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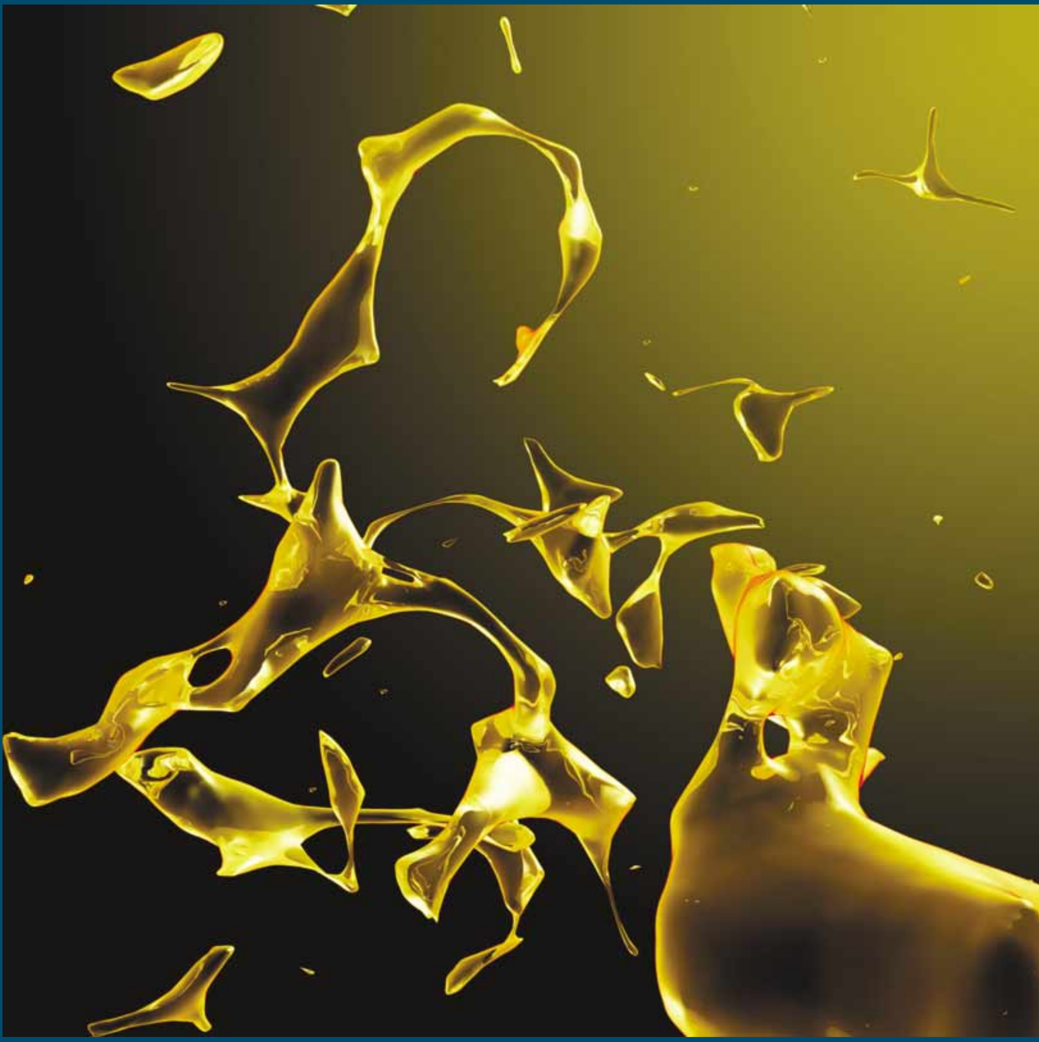
Sustainable biofuels: prospects and challenges



Policy document 01/08

January 2008

ISBN 978 0 85403 662 2

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Typeset by The Clyvedon Press Ltd, Cardiff, UK

Sustainable biofuels: prospects and challenges

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Summary

Sustainable biofuels, prospects and challenges

Our climate is changing and there is now scientific, social and political recognition that this is very likely a consequence of increasing anthropogenic greenhouse gas (GHG) emissions. Transport now accounts for about 20% of global anthropogenic carbon dioxide emissions and 25% of emissions in the United Kingdom (UK), and these figures are growing faster than for any other sector. If the UK is to reach its target of reducing emissions by 60% by 2050 then cuts will need to be made in the transport sector.

