 20%) will have resulted in the ring fencing of a number of programmes to 2014. It is essential that this capacity is not further eroded.
- Plant research and agronomic improvements need to be considered within the context of the whole bio-energy processing systems approach (*i.e.* working with pre-treatment and fuel chain developers) and in a framework of land-use sustainability (The Royal Society, 2008).

Figure 4.4: BBSRC funding for plant science institutes in the UK since 2005 (£M). This has consistently been between 16 to 18% of total BBSRC research spend^[1].



[1] This includes research grants, initiatives, Core Strategic Grants/Institute Strategic Programme Grants, fellowships, equipment and facilities. It excludes studentships, capital and buildings.

[2] BBSRC commitments to the BBSRC Sustainable Bio-energy Centre (BSBEC) totals £19.5M over 5 years from 2009 with a further £5M funding from industrial partners. One third of this is as cash contributions and the other two thirds as in kind contributions.

[3] BBSRC funding for plant sciences institutes data not available for 2010/11 and therefore assumed to be the same as 09/10.

More details on the innovation needs for energy crops can be found in Appendix 4. A high level review and assessment of issues regarding developing energy crops such as business value creation opportunities, deployment to date and cost reduction opportunities can be found in E4Tech (2011 a).

²⁶ Under EU legislation, GM organisms (e.g. seeds) and food or feed products will not be approved for trial release or marketing unless a risk assessment indicates that human health and the environment will not be compromised. Decisions on the marketing of GM products are taken at EU level, while decisions on R&D trials are taken nationally.

²⁷ This has occurred due to changes in the way that costs are accounted for which mid way through the last decade which included additional personnel costs thereby effectively reducing the funds that were dedicated to research.



New Oil crops

a. Issues

Jatropha and Camelina are two of the main oil crops that are gathering interest, in addition to a range of tropical trees bearing oil rich nuts - though only for use in bio-fuels for transport as a substitute for diesel. Estimates of bio-diesel production from oil crops stand at around 3.4 EJ pa (E4Tech, 2011a). With regards oil crop establishment:

- Jatropha ranges between >2 M ha in China, 0.5 Mha (with plans for an additional 13 Mha) in India and 120 kha in Africa; and
- Camelina for food is widely established as a food globally but as a bio-energy feedstock 9,000 ha is being developed in the US.

b. Potential research areas

Although the UK is renowned for its work on oil seed rape breeding and research, there is little work being carried out on new oil crops. This is partly because the main focus of work has been on tropical crops in particular Jatropha. The UK's capabilities in plant science suggests that there is scope for lab and glass house based research on these plants.

A high level review and assessment of issues regarding developing oil crops such as business value creation opportunities, deployment to date and cost reduction opportunities can be found in E4Tech (2011a).

Algae

a. Issues

The global algal potential is substantial, according to a high level study by Ecofys (2008) the technical potential for micro algae is of the order of 90 EJ pa and for macro-algae it is 6,145 EJ pa. There are, however, a number of issues that need to be addressed with regards this feedstock in order to realise such potential:

- The economics of micro-algae are highly uncertain. Though on the one hand:
 - Micro-algae have higher oil yields, greater photosynthetic efficiency and rapid growth rates means that they can produce 10 to 100 times more oil than land based plants.
 - high value products can be produced such as therapeutic supplements, pharmaceuticals, fertilisers, health food/nutritional supplements and energy carriers (hydrogen); and
 - the residues can also be used in CHP systems.

On the other, some work on micro-algae has suggested that:

- as an energy production system alone it is uneconomic (due to high capital infrastructure costs, problems of contamination (in open pond systems) and costs associated with harvesting and drying) and that only in conjunction with other high value products, wastewater treatment and / or bioremediation will the economics balance.
 - Micro-algae production economic viability may be best realised by the co-location next to energy plant operators for an accessible and cheap source of CO₂ to feed the algae, reducing the number of locations that plants may be located.
- As yet there is no accepted consensus on optimum design for large scale algal breeding though the two main emerging configurations are photobioreactors (within which there are a number of subsystems such as flat plate, bag and tubular designs) and open raceways - for case studies of each see IEA, 2009c - p11 and 9, respectively).
 - The availability of macro-algae as a natural occurring feedstock for energy production is poorly understood - though it is considered to be a vast resource for nations with the appropriate available coast line. The most likely route for large scale energy development is through cultivation rather than the exploitation of natural stocks. Already farmed as a food source on a large scale in the Far East, there are also small production programs in Europe, for example, in France for alginates, in Scotland at a research scale and Scintef in Norway for Statoil.



- The main area of interest for energy production from macro-algal biomass has been methane production from anaerobic digestion (AD). Subject to some processing the digestate is also suitable as a fertiliser in agriculture.
- b. Potential research areas
- For micro-algae, the main areas that require further research are (The Carbon Trust, 2010a):
 - The selection of algae from the enormous genetic diversity that has yet to be tapped;
 - optimisation of algae (relative to conditions such as light, temperature, nutrients, population density) to maximise oil output;
 - optimisation of photo bioreactor design such as light availability, density of algae, CO₂ concentration, harvesting of algae - this has been a difficult area to scale up;
 - oil extraction and separation; and
 - use of algae residues such as co-firing and other products to improve the economics of the system.
 - The fact that only a small proportion of the known species of micro-algae have been examined. Of the 40,000 to 100,000 species that are known to exist, only a few thousand have been studied. This means that there is a need to develop screening procedures which can be used to quickly filter those algae that are most appropriate for mass cultivation and the appropriate type of fuel production. There is also a need to better understand the metabolic pathways of algae which is vital to exploit the lipid oil potential of the organisms via genetic engineering. The ability to match strains to the most efficient growth systems is also important with a drive in the sector to reduce the number of steps in the conversion process.
 - The majority of micro-algae work that has been undertaken is US centric: US\$25 M was invested from 1978 to 1996. Recently, US\$170 M of US government funding has been dedicated to algae and globally US\$256 M in venture capital has been invested - mostly in the US (Accenture, 2009).
 - There are substantial variations in claimed yields, Life Cycle Assessment (LCA) and economics for micro-algae. Claimed yields range from an overly optimistic 90,000 l/ha/yr to the more realistic at 9,000 to 45,000 l/ha/yr (IEA, 2009c). Greenhouse gas LCA for algae varies depending upon the processing route with claims of -50% (IEA, 2009c) to -85% and +14% (Ecofys, 2008), relative to diesel. There are a wide variety of quoted costs with recent studies indicating US\$2 to 5/l for open pond and heterotrophic systems and US\$ 5 to 6/l for photobioreactors; with the algal production process under development it is considered that there is substantial scope to reduce costs and improve efficiencies.
 - The UK has substantial expertise in marine science and algal research. However, the EU's conservative stance on GMO may have an impact on the feasibility of conducting large scale field trials on algae that have been genetically modified and result in the location of this research outside of the UK and EU (see above).
 - The areas require further research in macro-algae work include (IEA, 2009c and E4Tech, 2011b):
 - Improve yield and quality through selective plant breeding at scale and with optimum nutrients;
 - pre-treatment optimisation to improve the performance for anaerobic digestion;
 - avoid toxicity problems caused by high levels of phenols, heavy metals, sulphides, salts etc which can inhibit methanisation;
 - the development of bacteria that can be used for both methanisation and bioethanol production; and
 - cross-develop AD technology from terrestrial feedstock designs to those specifically for seaweeds.
 - The nascent state of development of the macro-algae technology is such that yield claims, LCA and economics are poorly developed being dependent on the amount of fertilisation, sea conditions, total surface of covered area and species used though high level estimates suggest an LCA saving of between 42 to 88% relative to diesel fuels is possible (Ecofys, 2008).
 - Knowledge of the environmental and economic impact of large scale algal development for bio-energy has been poorly researched, for example, the potential for eutrophication, integration with marine cultures and season penalty. It is an important area of research to reconcile the benefits of utilising large quantities of algal biomass as a feedstock for bio-energy systems. The establishment of the NERC-TSB Algal Bio-energy Special Interest Group is seeking to address these issues.



With all this taken into account it is generally accepted that the potential of aquatic biomass production is high but will be extremely difficult to attain at a commercial level scale in the short-term and as a result will require long-term investment (>10+ years - Accenture, 2009, Carbon Trust, 2010). Nonetheless, it is generally considered that the potential contribution from the feedstock both as a fuel, industrial biotechnology platform and opportunity for bio-prospecting for novel pharmaceuticals is such that R&D projects should be dedicated to answer the extensive research questions.

The UKs expertise in both macro and micro algae makes this an attractive area for work due to the extent of fundamental research required and the need for an integrated approach to processing. To this end, for microalgae the Carbon Trust launched the Algal Bio-fuels Challenge and Scottish Association for Marine Science is co-ordinating the BioMara project for bio-fuels. For macro-algae the SUPERGEN Bio-energy II consortium has allocated £500,000 to research ethanol production and pyrolysis from seaweed. Though the Carbon Trusts Algal Bio-fuels Challenge was terminated in early 2011 this body of work should be consolidated and built upon - see Schlarb-Ridley (2011).

More details on the innovation needs for micro and macro algae can be found in Appendix 4. A high level review and assessment of issues regarding developing micro and macro algae such as business value creation opportunities, deployment to date and cost reduction opportunities can be found in E4Tech (2011b).

Ligno-cellulosic residues

a. Issues

- Though the projections of availability of forest / agricultural residues is substantial (between 45 to 220 EJ pa globally - figure 4.1) the ability to utilise these feedstock streams on a large scale basis is dependent on the ability to develop effective advanced, and as yet, commercially unviable conversion technologies such as gasification and pyrolysis and some presently commercially viable technologies but with limited deployment such as anaerobic digestion and combustion (- these are explored in detail in section 5.3).
- In 2006 in the UK it is estimated that agricultural residues stood at 2,912,000 t/pa and forest residues 1,987,000 odt pa (AEA, 2009b).
- There are, however, a number of issues that need to be addressed with regards these feedstocks:
 - With regards agricultural residues, though the projected availability is substantial, it is not a free resource. The removal of residues incurs the need for enhanced fertiliser use²⁸ in the following growing season, the cost of collection and bale-ing for transport to conversion plant.
 - And, in the case of forest residues collection can be energy intensive and expensive.

b. Potential research areas

- Recent work by the IEA (2010b) suggests that two thirds of the agricultural residue potential is located in developing countries, however, due to the fact that the agricultural sector in these nations is substantially different from OECD nations there is a substantial gap in understanding of material flows of these feedstocks. Therefore it is vital that the following be considered and assessed (after IEA, 2010b):
 - a detailed understanding on a country and residue stream basis be undertaken in order to ensure economic viability and sustainability issues are met.
 - The assessment of opportunity costs for residues is not possible without the existence of markets for these material flows - though indications are that they are cheaper than dedicated energy crops.
 - And, the impact of the absence of an effective logistical framework which is exacerbated by the complex land property structure and the predominance of small holdings which increase the intricacies of feedstock logistics.

²⁸ The impact of which will be dependent on the region of the world considered, the fertiliser type (which in turn have different GHG impacts both for production process and application on fields), the optimum yield and protein content of the crop (HGCA, 2009).



Waste

a. Issues

- Waste is an attractive feedstock as it avoids many of the sustainability issues that have been levelled at other feedstock streams. Global projections of waste range from 5 to 50 EJ pa (Figure 4.1). Other than power and heat generation Energy from Waste (EfW) combustion plants the ability to exploit this stream for intermediaries at scale is dependent on the ability to develop the appropriate conversion technologies. Energy from waste via combustion is a commercially viable technology having been successfully developed in Denmark where EfW systems provide up to 60% of the nations heat (via its well established district heating networks) and some power needs (IMechE, 2009). Based on ETI analysis (2011) ~30TWh electricity and +35TWh heat is the UK opportunity from energy from waste development. This includes the use of wet wastes in anaerobic digestion for the production of biogas as stipulated in the AD Strategy and Action Plan (Defra, 2010). However, in the UK EfW plants do suffer from substantial planning constraints due to public perception issues (IMechE, 2009).
- Though it is estimated that annually over 4 billion tons of waste are produced globally waste streams are extremely diverse ranging from municipal solid, construction and agricultural waste and knowledge of the availability of some of these streams is not well understood (IMechE, 2009). Waste can be expensive to collect due to the dispersed nature of the some of the streams and the fact that there is often a need to separate usable feedstocks and remove contaminants. The need to pick up small volumes of waste from dispersed locations may heavily impact the GHG balance of the processes though this would need to be considered against other available disposal methods and their GHG profile.
- Waste is a substantial resource in the UK with over 220M tonnes of controlled wastes produced annually (Municipal Solid Waste, Commercial and Industrial Waste, Construction and Demolition Waste and Bio-solids (AEA, 2009b)). However, the energy content of this waste and its distribution has not been subject to detailed assessment.

b. Potential research areas

- The heterogeneous nature of waste streams means that there are a number of technologies that are available in the conversion process ranging from biochemical, thermo-chemical, physiochemical and hybrid biochemical gasification. Each conversion processes tends to have different requirements for separation and processing and with no commercial scale tested technologies there is no standardisation process for waste pre-treatment for energy.
- Though some source segregated wastes have costs associated with their utilisation (e.g. separated waste wood) generally waste has a 'negative cost' due to authorities paying for disposal of waste. Should the value of waste for energy result in the feedstock becoming commoditised the economics of the stream would be radically altered as stockpiles of high energy materials are depleted. In some regions, such as Europe, which are facing a shortage of landfill capacity the utilisation of waste streams for energy is attractive and the economics should remain favourable; whether this will be the case in other regions is not known.
- Policies and legislation for managing waste as an energy source is not well co-ordinated or incentivised in many nation states (IMechE, 2009 and Accenture, 2009). In the UK for example, renewable energy policy incentivises the burning of waste for energy (through ROCs) whilst waste policy prioritises waste minimisation and recycling. Indeed the increasing drive for better resource use efficiency is advocating the greater need for recycling and waste minimisation (ICE, 2011) which might radically alter the composition of waste. This in turn would have a substantial impact on energy content as would occur, for example, with the removal of plastics and fibre.
- There is limited work on the indirect effects of wastes and residues. That undertaken suggests that, depending upon the waste type, these can be a positive (MSW), negative (Tallow) and have no consequential impacts (wheat straw) (Econometrica, 2009).

A detailed review and assessment of issues regarding developing the waste stream in the UK can be found in AEA (2009b) and for a high level review see NNFCC (2011a).



4.4 Summary and Recommendations

The estimates for global economically exploitable biomass potential for 2050 range from <50 to > 1,000 EJ pa. The highly uncertain nature of the projections is attributable to the substantial variations with regards to the input variables for scenario development and boundary conditions for feedstock studies.

- Harmonisation of methodologies and boundary conditions for biomass projections is a recognised priority and work is being undertaken in this area.
- The biomass projection dataset is also characterised by the lack of data at the appropriate resolution to derive reliable cost curves and the lack of integration of environmental and social issues. This would be addressed by the development of a database of project, country and regional case studies which when considering the economics of biomass also assessed opportunity costs, externalities and co-benefits of feedstock sources.
- With regards to dedicated energy crop feedstock streams, the potential impact of an expanding bio-energy sector and its interaction with other land uses, such as food production, biodiversity, soil and nature conservation, social issues, and carbon sequestration needs to be better understood. This may be facilitated by:
 - improving the accuracy of land datasets;
 - better projections of the availability of surplus land due to agricultural improvements; and
 - the need for the development of a database of regionally specific yields of different feedstocks from large field trials on both primary and marginal lands.
- In the case of other feedstock streams the complexities involved in projecting farming practices (for residues), livestock development (for manure / dung), interaction with a number of other markets (for forest feedstocks) and patterns of waste development will mean uncertainties are likely to remain in biomass projections for the foreseeable future.

The extent to which the sustainability debate has been applied to biomass for bio-energy has made it difficult to reconcile the ability to develop biomass to commercial scale and to design a sensible policy framework. Recognition of the relevance of sustainability issues beyond biomass for bio-energy but also across the whole of biomass streams, *i.e.* for food, feed and fibre as well, has improved the balance of the debate. However, though there are specific research needs salient to individual bio-energy sustainability issues the underlying need is for:

- The development of consistent methodological procedures for each sustainability issue to facilitate comparable accounting and monitoring procedures. This should result in assessments of feedstock production techniques which optimise environmental, social and economic value (The Royal Society, 2008). The culmination of this might be the development of a sustainability index for sustainability issues.
- Establishment of international collaborative networks for methodological frameworks and data collection in order to realise a more efficient use of **presently** cultivated land - without any further land use expansion (thereby preserving SOC and bio-diversity / eco-system services).
- the large scale development of biomass in degraded / marginal lands. Agricultural extension services can then be used to disseminate and adapt best practice to different regions.
- the realisation that the role of policy across the considerable number of drivers of LUC is relevant and integral to the minimisation of LUC to ensure that all forms of biomass development for food, feed, fibre and energy are produced in a sustainable manner.
- And, the UK to be engaged at an international level in this area. This is paramount in order to ensure the international development in energy biomass is both sustainable and scalable. It will also allow the monitoring of the impact of UK bio-energy targets on global sustainability issues.

There is potential to enhance presently used feedstocks to improve their economics and sustainability profiles, and develop dedicated energy crops. The UK has substantial capacity in plant science research with which to develop feedstocks. Key recommendations to develop this area is the need to better integrate feedstock improvement within a whole systems framework in bio-energy value chains and the utilise international development frameworks to close the yield gap in less developed nations.



Limited effort has been dedicated to increasing yields for future ligno-cellulosic energy crops therefore substantial uncertainty remains in terms of their potential economic and sustainability credentials. There is a need to have large scale field trials across the world. The following issues are relevant to the research in this feedstock:

- there is a need for consensus as to where to focus the work;
- it is essential that the UK maintains its present plant science capacity and that it seeks to collaborate with other international leaders in this field; and
- it is inhibited by the EU stance on GM crops which is where many believe the biggest novel opportunities lie. It is recommended that the UK stance on GM crops be re-assessed though it is recognised that this will require significant public engagement.

New oil crops are also being researched specifically as a bio-diesel substitute. There is limited work being undertaken in the UK for these crops though strength in plants sciences could be applied to the feedstock.

The substantial global technical potential for both micro and especially macro algae makes this a potentially rewarding area of feedstock research. In the case of micro algae, the majority of work is US centric and the US has heavily invested in this sector. With regards algae generally, so extensive are the research questions, so broad is the extent of work and approaches being undertaken, the fragmented nature of the programmes makes the potential for the attainment of commercial costs and scale in the near term extremely unlikely. There may, however, be spin off benefits for the bio-energy sector by studying algae within a broader research framework.

The use of ligno-cellulosic and waste streams as a potential realisable feedstock stream for bio-energy are attractive due to the following:

- its substantial potential ranging from 50 to 270 EJ pa, globally;
- the co-benefit of reducing the waste footprint; and
- that it is, at present, a relatively cheap feedstock.

Hindrances of the development of this stream lies in:

- lack of understanding of the availability and economics of collection of the feedstock streams - particularly in developing countries where potential is greatest and material flows are poorly understood;
- lack of knowledge of the indirect effects on other markets;
- for waste plants there is a public acceptance issue; and
- multiple conversion technology routes which makes pre-treatment and categorisation difficult.

Despite the uncertainties in biomass availability it is clear that the quantities of sustainably produced feedstock that is / will be available are material to the development of a bio-energy sector that will make a significant contribution to the future energy system. Information across a range of feedstock issues needs to be developed so as to allow better analysis of the interactions of biomass production for bio-energy with food production, biodiversity, soil and nature conservation, soil issues and carbon sequestration. This would assist in the better addressing of sustainability issues across all biomass production - for food, feed, fibre and energy. It would also allow more rational choices to be made as to how we allocate and use land for multiple objectives.

5 Bio-energy Logistics, Process Conversion Technologies and End Uses: Research, Development, Demonstration and Deployment

Evidence presented here supports the following elements of the ERP Bio-energy Technologies Review Executive Summary and Recommendations:

- **General**
 - Economics of processes and availability of feedstock will impact on penetration of the use of biomass in heat and power.
 - Multiple options for advanced transport bio-fuels with fragmentary activity.
 - Several process conversion technologies being addressed at different stages of development requiring a flexible process for understanding and evaluation of options.
 - Transport fuels are an internationally traded commodity suggesting that international co-ordination is needed to ensure future fuel developments conform to international market needs.
 - Need for understanding of spatial, logistics and value chain impact on biomass economics.
 - Need for whole system analysis to understand bio-energy impacts which should be standardised in a transparent, unbiased and internationally recognised Life Cycle Analysis.
- **UK deployment issues:**
 - Use UK knowledge to assist other countries in sustainable production.
 - Re-consider EU GMO policy with the need for public engagement.

5.1 Background

The complexity of bio-energy value chains was previously demonstrated in Figure 2.1. It is at the upgrading and process conversion to end use that the complexity is substantially amplified due to the adaptability of bio-energy for different end uses. These issues are discussed in section 5 where feedstock logistical issues, process conversion and end use issues with a focus on liquid transport fuels are reviewed. Whole systems issues such as life cycle analysis, value chain modelling, the bio-refineries concept, the use of biomass orientated technologies for negative emissions, role of genetic engineering and the best use of biomass are also discussed.

The logistics of getting feedstocks from the field to the site of process conversion is an important and under researched component of the bio-energy value chain. It is important due to the impact that it has on the economic viability of bio-energy supply chains, the need to consider trade-offs between enhancing biomass transport economics through densification and ensuring the feedstock remains usable as efficiently as possible in process conversion technologies; the need for integrated thinking is important. Furthermore, the development of an efficient logistics supply chains will facilitate an opportunity for areas of potential biomass surplus to supply regions of biomass deficit and therefore an international trade in sustainable biomass.

Bio-energy process conversion technologies are important for the following reasons: Firstly, the realisation of commercially viable conversion technologies facilitate the economic utilisation of different feedstock streams such as energy crops, waste, agricultural residues and algae. Secondly, life cycle analyses have broadly demonstrated that the conversion stage of biomass into bio-energy or intermediaries can be one of the most energy, and if fuelled by fossil fuel, one of the most GHG intensive phases within the bio-energy value chain. Finally, it is where a substantial proportion of research work is being undertaken due to the economic value creation that may be realised and it is where it is anticipated the majority of cost reduction will occur in bio-energy value chains (TINA, 2011c&d).

End use issues are touched upon for biomass to heat and power generation in respective sections on process conversion. A sub-section on end uses for transport fuels is allocated due to the potential range of products that are being considered.

As a caveat to each section, it is worth noting that the material for this review is based on the recent literature base and will therefore likely to be representative of developments to early 2010. Furthermore, much work in the process conversion component of the value chain is often proprietary which may result in developments not being reported publically and so the material accessible to this review may not represent perspectives of the actual state of those technologies to early 2010. Finally, the volume of material dedicated to each aspect of bio-energy does not in any way infer prioritisation of that particular dimension of bio-energy in the energy mix rather it represents the extent of technological development activity taking place in that area.

5.2 Feedstock Logistics: Field to Process Conversion

Feedstock logistics covers the operations of getting feedstock from the land where it has been grown to its site of process conversion; this includes harvesting, storage and transportation. Section 3 highlighted that projections of bio-energy demand to 2050 potentially required up to 15 billion tonnes of biomass to be developed. In order for this biomass to be economically, practically and cost effectively utilised feedstock logistical systems need to be developed. Though logistical feedstock systems differ depending upon biomass type there are a number of generic issues which need to be considered when developing a scalable logistical framework; these include:

- Biomass has a high moisture content and low energy density (depending upon moisture content this can range from 10 to 22 GJ/tonne; this is compared to fossil fuels such as coal (23 to 30 GJ/tonne and Oil 43 GJ/tonne).
 - The reducing of moisture content, which can be as high as 60 % for some woody biomass and 90% for sludge, can be achieved by:
 - Air drying which takes time, space and is only effective to 20%; or by
 - Energy intensive heating or centrifugal techniques which increase the GHG profile of the supply chain.
 - Increasing densification can be achieved by using pre-processing techniques such as pelletisation, briquetting, torrefaction etc.
- Biomass process conversion plants become more economical with increased size. Conversely, feedstock costs have a tendency to increase as feedstock volumes increase due to greater transport distances to supply such volumes. The ability to increase transport distances by energy densification will make longer transport distances more economical and facilitate larger plant sizes.
- In terms of economics and energy / GHG balance transport by boat is more efficient than by train or truck (Whittiker et al., 2009). Ocean vessels are now facilitating international biomass supply chains. For train and truck economic transport distances are substantially reduced particularly for low density energy carriers where for trucks the economic transport distances are usually limited to 50 to 100 km. Recent consideration has also been given to transportation of bio-based liquids or gases through pipelines. The extent of the research in this area is limited.
- Feedstock consistency, moisture content and quality requirements are dependent upon end use.
 - Electricity production and direct heat technologies are less quality sensitive; and
 - Feedstocks for gasification and transport fuel production are more quality specific.
- The need for all year availability for some uses and the minimisation of storage requirement. Storage is an issue for biomass producers for the following reasons (IEA, 2009a):
 - The bulky nature of biomass, the seasonal nature of harvesting and the need for all year supply for some processes utilising biomass. For example, straw has a relatively short harvesting period but may be required all year making the need for the allocation of large areas of dry storage space immediately after harvesting. Even perennials have at least a 3 year establishment time and optimum cropping periods therefore requiring storage.
 - Some feedstocks for specific uses do not lend themselves to long term storage. For example, sugar cane cannot be stored for more than 24 hours due to the reduction of sugar content (making the storage of the final product (ethanol) preferable).
 - And, biomass with high moisture content (>20%) can be subject to biochemical breakdown reducing dry matter content and enhancing the potential for self ignition.

In order to overcome these issues for large scale biomass supply chains the key areas that require development are:

- Advanced densification and reducing the water content (thereby increasing energy density and enhancing the economics of long distance transportation);
- pre-treatment technologies (thereby facilitating storage without degradation of feedstock quality and energy density); and
- diversification of procurement geographically and biomass types (thereby reducing the impact of seasonal availability of different feedstocks).

A summary of biomass main supply chain and logistical issues is summarised in a review of the literature by Gold et al., 2011 and in table 5.1, below.

Table 5.1: Summary of main biomass supply chain and logistics issues (extracted from Gold et al., 2011).

Stage in supply chain	Issues
Harvesting and collection	<ul style="list-style-type: none"> • Drying, baling, chipping as most relevant post-harvest biomass processing modes • Selective harvesting • Scattered geographical distribution of biomass and topographical constraints • Harvesting period and frequency • Negative environmental impacts of harvest machinery
Storage	<ul style="list-style-type: none"> • Matching biomass supply (natural growing cycles) and continuous bio-energy plant demands • Risks of storage regarding quality degradation and dry matter losses of biomass • Locations and types of storage facilities
Transport	<ul style="list-style-type: none"> • Transportation laws and infrastructure • Increasing value density of transported biomass while optimizing the utilization of carrier capacity • Environmental and social impacts of transporting biomass
Pre-treatment	<ul style="list-style-type: none"> • Drying and pelletization facilitate other operations, decrease deterioration risks, and enhance biomass energy value • Torrefaction and pyrolysis still under development
System design	<ul style="list-style-type: none"> • Individual adaptation and optimization of system design • High levels of complexities and inter-dependencies of bio-energy production systems • Strategy of cascading use of biomass • Search for technological and managerial innovations for enhancing economic and environmental efficiency and effectiveness while mitigating negative social impacts

Densification and pre-treatment technologies are discussed here and diversification of biomass supply through the development of an international bio-energy trade is covered in section 5.2.3, below.

5.2.1 Harvesting, Storage and Transport

The detailed configuration and maturity of feedstock logistical systems is dependent upon the feedstock type. For example, the harvesting and storage component of the logistical chain will differ considerably for dedicated energy crops and algae. The bio-energy supply chains which can use long established and scaled logistical systems, such as grain crops, waste and forest feedstocks, are able to piggy back off agricultural, waste and pulp-paper systems and are substantially better developed than those feedstocks that are under development such as for dedicated energy crops and algae. Those feedstocks that require substantial harvesting developments may incur substantial investment costs.

Though grain crops, waste and forest feedstock logistics are well established forest and crop management for biomass harvesting are research areas in their own right (The Royal Society, 2008) and there is scope for further development in the area of specialised equipment to improve the efficiency of large scale harvesting and the transport systems that reduce the number of trips to processing plants. In the case of waste, year round supply from waste streams may be facilitated from municipal and commercial sources yet the long term nature of waste contracts means that waste plants need to be well established before contracts can be made. Though commercial and industrial waste is traded on shorter term contracts and therefore potentially more accessible long term supply availability is problematic.

The development of algae as a feedstock is at such a nascent stage that configurations for large scale logistical frameworks have yet to be fully considered due to the uncertainties as to how the sector will develop (Section 4.3.3). The focus of the remainder of this section is on the issues that are being developed for dedicated energy crop feedstock logistics to demonstrate the issues that need to be considered in biomass logistical chains.



To improve harvesting economics there is a drive to increase the efficiency and scale of harvest equipment. Furthermore, with the land constraints highlighted in section 4.3.1 it is unlikely that dedicated energy crops will be developed on primary flat agricultural land leading to the need to develop harvesting techniques that can operate in difficult terrain. To optimise harvesting regimes it is suggested that there is a need for predictive models for sustainable harvesting (US DOE, 2010c).

With regards to dedicated energy crop storage there is a need to better understand the behaviour of feedstocks in storage and how to enhance stability of bulk systems. The impact of the differences in variety, geographical location and harvest methods on physical and chemical properties is not known nor the best storage configurations in terms of bulk density, moisture content, climate, ideal storage time and anticipated storage losses. This will have an impact on properties of feedstock and its consistency for processes conversion. Furthermore, instrumentation for measuring the physical and biomechanical properties of feedstock are lacking prohibiting the development of a database of feedstock behaviour in storage.

In the case of transport and handling, even with densification, specialised road transport equipment may be required to reduce costs and the number of trips to plants which in turn will require considerations when developing the infrastructure to storage sites - prepared base, drainage, main road access and loading areas. Bulk handling optimisation suggests moving away from discrete units to semi-continuous flow of materials such as pellets / granules.

Technologies for densification and pre-treatment include: densification and pelletisation, pyrolysis and hydrothermal upgrading (HTU) and torrefaction see table 5.3. They are at various stages of development (Figure 5.1) with pelletisation being the only commercially viable technology - remainder being pre-commercial or in the case of HTU at a pilot plant stage. A detailed assessment of biomass densification / pre-treatment technologies from a UK (East Midlands Region) perspective can be found in NNFC (2008a).

Finally, there has been the need for integrated thinking for feedstock logistics with process conversion technologies as the optimisation of feedstock pre-treatment for the economics of transport and storage may need to be traded off with the optimisation of feedstock for process conversion. The degree of integration is being prohibited by a lack of quantitative analysis to assess the benefits of various configurations.

State of Biomass Logistics RDD&D

Feedstock logistics is an area which has not been an area of focus. This may be attributed to a number of reasons:

- There is a need for sufficient economies of scale to be reached before specific logistics chains for bio-energy to be developed; these have yet to be reached. Indeed where scale cannot be reached the feedstock logistics will be based on adapting existing infrastructure.
- As the logistical infrastructure will be highly dependent on the feedstock and conversion technologies the development of logistical chains will have a tendency to only be prioritised once consensus on the dominant feedstocks and process conversion technologies have been established. At present research focus remains on feedstock development and process conversion with a lack of consensus as to where the likely breakthroughs will take place; this may impact the ability to develop efficient end to end bio-energy supply chains.
- Finally, there is a feeling amongst bio-energy practitioners that the market will develop the logistical infrastructure once the market has developed at scale.

Nation states that have focused on specific feedstock streams are able to better facilitate standardisation and specifications. For example, the US's logistical programme is able to progress due to the fact that stakeholders know that it is oriented around dedicated energy crops and studies are focused on crop residues, perennial grasses, perennial woody crops, and, forest managed residues.

Nation states that have no prescribed focus on specific feedstock supply chains, such as the EU, will be dependent either on the development of process conversion technologies which are able to tolerate multiple feedstocks or be on access to internationally produced biomass that can be economically transported to processing sites to ensure all year supply.



In order to facilitate the development of logistical frameworks in the current state of feedstock and process conversion development the following is recommended:

- Once consensus as to where the key areas of break-through will take place a drive to develop standardisation and specifications are essential across the supply chain - this is relevant to each stage as follows:
 - Harvesting equipment there is a need for feedstock specifications and standards against which to engineer harvest equipment, technologies and methods across all feedstock types. Uniformity of feedstock properties assists in the adoption of existing equipment and processes for bulk agricultural solids.
 - Pre-treatment for transport and process conversion. There is a need for the development of standards for biomass formats for each conversion process stream and integration of process conversion with the pre-treatment technology from harvesting through to delivery at the processing site.
- There is a need for the development of storage monitoring devices and the compilation of a database for storage behaviour of different feedstocks in different conditions over time.
- There is a need to assess the spatial impacts of bio-energy value chains on logistics configurations / mediums, economics and sustainability issues within national modelling frameworks (e.g. Italy) - for more details see section 5.4.2.

5.2.2 Development of International Biomass Trade

The development of international trade is an extension of biomass logistics issues. As stated in section 4.2.4, the biomass projections suggest that there will potentially be substantial regional surpluses and deficits resulting in a role for an international trade in biomass. Furthermore, International trade will provide all year supply delivery operations and avoid the need for storage; all year round supply is a barrier to the widespread development of biorefineries at scale (US DOE, 2010a).

Present Levels of International Bio-energy Trade

Though it is generally the case that the local use of biomass is presently more economically rational - some feedstock streams from international sources may be more economic to utilise than local biomass. As a result there is the beginnings of an international trade in biomass which has been facilitated by the economics of ocean vessels being realised. It is nonetheless highly illiquid (Faaij, pers coms) and the realisation of scale will be subject to the logistical barriers cited above being overcome allowing nations with lower production costs and high biomass potential to export.

International biomass trade was estimated that in 2004 to be 0.76 EJ (Heinimo et al., 2007) and in 2006 >1 EJ (Heinimo et al., 2009). It is, however, very hard to measure as though for some markets data exists (e.g. for pellets and ethanol), no comprehensive statistics exist which aggregate separate biomass streams²⁹. Furthermore, imports of some bio products may initially be for a non bio-energy purpose and yet after a period of time may end up in the bio-energy supply chain (Perry et al., 2007). This stream, what Heinimo et al. (2007), terms the indirect stream may actually be 2.5 times larger than directly traded bio-energy products though more recent estimates suggest that this gap is closing (Heinimo et al., 2009). In 2006, taking all streams (indirect and direct) in to account it is estimated that industrial round wood and wood material by-products comprises the majority of (0.68 EJ) world trade with ethanol (0.16 EJ) and biodiesel (0.09 EJ) also making up a significant share (the 2009 world trade in oil was 112 EJ (BP, 2010)).

The latest figures available from the IEA are displayed in table 5.2. Despite the small scale of the present bio-energy trade, statistics from the RFTO suggest that the bio-energy global market is already broad based with

²⁹ Determining international traded bio-fuel volumes is difficult for several reasons (after Heinimo et al., 2007):

- First of all, many biomass streams are traded for material purposes, but they finally end up in energy production;
- Second, biomass streams can have several final applications, for example palm oil (feedstock for bio-diesel or for food applications) or ethanol (as transportation fuel or as feedstock for the chemical industry); and
- Third, some biomass fuels such as wood pellets and bio-ETBE are recorded in aggregated form by foreign trade statistics. For example, wood pellets are recorded under the same code with wood waste in the EU's trade statistics, thus making it difficult to assess the volume.



ethanol and biodiesel in the UK being supplied by 18 countries (as widespread as N and S America, Asia, Europe and Africa) from 12 different feedstocks (RFA, 2010). The role of imported biomass is also assessed in a recent piece of work by Perry (2011 - chapter 4).

Table 5.2: Global Trade of Major Biomass Commodities in 2008 (IEA, 2009a).

	Global Net Trade (Mtons)	Main Exporters	Main Importers
Bioethanol	3.72	Brazil	US, Japan and EU
Biodiesel	2.92	US, Argentina, Indonesia and Malaysia	EU
Wood Pellets	Approx 4	Canada, US, Baltic Countries, Finland and Russia	Belgium, Netherlands, Sweden and Italy

Large scale transportation of biomass is at such a nascent stage and experience is so limited that there is significant scope for cost reductions to take place from learning by doing, the attainment of economies of scale and competition. In an assessment by Rosillo-Calle (2007), it is suggested that present international biomass trade is hindered by the fact that:

- There are very few ships designed today that are adapted for bio-energy transport and this results in higher transport costs;
- harbours and terminals that do not have the capacity to handle large volumes of biomass hinders the import and export of biomass to specific regions; and
- the size of the bio-energy trade is such that the incentives based on economies of scale have yet to be reached to develop these facilities.

These issues are assessed in detail by Bradley et al., 2009.

Potential for International Biomass Trade

Hansson and Bernades (2006) estimated that the theoretical upper limit for global biomass trade flow potential between different world regions to be 80 to 150 EJ in 2050. The attainment a logistical supply chain of anything approaching such scale would require substantial development of a specifically dedicated international logistical infrastructure for the biomass trade. Such development of a specialised international logistical supply chain is not without precedent. The Liquefied Natural Gas (LNG)³⁰ trade has been developed entirely due to the economic viability of compressing natural gas in a highly specialist supply chain over the construction of long gas pipelines from remote gas reserves to markets³¹. If the projected LNG capital investment of US\$ 252 Billion between 2000 to 2030 was applied to the biomass international logistical infrastructure it would go some way to attaining the scale of biomass export and import required to sustain a robust international trade in biomass.

Barriers and Opportunities for International Bio-energy Trade

The IEA Bio-energy Task 40 makes policy recommendations on sustainable international bio-energy trade. The following opportunities and barriers were identified with specific reference to international bio-energy trade in ethanol, biodiesel and pellets but are applicable to other feedstocks as well:

³⁰ Liquefied natural gas is natural gas that is stored and transported in liquid form at atmospheric temperature at a temperature of -260°F. Like natural gas that is delivered it is delivered by pipeline into homes and businesses it mainly consists of methane. Natural gas is turned into liquid using a refrigeration process in a liquefaction plant - this plant is called a train. Liquefying natural gas reduces its volume by a factor of 610. The reduction in volume makes the gas practical to transport and store. The international trade in LNG is undertaken in specially built tanks in double hulled ships to a receiving terminal where it is stored in heavily insulated tanks. The LNG is then sent to regasifiers which turn the liquid back into gas that enters the pipeline system for distribution to customers as a part of their natural gas supply (IEA, 2004a).

³¹ This increase in investment in the LNG chain has resulted in a very significant reduction in the costs of development in the value chain especially at the liquefaction and tanker stages. This has been a function of technological developments, more competition on the engineering and shipbuilding side and the attainment of economies of scale from larger train sizes. For example, between 1965 to 2010 the size of LNG ships has increased from 25,000 m³ to 266,000 m³ and the number of ships increased from 130 to 210 between 2001 and 2006 (IEA, 2010a). This has had a corresponding impact of total capital requirements falling from approximately US\$700 per tonne in the mid-1990s to around \$500 in early 2000. Costs were projected to fall to US\$420 per tonne by 2010 and US\$320 per tonne by 2030 assuming a shipping distance of around 4,000 km (IEA, 2009a).



- Need for market transparency for a broader range of biomass streams in internationally traded statistics; these should also include final application where possible. It is important to monitor both the effectiveness of policy and the development of international trade.
- Present bio-energy trade is in small volumes biomass fuel trade and effectively 100% bi-lateral. The reason for the small volumes is seen being due to the dependence of bio-energy sector being based on short-term policy measures.
- Tariff barriers and sustainability criteria for international feedstocks are perceived as a barrier. Nation states with large markets (US, Japan and EU) are closed or partially closed due to trade barriers preventing the open access to nation states that are able to produce feedstocks more cheaply than domestic supply chains.
- Technical and sustainability standards development are seen as an opportunity though at present difficult to develop due to the following reasons:
 - The adaptability of biomass to either food, feed, fibre or bio-energy makes the application of standards difficult as the level of stringency varies between each supply chain. Therefore where there is a chance of a feedstock being subsumed into the food chain the more stringent standards will be applied which can make costs prohibitive.
 - In a similar vein, phytosanitary measures are not seen as barrier for present feedstocks but might be for unprocessed biomass, such as wood chips, in the future.
 - And, the EU's opposition to import products which have undergone genetic modification creates complications.

These issues are reflected in World Trade Organization (WTO) rules which do not have a standard classification for bioethanol and biodiesel. Currently, there are three options: agricultural, industrial or environmental. The classification determines which WTO rules apply (for example, subsidies are allowed for some types of agricultural and environmental goods, but not industrial goods).

In light of these issues the following recommendations are suggested for a better understanding of and the enhancement of global bio-energy trade:

- The need to develop an understanding of the availability of biomass at a national and international level, priorities for biomass in respective national energy systems, the forms that bio-based products will be traded (solid, liquid or gaseous state), nature of the markets - bulk or niche, liquid or bi-lateral, interaction with agricultural commodities markets and different phases of development as the bio-energy commodities market matures.
- Bio-energy feedstock streams with their end use should be incorporated into internationally traded statistic.
- Harmonisation of technical and sustainability (GHG and energy balance) standards should be undertaken at an international level. The basis of this work can be the international review of sustainability standards undertaken by IEA Bio-energy Task 40 (see Dam et al., 2010).
- When large scale bio-energy supply chains are being developed consideration of the requirements of dedicated supply chains to facilitate large scale international trade should be borne in mind (Bradley, 2009).

5.3 Process Conversion and End Use

Bio-energy routes from feedstock to energy vector can be extremely simple, as in the case of combustion for heat, where the biomass feedstock is directly combusted to give the heat vector, or highly complex, such as in the case of production of a hydrocarbon for a transport bio-fuel, where the biomass may be pre-treated, upgraded and converted into a number of intermediaries. The multiplicity of chains is a function of the range of biomass feedstocks (section 4) and the different possible end-uses (heat, electricity or transport bio-fuel). Conversion technologies have been developed to account for the variety of feedstocks and end uses (Figure 2.1). Furthermore, many conversion processes also produce co-products which can enhance the economics and environmental profile of bio-energy products.

Details of process conversion across energy carriers and vectors can be found in excellent reviews by Faaij (2006), US DOE (2010b) and IEA (2009a). Here a summary of the main technologies are reviewed for heat, power and transport applications with a view to identifying the key RDD&D requirements.



5.3.1 Biomass for Heat Applications

Biomass to heat applications include direct combustion and small scale gasification (table 5.3) and are all mature technologies and available at the commercial and early commercial scale, respectively (see Figure 5.1). They have been successfully deployed in Finland and Denmark in rural and industrial areas where the infrastructure is appropriate for feedstock handling and heat distribution.

- Combustion involves burning biomass in a stove (domestic size) or boiler (larger units) to generate heat. This is the most dominant biomass heat technology with quarter of a million units installed in the EU annually.
- Gasification technology converts solid biomass into a syngas that can be combusted directly in a boiler and / or used to drive a turbine. Gasification technologies are often used for combined heat and power applications. There are several thousand units installed globally. Gasification as a generation technology for power and bio-fuels production and is also discussed in section 5.3.2, below.

More detailed innovation needs for combustion, gasification and CHP can be found in Appendix 5 - which have been extracted from the Technology Innovation Needs Assessments (2011c&d) for heat, CHP and biomass power generation.

The economic case for these heat technologies is often dependent on the relative cost of the reference fuel. In the case of distribution of the heat in district heating networks the techno-economic issues are complex. The network can account for 35 to 55% of the total investment cost of district heating plants and, in order to be economic, need to have high annual utilisation rates (>75%) and concentration of customers (IEA, 2009a).

As stated in Section 3, in the UK the difficulty in modifying the way in which industrial and domestic properties receive heat services makes the economics of bio-energy based heat generation unattractive. For example, the UK only deployed 400 boiler units between 2009-2010 (TINA, 2011c). This situation may be mediated by the introduction of building regulations to make distributed heat services more economically viable.

5.3.2 Biomass for Power and Combined Heat and Power Applications

A wide range of feedstock and conversion technology combinations are in various stages of development (see Figure 5.1) for power production and combined heat and power (CHP); these include: dedicated biomass and co-firing plants, municipal solid waste (MSW) to energy plants, biomass co-generation (CHP) plants and distributed cogeneration units (such as Organic Rankine Cycle (ORC) or Stirling Engines) - see table 5.3 for an overview of these technologies.

Fundamental to the economics of such systems is not only the capital outlay but also the availability of cost effective and substantial supplies of feedstock and relative cost of alternative production.

Though table 5.3 gives a summary of power generation from solid biomass technologies including dedicated / co-firing biomass power plants, anaerobic digestion and large scale gasification - these are also expanded upon below due to their potential and relevance in the UK.

Dedicated Biomass and Co-firing Plants

Power can be generated from biomass in three ways (Drax, 2009):

- Dedicated plants. Biomass and wastes are usually combusted in grate-fired or in fluidised bed boilers and are expensive compared to co-firing³² (e.g. MGT Power 295 MW plants in Tees and Tyne, Drax's JV with Siemens to develop 290 MW plants at Immingham and Selby and E.ONs 44 MW plant in Lockerbie).
- Co-firing with coal in existing coal-fired power stations. Biomass burnt alongside coal in a conventional coal-fired plant is recognised as a renewable fuel and carbon abatement technology. It has been undertaken in the UK since 2002 and, at low co-firing percentages, requires little capital outlay and minor technical modification (e.g. Drax).
- Generating unit conversion / Uniconversion. This involves retrofitting a coal-fired plant to burn biomass only. This may require major plant modifications including changes to the fuel handling systems and de-rating of

³² This is partially due to the age of the current coal fleet, which has been fully depreciated. At the same time many of these are scheduled to close or require major investment to meet emissions standards. There is the possibility that dedicated biomass might be competitive with new build coal (which would probably need higher levels of flue gas treatment than biomass plants to comply with emissions regulations should carbon targets be introduced).

the boiler output to account for the lower energy density of biomass, but the conversion costs are expected to be lower than those of a new-build dedicated plant.

All these forms of generation in the UK are not economically viable without support. The former two are covered in the Renewables Obligation³³ and latter is a new development. One of the most important aspects is that the capital outlays for many of the co-firing or dedicated plants have a pay back of over 15 years and the support policies are reviewed in shorter timeframes. This policy risk results in a lack of commercial confidence.

Dedicated plant is better suited for distributed power generation, has more scope in CHP applications (see above) and when using low energy density biomass are often more fuel flexible than pulverised coal plant. The two conversion technologies that can be used to generate electricity are:

- Combustion involves the burning of biomass in a boiler to produce high temperature steam to drive a turbine and generate electricity.
- Gasification involves the conversion of biomass into a syngas which is combusted in combined cycle gas turbines to generate electricity. It is considered that large scale gasification dedicated to power generation will be dominated by Biomass Integrated Gas Combined Cycle (BIGCC) plants.

In table 5.3, it can be seen electrical efficiency of dedicated biomass plants for electricity generation tend to be lower than coal plants (30 to 34% using dry biomass, and approximately 22 to 30% for MSW). In co-generation modes the total efficiencies can be as high as 85 to 90%. For more details, IEA (2007a), Nussbaumer (2003) and Ahan et al. (2009) provide good overviews of key technological issues with respective processes. Furthermore, the detailed innovation needs for combustion and gasification can be found in Appendix 5 - which have been extracted from the Technology Innovation Needs Assessments (2011c&d) for biomass power generation.

Dedicated plant, presently being deployed at the scale of up to 295 MW in the UK is considered to be likely to be deployed in the future as coal plant is closed, due to the well developed nature of the technology; 4.2 GW is in the planning pipeline. Indeed dedicated combustion plants (with CHP and CCS) are prominent in energy models to 2050 (Sections 3 and 5.4.4). Combined Heat and Power and distributed production is of increasing importance to the power industry in the UK, and it is more likely that these plants would be dedicated biomass plants rather than co-firing units. Replacement of the current coal fleet by new units capable of co-firing will be heavily dependent on the proving of the long-term viability of CCS - and its ability to cope with biomass components. As yet, there is no guarantee that technical, political and economic conditions will support new coal/co-firing plants with CCS.

The remainder of this section is mainly centred on co-firing. Once heat input increases to above 20% for co-firing the securing of a constant supply of feedstock is one of the main barriers to scale-up requiring capital expenditure for developing / scaling up supply chains, biomass processing, storage facilities, handling and firing systems. For example, Drax have invested over £80M to co-fire at 12 to 15% by heat - requiring over 1 M tonnes of biomass per year utilising 60 to 70 different feedstocks. Any move to fire higher percentages in large centralised units such as Drax would require further investment in the supply chain infrastructure. (Emery, pers coms).

The simplest method for biomass co-firing with coal is to mix the coal and biomass in the raw fuel feed, with the blend then milled in the coal mills (co-milling). There are, however, practical limitations to the amount of biomass which can be blended before mill performance is affected, which in general restricts this method to those applications where <10% biomass is co-fired. To obtain higher co-firing proportions, separate milling of the biomass followed by direct injection of the ground material into the system is used. The current technology options for direct injection co-firing include:

- Direct injection into the furnace without combustion air;
- direct injection into the furnace, with combustion air via a dedicated burner; and
- direct injection into the coal stream after the coal mills but before the burners.

There are different advantages and developments with these techniques - for greater detail see Flower (2011).

³³ Although it should be noted that co-firing currently attracts lower support than the same level of generation in a dedicated plant.



There are a number of technical issues with co-firing; these include (see DTI (2005), Drax (2009) and Flower (2011)):

- Fuel handling. Biomass is harder to handle than the coal usually used in UK power plant. Its hygroscopic properties results in a tendency to degrade if stored incorrectly and not used rapidly, increasing the risk of mould development (and its associated health risks). Biomass can also bridge over hoppers or 'hang' especially when biomass dusts are produced. High levels of fines in the biomass combined with the reactivity of the fuel compared to coal can also increase the risk of fires / explosions (DTI, 2005 and Drax, 2009).
- Biomass impact on boiler operation, ash chemistry and gaseous emissions. The different ash chemistry compared to coal affects deposition and sintering within the boiler. Knowledge of feedstock consistency, impurities and boiler impacts is integral to managing the deposit formation and corrosion problems. Biomass co-firing will also impact on by-product quality such as fly ash with limits set on biomass levels by standards such as BS EN 450 - fly ash for cement production. Gaseous emissions also differ depending upon the biomass feedstock but generally tend to have lower levels of contaminants compared to coal.

Biomass-based Cogeneration (CHP) Plants

The ability to source an economic application for waste heat from dedicated or co-fired power plant increases the efficiency and economics of power plants - see table 5.3. The development of infrastructure and proximity of heat sinks has a major bearing on the feasibility of developing this for large scale plants and recycling heat can result in a small reduction in power efficiency (IEA, 2009a). The role of smaller scale / distributed CHP is discussed in the section on biomass heat, above.

Anaerobic Digestion (AD) is a proven energy and waste management technology which reduces GHG by utilising methane from the decomposition of organic materials from a broad range of wet feedstocks to produce biogas (60% methane and 40% CO₂) which can be used to generate heat, power or road fuel. It produces a co-product called digestate which can be separated into 'liquor' and fibre for application to land to enhance soil properties or secondary processing.

Anaerobic Digestion is a technology which is a part of a major UK government initiative to increase its penetration in rural communities (Defra, 2010). The National Grid is also interested in large scale AD projects with a view to injecting methane into the UK gas grid. There is a rich literature on the technology, particularly with regards its deployment - this includes Scottish Agricultural College (2007), Andersons (2010), Frith et al. (2011), Hopwood (2009) and the AD Portal on the NNFCC website: <http://www.biogas-info.co.uk/>.

The technology options for AD are substantial in number and depend on the nature and source of the feedstock being used and the scale of the operation. The options are listed below (after Hopwood, 2011 - p13):

- Wet or dry depending on the moisture content of the feedstock.
- Mesophilic or thermophilic defined by the temperature that the digester vessel operates, which in turn is dependent on the nature of the feedstock. Mesophilic systems operate at 25 to 45°C and thermophilic at 50 to 60°C.
- Continuous and Batch Flow.
- Single or Multiple Digesters which either have the four stages of AD (hydrolysis, acidogenesis, acetogenesis and methanogenesis) taking place in the same tank or separate tanks.
- Vertical or Horizontal Plug Flow. The orientation of the tank is determined by the nature of the feedstock and the consistency.
- Retention Time which is again dependent on the feedstock type and the output requirements of the system.
- Pre-treatment options which depends on the feedstock and may require shredding or macerating.

The NNFCC assess that AD has the following issues with regards deployment in the UK (Hopwood, 2009):

- The economics of AD are variable depending on the scale and feedstock mix. Income comes from many streams each requiring optimum management to maximise returns.
- In the UK waste handling potential is of interest to the food processing and retail sector not just energy generation.



- Efficiency of scale and collaboration are important in AD especially working with local waste suppliers and heat / power users improves the economics significantly.
- The policy support for AD is uncertain especially the risk of becoming ineligible for higher banding of Renewable Obligations Certificates.
- And, distributed energy technologies with economic returns based on grid access are hostage to obligations for connection.

An AD evidence availability and gap analysis has recently been undertaken for an end to end deployment in the UK (Frith et al., 2011). The ability to use AD generated bio-gas for heat, power and transport fuel makes assessment of the best use subject to assessments based on carbon savings and economics - see The Carbon Trust, 2010b. It is worth noting that as a function of total biomass availability wet waste - which can be utilised in AD - represents a relatively small proportion of total biomass available for bio-energy production (AEA, 2009b).

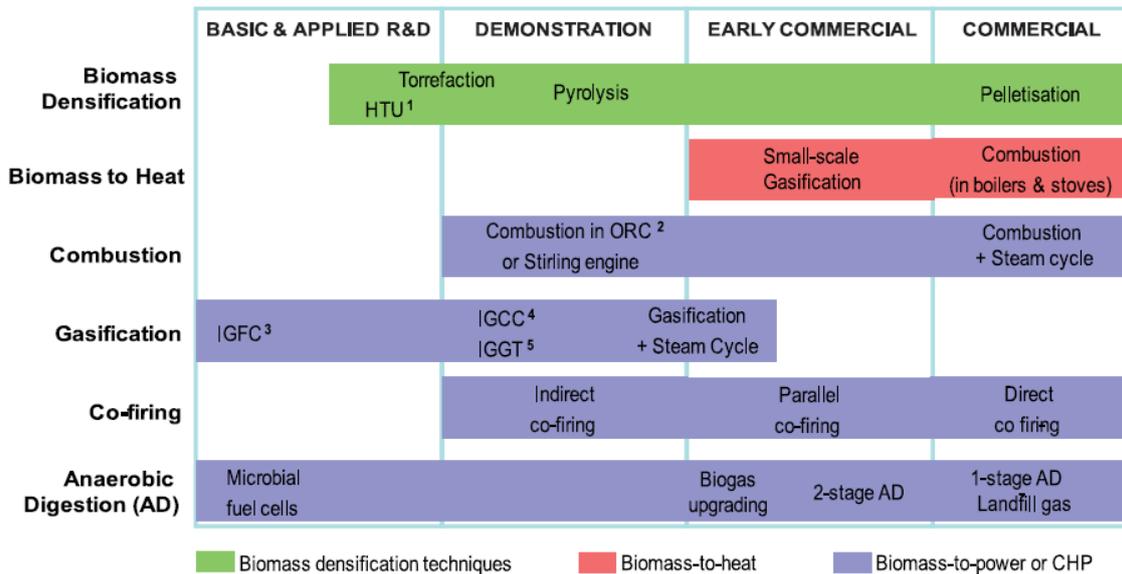
Large Scale Gasification

Bio-SNG is where biomass is gasified to produce syngas which is then either combusted in a gas turbine to produce electricity, reacted to produce methane or converted to bio-fuels using the Fischer-Tropsch (FT) process. Details of combustion to generate electricity and the use of the FT process to generate Bio-fuels are detailed in table 5.3 and section 5.3.3, respectively. With regards heat generation, when sufficiently well cleaned the biomass derived synthetic natural gas can be injected into the gas network and then used in a range of energy applications. The process involves feedstock preparation which comprises sizing to chips and drying. Unlike other process conversion technologies involving gasification (see section 5.3.3, below) all developers of bioSNG projects use Dual fluidised bed gasifier technologies to produce high H₂:CO ratios. The gas is cleaned and cooled and then via methanation gas is compressed and catalytically reacted to produce a gas mixture of CH₄ and CO₂ similar to the gas produced from AD.

In order to inject the gas into the grid the gas is purified and the CO₂ removed. The E4 Tech (2010b) study on BioSNG suggested that bioSNG *'could be economically attractive option for providing low carbon heat in the domestic sector, compared to direct use of biomass or electric heating....[and].....whilst not the lowest cost option when compared to direct use of biomass in commercial and industrial sectors it would result in decarbonisation where the direct use of biomass is not possible due either to space or air quality constraints'*. Take up will be dependent on the Renewable Heat Incentive with likely bioSNG plants of large size being most commercially attractive.

Many of the technical issues with large scale gasification for power and heat are relevant to use in the transport fuel process conversion - see section 5.3.3 on thermo-chemical routes.

Figure 5.1: Development status of the main technologies to upgrade biomass and/or to convert it into heat and/or power (E4Tech, 2009 after IEA, 2009a).



¹ Hydrothermal upgrading; ² Organic Rankine Cycle; ³ Integrated gasification fuel cell; ^{4/5} Integrated gasification combined cycle (CC) / gas turbine (GT)

The Use of Bioliquid Feedstocks for Heat, Electricity and CHP Technologies.

There is increasing interest in the use of bioliquids for heat and electricity generation due to the technologies involved being particularly well suited to small scale, urban and community owned energy schemes (NNFCC, 2011b).

The main bioliquids likely to be used for heat and power generation have been identified as: virgin vegetable oils (soy, palm, rapeseed and sunflower), used cooking oil, tallow, tall oil, pyrolysis oil and FAME (esterified vegetable oil). These are considered to be ideal for heat and power generation due to their higher energy density relative to solid biomass (and the impact that this has on transport economics, frequency and storage space) and their ease of transport.

An NNFCC (2011b) study identified the following technology options for using bioliquids in heat and power generation: pure plant oil (PPO) boilers, domestic heating oil / bioliquid blend boilers, biodiesel engine, pure plant oil (PPO) engine, oil / diesel and bioliquid co-firing, used cooking oil CHP, PPO CHP, pyrolysis oil CHP and flexible fuel CHP. Compared to other forms of bio-energy generation these have the advantage of being smaller in size per unit of energy output, are considered to be at a mature stage of development with some at commercial stage and they have a more responsive power on demand capacity.

Table 5.3: Summary of feedstock pre-treatment technologies for transporting biomass and conversion technologies for heat and power generation (modified from IEA, 2009a, E4Tech, 2007b, c and NNFFCC, 2007a)).

	Technology Description	Barriers to Development and Notes
Pre-treatment Technologies	Densification and Pelletisation. Pellets are made by the compression of small particles of biomass such as saw dust. Their use has become increasingly widespread due to the need to improve the economics of transporting low energy density / high moisture content material, development of quality standards and the fact that with a small subsidy they are an economic alternative to fossil fuels. An international trade in pellets has recently developed.	- Pellets tend to absorb moisture during transport and storage which can have a material impact on their integrity and net calorific value reducing their energy density to substantially lower than their dry weight of 15 - 17GJ/t. - Stability and resistance to abrasion of pellets as well as the dust emission during domestic handling.
	Pyrolysis is the controlled thermal decomposition of biomass in a low oxygen environment. It produces three products a liquid fraction (bio-oil), a gas fraction (syn-gas) and a solid fraction (biochar). The increased energy density of pyrolysis products (bio-oil has a calorific value of 17.5 GJ/t but 20-30 GJ/m ³) suggests better economic justifications for longer transport distances than pelletisation.	- Despite much in the way of work being undertaken in this area in the past 30 years limited advances have been made above the demonstration level. It is considered that both economic and technical issues around quality, consistency and stability of bio-oil which degrades over time. There is no prevailing technology. - The feedstock undergoes pyrolysis best when it has low moisture levels.
	A process called hydrothermal upgrading (HTU) generates bio-oil by liquefaction in the presence of water and solvents at high pressure (120 to 200 atmospheres) and temperatures of 200 to 400°C. The ability to use wet biomass and the fact that the bio-oil is less soluble in water relative to bio-oil derived from pyrolysis makes this process attractive.	- The least developed of the pre-treatment technologies with the most limited range of applications. It is the only one that enables a liquid biomass to be produced from a wet feedstock. The resulting bio-oil is highly energy dense at 30 to 35 GJ/tonne.
	Torrefaction involves the thermochemical (200 - 300°C) upgrading of woody biomass, which results in a relatively high energy density (19-23 GJ/t), potentially hydrophobic coal like substance. This facilitates economic transportation over distances and the potential ability to store material outside. The pelletisation of torrefied biomass further enhances energy density and transport economics.	- Though an old technique it is not available as a commercial technique. - It is highly friable making it easy to ground into a powder and therefore suitable for co-milling with coal.
	The combustion of biomass for heat is the oldest and most widespread method of converting biomass to energy. Traditional domestic systems have efficiencies of between 5-30% (developing world cooking stoves) to 90% (pellet boilers which are becoming increasingly popular). District Heating and Cooling are popular in Northern European countries but the high costs of incorporating appropriate scale district heating networks and ensuring system efficiency has been shown to be economically prohibitive in the UK (Section 3). Industrial scale boilers (0.5-10 MW _{th} range) are being established in industries that have a high heat requirement and have access to cheap biomass residues. The ability to develop these is highly dependent on industry type and flue gas quality and location.	- Increasing thermal efficiency and technologies that can burn biomass other than wood; and - The management of air quality from combustion emissions is a relevant issue which is particularly salient with biomass fuels high in N and ash in small scale stoves replacing gas and electric systems in urban areas. This is not relevant to large scale systems as biomass has lower ash and nitrogen than coal and flue gas clean up is well developed.
Heat Generation from Solid Biomass	Gasification. Gasifiers for heat applications (10 - 500 kW _{th}) are becoming increasingly widespread in China, India and South East Asia for intermittent operations. For more details of the process for conversion see combustion section below.	- Their economics for continued operations is questionable (IEA, 2009a).
	Municipal Solid Waste (MSW) to energy plants. These are able to consume diverse and often contaminated feedstocks. A variety of technologies are available depending upon the extent to which the MSW is separated with efficiencies ranging from 22 to 30%.	- High costs involved in ensuring emission controls and technologies to handle potentially contaminated feedstocks; and - public negative attitude to waste incineration which has lead to the technology being under exploited in the UK (IMechE, 2009).
	Biomass-based cogeneration (CHP) plants. The ability to find an economic application for waste heat in a power plant increases the overall efficiency and therefore economics of power plants. CHP / co-generation plants have combined heat and electricity efficiencies of 80-90%.	- Commercial and domestic heating applications can be limited by total local heat demand and seasonal variation which impacts on economics.

Distributed co-generation units. Low capacity technologies such as Sterling Engines (10 to 100 kWh_e and 12 - 20% efficiency) and the Organic Rankine Cycle (50-2,000 kW_e and 17% efficiency) have been shown to be promising for distributed co-generation.

- The technologies tend to be at the demonstration phase with further development needed to improve conversion efficiency, cost and reliability.

Biomass-based power plants. Though not as efficient as some other conversion technologies it is more developed, reliable and cheap. The need to realise economies of scale when sourcing large volumes of biomass has meant that plants have tended to be 30-100 MW_e though some smaller size plants are now being developed in Europe (5-10 MW_e).

- Dedicated plants tend to be of lower efficiency due to their smaller size making it uneconomic to install a reheat section of the boiler and the lower pressure steam conditions. Furthermore, feedstock handling and storage management, equipment wear, heavy metal contamination (level of which is dependent on feedstock) and inconsistency in feedstock moisture content can cause corrosion and deposit formation (IEA, 2009a).

Co-firing. The co-combustion of liquid and solid biomass materials with fossil fuels in thermal processes for heat and power production can be used for all scales of power generation. The most popular method³⁴ has been the co-firing of solid biomass with coal in existing power station boilers (e.g. Drax). Due to the fact this approach leverages existing infrastructure with costs being minor investment in pre-treatment and feeder systems it has become increasingly widespread in Europe. The efficiency of co-firing is augmented relative to the use of dedicated biomass plant due to the higher efficiencies of large coal plants (35 to 45%) - though the efficiency decreases with increased proportions of biomass used. Further efficiency may be gained by the utilisation of the heat component in district heating - though in the UK there is limited CHP potential.

- Direct co-firing is at a commercial state of development. There are however, limits to the proportion that may be co-fired particularly when using non-woody biomass which impact on the operation and life-time of coal plants.