However, access to energy underpins our current way of life and the hopes of peoples around the world for improved lives. Mobility is a core component of these aspirations. Transport has become the main driver for increasing global primary oil demand, which is predicted to grow by 1.3% per year up to 2030, reaching 116 million barrels[a] per day (up from 84 million barrels per day in 2005). The transport sector in particular relies almost entirely on oil, which is predicted to become increasingly scarce and costly in the next few decades and supplies of which are vulnerable to interruption.

Biofuels – fuels derived from plant materials – have the potential to address these two issues. At first sight they appear to be carbon-neutral (the carbon they emit to the atmosphere when burned is offset by the carbon that plants absorb from the atmosphere while growing), renewable (fresh supplies can be grown as needed) and capable of being cultivated in many different environments. In addition they are an integral part of the emerging 'bio-economy', where plant material is used to produce specific chemicals and bulk industrial chemicals. In the future these may increasingly replace chemicals derived from fossil oil. The full picture, however, is much more complex as different biofuels have widely differing environmental, social and economic impacts.

Biofuels are already entering the market, driven amongst other things by their potential to improve energy security and to contribute to climate change mitigation. While in certain conditions the best use of the plant material – biomass – is to burn it to produce heat and electricity, biofuels are one of the few technologies currently available that have the potential to displace oil and provide benefit to the transport system. There are real opportunities to develop efficient biofuel supply chains that can deliver substantial greenhouse gas savings. Biofuels on their own cannot deliver a sustainable transport system and must be developed as part of an integrated package of measures, which promotes other low carbon options and energy efficiency, as well as moderating the demand and need for transport. Given that biofuels are already in the market, however, it is vital that policies that promote biofuel development also address the environmental, economic and social impacts, so that they are made to perform their task effectively. Our conclusion that biofuels are potentially an important part of the future is therefore tempered with the following caveats:

- First, the term 'biofuel' covers a wide variety of products with many different characteristics and a wide range of potential savings in terms of greenhouse gas emissions: each biofuel must be assessed on its own merits.
- Second, each assessment must address the environmental and economic aspects of the complete cycle – growth of the plant, transport to the refinery, the refining process itself (including potential by-products such as specialty chemicals), wastes produced, distribution of the resultant fuel to consumers, end use, and potential for pollution. Such assessments would help to determine the extent to which different biofuels are carbon neutral.
- Third, widespread deployment of biofuels will have major implications for land use, with associated environmental, social and economic impacts that must in turn be assessed. Here, in particular, unintended consequences may reduce or override the expected benefits.
- Fourth, the assessments must address the global and regional impacts, not just local ones.

A coherent biofuels policy must address and balance all these factors if biofuels are to make a sustainable contribution to reducing climate change and improving energy security.

Our study draws attention to the above caveats but does not go into detailed analysis. Nevertheless it is vital that other studies fully assess these issues because such information will give a more complete picture of the extent to which biofuels are sustainable. We have focused in this report primarily on the research and development that would be needed to improve the efficiency of biofuels. Our analysis suggests that there is considerable potential to improve the performance of biofuels. This requires applying incentives for low carbon biofuels and will also accelerate the development of a range of technologies across the biofuel supply chain to ensure that more efficient technologies are brought into the market.

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[a] One barrel = 163.6 litres

Feedstocks and conversion processes

Biofuels are currently produced from the products of conventional food crops such as the starch, sugar and oil feedstocks from crops that include wheat, maize, sugar cane, palm oil and oilseed rape. Any major switch to biofuels from such crops would create a direct competition with their use for food and animal feed, and in some parts of the world we are already seeing the economic consequences of such competition.