- Limits to co-firing biomass for electricity generation (5-10% on heat input basis though 25% have been achieved) and the ash chemistry which result in deposits on the boilers and impact of flue gas on the gas cleaning equipment (IEA, 2009a).

- Biomass ashes which are very different than coal ash

Gasification is the thermochemical transformation of biomass into a fuel gas. It has advantages over direct combustion in that it has substantial feedstock versatility at high efficiency & can be used for heat and power or be upgraded to syngas for bio-fuel production or methane for use as a synthetic natural gas.

- Gasification technologies are dependent on pressurised operations which have not been demonstrated at large scale.

- Sensitivity to feedstock quality and moisture content and gas clean up.

- Gasification and production of syngas for multiple uses

When placed in combination with a power generation device, gasification can offer higher conversion and thermal efficiencies (85 to 95%) compared to combustion routes. It is thought that at small scale (<5-10 MW_e) these provide economic systems and in conjunction with combined gas cycle are effective up to >30MW_e; the reliability and efficiency of the latter have yet to be established. Biomass Integrated Gasification Combined Cycle (BIG/CC) plants are also in development in Northern Europe, US and Asia.

The diverse range of end products that gasification produces makes it an attractive conversion technology (figure 5.7).

Anaerobic digestion (AD) is the biological degradation of (non-woody) biomass in oxygen free conditions resulting in the production of methane rich biogas. The biogas is either burnt on site for power generation or upgraded to natural gas standards for injection into the gas grid as bio-methane or has been known to be used as a gas bio-fuel for some transport fleets. AD is able to utilise a broad range of feedstocks but is particularly suited to wet biomass with an organic fraction. Methane capture from landfill sites is also a source of biogas based on the same principles as AD.

The areas that are of priority, particularly for smaller units, include:

- Improvements in biomass pre-treatment and reduction in fermentation time;
- Improve biogas cleansing process;
- Improvements in biological digestion phase (ultrasound and enzymes) are at an R&D phase.
- Production of biogas from anaerobic digestion.

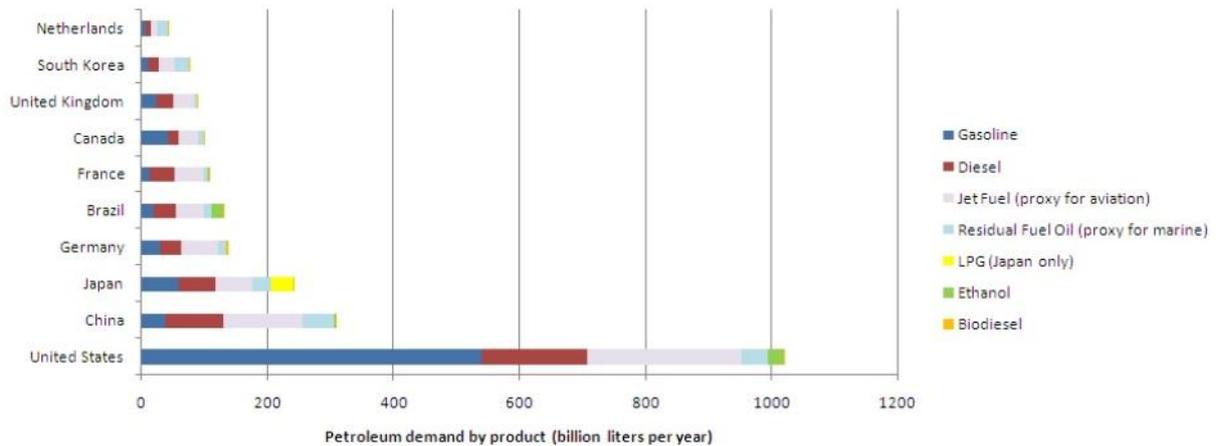
AD is a well established commercial technology with the need for easily accessible cheap feedstock. Co-product from AD is digestate, which can be used as a fertiliser and for soil remediation provided no contaminated feedstocks have been used.

³⁴ There are actually an additional 2 methods which involve indirect co-firing which involved the biomass being gasified for the syngas to be combusted in the coal furnace and parallel co-firing which involves biomass being combusted in a separate boiler and the steam being used in the coal power stations steam circuits (IEA, 2009a).

5.3.3 Biomass for Transport Applications

The use of biomass for transport applications in the form of bio-fuels is considered one of the most strategically useful uses of biomass due to the lack of presently available alternatives in the transport sector and the fact that ethanol and biodiesel, at low volumes, are relatively easy to incorporate into the present liquid fuel infrastructure. Figure 5.2, below displays the size of petroleum demand by market across a number of key nation states.

Figure 5.2: Demand for oil and bio-fuel based products across 10 markets Accenture (2009)



Three key points can be made from Figure 5.2, firstly the US market for transport fuels is over 3 times as large as the next largest (China), secondly the North American (US and Canadian) markets are heavily gasoline based where as the remainder are dominated by diesel and finally that jet fuel is already a substantial proportion of the total fuel market and from the scenarios reviewed in section 3 is projected to grow rapidly to 2050.

In the UK the consumption of diesel outstrips petrol (24 and 22 billion litres respectively in 2009 (UKPIA, 2010)) and the dominance of diesel will continue with annual projected growth at 0.9% pa and contraction of petrol at 0.5% pa. With the UK refining capacity configured for historic demand there is a built in surplus of petrol supply capacity and a deficit in diesel and jet fuel.

There are a number of high level issues that need to be considered when it comes to considering bio-fuels and their role in the transport sector; these include:

- Understanding of the infrastructure requirements of the different forms of bio-fuels including blending handling, distribution and refinery modifications. This requires engagement with fuel distributors and suppliers.
- Understanding the impact of non-fungible bio-fuels on compatibility with present vehicle fleet performance such as:
 - The blending wall in currently operating road vehicles. The extent of the bio-fuels market will be dependent on the rate at which supply fills the capacity in the transport market as dictated by the blending wall. This in turn is dependent on the willingness of Original Equipment Manufacturers (OEM) to honour their vehicle warranties at increasing blends (BEST, 2010). The blending wall stands as follows in respective bio-fuels markets:
 - In the EU bio-fuel blends of 10% are accepted.
 - In the US the 10% limit of ethanol that can be blended to gasoline is being approached and the Environmental Protection Agency has stated that 15% is acceptable for vehicles manufactured after 2001.
 - And, in Brazil ethanol is blended up to 25% and they also have 100% hydrous ethanol grade.
 - Other issues include assessment of lubricant interaction with bio-fuel content and durability issues at different blends and on air quality performance (AEA, 2009a).

This requires engagement with OEMs.



- Further increases in existing transport bio-fuels market capacity will be developed with the widespread roll out of Flexi-fuel vehicles which can tolerate blends of up to 85% ethanol and ethanol refuelling infrastructure (BEST, 2010).
- As yet there is no universally agreed classification for bio-fuels. The development of fuel standards for transport fuels would facilitate the international trade of bio-fuels.
- Much work in assessing the role of bio-fuels in terms of GHG mitigation and technical compatibility is focused on road transport and aviation due to the magnitude of current and projected future emissions from these sectors within transport (IEA, 2009b). There is some work in rail and the role in the marine mode is considered under researched (AEA, 2009a).
- And, the sustainability debate though predominantly focused on the feedstock production end of the value chain is also relevant to some downstream aspects. This is particularly relevant to energy / GHG profile and water footprints of conversion processes and the impact of widespread use of bio-fuels in the transport sector on air quality (Jacobson, 2007) - see appendix A3.7.

Classification of Transport Bio-fuels Technologies

There is no established classification of bio-fuels technologies. Here the generational classification has been adopted due to the extent that it is used in the literature, however, it is starting to be superseded by alternatives due to miss-leading flaws in the nomenclature. In this classification system, presently produced and commercially competitive fuels are termed 'first generation' - these include (E4Tech 2008):

- Bio-ethanol from sugar and starch crops produced by the fermentation of crops such as sugar cane, sugar beet, corn and wheat to produce bio-ethanol.
- Diesel substitutes from vegetable oils and animal fats which are produced by the crushing and transesterification of oil from rape seed, soy bean, palm and tallow to produce biodiesel.
- Hydrogenated Vegetable Oil which involves the use of vegetable oil feedstock to produce a high quality diesel product.
- And, biogas from the anaerobic digestion of organic fractions of MSW, sewerage sludge and wet farm and food wastes to produce methane and CO₂. The methane is separated from the CO₂, compressed and used in vehicles.

Delineating first from second generations is not rigid and can be based on feedstock type (for example the use of Ligno-cellulosic components of plants (straw, wood or grass) or novel oil (Jatropha), starch (Cassava) or sugar (Miscanthus) or conversion process (biochemical or thermo-chemical) which are at a demonstration level. There are some who consider the classification should be based on fuel attributes such as GHG savings or efficiency of resource use. In this review second generation pathways are:

- Ligno-cellulosic ethanol
- Ligno-cellulosic butanol
- Pyrolysis derived fuels
- Gasification and Fischer Tropschs Products

Third generation / advanced fuels are those novel routes that are at a R&D stage such as bio-fuels from algae, hydrogen from biomass.

There is an enormous volume of literature available on bio-energy technologies for converting biomass into liquid and gaseous transport fuels. For a high level over view see IEA 2004b, 2008, 2009a and 2011. For detailed reviews of conversion processes specifics (from a UK perspective) excellent reports include E4Tech (2008 and 2011e&f) and NNFCC (2007a and 2010b). Additional technology specific reports for Pyrolysis (E4Tech 2007b) and Gasification (NNFCC 2009a and 2010c) also provide insightful assessments of these processes states of development. Using these reports, the main processes conversion technologies for bio-fuels are reviewed in terms of their stage of development, areas where improvements are sought and examples of (UK) deployment to date.



First Generation Bio-fuels

Bioethanol from sugar and starch crops. Feedstock is either 'dry milled' which produces ethanol and distillers dry grains and soluble (DDGS) which can be used as a high protein animal feed or 'wet milled' where the feedstock is often combined with corn syrup which produces ethanol and gluten meal and corn oil. Biological fermentation processes to convert ethanol from sugars extracted from sugars and starch crops is technically mature and commercially widespread. The water is removed to produce ethanol of fuel quality in an anhydrous state and prevent separation of gasoline and ethanol when blended.

Ethanol can also be chemically converted to ethyl tertiary butyl ether (ETBE) as an additive to petrol. This can be undertaken from bio- or synthetic ethanol (see later).

Improvements that are being sought in the process include the:

- hydrolysis phase (converting sugar from starch);
- improved fermentation by producing yeasts which produce higher ethanol concentrations;
- water separation methods;
- process and plant optimisation mainly through scale; and
- greater value addition by the generation of co-products via a bio refinery route.

Presently operating UK production plants for bioethanol include the Wisington Plant which produces fuel from sugar beet and the Ensus plant at Wilton, Teesside which uses wheat feedstock.

Biodiesel and renewable diesel from oil crops, waste oils and fats (Fatty Acid Methyl Ester (FAME)). The conversion routes for diesel type fuels include trans-esterification and hydrogenation. Transesterification is a catalytic process and more dominant of the two processes due to its cheaper costs relative to hydrogenation and despite the fact the latter process produces a more superior biodiesel.

Transesterification of oils results in a glycerol byproduct which though often contaminated with methanol and catalyst can be sold as a co-product.

The process for the production of biodiesel FAME is relatively simple. Areas for focus in the development of the technology include:

- Modification and improvement in the transesterification process itself for example co-solvent process, heterogeneous catalysts, enzymatic conversion of triglycerides, and the in-situ conversion of oil in seeds.
- The production of higher grade glycerine by-product in order to enhance the economics with the existing markets being saturated with glycerine from existing FAME production.
- Improvement in GHG savings in production process.
- Fuel quality for FAME is specified by EN14214 but consistency of the product on the market has been an issue.

Biodiesel undergoes oxidative degradation by contact with air and metal which results in fouling impacting on engine wear and combustion properties. The early addition of antioxidants increases stability of biodiesel.

UK production plants for biodiesel include those run by Greenenergy and ESL producing fuels predominantly from vegetable oils and Argent Energy which produces from tallow and used cooking oil.

Vegetable Oil Hydrogenation. Vegetable Oil Hydrogenation involves the use of vegetable oil feedstock (e.g. palm oil, oil seed rape and soya beans) to produce a high quality diesel product which can be blended with diesel and integrated into the refuelling infrastructure. It is a well understood technology due to the fact that it uses existing refining techniques. The process involves the reaction of a vegetable oil with hydrogen in the presence of a catalyst to remove oxygen and impurities such as sulphur and nitrogen. There are two processing options:

- The Stand Alone option which is based on the addition of an additional step in existing refinery capacity to blend with diesel; and
- The Co-processing technique which involves use of the refinery hydro-treating capacity thereby reducing capital costs though it also reduces hydro-treating capacity for main product refinery capacity output.

The issues that require R&D in the hydrogenation process are (The Royal Society, 2008):



- Whether fuels are consistent across the feedstocks due to their differing chemical compositions i.e. feedstock input to fuel output;
- compatibility of fuel with existing fuels; and
- costs and benefits of re-refining the fuel produced.

This technology is at commercial scale operation already with Neste Oils having 4 NExBTL diesel plants operational: Two in Finland producing 190 kta of biodiesel each and one each in Singapore and Rotterdam both producing 800 kta. The only other commercial HV producer is Dynamic Fuels, a JV between Syntroleum and Tyson Foods.

Bio-methane. Though bio-methane can be used to generate electricity (in the form of biogas) it can also be used to power gas-powered vehicles (by removing the CO₂ from biogas). Cost reduction and simplification of the processes is required. There is interest in the use of bio-methane in HD, public service vehicles and other captured fleets as well as the possibility of injecting it into the gas network and off-taking / compressing it for vehicles where required and certifying the gas as renewable (e.g. the REA Green Gas Certification Scheme). Though there are substantial GHG savings the need for separate power-trains (i.e. bio-methane vehicles) and the need for the development of an independent distribution network suggests that this bio-fuel is unlikely to develop to a product in the wider bio-fuels for transport market (NNFCC, 2007a). Bio-methane for transport is not considered further in this review.

Methane as synthetic natural gas (BioSNG) can be synthesised from thermal gasification of solid biomass or bio-oil by a derivation of the FT synthesis process - see later. There is a need for scale to make this process economic which at present is not technically feasible.

Straight vegetable oil is also a niche transport fuel and again though has excellent GHG savings due to the inability to blend the bio-fuel with petroleum products and the need for vehicle modifications; it is no longer considered in this review.

The economic case for first generation bio-fuels is dependent on feedstock costs, which account for at least or more than half of the costs, and plant scale. In the case of bio-ethanol, production costs of Brazilian sugar cane are US\$0.31/ litre, US Corn US\$0.75/litre and UK wheat US\$0.87/ litre (Accenture, 2009). For biodiesel from waste feedstock the costs is US\$0.50/litre and vegetable oils at US\$1.60/litre (Accenture, 2009). Profitability is dependent on relative price of petroleum, commodity feedstocks used and policy support. The former two tend to fluctuate substantially and the later is subject to high levels of uncertainty.

Second Generation Bio-fuels

In order to utilise more component parts of biomass that may be converted to bio-fuels second generation process conversion technologies are being developed. Second generation technologies are split into bio-chemical routes and thermo-chemical routes. A good summary of these technology families is provided by The Royal Society Bio-fuels Review (2008 - p19 - 27) and more detailed information on the individual processes can be found in NNFCC 2007a - p 26 - 47 and E4Tech (2008, 2011e and f).

Bio-chemical Routes. Biochemical routes use fermentation as their base process.

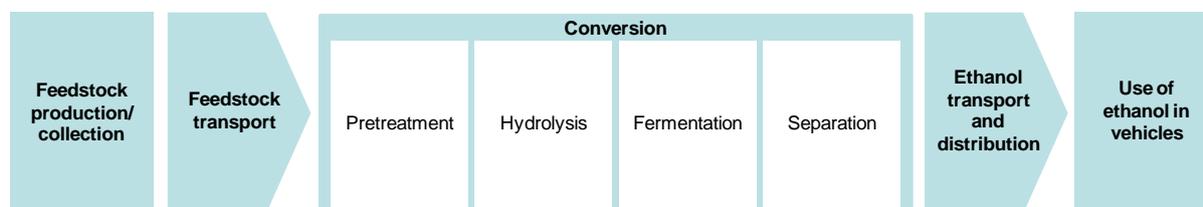
The following pre-conversion issues, which are relevant to bio-chemical routes, are under development:

- Fractionation is a process whereby the value of individual components can be increased prior to their subsequent conversion. At present the processes to allow biomass to be fractionated into high purity components are not well understood.
- And, the ability for conversion technologies to tolerate biomass variability in terms of physical and chemical composition, size, shape, bulk density etc. and its impact on conversion rate, efficiencies and costs is also poorly developed.

Bio-ethanol from Ligno-cellulosic feedstocks.

The steps involved in the bio-ethanol from ligno-cellulosic feedstocks process are shown in figure 5.3, below. The conversion process is the focus of this review.

Figure 5.3: Key Steps in the production of ligno-cellulosic ethanol (E4Tech, 2008)



Ethanol can be produced from ligno-cellulosic biomass (the organic matter containing a combination of lignin, cellulose and hemicelluloses). Feedstocks that can be used in this processes include dedicated energy crops, agricultural and wood residues. Some processes involve mechanical breakdown of the feedstock to increase surface area - following this the process involves (IEA, 2009a and E4Tech, 2008):

- Pre-treatment to separate biomass into cellulose, hemi-cellulose and lignin. There are a number of physical, chemical and biological processes in development the majority of which are for homogenous biomass stocks. The process can be an expensive phase of the production process.
 - Pre-treatment development spans early R&D and some demonstration stage (e.g. biological pre-treatment using fungi and ionic liquids) to nearing commercial (e.g. dilute acid hydrolysis). The most advanced processes involve homogenous feedstocks. The technologies that leave cellulose for hydrolysis to sugars include:
 - Biological pre-treatment such as the use of white-rot fungi which is slow and because of this the economics are uncertain.
 - Chemical pre-treatment such as acid and alkali treatment which often require high temperature / pressure are at commercial stage. Novel chemical techniques that do not require temperature / pressure are also being developed.
 - Physio-chemical pre-treatment such as steam explosion. This technique is not ideal as it can reduce efficiency of follow on processes. R&D is focused on improving the technique.
 - Combinations such as acid steam explosion, acid explosion, Liquid Hot Water and ammonia fibre explosion (AFEX). These have not shown to be very effective on feedstocks with high lignin content.

There is substantial potential for improvement in this process particularly with a view to improving costs and performance. An area where detailed R&D is needed is in understanding the structure of ligno-cellulose and the kinetics of each processes technique.

The following observations are made with regards this phase:

- There are a wide range of pre-treatment processes in development and more are being developed.
- There is no clear technology leader at present which each technique having its own advantages and disadvantages.
- It is also clear that they tend to be feedstock specific with none being able to function as a universal pretreatment technique across a wide range of feedstocks (NNFCC, 2007a).
- An issue impeding the development of this process is the lack of detailed, comparable data on each system from each feedstock though the US has sought to improve this via the establishment of the Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI).
- Hydrolysis of cellulose and hemicelluloses to produce sugars (this can be undertaken chemically (e.g. acid hydrolysis) or biologically (using enzymes)). Acid hydrolysis is a well developed process. However, biological hydrolysis routes are considered to provide better scope to reduce costs and preferable due to the use of milder operating conditions and non-corrosive reaction medium. The hydrolysis of cellulose produces C6 hexoses and the hydrolysis of hemicelluloses produces both C6 and pentoses (C5) sugars.
 - Again hydrolysis development spans early demonstration (e.g. biological using enzymes) to pre-commercial (e.g. acid hydrolysis). The remainder of this section focuses on enzymatic hydrolysis for which the challenges include (E4Tech, 2008):



- Reduce costs of enzymes.
- Improve product tolerances.
- Improve enzyme specificity.
- Increasing yield of sugars.
- And, separation and re-use of enzymes.

Bacteria and fungi are used to produce enzymes with anaerobic fungi being preferred e.g. Verenium are active in the identification of cellulase genes in the termite gut due to termite's ability to digest cellulose. There is much commercial work being undertaken in this area with 30-fold reduction in enzymes costs being claimed by some such as Novozymes.

Many organisations are using genetic modified organisms in this phase.

- Fermentation of the sugars to ethanol which for C6 sugars is a well known commercial process. For C5 sugars work is being undertaken to achieve this efficiently. With regards respective stages of development:
 - The fermentation of C6 sugars is commercial though there remain challenges such as inhibition from ligno-cellulosic pre-treatment by-products.
 - C5 fermentation is a late R&D and in early demonstration phase. The main R&D focus is manipulating organisms to metabolise C5 sugars which present organisms do not do. Effort has been focused on the genetic modification of bacteria to achieve this (NNFCC, 2007a).

Some organisations have developed bacteria that are able to concurrently ferment C5 and C6 sugars (e.g. TMO Biotech) whilst elsewhere there have been attempts to modify the feedstock to derive higher levels of accessible sugars by producing low levels of lignin.

- Separation of the ethanol from the co-products of fermentation. There are a number of separation processes. In the process of Separate Hydrolysis and Fermentation (SHF) the individual processes described above take place in separate steps. There are also processes which combine the steps being developed called Simultaneous Saccharification and Fermentation (SSF) for hexose sugars; Simultaneous Saccharification and Co-fermentation (SSCF) for hexose and pentose sugars simultaneously and Consolidated Bioprocessing (CBP) which all take place in a single reactor. The integration that results in the CBP technique suggests a potential fourfold reduction relative to a SSFC technique (NNFCC, 2007a). In these combined processes ethanol has to be separated from the co-products through distillation and other processes. Distillation is a commercial stage but is energy intensive therefore novel, less energy intensive technologies are being investigated which will reduce costs.

Waste water from the fermentation process and hydrolysis can be recycled back into the process once treated to recover chemical or biological catalysts and remove other impurities. The final product must be completely dry when added to petrol.

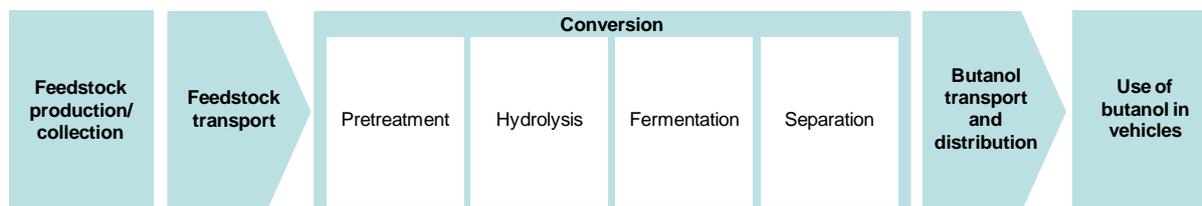
Further details of innovation needs for the bio-ethanol from ligno-cellulosic route can be found in Appendix 5.

The majority of ethanol from ligno-cellulosic R&D is being undertaken in the US though interest is being developed in Brazil and Europe. Plant developers with demonstration and pilot plants include amongst others Iogen, Abengoa, POET, Mascoma, Dupont Danisco and Verenium (Accenture, 2009). The majority of plants are based in the US and some in Canada and Europe. A study assessing the feasibility of developing a ligno-cellulosic plant in the UK was undertaken by NNFCC (2008b).

Ligno-cellulosic Butanol.

The steps involved in the ligno-cellulosic butanol process are shown in figure 5.4, below. The conversion process is the focus of this review.

Figure 5.4: Key Steps in the production of ligno-cellulosic butanol (E4Tech, 2008)



Butanol can be produced from the same ligno-cellulosic feedstock as for ethanol. The processes is similar to ethanol production as described in figure 5.3 above except at:

- The fermentation stage where sugars are converted to acetone, butanol and ethanol via the ABE process.
 - This is at a late R&D and early demonstration phase of development. Some working in this area are looking at improving the ABE process and others at novel routes such as through the genetic modification of microbes that produce butanol. R&D is required in the following areas (E4Tech, 2008):
 - Increasing butanol yield (relative to input feedstock) - its production from sugar is three times less efficient than converting to ethanol.
 - Increasing butanol concentration.
 - Increasing the tolerance of the micro-organisms, their productivity and rate of the process.
 - And, separation and purification of butanol.
- Separation of the low concentrations of butanol (1-2%) from the product stream is extremely difficult due to the fact that distillation cannot be used.

Further details of innovation needs for the ligno-cellulosic butanol route can be found in Appendix 5.

Commentators note that the economics of butanol production remains arguably one of toughest challenges facing the industry (Accenture, 2009).

Present butanol development has focused on converting the readily available starch and sugar components of biomass rather than the ligno-cellulosic components. A number of butanol plants opened in China at the end of the last decade to produce solvents rather than transport fuel.

Cobalt Bio-fuels have the only and most developed operational plant using ligno-cellulosic feedstock though other players have announced the intention to develop this route include Butacol and a Gevo/Cargill JV.

Alternative fermentation routes to butanol alone using modified bacteria have announced commercial plants to be opening by 2013 (e.g. Gevo). Developers have also stated the intention of retro-fitting ethanol plants for butanol production for example Butamax (BP and DuPont JV) in Brazil in 2013.

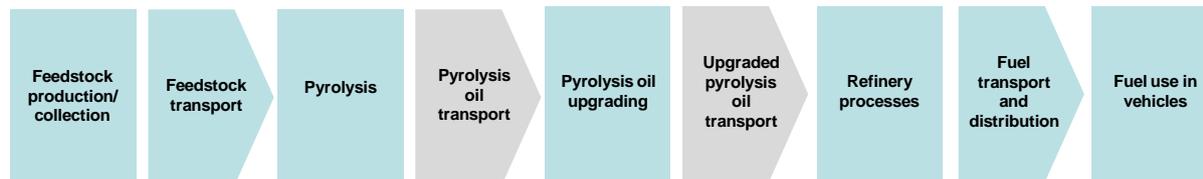
Thermo-chemical Routes involve the use of thermo-chemical process which can convert a wide variety of feedstocks into a range of intermediaries and transport fuels. A key characteristic of the process route is the need to obtain large quantities of feedstock - around 1 M tonnes - to make the economics balance. The thermo-chemical conversion processes routes described below include: Vegetable Oil Hydrogenation, Pyrolysis derived oils and Gasification and Fischer Tropsch (FT) products. The thermo-chemical routes involving Gasification and FT process are also known generically as Biomass to Liquids (BTL) (which fit into CTL family of Coal to Liquids (CTL), Gas to Liquids (GTL) and Waste to Liquids (WTL)).

Pyrolysis Derived Fuels.

The steps involved in the pyrolysis³⁵ derived process are shown in figure 5.5, below. The conversion process is the focus of this review.

³⁵ Pressure liquefaction is similar to fast pyrolysis but produces a bio-oil with an oxygen content of 15 to 20% compared to 35 to 40% in pyrolysis. Its main advantage is that it operates in a liquid phase allowing the use of wet feedstock.

Figure 5.5: Key Steps in the production of pyrolysis derived fuels (E4Tech, 2008)



A broad range of feedstocks can be used in pyrolysis based routes though the composition of liquid fraction is dependent on the feedstock mix (Brownsort, 2009). Fast pyrolysis is the process which optimises the production of the liquid fraction called bio-oil and reduces the co-products of char and gas. It involves the rapid combusting of biomass to $\sim 500^{\circ}\text{C}$ with a short hot vapour residence time (~ 1 second) in a low oxygen environment (Bridgewater, 2007). The feedstock may undergo pyrolysis twice to improve transport economics first near to feedstock source and then at scale at a centralised location (see section 5.2, above) and then upgraded (though plastic wastes (e.g. polyethylene and polypropylene) used to yield gasoline and diesel which can be blended with petroleum based products without upgrading). Upgrading is necessary to reduce acidity and water content which makes pyrolysis oils unstable. This allows the pyrolysis oil to be fed into an existing refinery to produce conventional products including diesel and petrol.

- Pyrolysis is at an early commercial stage though there are a number of novel options (which produce oil that requires less upgrading to be used) such as microwave pyrolysis which is at a late R&D stage. Areas of further research include (E4Tech, 2008):
 - Improvement of reactor design to improve heat transfer and reaction rates and reduction of impurities.
 - Improvement of oil quality such as by reducing char, alkali metals, water and viscosity of the oil.
 - Use of catalysts to enhance reaction and oil quality and the yielding of co-products.
 - And, optimising pyrolysis process for feedstock type. Feedstock has an important effect on bio-oil characteristics and its stability.
- Work on pyrolysis oil upgrading is at pilot phase has been an area of relatively little research though recently activity has increased. There are three routes, areas which require research within each pathway include (E4Tech, 2008):
 - Hydrotreatment a complex processes where prevention of catalyst deactivation and reactor clogging is a priority.
 - Catalytic upgrading (zeolitic cracking) to reduce coking, catalyst regeneration and optimise products formed.
 - And, Fractionation to remove fractions of pyrolysis oils that are high in oxygen content.

All routes require significant RDD&D.
- Integration into refineries is attractive due to capital cost reduction and the ability to fit into existing infrastructure and also at a pilot phase of development. The key areas of research in this area include (E4Tech, 2008):
 - How much upgrading is required to be undertaken to the oil before it can be fed into the refinery and where should it be integrated.
 - What products are best produced by the refinery.
 - How much extra hydrogen is required for the processing of biomass.
 - And, the ability to scale up present designed to produce commercially viable quantities of fuels (NNFCC, 2007a).

Further details of innovation needs for the pyrolysis route can be found in Appendix 5.

There is limited published material on the carbon savings of the process and product but 75 to 95% relative to diesel oil and petrol have been stated due to the efficiency of the process. There is also the possibility that other high value compounds from pyrolysis oils may be possible e.g. aromatics from lignin component of feedstock, flavourings from aqueous components etc. which would assist the economics of the process.

To date pyrolysis plants have been used for chemicals production or heat and power applications and small scale pyrolysis is approaching commercial scale. For large scale transport applications there is no consensus as to what the dominant design of pyrolysis plants. As a consequence a number of designs are at pilot to early

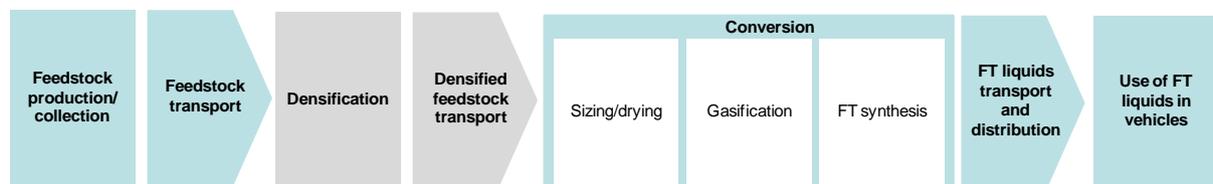
demonstration scale; these include: BTG Rotating Cone Reactor; Dynamotive Bubbling Fluid-bed Reactor, FZK / Lurgi Fast Pyrolysis Reactor, TNO Catalytic PyRos Reactor, UOP-Ensyn JV - Envergent Technologies, BioeCON, KiOR and Biomass Engineering (for more detail see NNFCC, 2007a - p55 - 61). Though opinion is polarised some consider that if breakthroughs are made at pilot scale and there is support from the oil industry that market penetration would be possible relatively rapidly (E4Tech, 2007b). The Carbon Trust Pyrolysis Challenge (2010c) estimated the development to a full scale plant demonstration scale plant in 2014).

Gasification and Fischer Tropsch Products.

There is a rich literature reviewing the state of gasification development. For example, The Royal Society 2008, US DOE 2010b, E4Tech 2008, 2011d,e,f and NNFCC 2009a and 2010c which are comprehensive covering the different options and descriptions of all the existing gasification pilot to demonstration plants for small scale heat and power, bio-fuels and BioSNG. A brief overview is made here.

The steps involved in the Gasification and Fischer Tropsch (FT) process are shown in figure 5.6, below. The conversion process is the focus of this review.

Figure 5.6: Key Steps in the production of Gasification Fischer Tropsch Products (E4Tech, 2008)



Though FT technologies can use a broad range of feedstocks the present projects focus on wood. In terms of feedstock selection for this route the following are areas for development:

- The establishment of standards for feedstock to enhance feedstock quality and thereby characterise optimum and difficult fuels.
- Drying feedstock is an expensive process (in economic, GHG and energy terms) and has raised the suggestion that there might a trade-off by feeding wet residues which would also broaden the range of feedstocks that could be used.
- And, Pyrolysis oil may also be atomised for gasification and subsequent synthesis. There are fewer uncertainties with regards the behaviour of pyrolysis oils undergoing gasification (Bridgewater, pers comms).