Future biofuels are likely to be produced from a much broader range of feedstocks including the lignocellulose in dedicated energy crops, such as perennial grasses, and from forestry, the co-products from food production, and domestic vegetable waste. Advances in the conversion processes will almost certainly improve the efficiency and reduce the environmental impact of producing biofuels, from both existing food crops and from lignocellulose sources. A significant advantage of developing and using dedicated crops and trees for biofuels is that the plants can be bred for purpose. This could involve development of higher carbon to nitrogen ratios, higher yields of biomass or oil, cell wall lignocellulose characteristics that make the feedstock more amenable for processing, reduced environmental impacts and traits enabling the plant species to be cultivated on marginal land of low agricultural or biodiversity value, or abandoned land no longer suitable for quality food production. Several technologies are available to improve these traits, including traditional plant breeding, genomic approaches to screening natural variation and the use of genetic modification to produce transgenic plants. Research may also open up new sources of feedstocks from, for example, novel non-food oil crops, the use of organisms taken from the marine environment, or the direct production of hydrocarbons from plants or microbial systems.

The key goal for these future biofuels must be the generation of substantially better results in terms of net greenhouse gas emissions. Additional sustainability metrics need to be agreed to guide developments in the supply chain, including energy efficiency, amount of fossil energy used, cost per unit of energy and environmental impacts such as local air and water pollution.

Land use and environmental impacts

The selection of land on which to grow the feedstocks is a critical component of the ability of biofuels to deliver sustainable solutions. Several competing factors have to be balanced. For example, changes in land use, such as clearing tropical forests or using peatlands for cultivation of crops, risk releasing enough greenhouse gases to negate any of the intended future climate benefits, as well as having major impacts on conservation of biodiverse habitats. Switching already cultivated land to producing biofuel feedstocks could create shortages in the previously grown crops. Planting uncultivated land could put pressure on such purposes as conservation of biodiversity, and amenity use. Developments in the agricultural sector for food and non-food crops will have important implications for water usage and availability. The input of artificial fertiliser to increase yield must be carefully regulated or reduced to prevent emissions of nitrous oxide, a potent greenhouse gas, either directly from the area of application or from drainage waters downstream. Such opportunity costs and side effects have to be fully factored into any decision to assign land to biofuel feedstocks.

The UK has 24.25 million hectares[b] (Mha) of land, of which 6 Mha is arable and 2.4 Mha forest. The amount of land the UK would need to be self-sufficient in biofuel feedstocks depends on, among other considerations, the mix of biofuels, the refining process, the proportion of the feedstock used to produce speciality chemicals rather than transport fuels and, of course, the proportion of total transport fuel intended to be met by biofuels (the EU has set a target of 10% by 2020). However, the UK will be very unlikely to achieve significant levels of fuel security by growing biofuels on its own land: there will always be a requirement to import products from crops and residues cultivated elsewhere in the world. It is therefore important to ensure that assessments of opportunity costs and side effects are also applied to such imported products.

Sustainability

In this report, we highlight the complexity of the biofuels issue and the sheer diversity of options already available. Whatever the mix of policy objectives, any particular biofuel option will only provide a useful element of the solution if it is economically, socially and environmentally sustainable. It is therefore a matter of priority to establish the frameworks and methodologies to create a robust evidence base to inform sustainability analyses and policy development. This will need effort in acquiring the data for comprehensive life-cycle analyses of both the biological and non-biological aspects of the complete fuel supply chains.

The sustainability requirement needs to be approached at the international level, partly because it is, ultimately, a global problem and partly because international trade in these commodities is likely to expand in coming years. It is essential to establish a common and accepted set of sustainability criteria by which to assess not only the different biofuels, but also the different feedstocks,

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[b] One hectare = 10^4 m^2

including food and non-food, and their production systems. This process is likely to involve extensive international collaboration to ensure comparability of results, and a high degree of transparency and stakeholder engagement to maximise public acceptability.