The conversion of FT liquids involves the following processes:

- Sizing and drying of the biomass. This stage is a commercial scale but drying to <10% moisture content can be expensive.
- Gasification where the biomass is heated in a low oxygen environment to produce a syngas consisting of carbon monoxide and hydrogen;
 - Gasification technology is nearing commercialisation but improvements are required in the following areas (E4Tech, 2008 and US DOE, 2010b):
 - Assessing the best gasifier and process design. There are a number of options (NNFCC, 2010c) - these include: Downdraft fixed bed, Updraft fixed bed, Bubbling fluidised bed, Plasma gasifier, Circulating fluidised bed, Dual fluidised bed and Entrained flow - these range in biomass capacity (in that order) in the range of 1 to 10,000 odt/day. The feedstock requirements of different gasifier types vary considerably. In the case of Entrained Flow particle sizes, optimal moisture content and consistent composition is required where as for plasma gasification minimal pre-treatment is required. The remainder have intermediate needs.
 - Understanding the impact of feedstock composition on gasification options and syngas produced. It is considered that plasma gasifiers produce the best syngas.
 - How to deal with tars, sulphur and carbon which need to be removed for further processing.



- Increasing gasifier efficiency.
- And, improving the quality of the syngas by the removal of impurities such as sulphur and nitrogen.

For greater detail of the stage of development of gasification technology types see E4Tech (2010b) - p24 Table 6. The following is noteworthy:

- None of the developers have plants in commercial operation with liquid fuels production and no technology type is a clear winner at this stage.
- There is a need for a substantial reduction in technical risk through the development of gasification technologies.
- And, a better understanding of the economics in order to attract developer and investment interest (E4Tech, 2010b).

The improvement of syngas is considered the most important stage. It is technically complex and the processes involved are dependent on the feedstock quality - the more impurities in the feedstock the more processes are needed. The syngas has to be sufficiently pure (to parts per billion range). The development of more tolerant catalysts to impurities, particularly tar, would offer cost savings (further details of R&D requirements for gas cleaning can be found in E4Tech (2010b) - p 38).

Due to current technologies such as wet gas scrubbing having efficiency and cost penalties alternative options such as hot gas and plasma clean up are being researched; currently there is no experience of large scale gas cleaning (The Royal Society, 2008). Co-processing with coal has been explored in the power generation sector.

- FT synthesis involves the conversion of syngas to a liquid hydrocarbon in the Fischer-Tropsch process - a chemical reaction that involves iron and cobalt catalysts (where the latter catalyst is used water gas shift is required to balance the molecular ratios of H₂/CO). Control of the range of products in the FT process is facilitated by controlling the temperature, pressure catalyst and reactor configuration. The following developments are needed in this process:
 - FT catalysts to produce diesel / naphtha / gasoline whilst removing contaminants has been commercially deployed for Gas to Liquid (GTL) and Coal to Liquid (CTL) technology for some time.
 - The selection of the catalysts that are more tolerant to impurities and that may be regenerated and recycled for the development of products is a key area of research as it impacts on the economics of the process. The ability to recycle is reduces the risk of the operation being impacted by shortages of catalysts.
 - The FT reaction is highly endothermic.
 - There are a number of reactor designs including fixed bed, fluid bed, slurry phase and ebullating reactors with no consensus as to the dominant design.
 - And, catalytic conversion from syngas to alcohols is at the demonstration phase with there being substantially less work in this area than in other routes.
- The individual technologies involved in the FT process are pre-commercial but integration of these processes is only at a demonstration phase. The following areas are in need of optimisation (E4Tech, 2008 and US DOE, 2010b):
 - Integration between gasification and the FT process in particular matching feedstock, gasification and synthesis processes to optimise chemical outputs for each phase to desired product.
 - And, development of sensors and controls to manage the process performance with varying feedstocks and desired outputs.

Further details of innovation needs for the BTL route can be found in Appendix 5.

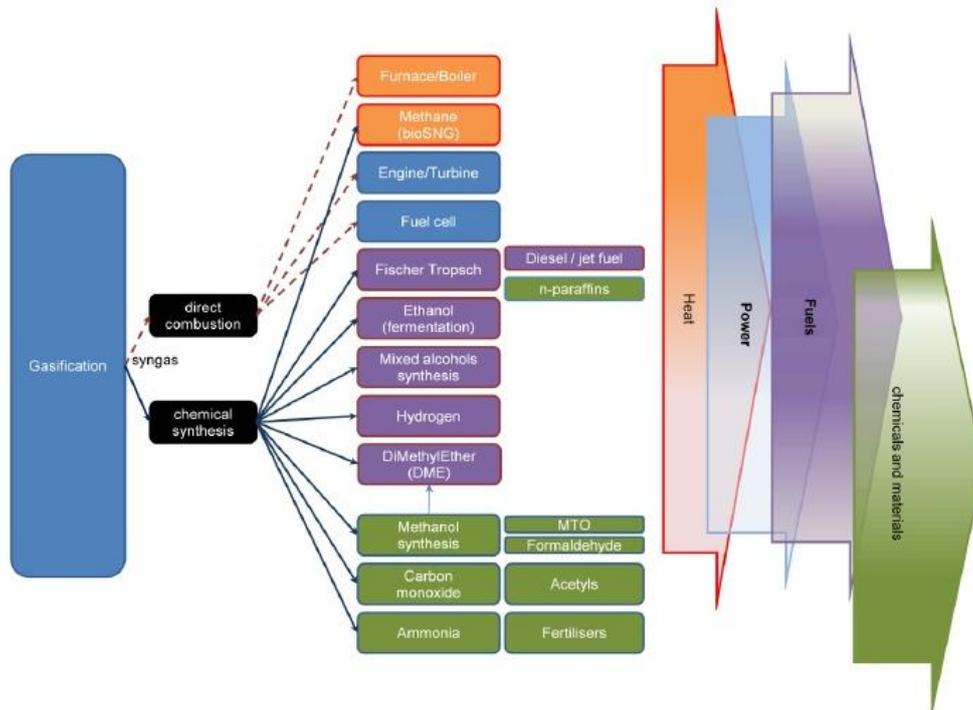
The product potential and potential GHG intensity makes this route an attractive option. A summary of BTL development activities is detailed in NNFCC, 2007a - p 72-76. It has been estimated that the minimum economic size of a gasification-FT processes is 0.5 to 1M tonnes of bio-fuels which would require the gasification of 2.5 to 5 Mt of feedstock per year. Present BTL plants are substantially smaller - in the US Rentech has a 24,000 tonnes per year FT diesel plant under construction which will be complete by 2012 and NSE bio-fuels a JV between VTT, Foster Wheeler, Stora Ensi and Neste Oil plan to have a 100,000 t/yr FT diesel commercial plant by 2013.

There are a number of bio-fuels that can be derived from the gasification-FT route. These are shown in figure 5.7, below. The products are discussed in the section below on end uses and more detail can be found in NNFC 2007a - p79-82 and NNFC, 2010d.

The following routes are noteworthy:

- Ethanol can be produced from gasification directly by a chemical process or fed through a biological fermentation process. In the latter process a number of barriers need to be overcome related to ensuring the ability for micro-organisms to operate efficiently.
- Methanol to Gasoline and Diesel is a route that may be undertaken via synthesising methanol and then use the methanol to gasoline (MTG) or methanol to olefins, gasoline and diesel (MOGD) process. Produces higher yields but because it involves another step impacts on the economics.
- Bio Dimethyl ether (DME) is produced by dehydrating methanol or directly from syngas. For further details of innovation needs for the DME route can be found in Appendix 5 and E4Tech (2011f).

Figure 5.7: Summary of broad range of products available through the gasification route (NNFC, 2010d)



Third Generation Bio-fuels - Novel Routes

The steps involved in the novel process are shown in figure 5.8, below. The conversion process is the focus of this review.

Figure 5.8: Novel Bio-fuel Routes (E4Tech, 2011f)



Novel bio-fuel routes are characterised by the following:

- They involve multiple routes using combinations of components of the above conversion technologies.



- Tend to be a limited number of developers often only one working on a particular specific conversion route often with a specific feedstock or product being investigated.
- And, tend to be private sector with majority at applied R&D to early demonstration and as a result little data on performance characteristics are available.

Novel routes would represent a significant development if the efficiency of resource use, carbon / energy intensity and production costs are found to be better than the main routes undergoing work described above.

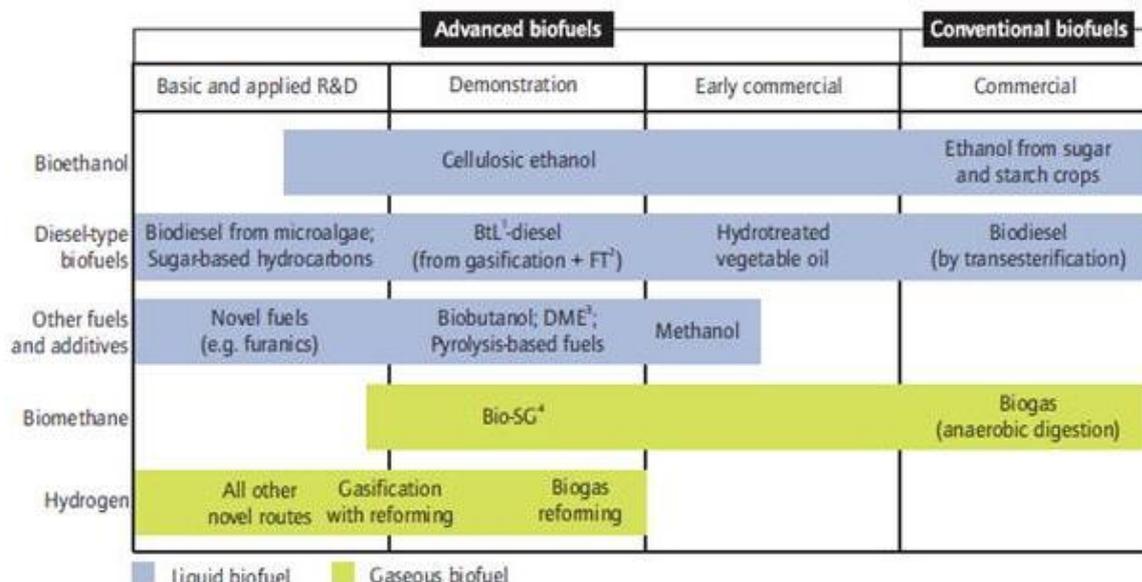
The types of routes and products that are being developed include:

- *Algae*. See section 4.3.3.
- *Liquid-phase catalytic processing of biomass-derived compounds*. Sugars and carbohydrates extracted from biomass components that can be biochemically or catalytically converted into hydrocarbons (e.g. Hydroxymethylfurfural (HMF) or its derivatives. One HMF derivative is stated has having an energy density 40% greater than ethanol and is not soluble in water. For example, Avantium in the Netherlands is producing ethoxymethylfurfural (EMF) directly from glucose.

Other similar products include:

- Isoprenoids - compounds which could substitute for gasoline, diesel and jet fuels via genetically modified organisms;
- Iso-butanol which is produced in a similar manner to butanol and can be used to produce octane, jet fuel, diesel fuel and rubber;
- Higher alcohols such as octanol; Other hydrocarbons such as bio-crude; Levulinic acid derivatives such as Methyl tetrahydrofuran (MTHF) and Levulinate esters; Alkanes from aqueous phase reforming and Esters
- *Hydrogen from biomass*. Hydrogen can be used as an energy carrier and is thought to potentially have a role in decarbonising the transport sector in the long term though it requires development of a dedicated fuel infrastructure. Potential conversion routes include biological routes, thermal routes and photosynthetic routes (IEA, 2009a).
- *Aqueous Phase Reforming*. Traditionally, sugars have been fermented into ethanol and distilled. BioForming® combines aqueous phase reforming (APR) and traditional petroleum refining technologies to generate hydrocarbon molecules by catalytically converting plant sugars. Virent is commercializing this advanced bio-fuel technology that catalytically transforms a wide range of soluble plant sugars into hydrocarbon molecules like those produced at a petroleum refinery. These renewable hydrocarbons can be blended seamlessly to make gasoline, jet fuel, and diesel. The sugars can be sourced from feedstocks such as wheat, corn and sugarcane and from non-food sources such as wheat straw and sugarcane pulp. These bio-fuels have the same properties as conventional gasoline and diesel.

Figure 5.9: Development status of main technologies to produce bio-fuels for transport from biomass (E4Tech, 2009 after IEA, 2011)



Significant cost reductions are required for second and third generation process conversion technologies for the products to compete with fossil fuel derived fuels. In a recent estimate of the cost reductions that might be feasible at different levels of innovation effort is displayed in table 5.4, below.

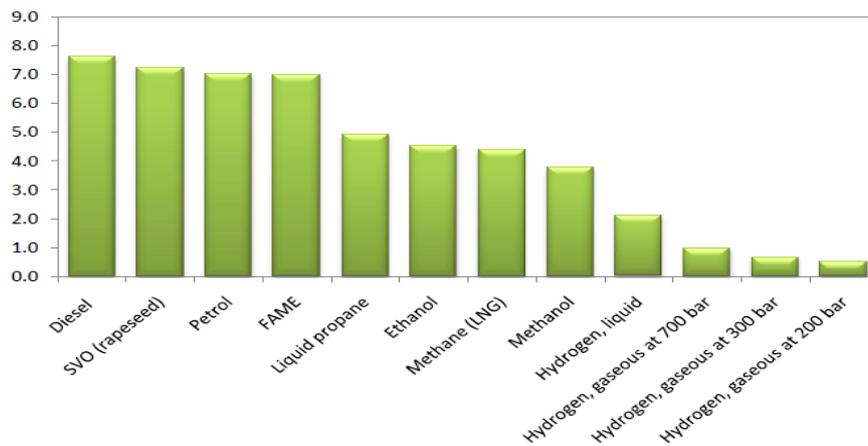
Table 5.4: Levelised cost reductions from innovation for each technology stream to 2020 and 2050 based on 2010 baseline costs of £35/GJ (E4Tech, 2011e&f).

Technology	2020 Reductions (%)	2050 Reductions (%)
Ligno-Cellulosic Ethanol	46 -52	52 - 63
Ligno-cellulosic Butanol	41	54 - 71
Bio-DME	32	56 - 60
BTL	46	55 - 65
Pyrolysis	0 - 50	0 - 75
Novel Bio-fuels	0 - 47	0 - 76

Based on the analysis undertaken in the E4Tech (2011e,f), the cost reductions are significant with greatest effort for pyrolysis and novel routes to 2050 with ligno-cellulosic ethanol, BTL, pyrolysis and novel routes showing great reduction potential to 2020. With the commercial feedstock yields post-processing highly uncertain (Murphy, pers coms) the derivation of such figures can only be considered indicative with the potential for disruptive advances in anyone route to radically change the economics of the process possible at any time - though this is unlikely to be soon.

A summary of the energy intermediaries for transport fuels is made in figure 5.10, below. Figure 5.10, displays the volumetric energy density of transport fuels. It can be seen that there is a wide variety of transport fuels and intermediaries of differing properties which require differing infrastructure needs.

Figure 5.10: Volumetric energy density of transport fuels adjusted for energy efficiency in GJ/m³ (NNFCC, 2010b)



Assessment of Bio-energy Process Conversion Technologies for Transport

The ultimate ambition is for a conversion technology that is able to accept a broad range of feedstock which can be converted highly efficiently (GHG, energy balance and resource use) and produce a consistent quality fuel that is able to be dropped into the future infrastructure with the minimum of modification (section 2.3).

The routes for conversion technologies for bio-fuels production are numerous involving bio-chemical and thermo-chemical routes or a combination of the two to create intermediaries or end products which are diverse. End products range from the production of drop in fuels to alternative fuels which have blending limits in the conventional fuel system or require their own dedicated infrastructure. There are often multiple, complex routes which can be used to derive the same fuel and extensive proprietary research at various stages of development for the same stage in conversion. With many phases within conversion process routes there are difficulties in scaling up, integrating the phases within the entire process conversion and broadening the feedstock types that may be used. The future potential of bio-fuels remains highly uncertain and full commercialisation is unlikely to occur for some years yet.

Regional clusters of refineries are centred in Europe and US at present. The fragmented and proprietary nature of the work being undertaken in transport bio-fuels process conversion makes it extremely difficult to assess the state of different technology routes. Some routes, particularly the novel ones, have a low level of awareness in the sector. Though the location, feedstock competition, and co-product dependency will influence conversion platform selected - consensus as to technology route has yet to develop so lock in has not happened.

Given the huge range of potential fuels available, and their varying characteristics, it will be essential to involve oil and auto experts in assessing what fuel requirements will be and how these fuels, or blends of them can meet them. From a UK perspective, the international nature of transport issues makes the need for engagement in international collaborative forums to be of paramount importance to ensure that fuel developments conform to internationally developing market expectations.

Table 5.5: Biomass conversion to energy intermediaries for transport fuels (NNFCC, 2010c, E4Tech, 2011e,f and IEA, 2011 - p14).

Bio-fuels - Non Fungible: Description and Routes	Barriers / Notes
<p>Straight vegetable oil (also known as pure plant oil) is obtained from the crushing of oil producing seeds. It requires no further processing prior to use.</p>	<ul style="list-style-type: none"> • Used as a diesel substitute but not blended; • Engine modifications are necessary to tolerate the greater viscosity and poor cold temperature performance of the bio-fuel; and • does not easily integrate with the existing fuel supply infrastructure. Captive fleet opportunities.
<p>Ethanol is the most established bio-fuel substitute for petrol fuel. Regulated by Fuel Standard EN228 in the UK Sugar and starch based ethanol is in commercial scale production. Ligno-cellulosic ethanol from biochemical routes is at a demonstration phase. A Ligno-cellulosic ethanol from gasification and chemical catalysis is at commercial scale. Ligno-cellulosic ethanol from gasification and fermentation are at pilot scale.</p>	<ul style="list-style-type: none"> • Blending wall E10 (no proper agreement for E15 in US despite EPA statement on cars manufactured after 2001) with FFVs required for higher blends up to E85; • The energy density of ethanol is 70% relative to petrol which can reduce fuel economy though this is partially compensated for by ethanol's higher octane number; • Hydrophilic and corrosive properties make blends of ethanol and petrol unsuitable for transportation through existing fuel pipelines.
<p>ETBE can be derived from ethanol and is currently added to conventional fuels as an octane enhancer and oxygenate to improve the efficiency of combustion. ETBE can be blended with petrol at up to 22% by volume, and has low water solubility compared to ethanol so blends of ETBE and petrol may be distributed through existing pipelines.</p>	
<p>Biodiesel - FAME (Fatty Acid Methyl Ester) is the most established bio-fuel substitute for diesel fuel Most of the FAME produced in the UK is made to standard EN 14214. FAME is at commercial scale production.</p>	<ul style="list-style-type: none"> • Blending wall B10 (in UK B7) though 30% blends possible for some makes of vehicles; • Similar energy content as diesel (90%) and with octane number has similar fuel economy; • FAME has a poorer cold temperature performance compared to fossil diesel and this can limit the amount of FAME that can be blended into diesel especially from vegetable oils (e.g. Palm).
<p>Bio Dimethyl ether (DME) is produced by the catalytic reaction of syngas or methanol. At atmospheric pressure, DME is a gas, but at a slight pressure, it may be handled as a liquid (like LPG) but this. DME is not blended with diesel fuel. A European consortium aims to complete the construction of a DME pilot plant in 2010.</p>	<ul style="list-style-type: none"> • Requires some modification at fuel injection to run in vehicles; • Liquefied DME contains approximately half the energy content of fossil diesel fuel; and • Requires a dedicated distribution infrastructure. Captive fleet opportunities.
<p>Butanol is produced by the fermentation of sugars. The technically mature ABE fermentation process produces butanol as a mixture of butanol, acetone and ethanol. Butanol is at commercial scale for chemicals but not bio-fuels. Economics of conversion are an area for work though once proven, this technology could potentially enter the market relatively quickly, through the modification of existing ethanol plants.</p>	<ul style="list-style-type: none"> • Butanol has a higher energy density, less corrosive nature and lower water solubility than ethanol. Butanol can be blended with petrol at up to 15% butanol by volume and it is anticipated that butanol will be logistically less challenging to distribute than ethanol. In addition, butanol may potentially be blended into diesel. • It has a lower energy density (80% of) petrol and (75% of) diesel.
<p>Biomethane BioSNG. Methane is a gaseous bio-fuel that is not suitable for blending with petrol or diesel fuels. However, it Methane can be produced by upgrading biogas produced by the anaerobic digestion (AD) of organic material, or by the catalytic methanation of syngas. In order to use methane as a road transport fuel, it must be cleaned of impurities and either compressed or liquefied. Process is at an early commercial level of development.</p>	<ul style="list-style-type: none"> • Can be used in vehicles with engines modified to run on compressed natural gas or liquefied natural gas or in combination with a small amount of diesel in dual fuel diesel engines (typically used in trucks). The availability of suitable vehicles is increasing. • Requires a dedicated refuelling infrastructure.
<p>Hydrogen has a major application in oil refinery operations and the manufacture of chemicals. However, hydrogen may be used as a fuel in fuel cell vehicles, or in modified internal combustion engines. Hydrogen may be derived from methane from syngas or AD. The development of hydrogen as a fuel from biomass is at an R&D stage.</p>	<ul style="list-style-type: none"> • The volumetric energy density of hydrogen is very poor and dependent on the pressure at which the gas is stored, as illustrated in Figure 5.10. • Developing appropriate on-board fuel storage is a major technical challenge. • Use of hydrogen would require a dedicated refuelling infrastructure. Captive fleet opportunities.



Methanol may be produced by the catalytic reaction of biomass-derived syngas.

An alternative use of methanol is in the manufacture of other bio-fuels including FAME, synthetic diesel, synthetic petrol, DME, and MTBE (methyl tertiary butyl ether). It can also be used to produce chemicals. At present, natural gas derived methanol is being used in the manufacture of FAME; converting to biomass derived methanol would potentially increase the greenhouse gas savings realised by FAME.

Methanol is produced from syngas by a catalytic process similar to FT synthesis. Commercial production of biomethanol from glycerol, a co-product of the FAME manufacturing process, started in 2009 by BioMCN in the Netherlands.

- Methanol may be blended with petrol up to 3% by volume, under the European Fuel Quality Directive. Alternatively, methanol may be used as a fuel in flexible fuel vehicles designed to accept methanol at up to 85% blend in petrol (M85).
- Toxicity and corrosion concerns.
- The energy density of methanol is low (Figure 5.10).

Other Novel Fuels. See main text

Bio-fuels - Fully Fungible: Drop-in Fuels. Description, Routes and Notes

BTL - Syndiesel (FT Diesel & HVO). Synthetic diesel fuels represent a high quality diesel blending component, typically having very high cetane, low or zero sulphur content and clean burning characteristics.

Synthetic diesel may be produced from syngas using the well-established FT process, from vegetable oils via hydro-treating or alternatively by the less well known MOGD process. Biomass derived FT diesel is expected to become commercially available in Europe during this decade. Hydro-treating vegetable oil (HVO) also produces a synthetic diesel fuel.

The FT process is at a demonstration stage for the production of bio-fuels and the HVO technology has been in commercial operation since 2007 in Finland.

- These fuels have very good cold flow properties. However, their density does not meet the current diesel standard which is generally being overcome by blending with crude oil derived diesel or through further fuel upgrading.
- Synthetic diesels can be completely integrated into the existing diesel fuel supply infrastructure, and used within existing vehicles provided the finished fuel as supplied to the consumer meets the quality standard EN590.

Upgraded Pyrolysis Oil can be used in existing crude oil refineries or in specific upgrading facilities to produce synthetic diesel and petrol fuels.

Pyrolysis technologies for producing pyrolysis oil are commercially available from Canada, but the upgrading process to convert the raw pyrolysis oil into petrol and/or diesel requires further research and development. This work is progressing; the technology is expected to be commercially available from around 2012/13.

- These fuels are expected to make good petrol and diesel blending components having properties similar in specification to crude oil derived petrol and diesel.

HVO/HRJ Synthetic jet fuel is a drop-in replacement for crude oil derived aviation fuel, being completely compatible with existing aviation fuel infrastructure, and suitable for blending with crude oil derived aviation fuel. Synthetic jet fuel is currently produced from coal, and is hence not a bio-fuel. However, technologies are being developed to produce synthetic jet fuel from biomass Hydrogenated renewable jet.

- Several airlines have conducted test flights using biomass derived jet fuels, mostly produced from vegetable oils through the hydro-treating route. A small number of test flights have demonstrated the use of synthetic jet fuel produced via the biomass FT route (i.e., BTL jet fuel).

Synthetic Petrol can be produced from methanol by the MTG or MOGD process. The fuel is a mixture of petrol-range hydrocarbons containing aliphatic and aromatic components, and has a low sulphur content.

It is understood that there are no manufacturing plants for producing synthetic petrol.

Synthetic petrol may be produced from vegetable oil in a very similar way to synthetic diesel. The synthetic petrol and diesel products are isolated by distillation, in the same way that crude oil products are currently isolated.

- Synthetic petrol is suitable for use in existing vehicles provided the fuel is upgraded or blended with crude oil derived petrol to meet the fuel standard EN228.

Other Novel Fuels. See main text



The likelihood of technological break-throughs has frequently been examined through elicitation of expert opinion and by considering the claims made by bio-energy technology developers; however, such projections can be wrong. It is likely that the majority of developments in this decade will be on routes that are currently at demonstration scale. For more unusual routes, the earliest that commercial scale development will occur will be the decade after this one. This is expected to be accompanied by a reduction in the cost of bio-energy so that it is more competitive with fossil fuels (IEA, 2011).

5.4 Whole System Analysis and Cross Cutting Issues

The need to analyse bio-energy chains from a whole systems perspective has been a recurring theme throughout this review. Here whole system issues such as life cycle analysis, spatial / value chain modelling analysis, the biorefineries concept and biomass as a negative emissions process technology are reviewed. Furthermore, cross-cutting issues such as the potential of the application of generic modification and synthetic biology at a number of points along and across bio-energy chains is discussed.

5.4.1 Life Cycle Analysis and Carbon Accounting under the UNFCCC

Life Cycle Analysis (LCA) is the process which underpins the assessment of GHG balance, environmental impacts and therefore sustainability profile of bio-energy chains (IEA, 2008, Brander et al., 2008 and Tipper et al., 2009).

There are two forms of LCA (definitions from Brander et al., 2008):

- Attributional LCA (ALCA) which provides information on the impacts of processes used to produce and consume and dispose of a product but does not consider the indirect effects arising from changes in the output of the product. It is best adopted for compliance with regulation;
- And, Consequential LCA (CLCA) which provides information on the consequences of changes and the levels of output (and consumption and disposal) of a product including effects both inside and outside of the life cycle of the product. It is best adopted for informing policy.

The importance of applying the correct form of LCA and avoiding combining the approaches in a single analysis is critical to ensuring appropriate interpretation and comparability of results. For greater details of ALCA and CLCA and the impact of their miss-application see Brander et al., 2008. The remainder of this section refers to ALCA.

There have been a substantial number of LCA's carried out and ever more are being added to the database. However, with regards the database the following is relevant (IEA, 2008):

- The majority of studies apply life cycle approaches but limited the focus to energy and GHG emission balances only - excluding environmental impacts.
- Almost all studies have a geographical scope limited to Europe and North American conditions and are based on western agricultural practices and average conversion technologies.
- As far as bio-energy crops are concerned, most studies focus on the more traditional feedstocks rather than advanced energy crops.
- And, the database is skewed to bio-fuels for transport use rather than bio-energy performance for stationary applications (probably due to the fact that these have complex supply chains).

Most importantly and despite the existence of an ISO standard for LCA work (ISO 14040), which defines assessment procedure, reviews of the LCA database highlighted methodological inconsistencies across studies including system boundaries, data transparency, choice of data sources, possible rebound effects and allocation methods especially for co-products (for further detail see UKERC, 2010a). This variability is augmented by variables that are omitted due to the fact that they are inadequately understood, difficult to quantify or the data simply does not exist (Whitaker et al., In Prep). There is a universal interest in ensuring that a more detailed LCA methodology is developed and universally applied in order that there can be credible database and accurate comparability is possible. The inclusion of areas of uncertainty such as the impact of SOC stocks and fluxes is important to ensure that bio-energy chains are delivering the environmental savings that they claim.

A proposed set of guidelines were proposed by UKERC see UKERC (2008) - table 4 and GBEP is formulating a harmonised framework of comparing LCA methodologies which will facilitate better understanding of the database. This will also form the basis for developing a template of good practice and standardisation; the work will need to be international to ensure world wide acceptance.



Implications and Recommendations:

- Without transparency and the implementation of best practice the credibility of the bio-energy LCA database is open to question.
- There is a need to harmonise LCA work internationally in order to ensure that bio-energy chains are indeed providing the sustainability benefits that they claim and make sure that biomass is allocated as effectively as possible. All new bio-energy supply chains need to be undertaken within the new framework.
- There is a need to broaden bio-energy LCA work across static uses, to broader range of feedstocks such as waste and residues, to other environmental metrics and with the implementation of new developments in bio-energy technology processes (see for example IEA, 2009a).
- There is a need to augment the LCA database to incorporate areas where adequate data is lacking. This is most salient with regards to SOC from LUC when cultivating biomass for bio-energy.

An application of LCA is the accounting of carbon under the UNFCCC National GHG inventory. The literature has highlighted a key area of leakage in the UNFCCC GHG accounting methodologies (e.g. Searchinger et al., 2009 and Bird et al., 2010). Under UNFCCC, emissions for burning biomass are allocated to the 'Land Use, Land Use Change and Forestry' (LULUCF) sector and not the energy sector. These emissions are not always accounted for in nation states reduction obligations as countries can opt to not include emissions from 'forest management'. Furthermore, under the UNFCCC accounting system for the Kyoto Protocol only those emissions count for Annex 1 countries allowing emissions from decreased forest stocks in non-Annex 1 countries to be excluded. This allows non-Annex 1 countries to export biomass to Annex 1 countries without accounting for the carbon either from harvesting nor when the biomass is combusted. This accounting gap needs to be filled within the context of the land management framework stated in section 4.3.2.

5.4.2 Spatial Issues and Value Chain Modelling

The sensitivity of the economics of bio-energy to transport costs and therefore the distances between the components of bio-energy infrastructure makes the understanding of spatial issues vitally important for the development of a better understanding of the relationship between the components involved in the entire value chain.

The role of modelling tools such as UK-MARKAL to inform UK policy is well established (Strachan et al., 2011), however, the need to incorporate constraints on the scale of bio-energy implementation at local (20 km radius) and regional scale (50 to 100 km ranges) is a relatively recent development.

Whole systems modelling approaches have the potential to provide insight into the technical and economic trade-offs, developing trends and potentially optimal performance of future bio-energy infrastructures. For example, incorporating resource availability, technology selection and logistical flows to provide insights to emergent spatial constraints facilitates the cost-optimisation of infrastructure location within heterogeneous supply and demand distributions (Dunnett et al., 2008).

There are, however, key features of bio-energy systems which have limited the key predicative power of quantitative modelling approaches - these include:

- (1) Applicability of specific local industry conditions and social relationships makes transferability difficult.
- (2) They still suffer from the key issue of the lack of data at the appropriate resolution as discussed in section 4.2.2b - some commentators consider that the ability to incorporate value and information structures that support heterogeneity in agents is an impenetrable barrier.
- (3) And, the by-product nature of bio-energy in contrast to the dedicated infrastructure results in a highly complex system which is at the whim of exogenous market forces.

Some commentators believe that for bio-energy case specific models can only be developed for any predictive dimension to be derived at all (see Dunnett 2009 - Chapter 2).

Despite the recent developments made in whole systems spatial assessment of bio-energy value chains there is a belief that there many gaps. These include, limited holistic assessment of GHG reduction, costs and energy security; limited modelling of aggregation and preparation aspects; and opportunity costs for forestry and agriculture, spatial mapping and how land can be used for different energy crops and their associated yields. The lack of adequate representation of bio-energy supply chains in whole system cost optimisation modelling

which is so important for informing UK policy (section 3) makes the need for this to be improved a vital priority. Indeed the sensitivity of the economic viability of bio-energy to transport costs means that any study which does not consider spatial issues and value chain impact will have a limited ability to optimise bio-energy use in the energy system. There is limited work in this area for the UK though the Energy Technologies Institutes' Bio Energy Systems Value Chain Modelling Framework and Optimisation Tools Work Package is seeking to assess this for the UK.

5.4.3 The Bio-refineries Concept

The Bio-refineries Concept³⁶ is emerging out of the realisation that efficient use of as much of the biomass feedstock into main and co-products as possible is required for the economics of the process technologies to be optimised.

The intention behind the largely, at present, conceptual development is to extract as broad range of materials, chemicals and products from a variety of feedstocks and intermediaries as possible. The Wisington Plant run by British Sugar (2010) in Norfolk with its multiple products including top soil, stones, animal feed, lime, sugar products, bioethanol, Betaine, electricity and heat for horticulture can be considered a first generation bio-refinery but the main research effort is being placed on ligno-cellulosic feedstock systems (NNFCC, 2007b).

Bio-refineries are a collection of other conversion technologies, many of which could be deployed individually in dedicated plants. Therefore the technical research challenges in bio-refineries are the same as those needed to develop individual routes. However, additional effort will be needed to optimise the feedstock, process and product integration and to address techno-economic and environmental questions for the bio-refinery as a whole (E4Tech, 2007d). The need for the modelling of process flow within a bio-refinery system is considered to be especially important (US DOE, 2010b). In terms of economics consideration needs to be made of bio-refinery product outputs and the size of the markets to absorb products. The size of the chemicals markets, for example, is substantially smaller than the energy markets suggesting that in the process of gaining economies of scale for energy production saturation of the chemical markets may result thereby undercutting the economics of the concept (EBI, 2010).

There will be a need for considerable technical development for a number of processes to produce materials, chemicals and energy for the concept to be realised. It is anticipated that the deployment of bio-refineries will be based on bio-energy conversion technology platforms which will become increasingly sophisticated in exploiting lower value streams and adding broader portfolios with increasing energy and GHG efficiency deployment of advanced bio-refineries by 2020 and beyond (IEA, 2009a and NNFCC, 2007b).

The multidisciplinary approach required for the development of the bio-refinery concept has spawned a number of co-ordination activities at a national and international level. For example, to the US, has a structured and coherent policy to develop bio-refineries as a part of its biomass programme (US DOE, 2010a). Similar programmes in the EU are more fragmented and though the UK has a small number of centres engaged in this area (e.g. CPI), there is considered to be a lack of broad engagement with international activities. This is disappointing particularly as the bio-refineries concept is attractive to the UK due to its UKs fragmented feedstock potential (Section 3).

A World Economic Forum (2010) report suggested that bio-refineries were a key component technology in addressing climate change and increases in demand for energy, fuels, chemicals and materials. The work that is being undertaken is fragmented with multiple small players though key large investors were starting to look.

³⁶ A biorefinery is the processing of biomass into a spectrum of marketable products and energy (IEA Bio-energy Task 42, after IEA, 2009a - p37). This implies that biorefineries:

- are a cluster of facilities, processes, and industries;
- are sustainable: maximising economics, minimising environmental impacts, replacing fossil fuel, while taking socio-economic aspects into account;
- contain different processing steps: upstream processing, transformation, fractionation, thermochemical and/or biochemical conversion, extraction, separation, downstream processing;
- can use any biomass feedstock: crops, organic residues, agroresidues, forest residues, wood, aquatic biomass;
- produce more than one product, each with an existing (or shortly expected) market of acceptable volumes and prices;
- can provide both intermediate and final products, i.e. food, feed, chemicals, and materials; and
- can co-produce energy as fuels, power, and/or heat.

Barriers: the need for co-ordinated action of non-traditional partners – feedstock producers, chemical companies, process engineers – to cover and integrate the complex chain. Finance problematic with technological risk and scale associated with concept.

5.4.4 Bio-energy Technology as a Carbon Negative Process

The role of geo-engineering³⁷ or negative emissions processes in the climate change agenda is gaining traction (IMechE, 2009; The Virgin Earth Challenge, 2007 and The Royal Society, 2009). Indeed some modelling projections suggest that 80% reductions in the UK emissions are not possible economically without some component of negative emissions - even though the transparency of the use of negative emissions technologies is limited. Geo-engineering technologies are broadly broken down into Solar Radiation Management and Carbon Dioxide Removal Techniques or Carbon Negative Technologies; it is the second branch of technologies which are especially being taken more seriously (McGlashan et al., 2010). Within the negative emissions technologies are a number which involve components of bio-energy technologies - these include Re / afforestation³⁸, Bio-energy with Carbon Capture and Storage (BECCS) and Biochar. Re / afforestation techniques effectively involves the prevention of or the expansion of terrestrial biomass to enhance the absorption of CO₂ emissions within a standing stock and is therefore subject to the same scrutiny of bio-energy feedstock production (section 4.3.2). This section will focus on the state of development of BECCS and Biochar.

Bio-energy and Carbon Capture and Storage. Bio-energy and Carbon Capture and Storage involves the direct combustion of (low grade) biomass fuels in a conventional power plant with the capture of greenhouse gas (GHG) emissions generated using carbon capture and storage (CCS) technology that is also being developed for use at power plants burning fossil fuels. This way atmospheric CO₂ utilised in photosynthesis for biomass production when re-released on biomass combustion is captured to be storage.

The quantities of negative emissions that might be generated from BECCS from domestic biomass are estimated to be in the range of 5 MtC/yr to 22 MtC/yr for the UK in 2030 (McGlashan et al., 2010), 50 to 100 MtC/yr in 2050 (ETI, 2011) and international estimates range from 800 MtC/yr to 24,000 MtC/yr in 2050 (McGlashan et al., 2010).

The following considerations make BECCS an attractive carbon negative technology:

- Of the portfolio of geo-engineering technologies it has the greatest technology maturity and can be introduced relatively easily in today's energy system (DECC, 2010a and McGlashan et al., 2010).
- It is likely, that monitoring, reporting and verifying of CO₂ stored in a BECCS project will be able to use many of the standard guidelines that can be expected for 'conventional' CCS projects with fossil fuels (which is not the case for other negative emissions technologies).
- And, the production of a saleable product (e.g. electricity from a biomass fired power plant) also contributes to making this an attractive option.

There are, however, a number of issues and barriers regarding the widespread deployment of BECCS; these include:

- The ability for CCS technology to reach commercial scale in a timely manner and for thermal power generation and CCS technology to be compatible to high levels of biomass feedstock (for example biomass has higher moisture content as fuel, produces a more variable, probably higher moisture flu gas (of lower CO₂ composition) and lower fly ash though it tends to be corrosive and has a greater tendency to slagging / fouling) and in what combination - co-firing or dedicated biomass.
- The need for the sustainable production of biomass on a large scale (4.3.1) and for the development of international markets (5.2.2) for a scalable supply chain to develop are also requirements; these are covered in cited sections.
- It also likely, however, that BECCS will require appropriate policy support and integration with general CCS strategy for significant commercial-scale deployment to occur. At present, the UK is producing a number of

³⁷ The definition of geoengineering according to the Royal Society is 'the deliberate large scale intervention in the Earth's climate system, in order to moderate global warming'.

³⁸ Avoided deforestation is also included in some of the literature - but this is considered a mitigation processes in this review.

Bio-energy plants for electricity production which are 295 MW (examples) these are below the CCS ready threshold suggesting that the UK is locking out the capacity for negative emissions (plants of such size will not make CCS technology economics work). Should this lock-in to carbon emissions from biomass be supported by guaranteed ROCs remains then it will certainly impact the 2020, 2030 and 2040 capacity for negative emissions - but may be correctable by 2050. It is recommended that ROCs should be conditional on the biomass plants being capture-ready, from quite small sizes and perhaps linked to supply sources so that small plants that genuinely have to be sited and sized to use local supplies don't get penalised (Gibbons, pers comms).

There is an increasing body of work being undertaken on BECCS for example the Energy Technologies Institute - Biomass to Power with CCS Flexible Research Programme Project which will consist of an assessment of the technology and cost barriers for biomass fuelled power and the optimum scale-up potential of single-source and co-fired biomass to power with carbon capture technology. This will include

- A landscape overview of current developments in biomass to power with CCS;
- Engineering study on the recommended technology process combinations to identify the gaps in the value chain;
- An optimization tool to perform whole system optimization to allow sensitivity analysis to assess which parameters have largest impact on cost, energy production and carbon capture; and
- Benefits case report on biomass with CCS as a development opportunity in the UK.

Biochar. Biochar is produced by the combustion of biomass in a low-zero oxygen environment, called (slow) pyrolysis. This produces three products: a solid fraction known as char; a liquid fraction; and a gaseous fraction. The latter two products can be used to generate energy and the char can be land filled or used to enrich agricultural land, where it has been known to enhance crop yields. Biochar could allow CO₂ to be removed from the air if carbon is effectively locked in to the soil.

Figures in the biochar literature states that the process could generate a potential carbon sink of 1 GtC/yr by 2050 rising to 5.5 to 9.5 GtC/yr by 2100 (Lehmann, 2006). For the UK, based on the availability of all biomass resource being made available for slow pyrolysis for biochar production - it is estimated that between 5.7 and 8.0 MtC/yr could be sequestered (Wallage et al., 2009) - the most recent projections ranging from 2.89 to 12.93 MtC/yr (McGlashan et al., 2010) in 2030.

The following considerations make biochar an attractive carbon negative emission technology:

- The process technology involved in producing biochar can be considered to be small scale and non-capital intensive, so the process lends itself to farmers, small landowners and local authorities in developed nations and could assist in rural diversification and poverty alleviation in developing nations (UKBERC, 2008/9, CSIRO, 2009 and Sohi et al., 2010).
- Emissions may be avoided at a number of points along the biochar life-cycle - these include:
 - Avoided emissions from the substitution of bio-oil / syn gas for fossil fuels;
 - The stabilisation and storage of carbon in biochar; and
 - The reduction in agricultural emissions due to reduced fertilizer input.
- Its multiproduct nature provides a driving force for early deployment. There is, however, some uncertainty on how much char would be used as a soil conditioner and how much might find its way into BECCS-type applications.

There are, however, a number of issues and barriers regarding the widespread deployment of biochar; these include:

- The fact that the majority of R&D has been focused on fast pyrolysis for the enhancement of bio-oil production for energy. Slow pyrolysis systems tend to be small scale systems ranging from commercial plants utilising feedstock at rates of 48 to 96 t/day to gasification stoves at a few kg/hr. The impact of scaling up processes, improvements from learning by doing and agronomic/yield benefits of adding biochar to soils make the economics of biochar production at the commercial scale difficult to deduce.

- The attractiveness of the process technology to small scale and widespread deployment as well as the lack of understanding of the stability of carbon in the char makes effective monitoring, reporting and verification problematic.
- Further work is required:
 - to improve understanding of the influence of the slow pyrolysis process conditions (temperature and residence times) and feedstock on biochar yield and stability (Brownsort, 2009);
 - the stability of carbon in the char (mean residence times, behaviour of super labile and labile components) and its interactions in different conditions (Brownsort, 2009); and
 - the storage capacity of the char in soils, its impact on soil properties and effects on yields in different climates (CSIRO, 2009 and Sohi et al., 2010).
- The benefits of the small scale nature of the biochar technology must also be weighed up against the increased number of individual installations that are then required for a similar level of CO₂ emissions reduction to be achieved relative to large scale technologies such as BECCS.
- The scalability of biochar as a CO₂ mitigation option will, like BECCS, depend on the availability of biomass feedstock and, should the technology become large scale, logistical considerations for international biomass feedstock supply chains.

There is an increasing body of work being undertaken on biochar; this includes:

- UK Biochar Research Centre (<http://www.biochar.org.uk/>) whose mission is to undertake leading edge multi- and interdisciplinary research on the role of biochar as a carbon storage and sustainable energy technology, and to provide an understanding of the agronomic, environmental and socio-economic impacts of biochar
- International Biochar Initiative (<http://www.biochar-international.org/>) which seeks a systematic transition from the promise of biochar to the practice of biochar production and application systems.

Within the broader context, consideration needs to be made on the governance of the development of negative emissions technologies, frameworks of assessment, policy, insurance mechanisms, legal liability, integration into international climate agreements, incorporation into carbon markets, dealing with environmental and perception issues, dealing with public opinion and mechanisms for scale up (Grantham Institute, In Prep).

5.4.5 Role of Genetic Engineering and Synthetic Biology in Bio-energy Technological Development

The importance of genetic modification in the development of bio-energy feedstocks was discussed in section 4. Here, its role across the value chain is emphasised with its potential to improve feedstock, deconstruction and conversion - often eliminating, combining or simplifying steps; examples are given in table 5.6.

Table 5.6: The wider applications of generic engineering (after Accenture, 2009 - p8).

	Application
Feedstock	<ul style="list-style-type: none"> • Genetically modified crops to improve characteristics: such as drought / disease resistance, faster, improved yield more uniform growth, decreased nutrient requirement, greater seed durability, and 'Single harvest only' growth; and advantageous composition for reduced enzymatic pre-treatment. • Genetically modified algae that have higher yields and can be cultivated and harvested at lower cost.
Enzyme	<ul style="list-style-type: none"> • Genetically enhanced microbial enzymes that are: more efficient: achieve higher sugar yields; more cost effective: requires lower dosage, lower temperatures; and more resilient to a range of inhibitors produced upstream. • Crop-produced enzymes (hydrolytic enzymes to reduce subsequent pre-treatment)
Conversion	<ul style="list-style-type: none"> • Biofermentation / biocatalytic conversion: Microbe-based conversion of either sugar to fuel (diesel, gasoline) or syngas to ethanol; • Microbes are cheaper than conventional catalysts, continually regenerate, can be engineered to be tolerant to more impurities and operate at a broader range of temperatures / pressures.
Co-product upgrading and other products	<ul style="list-style-type: none"> • Engineered organisms produce chemicals, with increased yield and productivity; • Upgrading of by-products of bio-fuel production (e.g. glycerine) process using modified organisms for the fermentation process (cheaper than petrochemical route).



An extension of genetic modification is the recent application of the biotechnology field of synthetic biology to bio-energy technologies. Though there is no specific definition of synthetic biology is essentially involves the design of novel biological systems and living organisms using genetic engineering principles. This new tool allows the development of microbes to be designed for specific purposes - at the moment the focus is on single cell bioreactors to generate hydrocarbon 'drop-in' fuels which has resulted in the development of the sugarcane to diesel route (Amyris and LS9). Though there are substantial hurdles for synthetic biology³⁹ to be applied on a widespread basis such as concerns over safety, IP ownership of gene traits and regulation there are approaches which can mitigate the impact of these issues (Accenture, 2009).

The potential for genetic engineering and synthetic biology to deliver a radical disruptive development in bio-energy technologies is substantial and reflected in the amount of work that is taking place in this field.

5.4.6 Hybridisation of Technologies

There is increasing awareness that breakthroughs in bio-energy technologies are likely to be developed through a combination of technologies across and along existing bio-energy chains rather than by one technology in isolation (Accenture, 2009 and IEA, 2008). Examples include:

- Custom application of novel technologies for multiple, differing processes;
- Integrating new technologies into existing plants;
- A blurring of the traditional chemical processes with the integration of thermochemical and bio-chemical processes; and
- Deriving benefits from integrating existing processes with other technologies.

It is hope that these advances will reduce the tendency of many process conversion technologies, particularly those associated with bio-chemical processes to have feedstock specificity (Accenture, 2008).

5.5 Best Use of Biomass: Analysis Framework and Performance Metrics

The versatility of biomass in its ability to provide renewable energy services in the present energy system, the wide array and complexities of bio-energy pathways at various stages of development, its present finite availability and its substantial potential has resulted in the evolution of the debate as to ' *what is the best use of biomass?*'. This topic was assessed by a recent paper from UKERC (2010a).

The UKERC (2010a) work essentially stated that debate can be broken down into the following related constituent parts: what is your framework of assessment and what metrics best encapsulate the relevant information to make the appropriate decision. With regards the framework of assessment - the best use of biomass is highly dependent on what you are attempting to achieve. For example, with present technological knowledge if efficiency of conversion is the key requirement then biomass use in heat and CHP systems is the best option. If on the other hand carbon abatement is a priority then focus on Bio-energy with Carbon Capture and Storage should be made. If targeting the sector(s) where there are a lack of alternatives for carbon abatement is the priority this suggests biomass should be used in bio-fuels for transport - particularly HD vehicles and aviation - as the best use.

In the case of the derivation of metrics to make the appropriate decision - the following is salient (extracted from UKERC, 2010a):

- The diversity of bio-energy feedstocks and conversion technologies means that there is unlikely to be a one-size-fits-all best use of biomass.
- In seeking to develop a strategic approach to biomass use, none of the commonly used metrics capture all pertinent information. Furthermore, some metrics are open to subjective judgement (particularly for measurements of social and ecological impacts), methodological differences (which are still evolving) in derivation and a lack of transparency making cross-comparisons difficult.
- Not all energy services are equally valuable. Some bio-energy applications - e.g. second generation bio-fuels - may be strategically important even if at current prices the cost-per-tonne-of-carbon-saved appears

³⁹ Synthetic biology is being funded in the UK by BBSRC and EPSRC through their response mode funding schemes. The EPSRC have funded a new Research Centre for Synthetic biology and Innovation for £8M over 5 years and the BBSRC, EPSRC, AHRC and ESRC have set up 7 networks in Synthetic biology with £0.97M of funding (House of Commons STEC Biotechnology Inquiry dated 2nd Dec 2009).

unattractive. The option value of individual bio-energy pathways and the availability of alternatives should be considered.

- Slavish adherence to a single metric - e.g. cost-per-tonne-of-carbon-saved - is best avoided.
- When deciding upon their strategic direction, companies and investors do not seek to find the optimum course of action from the universe of possible alternatives. Instead they look at how the acumen and assets they already have can best be turned to their advantage.
- From a strategic policy perspective, a holistic view of the merits of alternative bio-energy pathways is desirable because ongoing (and future) policy interventions play an important role in prescribing technology choices. Nevertheless, consideration should be given to whether such a view is attainable, and the extent to which it could be implemented.

In summary, the desire to assess what is best use of biomass is highly problematic and dependent on desired intent. Furthermore, relevant to this issue in the UK - it is worth emphasising the following issues:

- That the sensitivity of the economic viability of bio-energy to transport costs means that any study which does not consider spatial issues and value chain impact will have a limited ability to optimise bio-energy use in the energy system (Dunnett, 2009).
- Though there is considerable work that has / is being undertaken on bio-energy in the UK there is insufficient information available to develop a 2050 strategy based on what we know now. However there is a body of work that is being presently undertaken which will allow some key issues to be addressed in the next few years and in turn allow a strategy to be developed from a more solid evidence base. The establishment of a UK bio-energy projects database would allow the monitoring of this work to better inform strategy development - section 6.
- And, the development of a standardisation of bio-energy performance metrics so as to make sure direct comparability for different frameworks of analysis is possible is vitally important to ensure that the biomass is utilised optimally in the energy system.

Indeed such is the state of this aspect of the bio-energy debate that it has been seen as a distraction by some commentators and that there is a need to focus on UK bio-energy technological strengths to learn by doing rather than be paralysed by the over analysis of the ideal use of biomass. Furthermore, even if an optimum bio-energy system was identified, incentivising actors to make the appropriate investment decisions would still be problematic (section 6).

5.6 Summary and Recommendations

In section 5 feedstock logistical issues, process conversion and end use issues with a focus on liquid transport fuels and whole systems issues are reviewed.

Bio-energy Logistics and International Trade

Logistics, i.e. getting feedstock from field to process conversion plant, is an area which is largely under researched. There is substantial variation in harvesting, transport and storage systems and their state of development depending upon the type of biomass being cultivated. It is recommended that there is a need for standards and specifications for each feedstock type in order to develop optimum harvesting systems.

There is a need for the development of a database of feedstock type and behaviour when under storage and assessment of any impact on downstream process conversion efficiencies. The instrumentation to measure these metrics effectively also needs to be developed.

International trade in biomass is at present small scale though there is substantial potential for development subject to the establishment of a dedicated supply chain, removal of tariff barriers, unification of sustainability criteria and clarification of WTO rules on bio-energy.

On the understanding that the UK will develop a scalable domestic biomass capability, the UK should seek to develop its own capacity in harvest, transport and densification technologies for bio-energy crops as these are fundamental to making bio-energy production economic. Where appropriate, collaboration with other R&D programmes should be undertaken and assistance provided in the development of international standards.



Bio-energy Conversion Technologies

Biomass to heat applications including direct combustion and small scale gasification which are at commercial and pre-commercial stages of development, respectively - though the economic case for these technologies is often dependent on the relative cost of the reference fuel. There are limited technical issues with regards biomass to heat applications though the economic proposition is a significant barrier. In the UK the low development in the sector lies in the limited access to heat sinks, though this may be remedied in the long term by the establishment of buildings standards which encourage local heating networks.

Biomass to power and combined heat and power (CHP) applications include a wide range of feedstock and conversion technology combinations that are in various stages of development; these include: biomass power plants (dedicated, co-fired and repowered coal plant), waste to energy plants, biomass co-generation (CHP) plants, distributed cogeneration units (such as Organic Rankine Cycle (ORC) or Stirling Engines), large scale gasification and Anaerobic Digestion. Fundamental to the economics of such systems is not only the capital outlay but also the availability of cost effective and substantial supplies of feedstock and the relative cost of alternative production. There are some technical and scale issues with power and CHP conversion processes.

Transport applications are one of the most strategically attractive uses of biomass due to the lack of alternatives in the this sector. There are a number of issues which need to be considered for the deployment of bio-fuels in this sector including:

- Understanding of the infrastructure requirements of the different forms of bio-fuels including blending, handling, distribution and refinery modifications;
- impact of non 'drop-in' bio-fuels on compatibility with present vehicle fleet performance; and
- the role of bio-fuels in marine applications is vastly under researched compared to other transport modes (AEA, 2009a).

The ultimate process conversion technology is one which has flexibility in terms of type and quality of feedstock, operates effectively at a range of scales and is able to produce a 'drop in' fuel negating the need for modification to future power trains or fuel infrastructure. The fragmented and proprietary nature of the work being undertaken in transport bio-fuels process conversion makes it extremely difficult to assess the state of different technology routes.

With regards end uses for transport fuels, the blending limits and handling properties of different non 'drop in' fuels bio-fuels vary considerably as do the energy densities of all biomass derived fuels. Outside of the main fuels there are a number novel routes such as Furanics, Isoprenoids, Iso-butanol etc which tend to have only one private developer working on specific conversion routes with only one feedstock and product being investigated.

The international nature of transport issues makes the need for the UK to be engaged in international collaborative forums to be of paramount importance to ensure that liquid bio-energy fuel developments conform to internationally developing market consensus.

Whole System and Cross-cutting Issues

The following recommendations have been made regarding the following cross-cutting issues:

- There is a need to ensure transparency and harmonise LCA work internationally in order to ensure that bio-energy chains are providing the sustainability benefits that they claim. All new bio-energy supply chains need to be undertaken within an established best practice framework.
- The sensitivity of the economic viability of bio-energy to transport costs means that any study must consider spatial issues and value chain impact to optimise bio-energy use. The importance of the value chain impact on the economics and sustainability of value bio-energy is under researched.
- The bio-refineries concept is emerging out of the realisation maximum conversion of biomass feedstock components is required for the economics of process technologies to be optimised. However, additional effort will be needed to optimise the feedstock, process and product combination, and to address techno-economic and environmental questions for the biorefinery as a whole.
- A future strategically important use of biomass may be in negative emissions process technologies such as bio-energy and carbon capture and storage (BECCS) and biochar. Some modelling projections suggest that



the UK's carbon reduction target of 80% by 2050 cannot be achieved economically without them. There is a need to assess these technologies in the light of the continued increase in global emission trajectories and, should they be needed, to develop the appropriate policy framework to encourage their development and scale up.

- The significance of the potential role of genetic engineering and synthetic biology in bio-energy technological development is highlighted along the entire bio-energy value chain; the importance of public opinion must be recognised.
- Finally, the best use of biomass need not be reconciled before the development of a strategic policy framework - enough is known in order to develop sound and sustainable policy which may be augmented as future research is undertaken. Coherent and consistent metrics / methodology for reporting would assist in facilitating direct comparison between different value chains.

6 International and UK Bio-energy Policy, Research Activity and Innovation Landscape

Evidence presented here supports the following elements of the ERP Bio-energy Technologies Review Executive Summary and Recommendations:

- **Key finding:** Need for a co-ordinated bio-energy strategy, and clear government departmental responsibilities with a single department (DECC) taking the lead role.
- **UK R&D:**
 - Develop areas where we have potential to become leaders: algae, drop in fuels, Biomass with CCS and bio-refinery.
 - The development of a unified, open source database of UK capacity and bio-energy projects.
 - Encouragement of multi-disciplinary research and market potential of bio-energy work at Research Councils.
 - Concentration of research activity at particular establishments and funding for extended periods (5 years) with a strategic review half way.
- **UK deployment issues:**
 - Increasing specialist knowledge available to the appropriate government departments.
 - Support along whole of supply chain to minimise financial risk (from farmer to end-user).

6.1 Introduction

From section 5, it can be seen that only a limited number of bio-energy technologies are presently competitive economically and at scale. This means that governments will be the biggest players in the incentivisation of bio-energy innovation and market development (Mambee et al., 2009). According to the IEA (2010c) they already are - bio-fuels receive more support than any other renewable energy source. In 2009, out of US\$ 57 B of incentives for all renewables⁴⁰ total support for bio-fuels was US\$20 B - of which 13 B was for ethanol - the majority of this being dispensed in the US and EU. Despite the present extent of support, the willingness for governments to retain coherent long term bio-energy targets and strategies in the context of the polarising nature of the sustainability debate, continued agricultural commodity price fluctuations and food security impacts is a key variable in the manner in which the bio-energy sector will develop: incentives are expensive.

Here a high level assessment of the extent and nature of international bio-energy research activity is made including a review of ongoing EU initiatives. A UK bio-energy capability assessment is then described to identify areas that the UK has strengths to develop specific bio-energy technologies, in the context of 2050 needs, as well with the manner in which the UK should collaborate internationally for the development of bio-energy technologies. Finally, the nature of the UK bio-energy policy and innovation landscape is reviewed in order to make recommendations as to how to improve the present disjointed supporting policy and innovation landscape in order to enhance the development of an internationally competitive bio-energy technologies sector.

The initial findings of the review, especially those relevant to this section, have been fed into government since October 2010 and therefore some of the recommendations are in hand.

6.2 International Bio-energy Research Activity and Innovation Landscape

The drive to establish robust bio-energy markets is reflected in the extent to which policies have been enacted and the scale of RDD&D programmes across nation states; these are covered below.

⁴⁰ To place this into context the cost of consumption subsidies for fossil fuels in 2009 was US\$ 312 B.



6.2.1 International Bio-energy Policy

Over 40 countries have implemented bio-energy policies (REN21, 2010). Descriptions and analysis of national bio-energy policy and programmes is well documented (e.g. Mambee et al., (2010), Accenture (2009), EU (2010), Harvey et al. (2010) and IEA Global Renewable Energy Policy and Measures Database)⁴¹.

These reviews highlight that such is the extent of bio-energy development - market projections, based on present and announced policy, indicate that though the US, Brazil and EU are the main markets for bio-energy at present - in the next 5 years, it is anticipated that Latin-America and the Asia-Pacific will display substantial growth in bio-energy supply and demand. The motivation behind this being to encourage economic development, reduce oil imports and add value to their agricultural chains (Hart Energy, 2009). The IEA Blue Maps scenario (IEA, 2011) also anticipates that 70% of 2050 bio-fuel demand will come from non-OECD nation states.

A key observation here is that, based on present and future policies, the need for advances in bio-energy technology development to enhance the use of present feedstocks and broaden the feedstock streams that may be economically utilised in bio-energy value chains is becoming increasingly urgent. Only with rapid development can the utilisation of agricultural products as efficiently as possible, required for compliance with sustainability issues addressed in section 4.2.2 and economic competitiveness, be realised.

6.2.2 International Bio-energy RDD&D Bio-energy Expenditure

Estimates of RDD&D expenditure on bio-energy from the IEA is displayed in figure 6.1, below. The following is noteworthy:

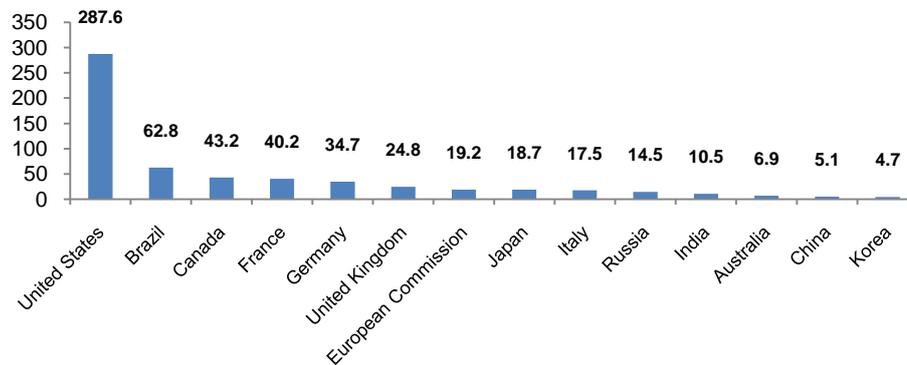
- firstly that the figures only reflect public sector funding to dedicated bio-energy programmes and may underestimate total funding dedicated to bio-energy. For example, in the US other funding streams such as the Recovery and Reinvestment Act (2009) loan guarantees of US\$ 564 for biorefinery development and the private sector funded BP Energy Biosciences Institute US\$ 500 M, 10 year programme - are not reflected in the statistics. Indeed the fragmented nature of private sector funding would make the capture of this data extremely difficult.
- Secondly, the UK is stated as having a dedicated bio-energy RDD&D budget of US\$ 24 M pa. This differs from the BBSRC derived figures on plant science institute funding of US\$ 77.9 (i.e. £48.7 at US\$ 1.6 to £1) for FY 2009/10 - as shown in figure 4.4.

This suggests that estimating bio-energy RDD&D expenditure is highly problematic due to the difficulty capturing data from a broad suite of programmes (this is discussed in greater detail in Kempener et al., 2010). The data in figure 6.1 can therefore only be considered a proxy for the capacity of each nation state to undertake bio-energy RDD&D; despite this it is still useful - as the extent of US funding with its US\$ 287M budget is reflected in the capacity of its advanced feedstock research institutes - figure 6.2 (the illustration also displays private sector funded institutes). With these caveats in mind the following observations may be made:

- The three largest public sector bio-energy RDD&D budgets are for nation states in North and South America with the US's RDD&D budget being larger than the next 10 nation states / regions put together.
- The UK has the sixth largest dedicated bio-energy RDD&D budget amounting to 5% of total public sector bio-energy RDD&D funding of all the nation states represented in figure 6.1.
- And, there is an absence of public sector bio-energy funding in nations where the greatest potential has been identified in biomass assessments - especially Africa and Asia (Section 4).

⁴¹ <http://www.iea.org/textbase/pm/index.html>

Figure 6.1: Estimated Public RD&D Expenditure on Bio-energy (M US\$) after IEA (2010c)⁴².



The scale of UK bio-energy research programme relative to other nation states has led to the observation that UK research in bio-energy is lagging behind international leaders (BBSRC, 2006). Therefore in order to alleviate this problem, UK research establishments should maintain awareness of relevant international bio-energy investments and rather than replicate them utilise existing resources to collaborate and develop strategic partnerships. This may be achieved at three levels:

- i. Engagement at international platforms in the field of bio-energy such as IEA Bio-energy Implementation Agreement⁴³, IEA Advance Motor Fuels Implementing Agreement⁴⁴, Global Bio-energy Partnership⁴⁵ etc.
- ii. Engaging in bi-lateral arrangements with other nation states research programmes.
- iii. And, leveraging UK expertise within the framework of the EU research programmes.

⁴² **Notes.**

1. The data in graph 6.1 is attributable to direct bio-energy research and may not reflect biotechnology capacity and other sources of funding. For example, figures for the UK differ from figure 4.4 (section 4) and in the US the Recovery and Reinvestment Act (2009) resulted in substantial sums of funding being dedicated to bio-energy including investing US\$ 564 M for 19 integrated bio-refinery projects.