Research needs – are we there yet?

For biofuels to deliver a realistic substitute for conventional fuels *and* meet sustainability criteria there must be substantial improvements in efficiency throughout the supply chain linking feedstocks to their final uses. A major research and development effort is needed in both public and private sectors. Key objectives include:

- increased yield per hectare of feedstock while reducing negative environmental impacts;
- development of new feedstocks that can, for example, be grown in more hostile environments, be more readily processed and be capable of generating a variety of products;
- improved methods of processing, in particular for lignocellulose feedstocks;
- new physicochemical systems for biofuel synthesis;
- development and demonstration of integrated biorefineries;
- integration of the supply chain to gain the maximum efficiencies;
- integration of biofuel development with engine development;
- internationally agreed methods of assessing sustainability.

These multiple but linked aims will require considerable effort and investment, particularly to achieve global policy objectives. The research and development must be multi-disciplinary, drawing in a broad range of expertise from, for example, lifecycle analyses to fast-track plant breeding, socio-economics and systems biology to chemical engineering, biotechnology to engine design and classical chemistry. Although the UK cannot afford to invest in every potential opportunity, there are areas where UK science can make a significant contribution, including research, development and demonstration of biofuel crops, feedstocks, processing techniques and end products – particularly those relevant to the UK, parts of the EU and developing countries; understanding and quantification of soil N_2O emissions for biofuel production; calculating more accurate land use figures and biofuel supply potential. These areas should be stimulated to achieve the most effective demonstration of sustainable biofuels. Incentives to take the outcomes from research and development through to demonstration and deployment are essential. However much of the research and development is very fragmented and lacks coordination. In addition, there are research groups throughout the supply chain that are working on related areas, which are not yet focused on biofuels. There is an urgent need to bring greater coherence across both public and private sector funders and the research community.

Policy needs

Biofuels have the potential to be a useful element of the overall approach to the issues of climate change and energy supply. However, policy frameworks, such as the European Directive on biofuels (5% of transport fuel supply from biofuels by 2010 and 10% by 2020) and subsidies for biofuels focus only on supply targets. As a result important opportunities to deliver greenhouse gas emission reductions are being missed, as there is no direct incentive to invest in systems that would actually deliver low greenhouse gas biofuels and wider environmental, social and economic benefits.

While improvements can be made in the environmental performance of the existing supply of biofuels, many of the technologies and production systems are at early stages of conception and development. These technologies are building on the immense progress that is occurring in the fundamental understanding of biological, thermal and chemical systems. This new knowledge can support an extraordinarily wide diversity of opportunities and pathways for the efficient and environmentally beneficial exploitation of plant products for biofuels.

This diversity of options prevents a simple focus on a narrow set of production and conversion pathways, so each of the options should be assessed individually for the relative benefits they provide. A carbon reporting and sustainability certification scheme such as that being developed as part of the UK's Renewable Transport Fuel Obligation could go some way towards providing an overall process and metrics to compare such options.

However biofuels have a limited ability to replace fossil fuels and should not be regarded as a 'silver bullet' to deal with transport emissions. Progress towards a sustainable solution for transport and the demand for mobility requires an integrated approach, which combines biofuels with other developments, including vehicle and engine design, the development of hybrid and fuel cell vehicles and supporting infrastructure, public transport, better urban and rural planning to address the increasing demand for transport as well as more specific policies to reduce demand and encourage behavioural change.

Should the UK wish to successfully develop a strong and stable biofuels industry, then there is an urgent need for further formulation and application of government policies that promote the commercialisation of biofuels and stimulate the development of new technologies that are efficient and environmentally beneficial. In particular, industry needs clear and coherent policy signals that provide a long-term, favourable framework for development. An obvious step forward would be to extend the Renewable Fuels Transport Obligation or the fuel duty allowance to 2025, to extend carbon pricing to transport fuels and to bring forward the early development of an agreed and consistent set of metrics that indicate the properties of 'efficient' biofuels supply chains. Currently, there is a lack of policy integration between the various government departments involved, directly or indirectly, with biofuels in the UK. Without such integration, there is considerable potential for the creation of conflicting policies that cause confusion and uncertainty in commercial decision-making that seriously hampers commercial development. More integrated analysis is required within government to predict the consequences of diverse policy formulation.