2. Data reported in the graphs are based on 2009 estimates, except for Brazil which was based on 2008 expenditures on the Biodiesel Technological Development Program and Ethanol Science, Technology and Innovation Program (Ministry of Science and Technology); and investments under the National Agroenergy Development Program (Ministry of Agriculture, Livestock and Food Supply); China (Government expenditure of 35 million Yuan (US\$ 5.1 million) on biomass for energy R&D in 2006); European commission (based on ED funds under the Sixth Framework Programme for Research and Technology Development - FP6); France (2007); India (reported budget of R1 510 million (US\$ 10.5 million) for the period 2007-2008 for biomass program of the Ministry of New and renewable Energy - currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

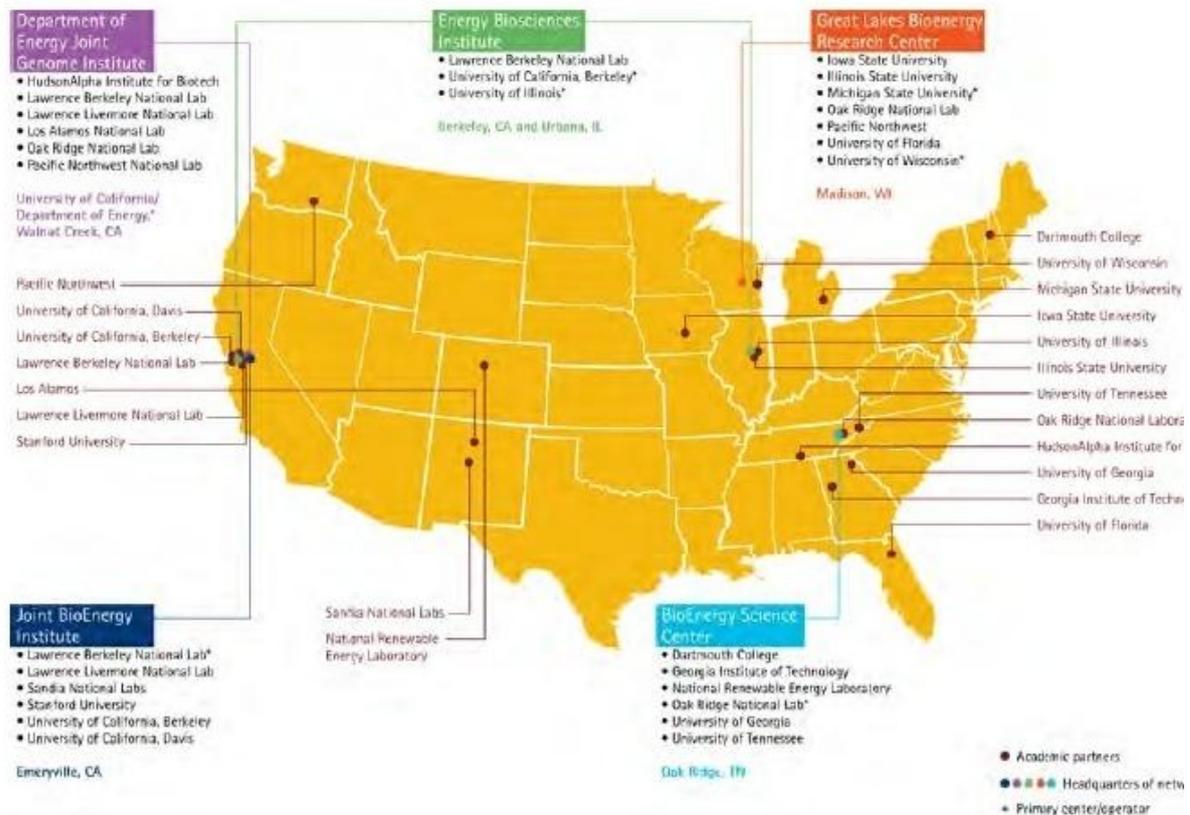
3. Government budgets for bio-energy RD&D in IEA member countries include data on production of transportation bio-fuels (includes conventional bio-fuels, cellulosic conversion to alcohol, biomass gas-to-liquids, and other), production of other biomass-derived fuels (includes biosolids, bioliquids, biogas thermal, biogas biological, and other), application for heat and electricity (includes improvement of energy crops, assessment of bio-energy production potential and associated land-use effects), and other bio-energy expenses (includes improvement of energy crops, assessment of bio-energy production potential and associated land-use effects). The total investment reported below is provided by the IEA Statistics, supplemented by MEF countries' data submissions.

⁴³ <http://www.ieabio-energy.com/>

⁴⁴ <http://www.iea-amf.vtt.fi/>

⁴⁵ <http://www.globalbio-energy.org/>

Figure 6.2: Key research networks for advanced feedstocks in the US (after Accenture, 2009).



Assessing UK performance at engagement at each of these levels:

i. **International Platforms.** It is considered that the UK is moderately well engaged on international platforms but there is concern that what little engagement does take place will be further weakened due to budget cuts.

ii. **Bi-lateral Arrangements.** In the case of bi-lateral arrangements, a review of international bio-energy policy development, research co-ordination and the degree of UK collaboration with nation states was undertaken by the BIS/FCO Science and Innovation network for this Review in August 2010 - details can be found in Appendix 6. The following observations can be made from this survey:

- International work in bio-energy RDD&D, it is well developed across a number of nation states and the motivations for the programmes are very different reflecting different resource endowments and existing energy policy landscape.
- The degree of bio-energy RDD&D coordination differs making the ease of establishing bi-lateral agreement highly variable. In the case of the US and Brazil research activity is strategically coordinated. For example, in the US, a multi-year biomass technical program with strong focus on ligno-cellulosic ethanol ensures that all aspects of the route are considered in detail in the different research institutions. China, despite plans on being the 2nd largest ethanol producer, has no centrally planned bio-energy research - it is considered to be uncoordinated and fragmented.
- The emphasis of work in bio-energy varies between nations with some focused on the fundamental research aspects (as is the UK) and others on the applied end of the value chain such as Brazil and the US. This makes the 'fit' for collaborations difficult as they tend to require the exchange of knowledge but if the focus is on different aspects of work then the value of collaboration is much reduced.
- And, the UK already undertakes much in the way of collaborative work with international leaders - including the US and Brazil.

iii. **EU.** The European bio-energy agenda is highly heterogeneous due to diverse feedstock choice and the fact that environmental considerations have been foremost in the policy formulation. The impact of the latter is that



EU policy has been subjected to far greater impact of NGOs influencing sustainability regulation and target moderation. Despite this the EU has substantial work in bio-energy research / innovation with which the UK is well engaged. The following programmes are most relevant: The EU Strategic Energy Technologies Plan (2009) and the Seventh Framework Programme (2006-2013).

The Strategic Energy Technology Programme was initiated in 2008 and seeks to increase and focus EU support on key low carbon energy technologies. The programme involves the European Energy Research Alliance (EERA)⁴⁶, the European Technology Platforms (ETPs)⁴⁷ and the Energy Industrial Initiatives (EIs)⁴⁸.

- EERA work streams at present are focused on bio-fuels and include:
 - Thermochemical processing of biomass into NextGen bio-fuels for transport;
 - Sugar platform on NextGen bio-fuels for transport;
 - Bio-fuels from algae; and
 - Cross-cutting issues in bio-energy.

Further work streams may be introduced at a later stage.

- EII workstreams are summarised in table 6.1, below.

Table 6.1: Summary of European Industrial Bio-energy Initiative work streams (EU EIBI, 2010).

Thermochemical pathways

- 1: Synthetic liquid fuels and/or hydrocarbons (e.g. gasoline, naphtha, kerosene or diesel fuel) and blending components through gasification.
- 2: Bio-methane and other bio-synthetic gaseous fuels through gasification.
- 3: High efficiency heat & power generation through thermochemical conversion (propose limit e.g.: $\eta_{el} > 45\%$)
- 4: Intermediate bio-energy carriers through techniques such as pyrolysis and torrefaction

Biochemical pathways

- 5: Ethanol and higher alcohols from ligno-cellulosic feedstock through chemical and biological processes
- 6: Hydrocarbons (e.g. diesel and jet fuel) through biological and/or chemical synthesis from biomass containing carbohydrates
- 7: Bio-energy carriers produced by micro-organisms (algae, bacteria) from CO₂ and sunlight

Complementary measures and activities

- 8: Biomass feedstock for bio-energy
 - 9: Set of activities on longer term R&D&D on emerging and innovative bio-energy value chains
-

EERA is presently funded from existing national funding pools and the funding mechanisms for the EIs are not clear at time of writing - though the desired budget is €8 B over 10 years to support 15 to 20 projects. There is a consensus that there is a need for resources to enhance co-ordination of UK engagement in both these forums - particularly EERA.

As a part of the EIBI the UK needs to establish its capabilities / strengths, draw a high level roadmap and identify projects to achieve EIBI objectives⁴⁹. This is in hand with the UK lead being headed up by the CPI.

The Seventh Framework Programme funds fundamental research across all EU programmes and is not limited to energy. There are a number of programmes dedicated and associated with bio-energy see: http://cordis.europa.eu/fp7/projects_en.html. The Framework Programme is often criticised for its overly bureaucratic nature but nonetheless remains a good source of research funding for bio-energy programmes.

⁴⁶ EERA provides research for the SET plan in terms of conceiving and implementing joint programmes of research, pooling and integrating activities and resources. In terms of bio-energy Professor Tony Bridgewater heads up UK engagement in the EERA Joint Programme on Bio-energy.

⁴⁷ The European Technology Platforms influence the EU research agenda by providing guidance, prioritisation and promotion of RD&D. There are 33 ETPs the most relevant to bio-energy are: European Bio-fuels Technology Platform, Plants for the Future, Renewable Heating and Cooling, Forest based Sector Technology Platform and Sustainable Chemistry.

⁴⁸ There are 7 EIs covering a number of areas in the energy system taking technologies (these include: Wind, Solar, Nuclear, Bio-energy, CCS, electricity grids and smart cities) from demonstration to commercial deployment (flagship projects) with industrial partners. The bio-energy EII is called the European Industrial Bio-energy Initiative - UK representation is headed up by Chris Dowle of the CPI.

⁴⁹ Which are to: Enable commercial availability of advanced bio-energy at a large scale by 2020; reduce production costs relative to fossil fuels; deploy advanced bio-fuels covering 4% of EU transport needs by 2020 particularly in mid-distillates; strengthen EU leadership for renewable transport fuels for diesel and jet engines; develop the use in EU of sustainable biomass resources for bio-energy applications; and green job creation.



A number of observations can be made with regards the EU programmes:

- EERA's focus is on bio-fuels and the centre of gravity of the EIBI appears to be on bio-fuels as well.
- There appears, at present, to be a lack of alignment between the EERA and EIBI work streams though the relatively nascent state of the EIBI will give time for the streams to converge.
- And, the likely importance of bio-energy as a negative emissions technology in the 2050 energy system means that the EIBI should be linked in some way to the Carbon Capture and Storage EII in due course.

UK engagement in these initiatives is important for the following reasons:

- EERA allows the UK to be aware of EU wide bio-energy capacity within the research community and identify areas for collaboration; and
- in the case of the EIBI, though these initiatives are at an early stage there is the opportunity, should funding targets be met, to acquire significant sources of funding to develop scalable bio-energy projects.

6.3 UK Bio-energy Technology RDD&D Capacity, Bio-energy Policy and Innovation Landscape

6.3.1 UK Biotechnology Capacity Assessment

One of the key objectives of the ERP Bio-energy Technologies Review was to assess the UK's capacity⁵⁰ in bio-energy RDD&D. This will allow prioritisation of aspects of bio-energy that the UK should seek to:

- undertake international leadership in; and
- form strategic partnerships and collaborate with International partners (based on the assessments of work being undertaken in other countries - section 6.2 (BBSRC, 2006)).

There are, however, a number of difficulties in undertaking an assessment of UK bio-energy capacity; these include:

- Bio-energy capacity and especially capability are difficult traits to define and measure. Research and development in an area that may not at all initially relate to bio-energy when applied to a need within a bio-energy process technology may suddenly provide a key breakthrough. This is particularly relevant to plant science and industrial biotechnology capability. Plant science, which due to its association with biomass production, and industrial biotechnology, with its use of advanced biologically related techniques, suggests that all forms of plant science and industrial biotechnology should be considered in an assessment of bio-energy capacity. However, incorporating all plant science and bio-technology capability may overestimate bio-energy capacity as the work may not be focused on bio-energy.
- There is no established open source UK bio-energy capacity database. Though there are some useful project databases such as the UKERC Research Atlas no comprehensive database of academic and industrial bio-energy capacity exists.
- The bio-energy assessments of UK capacity and capability have tended to be highly qualitative (UKERC, 2009, Industrial Bio-technologies Innovation Growth Team (IB - IGT), 2010) or semi-quantitative and tended to focus on specific technologies within the bio-energy sector (e.g. E4Tech, 2010).
- Though publically funded work from the Research Councils, Technology Strategy Board, Energy Technologies Institute, The Carbon Trust and Government Departments may be accessible and relatively easy to landscape data on commercial work is less accessible for two reasons:
 - Firstly commercial confidentiality for R&D in organisations means that they are less willing to disclose work that they are doing (any work that they are undertaking with academics often involves confidentiality agreements); and
 - secondly, the limited information that organisations are willing to disclose may not be entirely representative of the actual programmes objectives;

and

⁵⁰ In this Review capacity is defined as the quality of being directly involved in bio-energy activity or work. Capability is the quality of undertaking work that is relevant to bio-energy but the present is applied to other fields. Biotechnology funding is a measure of capability as not all work is directed at bio-energy programmes.

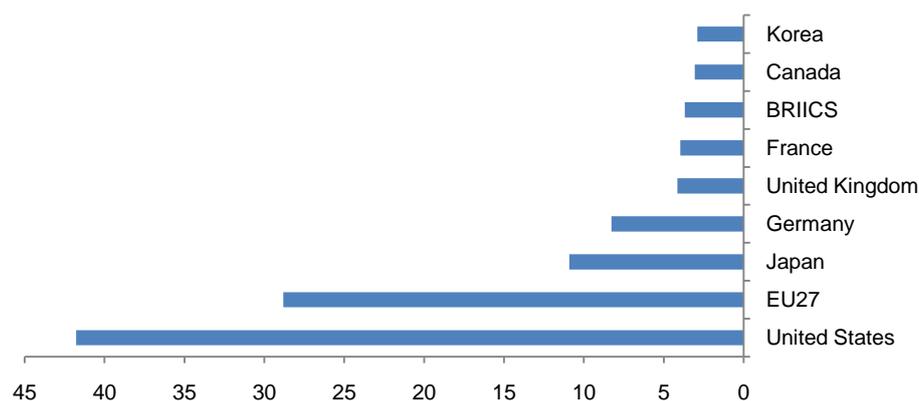
- finally, when considering where the UK has strengths - this has to be considered in the context of international bio-energy work and an assessment of other nation states capacity in specific sub-sectors of bio-energy.

Taking these points into account this review sought to undertake a high level review of UK bio-energy capacity based on (i) a bio-technology capacity assessment undertaken by the Industrial Biotechnologies - Innovation Growth Team (IB-IGT, 2009), (ii) the assessments that had already been undertaken for specific bio-energy technologies; and (iii) expert input. The assessment was undertaken in conjunction with Dr Claire Smith of the National Non-Food Crops Centre which produced a review of UK Capacity in Advanced Bio-fuels for the Department for Transport; this work forms an integral part of this review.

UK Biotechnology Capacity

Bio-technology is defined as the use of advanced biologically related techniques and processes to sustainably produce chemicals, materials and fuels; it is therefore an assessment of UK capability in bio-energy. Figure 6.3 displays a breakdown of biotechnology patents in 2007. It shows that the US is clearly leading but Europe, especially Germany, France and UK are competitive with Japan.

Figure 6.3: Share of countries in biotechnology patents (%) filed under PCT, 2007 (OECD, 2010)



The UK's delivery of 5% of global patents in 2007 is put into context by the IB-IGT (2009) assessment of UK's standing relative to the rest of the world where the following observations were made:

- Historically, UK's biotechnology activities focused on pharmaceutical sector / life science sector (i.e. target products were mainly high value / low volume) but the opportunity for the production of energy, chemicals and materials from renewable resources has resulted in a drive to adapt this capability. The research base which underpins bio-energy technologies has a strong applied side focus on healthcare technologies but a small base in biomass-based chemicals and materials. The transferability of the former to the latter depends on the ability to commoditise and adapt the processes;
- A number of countries are interested in development of biotechnology, most with a strong focus on bio-fuels and bio-energy with energy security and environmental issues at the heart of the agenda. The UK is seeking to adopt its bio-technology capacity to bio-fuels and bio-materials. The UK is seen as competitive on underpinning research but lagging on interdisciplinary research (IB-IGT, 2009); and
- The UK has the capability to become one of the world leaders in industrial biotechnology. In order to do so a number of weaknesses need to be overcome particularly in the area of dedicated funding programmes, demonstration facilities, supporting industry and government support.

UK Bio-energy Capacity

The ERP UK capacity review was undertaken in conjunction with the NNFC (2011c and d). In this review, UK bio-energy capacity is defined and assessed based on the following criteria:



- whether the UK has world class researchers or companies in the sector or sub-sector;
- the ability to take that fundamental research through to application development and commercial deployment; and
- assessment relative to the capabilities of other nation states.

The rating is not based on the number of these actors working in each sector / sub-sector.

The rating is based on the following categories relative to the rest of the world:

- UK university / research institute capability;
- UK industrial capability;
- active in pilot and scale up facilities; and
- active and planned demonstration and commercial facilities.

The bio-energy value chain is broken down as follows

- **Feedstocks:** Micro-algae, Macro-algae, Arable Crops, Perennial Energy Crops, Forestry and Waste
- **Logistics - Harvesting, Transport and Densification**
- **Process Conversion - Intermediaries:** Lipids, Biogas, Sugars, Syngas Production and Pyrolysis Oil Production
- **Process Conversion - Conversion to End Fuels / Energy Carrier / End Use:** Thermal Combustion for Power, Thermal - Heat and Combined Heat and Power, Bio-CCS, Bio-methane for Heat and Power and Hydrogenated Vegetable Oil.
- **Syngas Upgrading to Production:** Synthetic Diesel / Aviation (FT), Hydrogen, Methanol and Derivative (DME), Ethanol from Gasification (Catalysis and Fermentation) and BioSNG from Gasification.
- **Other Routes:** Biomethane for transport, Furanic / Novel Sugar Fuels, Ethanol (from Bio-chemical processing), Butanol and Upgraded Pyrolysis Oil.
- **End Use - Bio-energy System Integration.**

Detailed assessments of each of these issues can be found in Appendix 7 which is an extraction of the Appendix on UK Capacity in Advanced Bio-fuels produced by the NNFFC with the ERP for the Department for Transport. This was based on detailed bio-energy technology landscaping reports by amongst others The Carbon Trust, E4Tech and NNFFC and expert assessment from a number of stakeholders in the UK bio-energy space.

The assessments of UK identified strengths and assessments of competitiveness in elements of the bio-energy value chain is summarised in Table 6.2, below. The table is laid out with a general commentary as to how the UK performs in the sector - where the UK is perceived to have a strength further commentary is made with specific reference to the category. It is worth emphasising that the table in no way suggests any form of prioritisation in its layout.

Table 6.2: Summary assessment of UK key strengths in bio-energy capacity based on a survey of detailed bio-energy landscape reports and expert input undertaken in March 2011 (see also Appendix 7)

Sector of Bio-energy Value Chain	Assessment of UK Bio-energy Capacity Relative to Other Nation States - UK internationally recognised strengths highlighted as appropriate
Feedstocks	
Micro-algae	<p>The UK has a strong competitive position in basic and applied research in microalgae based technologies, and a strong capability investigating the use of microalgae for bio-fuels, on par with other leading countries. There is some industrial activity in this area in the UK, this is focussed on the production of microalgae for high value products and aquaculture feed and bioremediation of waste water and CO₂ rather than for large scale fuels applications, so the UK is weak compared to countries such as the USA. Given the UK climate it is unlikely that the UK will produce oil based fuels from algae at scale, so will be an IP developer rather than an implementer. However, after the removal of high value products, algal residues could be used in AD processes, to provide biomethane which could be used for heat, electricity or biomethane fuels. The UK has the potential to lead in this area, but the Netherlands are also actively researching this area. A key concern for the UK algae community has been the lack of co-ordination (DECC, 2009b).</p> <p>UK Strength at University / Research Institute Activity: Culture collections at SAMS and Marine Biological Association. Excellent underpinning algae capability at CEFAS, SAMS, Plymouth Marine Labs, Swansea, Bangor and Stirling Universities. Other relevant expertise in algae fuels and products at Birmingham City University, University of West England, Cambridge, Queen's University Belfast, Newcastle, University College London and University of East Anglia. Research on growth systems at Plymouth Marine Labs, Heriot Watt, Sheffield, Loughborough, UCL (photobioreactors) and Cranfield (sea growth).</p>
Macro-algae	<p>Despite the UK's strength in basic macro-algae research, the UK is lagging in the deployment of macro-algae cultivation, especially compared to Asia and Chile. The UK is generally on par with the capabilities of leading countries within the EU for macro-algae farming at scale, although plans for macro-algae farms elsewhere appear further developed than in the EU. The UK has a strong competitive position in the thermal conversion and anaerobic digestion of macro-algae to fuels and energy at the basic research level, and is leading in the utilisation of macro-algae within AD facilities. However, despite a strong academic and industrial capability in sugar conversion to ethanol and butanol, the UK is lagging other countries in the developing macro-algae as a source of ethanol and butanol. A key concern for the UK algae community has been the lack of co-ordination (DECC, 2009b).</p> <p>UK Strength at University / Research Institute Activity: Excellent, world-class research capability at Scottish Association for Marine Science. Expertise at Plymouth University, Newcastle University and Queens University Belfast on macro-algae growth. There is a germplasm collection at Culture Collection of Algae and Protozoa. Research into macro-algae conversion for thermochemical and biochemical processing at Leeds and IBERS as part of the SUPERGEN project. Research at Plymouth, Leeds and Aston Universities on thermochemical conversion processes. There has been research on macro-algae AD at Newcastle University and SAMS under the Scottish Enterprise Seaweed AD project.</p>
Arable Crops	<p>The UK expertise in plant genetics is on par with that elsewhere in the world. The UK has particular strengths in photosynthesis, cereal and oilseed genetics and in high throughput screening technologies which can be used to identify novel, agronomically useful traits. However, the UK has a major gap in the development of new varieties and so fails to capitalise on its plant genetics strength. This is because all of the major plant breeders are located outside of the UK and the agrobiotechnology companies left the UK with the EU moratorium on GM crops in the 1990s. While the UK will inevitably need to import new varieties from abroad, the UK does have a good capability in trialling varieties. Therefore, while elements of arable crop development are strong, there are gaps.</p> <p>UK Strength at University / Research Institute Activity: World class research into plant science at Rothamsted Research, John Innes Centre, Sainsbury Laboratory, Oxford, Cambridge, IBERS and NIAB. Considerable expertise in photosynthesis with particular expertise at Cambridge University, Imperial College London, York. Expertise in plant manipulation and breeding at Rothamsted, John Innes Centre, IBERS, Warwick, CNAP, Southampton, Oxford Nottingham and Manchester amongst others.</p>



<p>Perennial Energy Crops</p>	<p>As for arable crops, the UK is extremely strong at plant genetics and high throughput screening technologies which could be used for variety development; however, this is not supported by an active energy crop breeding sector so varieties may have to be imported. The UK has world leading expertise in the agronomy and utilisation of perennial energy crops. However, this could be compromised by the removal of funding for maintenance of the national willow collection at Rothamsted and <i>Miscanthus</i> collection at IBERS. There is a feeling that energy crop breeding would be best integrated into the wider UK crop breeding sector.</p> <p>UK Strength at University / Research Institute Activity: There is world class expertise in <i>Miscanthus</i> at IBERS and world class expertise in Short Rotation Coppice at Rothamsted Research and at University of Southampton.</p> <p>IBERS have a collection of <i>Miscanthus</i> varieties, and Rothamsted Research has the National Willow Collection. These facilities not only allow the trialling of specific varieties to see how they apply to the UK, but also allow studies into the natural variation of these varieties which could infer novel traits for fuels and energy applications.</p>
<p>Forestry</p>	<p>Through Forest Research, the UK has one of the leading research institutes in the world investigating forestry systems. The UK forestry community is also well linked both within the UK and to other forest associations world-wide through involvement in networking activities and research projects. Given that the UK has one of the lowest coverage of forestry areas in the EU at 12%, it cannot compete in terms of production quantities with other countries, particularly Scandinavian countries. However, the work of Forestry Research and other UK research institutes can be combined with the UK's developing biomass transport infrastructure (e.g. ports) to develop the use of imported sustainable forestry products.</p>
<p>Waste</p>	<p>The UK has a strong capability in waste collection and processing of wastes; wastes arise densely in large conurbations and are collected to key centralised points. The increasing pressure to divert waste from landfill has led to an increase in the deployment of Mechanical Biological Treatment (MBT)/ Mechanical Heat Treatment (MHT) facilities in the UK over the last five years. However, the withdrawal of Private Funding Initiative (PFI) funding may mean that many of the planned facilities in the UK will not now reach fruition. The UK has a good research capability in this area and there is a strong networking capability. The increased deployment of MBT/MHT facilities in the UK should help provide confidence in the deployment potential of this technology in the UK for bio-fuel plants.</p> <p>A potential risk to accessing wastes for bio-energy projects will be limitations arising from the waste hierarchy, circular economy initiatives and subsequent competition for available wastes.</p>
<p>Logistics</p>	
<p>Harvesting, Transport and Densification</p>	<p>There is little basic research being undertaken in the UK for this part of the bio-energy value chain for all the reasons stated in section 5.2.1. Though anecdotally private sector efforts into torrefaction are thought to be an area undergoing development.</p> <p>It is worth stating that the supply chains for existing power plants that utilise biomass are well developed, organised and proven to be commercially viable under present policy regime e.g. Drax (bales, SRC), E.ON in Lockerbie (forest residues), Eccleshaw (<i>Miscanthus</i>), Ely (straw) etc. These organisations have undertaken considerable research, capacity building and infrastructure development in the supply chain including extension services to feedstock producers to ensure a reliable supply of feedstock.</p>
<p>Process Conversion - Intermediaries</p>	
<p>Lipids</p>	<p>The UK currently has three oilseed crushers, with a combined capacity of around 2 million tonnes per annum. As a commercial technology, there is little research in this area either in the UK or elsewhere. The notable exception of the Creol facility in France which provides process optimisation facilities for different oilseeds. The UK does have some strengths in cavitation technologies which could be applied to the extraction of oils from algae, although this is likely to be deployed outside of the UK.</p>
<p>Biogas</p>	<p>While the UK has historically lagged other leading countries such as Germany and Denmark in anaerobic digestion, it is developing both its applied research capabilities and infrastructure rapidly and thus could develop a late-mover advantage. The UK is, alongside Italy, leading the utilisation of food wastes for anaerobic digestion at larger scale. The UK has less capability, especially at the commercial level in the digestion of energy crops as say Germany or the USA. Deployment potential will however be constrained by the availability of land to utilise digestate.</p>
<p>Sugars</p>	<p>The UK has a significant strength in the production of cereal crops, particularly wheat and has developed a commercial industry for both extraction of starch and utilisation in bioethanol. This will facilitate the development of other starch based fuels such as biobutanol. The UK is on par with leading countries world-wide in the development of pre-treatment of lignocellulosic biomass to extract sugars at the academic level, but, with limited industrial activity, significantly lags the principal technology developers throughout the world. Though the UK is working on pre-treatment and hydrolysis technologies there is a consensus that the UK will likely need to import the technology from elsewhere should it develop a lignocellulosic ethanol or butanol capability.</p> <p>UK Strength at University / Research Institute Activity: Wide range of research capability producing sugars from lignocellulosic biomass. Research on ionic liquids at Imperial College, Queens University Belfast, and University of York, supercritical fluids research at University of Nottingham and Birmingham and steam explosion at Institute of Food Research and</p>



	<p>Bangor BC. Dilute acid research at Queens University. Research on biological pre-treatments at University of York, Liverpool John Moores University and University of Dundee.</p>
Syngas Production	<p>The UK is lagging on the gasification of biomass for bio-fuels at the research level, although there is some experience in applying gasification processes for energy. As a result the UK would have to buy in gasification technologies for the scales needed for bio-fuels production. Syngas clean up research and syngas upgrading is on par with the rest of the world. The UK is considered to be developing a leading position in the gasification of wastes to fuels through the announced but as yet undeveloped INEOS Bio and BA/Solena projects, and while the Air Products and Biossence waste to energy facilities are focussing initially on energy, these could convert to fuels production at a later date. The implementation of these projects could provide an impetus for further research and development work in biomass gasification in the UK.</p>
Pyrolysis Oil Production	<p>The UK has strengths in pyrolysis research but industrial activity is limited and may only in the near term develop for heat and power. As a result, the UK is likely to bring in technologies developed elsewhere as they develop. Wide scale pyrolysis won't develop until the upgrading technology (whether mild for power generation via engines or extensive for fuels production) is available. UK Strength at University / Research Institute Activity: There are a handful of world class research groups in this area, including the Aston University, University of Leeds, Newcastle University, Southampton, Imperial College and Nottingham. University of York and University of Exeter are investigating microwave pyrolysis methods.</p>
Process Conversion - Conversion to End Fuels / Energy Carrier / End Use	
Thermal - Combustion for Power	<p>Direct combustion for electricity generation capability is strong and there is significant momentum being developed in this area, with an estimated installed capacity of <0.5 GW but over 3GW of biomass projects being developed.</p>
Thermal - Heat and CHP	<p>UK renewable heat and CHP market is limited by the relative absence of heat sinks and lock-in to the present gas grid system (Section 3). The impact of the Renewable Heat Incentive on uptake of bio-energy derived heat and CHP remains to be seen. It is considered that any development in capability for CHP will be based on imported equipment.</p>
Bio-CCS	<p>Considered strength in this nascent area is based on UK developing expertise on large scale CCS and the increasing number of co-firing and dedicated bio-energy plants. There is a need to integrate the two processes for which work is being undertaken to assess the techno-economic feasibility of doing so. A second option for CCS is the extraction of CO₂ under pressure from thermal processing; as the CO₂ is already separated out the economics are attractive.</p>
Bio-methane for Heat and Power	<p>The UK has strong academic R&D capability in AD to bio-gas. Anaerobic Digestion is a rapidly growing, commercial technology in the UK with 54 active plants at the beginning of 2011, 31 on farm and 23 off farm. The majority of these plants use biogas for the production of heat and or electricity. Opportunity exists to inject bio- methane into local distribution networks at low pressures; this is being demonstrated at two sites in the UK, Adnams Brewery, Suffolk and Didcot Water Treatment Works, Oxon.</p>
Hydrogenated Vegetable Oil (HVO)	<p>The UK is weak compared to other countries world-wide in both HVO development and deployment. HVO technologies would therefore need to be imported from elsewhere. There may be some interest in using HVO processes in the UK but this is unclear at the moment. Although HVO is highly compatible with the UK fuel infrastructure, the potential uptake of this technology would be limited as a result of vegetable oil availability and due to potential issues surrounding the utilisation of the UK hydrocracking infrastructure.</p>
Syngas Upgrading to Production	
Synthetic Diesel / Aviation (FT)	<p>The UK could potentially develop a leading position in syngas upgrading technologies. In particular, the UK could develop a leading position in the development of BTL fuels from waste materials (with the announced but as yet undeveloped BA/Solena aviation fuel project and Ineos Bio waste to ethanol project). However, several other countries are interested in this. UK Strength at University / Research Institute Activity: Aston University, Manchester, Sheffield, Imperial, UCL, Newcastle all have capability in this area but few work directly on gasification to synthetic diesel production. Newcastle University are working on developing micro FT reactors. University of Sheffield are working on GTL aviation fuels. UK Strength at Industrial Activity: Catalyst expertise at Johnson Matthey and Oxford Catalysts. Compact GTL are developing production of synthetic diesel from gas via steam methane reforming. Oxford Catalysts are developing microchannel FT processes for diesel production. BP has expertise on FT. Significant interest in FT fuels from the aviation industry BA, Airbus and</p>



	<p>Rolls Royce.</p> <p>UK Strength at Pilot and Scale Up: Test facilities/ongoing research at Compact GTL (North East), BP (Hull), Johnson Matthey and Oxford Catalysts</p> <p>UK Strength at Demonstration and Commercial Scale: Potential strength with the announced but as yet undeveloped BA/Solena plant in East London which is specified to produce 50,000 tonnes of aviation kerosene from 2014/15 using wastes</p>
Hydrogen	<p>The UK has a strong international position on hydrogen research and development which is possibly on par with other countries. There are a number of universities investigating the production of hydrogen from biomass in the UK, and a wider, extensively networked community of academic and industrial players looking at the infrastructure and storage requirements needed for hydrogen utilisation. The UK is also well linked in with major international projects in this area. There is some interest in the deployment of hydrogen in the UK with advanced plans for the development of a waste to hydrogen plant in the UK from 2014. In the short term, infrastructure will limit the deployment of hydrogen for transport fuel, but it may be a longer term opportunity.</p> <p>UK Strength at Demonstration and Commercial Scale: An area of potential strength with Air Products, a French company, announcing plans to develop a 49 MW waste to power plant on Teesside (2014). They may convert this to produce hydrogen.</p>
Methanol & Derivative (DME)	<p>The UK is lagging other countries, especially Scandinavia, in the development of methanol and DME based fuels. There is negligible academic activity into the production of either methanol DME in the UK and while the development of other BTL based processes could provide an impetus and the practical knowledge base to catalyse the development of methanol and DME production, it is likely that the UK will be a technology importer in this area. The development of UK projects in this area will be limited without the development of a specific infrastructure for utilisation of these fuels.</p>
Ethanol from Gasification (Catalysis & Fermentation)	<p>The UK has little research activity in the production of ethanol from syngas. However, the UK does have significant strengths in both fermentation and catalysts which could be applied to the conversion of syngas to ethanol. Despite this lack of activity, there are plans to develop a pilot scale facility on Teesside from 2012 and for a commercial scale plant between 2014 –2015, both of which will use a fermentation process to convert syngas to ethanol. Although there are several other waste to ethanol plants planned globally, all except one will use a catalytic mechanism to convert the syngas to ethanol. The UK has the potential therefore to develop a leading position in the utilisation of syngas for ethanol via fermentation based processes.</p>
BioSNG from Gasification	<p>The UK lags other countries, particularly Sweden, Netherlands and Switzerland in the development of BioSNG. To our knowledge, there is no academic or industrial research undertaken into BioSNG production in the UK, and as a result, any technology would need to be imported from abroad. There is some interest in BioSNG from UK stakeholders and the development of UK based gasification processes could provide expertise which could be leveraged for the development of BioSNG. The deployment potential of BioSNG for transport will, as for biomethane, be limited by the need to develop a fuelling and distribution infrastructure and any differential in incentive between the different end markets in which the SNG (or methane) could be used.</p>
Other routes	
Biomethane for Transport	<p>The UK has a rapidly developing AD sector, but the UK lags other countries, especially Sweden and Switzerland, in both the development and deployment of biomethane for transport fuel use. Although there is an increasing interest in the use of biomethane for transport, and a number of trials completed, it is likely that technology for gas upgrading will be brought in from elsewhere. Commercial interest in biomethane for transport, as for BioSNG, is limited by the need to develop a fuelling and distribution infrastructure and any differential in incentive between the different end markets in which it could be used.</p>
Furanic / Novel Sugar Fuels	<p>The UK lags countries, particularly the Netherlands and USA, in the development of sugar-based hydrocarbon fuels. The UK would therefore likely to be an importer of these technologies rather than a developer.</p>
Ethanol (from Bio-chemical Processing)	<p>The UK has significant strengths in fermentation of both C5 and C6 sugars and is on par with the leading countries world-wide both in terms of academic research and industrial research. While the UK has been developing facilities for the scale up of fermentation based technologies, it is likely that technology developers will commercialise their technology elsewhere before the UK due to the better support and incentives elsewhere, thus, at least initially, the UK is likely to be an IP exporter and buy in technologies developed and demonstrated elsewhere.</p> <p>UK Strength at University / Research Institute Activity: There is expertise in fermentation of C5 sugars at University of Ulster, Imperial College, Bath University and Nottingham</p>



	<p>University. Wider fermentation expertise at Heriot Watt International Centre for Brewing and Distilling and Scottish Whisky Research Institute.</p> <p>UK Strength at Industrial Activity: The UK has a number of innovative companies in the UK all of which are based on the development of thermophilic bacteria to ferment C5 and C6 sugars from lignocellulosics. These are Agrol, Biocaldol and TMO. Hycagen in Cambridge may also have capabilities in this sector.</p>
Butanol	<p>The UK activity in bio-butanol is on par with the leading activity elsewhere in the world, with a number of innovative companies in this area, especially in respect to R&D work on fermentation routes to biobutanol. However, while the UK has plans for the development of both pilot and commercial scale butanol production plants, biobutanol production has already been piloted in Germany and the USA, and will be commercialised in 2011, so the UK will be lagging the leading countries in this area.</p> <p>UK Strength at University / Research Institute Activity: Academic groups working in this area include Nottingham University who have expertise in <i>Clostridium difficile</i> and are part of the BBSRC Sustainable Bio-energy Centre, Napier University who are investigating both Clostridia and algae as butanol feedstocks, and IBERS who have done gene expression studies in Clostridia.</p> <p>UK Strength at Industrial Activity: The UK has a number of innovative companies in this area. E.g. Green Biologics are working on manipulating the ABE process to enhance butanol yield. Solvert are also using the ABE process to produce butanol and other chemicals. Other research is through Kingston Research Limited who will provide a technology package to Butamax advanced fuels, another BP/ Dupont joint venture.</p>
Upgraded Pyrolysis Oil	<p>Although the UK has strengths in pyrolysis, activity in the upgrading of pyrolysis oil for transport fuel use has been less well developed. The Carbon Trust's Pyrolysis Challenge has provided some impetus in this area and there is evidence of some companies developing pyrolysis processes which could be used for transport fuel use. Thus, pyrolysis oil upgrading is a growing area of interest in the UK. However, elsewhere in the world, there are several developers investigating pyrolysis oil upgrading, and it is estimated that this could be commercial within the next 5 years. Thus, the UK is likely to import this technology.</p>
End Use	
Bio-energy System Integration	<p>To certain levels capability is well developed by Oil Majors and OEM manufacturers for bio-fuels. Though there needs to be better awareness of specifications and limitations for all members of the supply chain which might be achieved with the establishment of quality standards.</p> <p>The UK is undertaking world class research on the integration and optimisation aspects biorefinery systems (e.g. CPI, SUPERGEN Bio-energy and BSBE).</p> <p>The UK has the capacity to derive chemicals from biomass but has not thought about what they want from bio-based chemicals.</p> <p>UK Strength at University and Industry Collaborative Activity: The Centre for Excellence in Biocatalysis, Biotransformations and Biocatalytic Manufacture (CoEBio3) based in Manchester. CoEBio3 is a national centre for commercialisation and scale up of biocatalysts. It works with a number of partners, including the Centre for Process Innovation (CPI), the Universities of York, Strathclyde and Heriot Watt.</p> <p>The Centre for Process Innovation, located on Teesside, contains the National Industrial Biotechnology Facility. It provides pilot scale fermentation, anaerobic digestion and gasification (to be built) facilities.</p>

For a greater resolution on the relative competitiveness of the UK capacity for bio-energy in the following sectors

- Biomass to Power;
- Biomass to Heat and Combined Heat and Power;
- Woody, Grassy and Oil based Energy Crops;
- Micro- and Macro-algae;
- Ligno-cellulosic Ethanol, Butanol and Bio-DME;
- Biomass to Liquids, Pyrolysis and Novel routes; and
- Bio-energy Carbon Capture and Storage

see E4Tech (2011a, b, c,d,e,f) Technological Innovation Needs Assessments.



This review confirms the observation by the Industrial Bio-technologies Innovation Growth Team (2009) that the UK has an international reputation for the quality of its research and development, both in universities and in industry. The UK bio-energy research base has pockets of world leading bio-energy expertise in a broad range of areas along and across the bio-energy value chain. Areas of UK R&D strength include (after NNFFC, 2011e):

- Fundamental R&D capability in the development and use of plant biomass resources. A number of institutions have expertise in the development of genomic tools underpinning crop improvement while university based establishments carry out fundamental applied research into plant biomass productivity, particularly willow and miscanthus.
- Algal technology fundamental research - albeit fragmented and lacking in coordination.
- The development (fundamental research) of micro-organisms for ligno-cellulosic bio-ethanol, in particular in the areas of biomass pre-treatment and fermentation (especially conversion using thermophilic microbes to metabolise pentose sugars) - UK expertise is less strong in the area of biomass hydrolysis.
- Biobutanol fundamental and industrial research.
- Syngas upgrading industrial research - there are a variety of UK based companies developing syngas upgrading technologies and a number of UK projects which will use a syngas intermediate derived from wastes. UK research in syngas production (i.e. via gasification) is not a strength.

There are also several centres within the UK working on industrial pilot and demonstration scale up. These centres have sponsors drawn from both the academic and industrial arenas, and thus provide an important link between academic research and the industrial application of science⁵¹. However, other than a few areas (e.g. bio-energy power generation, butanol, potentially waste to bio-fuels via thermal routes) the UK has a deficiency in its ability to deliver the appropriate applied research, support the development of demonstration plants and commercial roll out. There is a feeling amongst interviewees and a number of recent reports that there is a lack of strategic leadership and coherent, dedicated funding incentives / support from government to drive the bio-energy agenda and allow a focus for industrial and academic collaboration, co-ordination, integration and value chain development (see next section).

Based on the UK capacity assessment made above, bio-energy landscape reviews in section 4 and 5 and in the context of what is likely to be important in the 2050 energy system (Section 3), it is the ERP's recommendation that the UK should seek to prioritise bio-energy technology development in the following areas for the following reasons:

- (1) **Both fundamental plant science and applied agronomy of bio-energy crops.** The UK's international standing in plant science and the importance of the efficient development of biomass to address global needs for food, feed, fibre and energy as well as using land effectively makes this a priority area that the UK should undertake research. This reinforces the BBSRC (2006) strategic desire '*to focus on sustainable, low input agriculture as part of a whole system approach to land use / natural resource management, and to optimising environmental and ecological benefits*'. The development of a better understanding of the behaviour of soil organic carbon and land use related issues is also considered a high priority. It also recommended that the UK maintain its strategic alliances with the US DOE and Brazil to complement the work undertaken in the UK.
- (2) **Micro and Macro-algae - not necessarily purely as a feedstock source for energy but within a larger framework of research of which energy should play a part.** The UK has internationally recognised strengths in algal research. There is an enormous amount of work that needs to be undertaken in micro-algae research - especially on fundamental biology - that is likely to result in spill over benefits for other biotechnology applications as well as the licensing of the intellectual property. With regards macro-algae it is also recommended that, subject to the economics and sustainability requirements (both of which are substantial research areas) be appropriate, the UK consider pursuing a domestic macro-algae production capacity for bio-energy due to the natural resource endowments that the UK possess. In order to enhance

⁵¹ However, it should be noted that although developing a research base is desirable and can provide advantages, it is not essential with respect to pathway deployment in the UK as evidenced by the cases of Ineos Bio whose technology was wholly developed in the USA and British Airways whose proposed plant will use US gasification and Fischer-Tropsch technologies (after NNFFC, 2011f).

R&D in these areas there is there is a need for develop a strategic focus and integrated approach to the algal sector in the UK as well as increase funding (DECC, 2009b).

- (3) **Bio-energy and Carbon Capture and Storage systems development as a negative emissions technology.** The increasing importance of negative emissions technologies in attaining GHG reduction targets economically (UNEP, 2011), the robust dedicated biomass and co-firing sector in the UK and internationally recognised leadership on R&D in carbon capture and storage makes this a key area that the UK would be in a position to lead in. Fundamental work in this area is being undertaken by the Energy Technologies Institute.
- (4) **The development of process conversion technologies for liquid drop-in fuels for heavy duty and aviation sectors but covering all product categories.** The UK has strong capacity in thermal routes and despite the weak domestic capacity for gasification development the UK has managed to attract the development of advanced waste to fuel thermal conversion plants (e.g. Solena). This could potentially springboard UK into a leading position in this area if the waste can be utilised economically. Furthermore, the UK has strengths in fast pyrolysis research. A process whereby feedstock undergoes fast pyrolysis and the bio-oil produced is gasified may overcome the development concerns with large scale gasification. This route has lower risks associated due to better understanding of the process and large scale fast pyrolysis plants are being developed by organisations abroad such as UOP which may be purchased off the shelf with guaranteed performance standards.

Two issues are noteworthy regarding the UK focus on waste. Firstly, as a feedstock for advanced conversion technologies there is the need for the development of systems to make waste economic to collect and manage as a priority area for work - most of the issues related to this are not technical. Secondly, as a resource it has limited potential to contribute to UK energy needs (<4%) whereas biomass has the potential to contribute substantially more (>10%).

The UK also has strengths in elements of bio-chemical routes (e.g. BSBECC) which may also be used to potentially develop drop-in fuels. The optimal route for the development of drop-in fuels will be the subject of ongoing assessment though in order to incentivise the development of 'drop-in' fuels there would be a need for suitable policy and recognition within accounting frameworks.

- (5) **Integrated systems for bio-refinery development.** The UK has pockets of international research strengths in specialist conversion areas such as pyrolysis and elements of ligno-cellulosic to ethanol / butanol process conversion. It also has substantial capacity in bio-processing for therapeutics which are of high value. The skills and equipment for therapeutics are broadly transferrable to the bio-energy sector though there is a need to commoditise the processes to bring costs down to make bio-energy production economic. It is considered that with integration of chemical engineering / refining aspects and by learning the lessons from pharma, integrating bio-science, physical science and engineering concurrently may allow the UK to develop leadership in this space. The US focus in the past has been on the bioscience aspects of the value chain without integrating the chemical engineering aspects - there appear to be initiatives in the US which are leading to increasing integration. To optimise UK work in this area there is a need for the UK to learn from international activities in this area.

Though the bio-refinery concept has yet to be proven (Section 5.4.3) there will certainly be benefits from developing thinking around the concept due to its resource optimisation and integrated framework.

In terms of *Field to Process Conversion* (harvesting, storage, transport and densification) component of the value chain, on the understanding that the UK will develop a scalable domestic biomass capability from energy feedstocks on marginal lands which are not flat, this is an area which is under-researched. The bespoke nature of the requirement will mean that there will be a need for the UK to develop its own organic capacity in this area; this should be fed into an international development of development of standards (US DOE, 2010a).



6.3.2 Bio-energy Policy Development in the UK

A recurring theme in recently produced literature on UK bio-energy policy is the lack of overarching strategy e.g. Dunnett (2009), ETI (2011), DECC (2009b), NNFCC (2009c, 2010d, 2011d). In the UK, the need for the development of a coherent frame work of energy policy planning, regulation, support, continuity of plans⁵² and priorities to generate confidence for the private sector to invest in large scale projects and relatively expensive low carbon technology such as bio-energy is compromised two main issues. Firstly, by the UK's liberalised energy markets that require governments to develop technology neutral policies tend to favour existing and close to market systems and does little to address fundamental innovation and next generation renewable technology (Watson, 2008)⁵³. Secondly, the complexity of bio-energy supply chains is such that there is substantial need for an interdepartmental multi-ministerial approach which can result in a lack of strategic oversight and/or coherence in policy development.

The manner in which UK bio-energy policy has been developed suggests that in the balance to reconcile the needs of a liberalised energy market and the innovation policy requirements identified by Watson (2008) - the considerations of the former have been paramount at the expense of the latter. Analysis by Slade et al., (2009) demonstrates that though the body of work⁵⁴ assessed the potential for biomass in the UK well they were characterised by:

- A lack of increased financial support;
- the government's decision not to have quantifiable unambiguous outcomes; and
- failure to develop causal relationships between policy proposed and expected outcomes link between UK renewable targets and those for bio-energy.

Furthermore, the interdepartmental nature of bio-energy has resulted support mechanisms and regulatory instruments for the bio-energy sector being highly fragmented (involving DECC, Defra, BIS, HMRC, Environment Agency, The Research Councils, Ofgem, Carbon Trust and Energy Savings Trust), change frequently and are complex - see, for example, the bio-energy related policies and schemes in table 6.3, below.

In such a policy context it is therefore extremely difficult to assess bio-energy policy effectiveness as the number of tangible outcomes is limited. Is it that progress has been slow suggesting that the policies have been ineffective or that the rate of progress is desirable? It is not possible to measure bio-energy penetration rates against targets as they are few and far between (Slade et al., 2009).

Table 6.3: Examples of UK Bio-energy Related Policy and Schemes (IEA Global Renewable Energy - Policy and Measures Databases, Adams et al., 2010, Sherrington et al., 2008 and Slade et al., 2008).

- UK obligation to the EU **Renewable Energy Directive** (2010) is for 15% of UK energy to come from renewable sources with an indicative realisation by: 30% electricity generation, 12% heat and 10% transport. The transport target is fulfilled by the **Renewable Transport Fuel Obligation**. Alongside the transport component is the **EU Fuel Quality Directive** requiring a reduction in fuel supply GHG footprint by 10%.
- **Renewable Obligation Certificates** obliges energy generators to obtain a fixed proportion of their energy from renewable sources (9.7% in 2010 and incrementally increasing year on year). It was banded in 2010 with commercially mature bio-energy sources being penalised (e.g. Landfill gas 0.25 ROC/MWh) and less well developed being rewarded (e.g. Gasification / Pyrolysis, Anaerobic Digestion 2 ROC/MWh).
- **Feed In Tariffs** whereby households / organisations are paid a fixed rate for the electricity that they generate when they use biomass or other low carbon sources.
- The Government has announced £860M to be made available for the **Renewable Heat Incentive** to be introduced in 2011 which seeks to encourage renewable heat generation sources within which bio-energy sources comply.
- Feedstock related schemes include **Single Payment**, **Entry Level Environmental Stewardship Scheme**, **Energy Crops Scheme**, **Woodland Grants Scheme** and **Energy Aid Payment Scheme**.
- Other schemes include: **Bio-energy Infrastructure Scheme**, **Bio-energy Capital Grants Scheme** others are run by the Forestry Commission

Further details of UK Government policy to support biomass power can be found in Appendix 8.

⁵² Recent work by Foresight (2010), based on focus groups of energy technology experts, goes so far as to suggest that there should be encouragement of the continuity of plans with the changes of government.

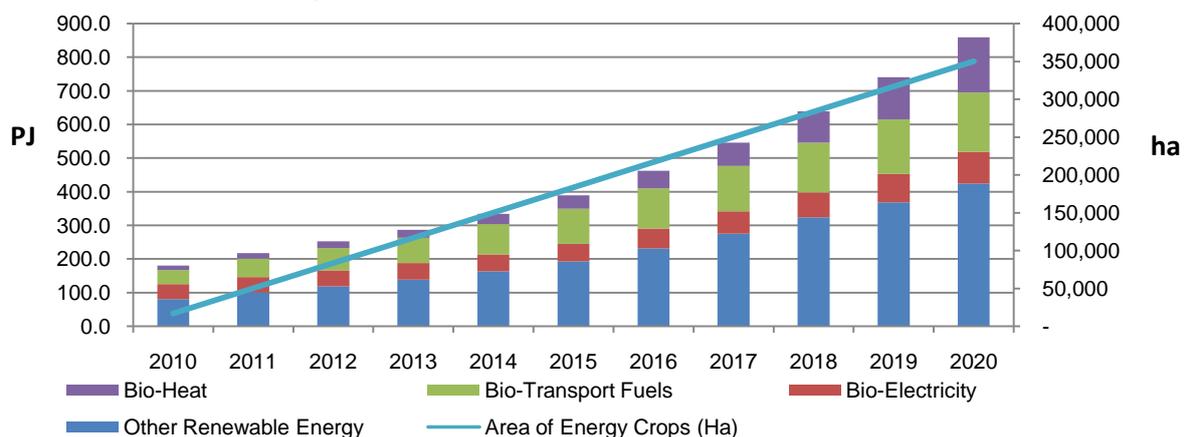
⁵³ Though this is being redressed with the banding of the Renewable Obligation Certificates and Electricity Market Reform - some consider this to be insufficient.

⁵⁴ The UK bio-energy policy and delivery may be traced back to four reports produced between 2004 and 2007: Biomass as a Renewable Energy Source by RCEP (2004), Biomass Task Force (2005), The Governments response to the Biomass Task Force (2006) and the UK Biomass Strategy (2007).

The following strands of evidence suggest that more thorough policy development is a key requirement in the development of a robust bio-energy sector in the UK.

- (1) In an EU wide review of bio-energy by Thornley (2008), energy policy is considered to be the single most important barrier preventing the whole sale expansion of the bio-energy industry. Due to the unique nature of bio-energy as a renewable resource the review highlighted the need for programmes that focus on bio-energy rather than technology neutral and need for long term investment subsidies. This was further reinforced in a review by the IEA on policy recommendations which also stated that not only should a clear policy target be set but it should be accompanied by a clear vision as to the resources that should be utilised, sectors (of industry and agriculture) that should be involved, and the appropriate technologies linked to the resources and sectors (IEA, 2007b).
- (2) There is a disconnect between the indicative trajectory for the share of bio-energy of renewable energy for electricity, heat and transport in UK National Allocation Plans (NAP) for the EU Renewable Energy Directive and the ability to supply domestic sustainable biomass to meet these trajectories. The indicative trajectory (displayed in figure 6.4, below) suggests that by 2020 from 2010 there will be a 2 fold increase in the use of biomass in electricity, 4 fold increase in road transport and 12 fold increase in heat. The NAP models that 83% and 91% of ethanol and biodiesel for road transport will be imported. To meet the heat and electricity component from domestic biomass will require 350,000 ha of energy crops to be cultivated (Defra et al., 2007). At present only 17-20,000 ha have been planted (Howard et al., 2009) meaning that an area twice the size of Greater London needs to be planted in the next 10 years to attain the target. The line in figure 6.4 displays the plant rate trajectory required to attain 350,000 ha (this does not take into account the fact that both SRC and miscanthus require further time to propagate before commercial harvesting can take place). At over 33,000 ha of domestic energy crop establishment per year for the next 10 years required to hit the target for bio-heat and bio-electricity component of the renewable portfolio from domestically produced sources will be difficult. This also indicates a possible oversimplification of representation of bio-energy in modelling for UK policy development (Section 3).

Figure 6.4: Indicative use of bio-energy as a proportion of all renewable sources to attain the UK renewable energy directive target (in PJ - left hand axis). Plant rates (in ha - right hand axis) of energy crops required to attain the area of energy crops suggested by UK Biomass Strategy (Defra et al., 2007) to attain UK bio-energy component of renewable energy directive.



- (3) The lack of adoption of energy crops by farmers was studied by Sherrington et al. (2008 and 2010). The work found that the long lock-in times, lack of confidence of a reliable market (made worse by the failure of Project ARBRE (Piterou et al., 2008)), high capital outlay and delayed cash flow returns, reductions upfront grant payments for energy crops and the record global food commodity prices has made feedstock producers unwilling to invest in the energy crops. The review suggested that the structure of contracts be amended to bring forward payments and the establishment of insurance schemes to increase financial security for farmers.



- (4) In a literature based review of the general barriers and drivers for UK bio-energy development (Adams et al., 2010) highlighted that though they differed for each stakeholder the overarching concern across all stakeholders was the fact that the economic proposition for bio-energy was unproven along the value chain within the present policy and grants framework - see table 6.4, below.

The implied need for increased economic incentives comes at a time when, as a result of the Comprehensive Spending Review (2010), cuts are being made to the final rounds of the Bio-energy Capital Grants Scheme and Bio-energy Infrastructure Scheme (£4.7 M), within the Environmental Transformation Fund - effective for FY 2011/12. The impact of DECC cutting £34M on the expenditure of low carbon technology on the bio-energy sector is not yet clear.

The need to develop coherent policy frameworks to provide financial security along the entire bio-energy chain is vital to the development of effective pull through for bio-energy innovation, development and deployment in the UK energy system (REA, 2009).

Table 6.4: Stakeholder concerns for investing in bio-energy across UK stakeholder groups (Adams et al., 2010).

- **Feedstock Suppliers** main concerns were that present annual crops are more economic than perennial energy crops and there was uncertainty in their viability in the short term. Additional concerns included uncertainties surrounding production costs, yield, market prices, being tied into long term contracts, duration of grant funding and land availability.
- **Process plant developers / owners** primary issue was technology uncertainty and the lack of UK knowledge and experience. Further concerns included development and operational costs, the broad range of legislative issues and resource availability. A summary of problems for UK bio-energy projects include:
 - financial problems during operation and lifespan of plant;
 - increased transport around bio-energy plants;
 - local planning approval and location of bio-energy plant—visual impacts;
 - mistrust between local community, developers and agencies; and the credibility of developer;
 - other environmental impacts, for example odours, noise, etc.;
 - technical problems associated with conversion techniques.
- **Primary end users of bio-energy** main concern was cost alongside legislative issues and infrastructure requirements.
- **Government / policy stakeholders** primary issue was that of resource availability, the need for technological advances in the conversion technologies and the lack of skilled workers.

As of February 2011, the UK government has established a DECC lead, cross-departmental bio-energy strategy refresh which is seeking to address a number of these issues.

6.3.3 UK Bio-energy Innovation Landscape

The review of bio-energy as a process technology (sections 4, 5 and 6.3.2) allows a number of key issues to be stipulated regarding the requirements of an effective innovation landscape for enhanced bio-energy technology development. These may be summarised as follows:

- The fragmented and multi-disciplinary nature of bio-energy issues requires there be multi-departmental involvement with strategic oversight by a single government department that has responsibility for developing a vision, co-ordination of work and accountable for the delivery of project milestones within a long term strategic plan.
- The integrated nature of bio-energy process technologies with modification of one aspect potentially having impacts on others ranging from energy and GHG balance for ease in processing requires that co-ordination across and along bio-energy chains be a priority. The scale and extent of this co-ordination is emphasised by the need for:
 - Whole systems thinking across and along bio-energy value chains;
 - A global perspective due to the impact of biomass feedstock production being international in nature; and
 - That due to the broad extent of disciplines that are relevant to bio-energy there is a strong need for market orientation in order to prioritise research needs.
- To assist with co-ordination, where possible, open source centralised information sharing of bio-energy issues within UK RDD&D landscape should be encouraged with a single organisation being responsible for the maintenance of the database.

Against each of these requirements, the state of the UK innovation landscape can be assessed.

There is a need for a long term strategic vision (beyond 2020) and oversight of the UK bio-energy agenda from a policy and innovation needs perspective. The market for bio-energy technologies and products, especially advanced bio-fuels is policy driven and will be for some time. There is a need for clear and stable long term policies to maintain investment required to generate strategic 20-30 year R&D, most of which at present is at an early stage, and needs to be accelerated to assist in achieving the 2050 targets - particularly in the transport sector. Market certainty is also required for feedstock producers (e.g. plant breeders and farmers) in order to invest in bio-energy feedstock production for the long term.

There are four main government departments which have a key role in the UK bio-energy agenda; these are DECC, Defra, BIS and DfT. Other departments which are also involved include DFID/FCO and HM Treasury. There is a lack of co-ordination between departments with regards bio-energy activity. For example, currently the roles of key dedicated biomass crops in the UK energy strategy, willow and miscanthus and also of UK forestry and wastes from other agricultural crops for bio-fuel and biopower production are unclear. According to the DECC Renewables National Action Plan (see above) over 50% of the renewable target is to be achieved by bio-energy which a number of studies indicated that the heat and electricity component could be provided by domestically produced biomass without impacting on food production (e.g. TSEC). However Defra have discontinued sustained funding for the willow and miscanthus breeding programmes that are necessary to provide the essential improvements in these crops to realise the domestic potential. This is inconsistent with having a coherent and supported strategy for renewable energy.

There is the need for a single long term vision (beyond 2020), more co-ordination between departments and ownership of the bio-energy strategic vision by a single department. This will result in the development of better links between high level intentions, policy framework and implementation planning - particularly with regards the role of advanced bio-fuels. At present work streams are fragmented and the regulatory framework to support bio-energy projects complex (Taylor, 2008)⁵⁵. The limited strategic material that has been produced is either vague with a lack of assignment of responsibility and milestones (Biomass Strategy, 2007) and/or lacks clear implementation planning to back up well intended milestones (UKERC, 2007). This is in stark contrast to the US and Brazilian bio-energy planning, framework and implementation systems (e.g. US DOE, 2010a)⁵⁶.

With UK policy thinking now becoming increasingly aware of the strategic importance of biomass in the attainment of the UK 2050 energy and emission targets (e.g. DECC Pathways, 2010a). There is a very real possibility that the lack of coherence between the components of UK bio-energy will result in a missed opportunity to develop and deploy a robust and internationally competitive UK bio-energy sector. Though it is not ERP's suggestion that the UK should mimic the US and Brazilian bio-energy programmes exactly, as there are substantial differences between the UK / European sector compared to those of the US and Brazil, but there are lessons that can be learnt. It is recommended that DECC take the lead in framing policy and research to inform policy.

There was a strong feeling amongst interviewees that there was a lack of specialist bio-energy expertise in government departments was inhibiting coherent and realistic bio-energy policy development. Additional comments included the fact that too much dependence on bio-energy issues is being placed on consultancies. It is recommended that government expertise in bio-energy be enhanced to ensure that policies are designed and resourced appropriately. This could be achieved by either resourcing externally or working with appropriate external bodies. These include the National Non Food Crop Centre (NNFCC)⁵⁷, National Farmers Union (NFU), Home Grown Cereal Association (HGCA), Forestry Commission (FC), The Waste Management Association and Renewable Energy Agency (REA) etc. These should also be engaged during bio-energy related policy formulation, whether integral to or on a consultation basis, as they will understand impact of proposed policy on respective feedstock streams.

⁵⁵ More than 17 different schemes were identified in the Biomass Task Force (2005).

⁵⁶ The US Biomass Multi-Year programme (2010) has a clear vision, mission, strategic goal and performance goals and responsibility for implementation lies with the Office of the Biomass Programme within the US Department of Energy. It strategically coordinates all aspects of biomass and bio-energy technologies research in detail including the allocation of responsibility to specific research institutions.

⁵⁷ National Centre for Renewable Fuels, Materials and Technologies which assists in the introduction of renewable fuels and materials into the marketplace and the provision of independent information and advice to agriculture, academia, Government, industry, the media and the public.



There is a need for better co-ordination, with some consolidation, of support along the bio-energy innovation chain. The complexity and prolific number of bio-energy chains, many of which are interconnected with R&D in one part potentially having an impact on multiple aspects such as economics, GHG reduction, sustainability and ease of processing and conversion (see section 4.3.3 on getting more from feedstocks), makes the need for co-ordination through the entire innovation chain important in order to realise potential bio-energy technologies to market.

Bio-energy research needs to be coordinated across the Research Councils. Five of the seven research councils (BBSRC, NERC, EPSRC, STFC and ESRC) are involved in bio-energy technology related work. This has recently been realised with Research Councils having formed the RCUK Cross Council Bio-energy Strategic Coordination Group. Membership is drawn from BBSRC, EPSRC, NERC, ESRC, STFC and TSB. An aim of the group is to form links with relevant government Departments such that they can inform and be informed by the development of policy.

Impact of loss of the Regional Development Authorities. Established in 1998, the Regional Development Authorities will be abolished by March 2012 but the extent of budget cuts will mean that they ceased to be effective in March 2011. They supported regional R&D through grants, capital (for state aid exempted projects - partnering with the TSB and EU programmes) and networking capacity. With their abolition, the capacity for energy related R&D funding and development of biomass supply chains best suited to local needs and resources as designated in the Biomass Strategy (2007) has been lost. The importance of this capacity for the economic realisation of bio-energy value chains was outlined in section 5.4.2. Whether the Local Enterprise Partnerships will be able to fill the gap or the mandates of the Carbon Trust and / or Technology Strategy Board will be extended to cover these roles is, at present, unclear.

R&D to be strengthened and more strongly focussed on market need. The Research Councils produce world class research of high academic value which needs to be prioritised to the needs of the bio-energy market. This needs to be addressed at a number of levels:

- Research application impact assessments tend, at present, to be secondary issue relative to scientific criteria. There is a need to give equal weighting to market application for impact assessments in order to assist in the prioritisation of technologies that hold the most promise to lead to commercial technologies. Research proposers should continue to make economic and business cases when formulating their submissions on a programmatic level (RCUK, 2011);
- The focus of research establishments in the UK is on the pursuit of academic excellence rather than the development of applied market orientated work. The balance of this needs to be shifted to the latter;
- Much bio-energy work is multidisciplinary in nature. There is a lack of appreciation of multidisciplinary work at RCs and in the Research Assessment Exercise (RAE) mechanism does not encourage such work. There is a need to value multi-disciplinary work and develop system within RCs to allow better assessment and appreciation of the work (RCUK, 2011). This should be translated into the RAE system; and
- Though the research councils undertake industry collaboration e.g. the LINK programme, Industrial Partnership Award Scheme, TSEC SUPERGEN, BSBE, it is suggested that there is a need for more informal relationships to be developed between individual researchers / departments that the private sector tends to prefer. It is believed that this is being addressed.

6.4 Summary and Recommendations

The review of UK and International bio-energy policy and RDD&D activity has highlighted the following:

- The number of policies that have been launched by developed and emerging economies makes the need for innovation and development in the bio-energy value chain important in order to maximise efficiency and to comply with sustainability requirements.
- It is difficult to acquire information on international bio-energy RDD&D - especially for private sector work.

International Bio-energy Policy and Research Activity: UK Collaboration

It is recommended that the UK should:



- Ensure that it maintains the close ties with US and Brazilian bio-energy programmes but also seek to develop collaboration with areas where biomass has the greatest technical potential for development such as Africa and Asia.
- Maintain close links with the European Energy Research Alliance (EERA) network in order to identify key European institutions.
- And, advocate the linking of the EILs for CCS and European Industrial Bio-energy Initiative (EIBI) and ensure better linking of the work streams for the development of BECCS and negative emissions capacity.

UK Bio-energy Capacity Assessment Recommendations

With regards UK bio-energy capacity the review found the following:

- There is a lack of easy access to a consolidated database of information on UK bio-energy capability.
- Much of the work on bio-energy research is funded by public sector organisations (e.g. Research Councils, Energy Technologies Institute, Technology Strategy Board and The Carbon Trust) which is easily available and a useful proxy of the capacity of research organisations. A regularly updated list of organisations that are carrying out bio-energy work would address co-ordination and collaboration issues.

Areas of UK R&D strength include (after NNFCC, 2011e):

- Fundamental R&D capacity in the development and use of plant biomass resources.
- The development (fundamental research) of micro-organisms for ligno-cellulosic bio-ethanol.
- Biobutanol fundamental and industrial research.
- Syngas upgrading industrial research.
- Industrial pilot and demonstration scale up (such as the Centre for Process Innovation and CoEBio3).
- And, algal technology fundamental research;

The following bio-energy technology specific areas are suggested as areas where the UK should build up on its strengths:

- Both fundamental plant science and applied agronomy of bio-energy crops.
- Micro and Macro-algae - not necessarily purely as a feedstock source of energy but within a larger framework of research of which energy should play a part.
- Bio-energy and Carbon Capture and Storage systems development as a negative emissions technology.
- The development of process conversion technology for liquid 'drop-in' fuels for prioritisation into HD and aviation applications but covering all product categories.
- And, integrated systems for large scale bio-refinery development.

UK Bio-energy Policy

- The ERP supports the REA (2009) recommendation that *'there is a need to develop coherent policy frameworks to provide financial security along the entire bio-energy chain is vital to the development of effective pull thorough for bio-energy innovation, development and deployment in the UK energy system.* Within this framework the following is salient:
 - There is a need for changes in how biomass producers are compensated. Suggestions include the establishment of energy crop contracts that bring forward cash flow payments in line with conventional food crops or the development of insurance schemes.
 - Biomass crop developers also need to be financially rewarded for reducing GHG profiles of feedstock streams.
 - Policy should link GHG savings to the financial rate of return in order to incentivise the attainment of the most sustainable practices rather than the tiered system presently in place, which discourages ongoing development of resource use efficiency and sustainability practices.
 - And, in the longer term a broader suite of sustainability issues should be considered to be linked to financial rate of return (NNFCC, 2011f).



The ERP is aware of the DECC led cross-departmental bio-energy strategy refresh that is seeking to address these issues.

UK Innovation and RDD&D Landscape Recommendations

The key finding from this review is that there is need for a co-ordinated bio-energy strategy, and clear government responsibilities. The following are recommended with regards to the UK policy landscape:

- A single government department should take overall responsibility for bio-energy development in the UK with the other departments working to and the overarching strategy framework. It is recommended that Department for Energy and Climate Change (DECC) should take on this role.
- There is a need for clear understanding of respective of government departments (DECC, Department for Environment and Rural Affairs (Defra), Department for Business, Innovation and Skills (BIS), Department for International Development (DfID) / Foreign and Commonwealth Office (FCO) and HM Treasury) for different aspects of the UK bio-energy value chain.
- A biomass strategy which includes long-term policy driven demand signal (30 to 40 years) should be established. The literature advocates that:
 - Clear targets are set.
 - Assessment of the ability to fulfil bio-energy policy targets by consideration of the needs along the entire bio-energy supply chain within which coherent plans as to how to achieve these targets in terms of resources that should be utilised, sectors (of industry and agriculture) that should be involved and the appropriate technologies linked to the resources and sectors.
 - The development of causal mechanisms between proposed policy and outcomes.
 - The establishment of simple bio-energy grant / support schemes.
 - And, where subsidies are temporary their temporary nature should be explicitly stated as well as how they will be gradually reduced (IEA, 2007b).

Though there is insufficient information available to develop a comprehensive 2050 strategy based on what we know now. There is sufficient information to develop an informed strategy that can be improved with time. Furthermore, there is a body of work that is being presently undertaken which will allow some of the key issues to be addressed over the next 2 - 3 years to inform policy. The establishment of a UK bio-energy projects database would allow the monitoring of this work to better inform strategy development - see below.

The development of a stable strategic framework with long term policy frameworks will do much to establish commercial confidence in the UK bio-energy market to develop products for in the UK. There is a need to reduce the economic risks of investing in the bio-energy sector which can only be supported by government backed financial incentives of the appropriate scale (see below).

- There is a gap in government's understanding of bio-energy issues. Bio-energy specialists are required within government to ensure that policies have the impact that they are designed for. This would also ensure better ownership of the bio-energy agenda by government departments.
- All biomass stakeholders need to be integrated into bio-energy policy formulation (RCUK, 2011).

The following are recommended with regards to the UK RDD&D landscape:

- There is a need for co-ordination of and alignment of biomass research innovation at government departments, along the UK energy innovation chain and at the Research Councils. The establishment of a single cross-departmental body being assigned oversight for the innovation research needs of the bio-energy sector is recommended.

As a matter of priority the department should seek to address the innovation needs for effective bio-energy policy development to fulfil possible trajectories that bio-energy will play in the 2050 UK energy system. The detailed landscaping work being undertaken by The Carbon Trust (CT) and the Energy Technologies institute (ETI) could be able to form a substantial component of this. The establishment of the following would also assist:

- A UK bio-energy capacity database which identifies the key players and strengths that the UK has in bio-energy research, development, demonstration and deployment. SUPERGEN Bio-energy III might be the appropriate organisation to co-ordinate the development of such a platform; and



- A bio-energy projects database of publically funded research being undertaken so as to develop a central repository of information and avoid duplication of work by different departments; the basis for this might be the present UKERC Research Database platform.
- The components of the UK innovation chain (The CT, ETI, The Technology Strategy Board (TSB) and Research Councils (RCUK) are funding world class bio-energy research. However, the landscape is intricate which results in this fragmented funding potentially resulting in reduced effectiveness. The following is also relevant:
 - Though the co-ordination between diverse agencies involved in the UK bio-energy innovation chain is institutionalised the coordination of projects would be enhanced by the development of a long term vision of the role of bio-energy in the UK energy system and an innovation needs assessment.
 - Bio-energy research needs to be coordinated across the Research Councils. This has already started to happen with the formation of the RCUK Cross Council Bio-energy Strategic Coordination Group and the BBSRC Bio-energy Champion has taken the lead in bio-energy issues.
 - The ERP also fully endorses the findings of the RCUK International Review relevant to bio-energy. This is particularly relevant to:
 - The need to give equal weighting to market application, economic and business cases for impact assessments in research proposals.
 - The need to develop a system within RCs to allow better assessment and appreciation of multidisciplinary work.
 - And, the need to overcome complications caused by multiple universities working in parallel on the same field for short periods of funding. The ERP suggests that there should be consideration of the focusing of elements of bio-energy relevant work on key research groups / individuals which / who are funded on a rolling basis for sustained periods of time.
- The ERP supports the RCUK (2011) recommendation that *'The crop breeding programmes and associated germplasm management for miscanthus and willow should be sustainably funded urgently before the teams become disbanded. It is likely that the preferred solution to enhance co-ordination is for these activities to be taken over by RCUK, closely linked to other aspects of plant science, soil chemistry, agriculture and energy production pipelines.'*
- The role filled by the RDAs is covered in order to optimise bio-energy chains best suited to local needs and resources which is fundamental to the economic viability of bio-energy systems.

7 Summary of Conclusions and Recommendations

7.1 Overarching Issues

The ERP Review has sought to *describe the opportunities and challenges to further development of bio-energy technologies in the 2050 energy system in order to identify the role that UK Research, Development, Demonstration and Deployment (RDD&D) should play in the sector.*

The central conclusion from this Review is that:

There is an urgent need for of strategic oversight, policy alignment and coherence of the components involved in the UK bio-energy sector. Without this the UK risks missing the opportunity to optimise the contribution of bio-energy in the energy system for pathways to 2050.

From this Review it can be seen that the key challenges for bio-energy can be categorised along three main areas:

- What is the bio-energy resource?
- How much of this resource can be grown sustainably?
- What is the best use of that bio-energy resource or put another way - what are you trying to achieve with the biomass that you have got?

Within these categories are a multiplicity of research issues that need to be addressed along the bio-energy value chain. Overarching these categories is the issue of the spatial component in the bio-energy value chain and the impact that it has on infrastructure development, scalability, GHG emissions profile and the economics of bio-energy.

The most salient issues relevant to the development of bio-energy in the UK include:

- the sensitivity of the economic viability of bio-energy to transport costs means that any study which does not consider spatial issues and value chain impact will have a limited ability to optimise bio-energy use in the energy system.
- There is considerable work that has / is being undertaken on bio-energy in the UK. However, there is insufficient information available to develop a comprehensive 2050 strategy based on what we know now. For example, there is a need to better understand the impact of soil organic carbon and value chain issues to avoid locking bio-energy into parts of the energy system which may not be economic or sustainable in the long term.
- There is a body of work that is being presently undertaken which will allow some key issues to be addressed over the next few years and in turn allow a strategy to be developed from a more solid evidence base. The establishment of a UK bio-energy projects database, as suggested in the ERP Review, would allow the monitoring of this work to better inform strategy development.

The summaries for each section of the review are collated below.

7.2 Framing Issues and State of the Bio-energy Agenda

The key issues from section 2 were as follows:

Bio-energy is a unique renewable energy resource with complex and highly heterogeneous value chains. The low carbon profile of the conversion of biomass is generally accepted but should not be assumed particularly where the biomass utilised has a long maturation period. Indeed the avoidance of the utilisation of unmanaged high carbon stocked habitats as a source of biomass feedstock is imperative not only to avoid compromising its low carbon credentials but also within the larger sustainability debate.

Globally bio-energy provides about 14 % of global primary energy consumption most of which is for traditional uses (13 %). The bio-energy technologies reviewed in this report represent ~1 % of all primary energy consumption. With regards the role of bio-energy in the UK energy mix, though the consistency of statistical



material is questionable, especially for heat, it represents a substantial proportion (~80%) of all UK renewable energy consumption which stood at 3.2% of total energy consumption in 2009. Of all renewables it also has the potential to grow most rapidly.

The rapid development of bio-energy in the heat and power sector has been as a result of the introduction of incentives to encourage renewables and the availability of biomass as a base load generation source. In the case of bio-fuels for transport and the development of novel techniques has been greatly assisted by the recent revolution in life sciences and industrial biotechnology. This has re-invigorated the potential for advances in bio-energy technology, at all stages of the bio-energy value chain, to be made which could allow bio-energy to make a tangible contribution to the future global energy system. This has resulted in policy makers heavily subsidising the sector. However, extrapolation of present R&D activities is dangerous as the strategic objective will be the production of a renewable fuel which behaves and can be handled in the same way as the fossil fuel that it substitutes in the future energy system of 2050.

The likely sustained high price for fossil fuels, its impact on energy security and the potential for cost reductions to be made in bio-energy make the option of doing nothing untenable. The knowledge and experience to deliver stable policy to supply sustainable feedstocks at scale and support technological learning curves is available as demonstrated by Brazil where sugarcane provides 15% of its energy on 0.4% of its land.

Finally, the realisation of scale and liquid bio-energy markets will need the concurrent establishment of a wide range of factors - ranging from feedstock development, technology development, financial markets and infrastructure development - the complexity of which should not be underestimated.

7.3 Sustainable Bio-energy in the 2050 Energy System

The key issues from section 3 were as follows:

The scenarios reviewed demonstrate multiple development opportunities for bio-energy. However, there is no consensus as to the scale (ranging from 46 to 140 EJ pa), timing or sector of the 2050 energy system that bio-energy will dominate. The reasons for the uncertainties are attributable to a number of factors which include:

- The economics of decentralised CHP systems, which would facilitate high levels of bio-energy penetration, are unattractive due to the established centralised generation systems in the electricity sector and for heat - take-up is limited by the difficulty in modifying the way in which domestic, commercial and industrial properties receive heat services.
- In the case of bio-fuels for transport, the enormous uncertainty lies in the degree of development of PHEV, EV, Fuel Cell and advanced bio-fuels (including 'drop-in' fuels) and their ability to address the needs across all transport modes or only in selected niches as well as the costs involved in modifying the transport fuel infrastructure; and
- Finally, the complexity and uncertainties of costs / performance of bio-energy pathways are extremely difficult to capture and model accurately in whole system cost-optimisation models. The key role that whole system scenario modelling plays in determining the role of energy policy and of energy RDD&D may therefore inadequately represent the role of bio-energy technologies.

With the extent of the role of bio-energy subject to such uncertainty, designing the appropriate policy incentives is highly problematic. Furthermore, it is worth emphasising that the need for globally compatible transport systems suggests that international co-ordination be undertaken in order that the most efficient evolution of transport technology be realised.

7.4 Biomass Feedstock Production and Areas of Research

The key issues from section 4 were as follows:

The estimates for global economically exploitable biomass potential for 2050 range from <50 to > 1,000 EJ pa. The highly uncertain nature of the projections is attributable to the substantial variations with regards to the input variables for scenario development and boundary conditions for feedstock studies.

- Harmonisation of methodologies and boundary conditions for biomass projections is a recognised priority and work is being undertaken in this area.



- The biomass projection dataset is also characterised by the lack of data at the appropriate resolution to derive reliable cost curves and the lack of integration of environmental and social issues. This would be addressed by the development of a database of project, country and regional case studies which when considering the economics of biomass also assessed opportunity costs, externalities and co-benefits of feedstock sources.
- With regards to dedicated energy crop feedstock streams, the potential impact of an expanding bio-energy sector and its interaction with other land uses, such as food production, biodiversity, soil and nature conservation, social issues, and carbon sequestration needs to be better understood. This may be facilitated by:
 - improving the accuracy of land datasets;
 - better projections of the availability of surplus land due to agricultural improvements; and
 - the need for the development of a database of regionally specific yields of different feedstocks from large field trials on both primary and marginal lands.
- In the case of other feedstock streams the complexities involved in projecting farming practices (for residues), livestock development (for manure / dung), interaction with a number of other markets (for forest feedstocks) and patterns of waste development will mean uncertainties are likely to remain in biomass projections for the foreseeable future.

The extent to which the sustainability debate has been applied to biomass for bio-energy has made it difficult to reconcile the ability to develop biomass to commercial scale and to design a sensible policy framework. Recognition of the relevance of sustainability issues beyond biomass for bio-energy but also across the whole of biomass streams, *i.e.* for food, feed and fibre as well, has improved the balance of the debate. However, though there are specific research needs salient to individual bio-energy sustainability issues the underlying need is for:

- The development of consistent methodological procedures for each sustainability issue to facilitate comparable accounting and monitoring procedures. This should result in assessments of feedstock production techniques which optimise environmental, social and economic value (The Royal Society, 2008). The culmination of this might be the development of a sustainability index for sustainability issues.
- Establishment of international collaborative networks for methodological frameworks and data collection in order to realise a more efficient use of **presently** cultivated land - without any further land use expansion (thereby preserving SOC and bio-diversity / eco-system services).
- the large scale development of biomass in degraded / marginal lands. Agricultural extension services can then be used to disseminate and adapt best practice to different regions.
- the realisation that the role of policy across the considerable number of drivers of LUC is relevant and integral to the minimisation of LUC to ensure that all forms of biomass development for food, feed, fibre and energy are produced in a sustainable manner.
- And, the UK to be engaged at an international level in this area. This is paramount in order to ensure the international development in energy biomass is both sustainable and scalable. It will also allow the monitoring of the impact of UK bio-energy targets on global sustainability issues.

There is potential to enhance presently used feedstocks to improve their economics and sustainability profiles, and develop dedicated energy crops. The UK has substantial capacity in plant science research with which to develop feedstocks. Key recommendations to develop this area is the need to better integrate feedstock improvement within a whole systems framework in bio-energy value chains and the utilise international development frameworks to close the yield gap in less developed nations.

Limited effort has been dedicated to increasing yields for future ligno-cellulosic energy crops therefore substantial uncertainty remains in terms of their potential economic and sustainability credentials. There is a need to have large scale field trials across the world. The following issues are relevant to the research in this feedstock:

- there is a need for consensus as to where to focus the work;
- it is essential that the UK maintains its present plant science capacity and that it seeks to collaborate with other international leaders in this field; and

- it is inhibited by the EU stance on GM crops which is where many believe the biggest novel opportunities lie. It is recommended that the UK stance on GM crops be re-assessed though it is recognised that this will require significant public engagement.

New oil crops are also being researched specifically as a bio-diesel substitute. There is limited work being undertaken in the UK for these crops though strength in plants sciences could be applied to the feedstock.

The substantial global technical potential for both micro and especially macro algae makes this a potentially rewarding area of feedstock research. In the case of micro algae, the majority of work is US centric and the US has heavily invested in this sector. With regards algae generally, so extensive are the research questions, so broad is the extent of work and approaches being undertaken, the fragmented nature of the programmes makes the potential for the attainment of commercial costs and scale in the near term extremely unlikely. There may, however, be spin off benefits for the bio-energy sector by studying algae within a broader research framework.

The use of ligno-cellulosic and waste streams as a potential realisable feedstock stream for bio-energy are attractive due to the following:

- its substantial potential ranging from 50 to 270 EJ pa, globally;
- the co-benefit of reducing the waste footprint; and
- that it is, at present, a relatively cheap feedstock.

Hindrance of the development of this stream lies in:

- lack of understanding of the availability and economics of collection of the feedstock streams - particularly in developing countries where potential is greatest and material flows are poorly understood;
- lack of knowledge of the indirect effects on other markets;
- for waste plants there is a public acceptance issue; and
- multiple conversion technology routes which makes pre-treatment and categorisation difficult.

Despite the uncertainties in biomass availability it is clear that the quantities of sustainably produced feedstock that is / will be available are material to the development of a bio-energy sector that will make a significant contribution to the future energy system. Information across a range of feedstock issues needs to be developed so as to allow better analysis of the interactions of biomass production for bio-energy with food production, biodiversity, soil and nature conservation, soil issues and carbon sequestration. This would assist in the better addressing of sustainability issues across all biomass production - for food, feed, fibre and energy. It would also allow more rational choices to be made as to how we allocate and use land for multiple objectives.

7.5 Bio-energy Logistics, Process Conversion Technologies and End Uses: Research, Development, Demonstration and Deployment

The key issues from section 5 were as follows:

Bio-energy Logistics and International Trade

Logistics, i.e. getting feedstock from field to process conversion plant, is area which is largely under researched. There is substantial variation in harvesting, transport and storage systems and their state of development depending upon the type of biomass being cultivated. It is recommended that there is a need for standards and specifications for each feedstock type in order to develop optimum harvesting systems.

There is a need for the development of a database of feedstock type and behaviour when under storage and assessment of any impact on downstream process conversion efficiencies. The instrumentation to measure these metrics effectively also needs to be developed.

International trade in biomass is at present small scale though there is substantial potential for development subject to the establishment of a dedicated supply chain, removal of tariff barriers, unification of sustainability criteria and clarification of WTO rules on bio-energy.

On the understanding that the UK will develop a scalable domestic biomass capability, the UK should seek to develop its own capacity in harvest, transport and densification technologies for bio-energy crops as these are



fundamental to making bio-energy production economic. Where appropriate, collaboration with other R&D programmes should be undertaken and assistance provided in the development of international standards.

Bio-energy Conversion Technologies

Biomass to heat applications including direct combustion and small scale gasification which are at commercial and pre-commercial stages of development, respectively - though the economic case for these technologies is often dependent on the relative cost of the reference fuel. There are limited technical issues with regards biomass to heat applications though the economic proposition is a significant barrier. In the UK the low development in the sector lies in the limited access to heat sinks, though this may be remedied in the long term by the establishment of buildings standards which encourage local heating networks.

Biomass to power and combined heat and power (CHP) applications include a wide range of feedstock and conversion technology combinations that are in various stages of development; these include: biomass power plants (dedicated, co-fired and repowered coal plant), waste to energy plants, biomass co-generation (CHP) plants, distributed cogeneration units (such as Organic Rankine Cycle (ORC) or Stirling Engines), large scale gasification and Anaerobic Digestion. Fundamental to the economics of such systems is not only the capital outlay but also the availability of cost effective and substantial supplies of feedstock and the relative cost of alternative production. There are some technical and scale issues with power and CHP conversion processes.

Transport applications are one of the most strategically attractive uses of biomass due to the lack of alternatives in the this sector. There are a number of issues which need to be considered for the deployment of bio-fuels in this sector including:

- Understanding of the infrastructure requirements of the different forms of bio-fuels including blending, handling, distribution and refinery modifications;
- impact of non 'drop-in' bio-fuels on compatibility with present vehicle fleet performance; and
- the role of bio-fuels in marine applications is vastly under researched compared to other transport modes (AEA, 2009a).

The ultimate process conversion technology is one which has flexibility in terms of type and quality of feedstock, operates effectively at a range of scales and is able to produce a 'drop in' fuel negating the need for modification to future power trains or fuel infrastructure. The fragmented and proprietary nature of the work being undertaken in transport bio-fuels process conversion makes it extremely difficult to assess the state of different technology routes.

With regards end uses for transport fuels, the blending limits and handling properties of different non 'drop in' fuels bio-fuels vary considerably as do the energy densities of all biomass derived fuels. Outside of the main fuels there are a number novel routes such as Furanics, Isoprenoids, Iso-butanol etc which tend to have only one private developer working on specific conversion routes with only one feedstock and product being investigated.

The international nature of transport issues makes the need for the UK to be engaged in international collaborative forums to be of paramount importance to ensure that liquid bio-energy fuel developments conform to internationally developing market consensus.

Whole System and Cross-cutting Issues

The following recommendations have been made regarding the following cross-cutting issues:

- There is a need to ensure transparency and harmonise LCA work internationally in order to ensure that bio-energy chains are providing the sustainability benefits that they claim. All new bio-energy supply chains need to be undertaken within an established best practice framework.
- The sensitivity of the economic viability of bio-energy to transport costs means that any study must consider spatial issues and value chain impact to optimise bio-energy use. The importance of the value chain impact on the economics and sustainability of value bio-energy is under researched.
- The bio-refineries concept is emerging out of the realisation maximum conversion of biomass feedstock components is required for the economics of process technologies to be optimised. However, additional



effort will be needed to optimise the feedstock, process and product combination, and to address techno-economic and environmental questions for the biorefinery as a whole.

- A future strategically important use of biomass may be in negative emissions process technologies such as bio-energy and carbon capture and storage (BECCS) and biochar. Some modelling projections suggest that the UK's carbon reduction target of 80% by 2050 cannot be achieved economically without them. There is a need to assess these technologies in the light of the continued increase in global emission trajectories and, should they be needed, to develop the appropriate policy framework to encourage their development and scale up.
- The significance of the potential role of genetic engineering and synthetic biology in bio-energy technological development is highlighted along the entire bio-energy value chain; the importance of public opinion must be recognised.
- Finally, the best use of biomass need not be reconciled before the development of a strategic policy framework - enough is known in order to develop sound and sustainable policy which may be augmented as future research is undertaken. Coherent and consistent metrics / methodology for reporting would assist in facilitating direct comparison between different value chains.

7.6 UK and International Bio-energy Policy, Research Activity and Innovation Landscape

In section 6, the review of UK and International bio-energy policy and RDD&D activity has highlighted the following:

- The number of policies that have been launched by developed and emerging economies makes the need for innovation and development in the bio-energy value chain important in order to maximise efficiency and to comply with sustainability requirements.
- It is difficult to acquire information on international bio-energy RDD&D - especially for private sector work.

International Bio-energy Policy and Research Activity: UK Collaboration

It is recommended that the UK should:

- Ensure that it maintains the close ties with US and Brazilian bio-energy programmes but also seek to develop collaboration with areas where biomass has the greatest technical potential for development such as Africa and Asia.
- Maintain close links with the European Energy Research Alliance (EERA) network in order to identify key European institutions.
- And, advocate the linking of the EIs for CCS and European Industrial Bio-energy Initiative (EIBI) and ensure better linking of the work streams for the development of BECCS and negative emissions capacity.

UK Bio-energy Capacity Assessment Recommendations

With regards UK bio-energy capacity the review found the following:

- There is a lack of easy access to a consolidated database of information on UK bio-energy capability.
- Much of the work on bio-energy research is funded by public sector organisations (e.g. Research Councils, Energy Technologies Institute, Technology Strategy Board and The Carbon Trust) which is easily available and a useful proxy of the capacity of research organisations. A regularly updated list of organisations that are carrying out bio-energy work would address co-ordination and collaboration issues.

Areas of UK R&D strength include (after NNFFC, 2011e):

- Fundamental R&D capacity in the development and use of plant biomass resources.
- The development (fundamental research) of micro-organisms for ligno-cellulosic bio-ethanol.
- Biobutanol fundamental and industrial research.
- Syngas upgrading industrial research.
- Industrial pilot and demonstration scale up (such as the Centre for Process Innovation and CoEBio3).
- And, algal technology fundamental research.



The following bio-energy technology specific areas are suggested as areas where the UK should build up on its strengths:

- Both fundamental plant science and applied agronomy of bio-energy crops.
- Micro and Macro-algae - not necessarily purely as a feedstock source of energy but within a larger framework of research of which energy should play a part.
- Bio-energy and Carbon Capture and Storage systems development as a negative emissions technology.
- The development of process conversion technology for liquid 'drop-in' fuels for prioritisation into HD and aviation applications but covering all product categories.
- And, integrated systems for large scale bio-refinery development.

UK Bio-energy Policy

- The ERP supports the REA (2009) recommendation that *'there is a need to develop coherent policy frameworks to provide financial security along the entire bio-energy chain is vital to the development of effective pull through for bio-energy innovation, development and deployment in the UK energy system.* Within this framework the following is salient:
 - There is a need for changes in how biomass producers are compensated. Suggestions include the establishment of energy crop contracts that bring forward cash flow payments in line with conventional food crops or the development of insurance schemes.
 - Biomass crop developers also need to be financially rewarded for reducing GHG profiles of feedstock streams.
 - Policy should link GHG savings to the financial rate of return in order to incentivise the attainment of the most sustainable practices rather than the tiered system presently in place, which discourages ongoing development of resource use efficiency and sustainability practices.
 - And, in the longer term a broader suite of sustainability issues should be considered to be linked to financial rate of return (NNFCC, 2011f).

The ERP is aware of the DECC led cross-departmental bio-energy strategy refresh that is seeking to address these issues.

UK Innovation and RDD&D Landscape Recommendations

The key finding from this review is that there is need for a co-ordinated bio-energy strategy, and clear government responsibilities. The following are recommended with regards to the UK policy landscape:

- A single government department should take overall responsibility for bio-energy development in the UK with the other departments working to and the overarching strategy framework. It is recommended that Department for Energy and Climate Change (DECC) should take on this role.
- There is a need for clear understanding of respective of government departments (DECC, Department for Environment and Rural Affairs (Defra), Department for Business, Innovation and Skills (BIS), Department for International Development (DfID) / Foreign and Commonwealth Office (FCO) and HM Treasury) for different aspects of the UK bio-energy value chain.
- A biomass strategy which includes long-term policy driven demand signal (30 to 40 years) should be established. The literature advocates that:
 - Clear targets are set.
 - Assessment of the ability to fulfil bio-energy policy targets by consideration of the needs along the entire bio-energy supply chain within which coherent plans as to how to achieve these targets in terms of resources that should be utilised, sectors (of industry and agriculture) that should be involved and the appropriate technologies linked to the resources and sectors.
 - The development of causal mechanisms between proposed policy and outcomes.
 - The establishment of simple bio-energy grant / support schemes.
 - And, where subsidies are temporary their temporary nature should be explicitly stated as well as how they will be gradually reduced (IEA, 2007b).



Though there is insufficient information available to develop a comprehensive 2050 strategy based on what we know now. There is sufficient information to develop an informed strategy that can be improved with time. Furthermore, there is a body of work that is being presently undertaken which will allow some of the key issues to be addressed over the next 2 - 3 years to inform policy. The establishment of a UK bio-energy projects database would allow the monitoring of this work to better inform strategy development - see below.

The development of a stable strategic framework with long term policy frameworks will do much to establish commercial confidence in the UK bio-energy market to develop products for in the UK. There is a need to reduce the economic risks of investing in the bio-energy sector which can only be supported by government backed financial incentives of the appropriate scale (see below).

- There is a gap in government's understanding of bio-energy issues. Bio-energy specialists are required within government to ensure that policies have the impact that they are designed for. This would also ensure better ownership of the bio-energy agenda by government departments.
- All biomass stakeholders need to be integrated into bio-energy policy formulation (RCUK, 2011).

The following are recommended with regards to the UK RDD&D landscape:

- There is a need for co-ordination of and alignment of biomass research innovation at government departments, along the UK energy innovation chain and at the Research Councils. The establishment of a single cross-departmental body being assigned oversight for the innovation research needs of the bio-energy sector is recommended.

As a matter of priority the department should seek to address the innovation needs for effective bio-energy policy development to fulfil possible trajectories that bio-energy will play in the 2050 UK energy system. The detailed landscaping work being undertaken by The Carbon Trust (CT) and the Energy Technologies institute (ETI) could be able to form a substantial component of this. The establishment of the following would also assist:

- A UK bio-energy capacity database which identifies the key players and strengths that the UK has in bio-energy research, development, demonstration and deployment. SUPERGEN Bio-energy III might be the appropriate organisation to co-ordinate the development of such a platform; and
- A bio-energy projects database of publically funded research being undertaken so as to develop a central repository of information and avoid duplication of work by different departments; the basis for this might be the present UKERC Research Database platform.
- The components of the UK innovation chain (The CT, ETI, The Technology Strategy Board (TSB) and Research Councils (RCUK) are funding world class bio-energy research. However, the landscape is intricate which results in this fragmented funding potentially resulting in reduced effectiveness. The following is also relevant:
 - Though the co-ordination between diverse agencies involved in the UK bio-energy innovation chain is institutionalised the coordination of projects would be enhanced by the development of a long term vision of the role of bio-energy in the UK energy system and an innovation needs assessment.
 - Bio-energy research needs to be coordinated across the Research Councils. This has already started to happen with the formation of the RCUK Cross Council Bio-energy Strategic Coordination Group and the BBSRC Bio-energy Champion has taken the lead in bio-energy issues.
 - The ERP also fully endorses the findings of the RCUK International Review relevant to bio-energy. This is particularly relevant to:
 - The need to give equal weighting to market application, economic and business cases for impact assessments in research proposals.
 - The need to develop a system within RCs to allow better assessment and appreciation of multidisciplinary work.
 - And, the need to overcome complications caused by multiple universities working in parallel on the same field for short periods of funding. The ERP suggests that there should be consideration of the focusing of elements of bio-energy relevant work on key research groups / individuals which / who are funded on a rolling basis for sustained periods of time.



- The ERP supports the RCUK (2011) recommendation that *'The crop breeding programmes and associated germplasm management for miscanthus and willow should be sustainably funded urgently before the teams become disbanded. It is likely that the preferred solution to enhance co-ordination is for these activities to be taken over by RCUK, closely linked to other aspects of plant science, soil chemistry, agriculture and energy production pipelines.'*
- The role filled by the RDAs is covered in order to optimise bio-energy chains best suited to local needs and resources which is fundamental to the economic viability of bio-energy systems.

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