Public attitudes and the actions of stakeholders can play a crucial role in realising the potential of technological advances. Biofuels raise several concerns and opportunities that require an informed discussion, based both on the scientific case and an understanding of public and stakeholder views. It is important therefore to foster a process of iterative dialogue with the public and interested sections of society to help frame, identify and think through the issues.

A coherent approach to policy will:

- avoid the unintended consequence of solving one problem at the expense of exacerbating another;
- see biofuels as part of a portfolio of approaches that also includes, for example, greater energy efficiency, electric vehicles, hydrogen and fuel cells, and price and tax incentives such as carbon pricing based on avoided greenhouse gas emissions;
- balance growth of feedstock supply against other existing and potential uses of land;
- deploy an assessment of sustainability that encompasses the complete cycle from growth of the raw material to end use irrespective of where each stage in the cycle takes place;
- commit to adequate public and private investment in the required research and development (R&D);
- provide aptly targeted regulatory and fiscal incentives;
- develop a process for effective public engagement on biofuel issues.

We have not attempted a systematic assessment of the UK's competitive position in the production and exploitation of biofuels. However, it is clear that the UK must commit wholeheartedly to the approach outlined above if it is to be among the global leaders in future.

1 Introduction

There is clear scientific evidence that emissions of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), arising from fossil fuel combustion and land-use change as a result of human activities, are perturbing the Earth's climate (IPCC 2007a). The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report highlighted that the world's growing population and per capita energy demand are leading to the rapid increase in greenhouse gas (GHG) emissions. Over the past ten years, transport has shown the highest rates of growth in GHG emissions in any sector. By 2030, energy use and carbon emissions from transport are predicted to be 80% higher than current levels (IPCC 2007b).

The world's primary source of energy for the transport sector is oil. World demand is approximately 84 million barrels a day[c] (mb/d) and is projected to increase to about 116 million barrels a day by 2030[d], with transport accounting for some 60% of this rising demand (IEA 2007). While the transport sector continues to expand in the US and Europe, growth in the emerging economies of India and China is predicted to be substantially greater, growing by at least 3% per year (IEA 2006).

Against this background of rising demand, issues of supply are coming to the fore. The availability of conventional oil is once again becoming geographically restricted. As a result of both supply and demand constraints, and with the growing dependence of world supplies on OPEC (Organization of the Petroleum Exporting Countries) and other producers such as Russia, the world may have entered a new era of sustained high oil prices. In turn, this is leading to extraction from unconventional sources including oil from oil shale and tar sands, both of which are very carbon intensive, as well as a renewed interest in producing synthetic fuels for example from coal and gas, again highly carbon intensive (IEA 2006).

Several alternative options are already in development to reduce the dependence on oil and simultaneously reduce GHG emissions from transport. It is becoming recognised that there will be no single solution to these problems and that combined action will be needed, including changes in behaviour, changes in vehicle technologies, expansion of public transport and introduction of new fuels and technologies. Even the development and widespread use of full hybrid vehicles by 2030 will only reduce world demand for transport fuel by 10%, leaving it about 40% higher than today (IEA 2006).

Biofuels and the energy sector are one component of the newly emerging knowledge-based bio-economy. Society is only now beginning to recognise the opportunities offered by such a bio-economy and is starting to develop the technologies required. It is increasingly recognised globally that plant-based raw materials will eventually replace fossil reserves as feedstocks for industrial production addressing both the energy and non-energy sectors including chemicals and materials (EC 2004). An integrated approach, that recognises and supports the variety of uses of plant material, is necessary to realise the full range of potential benefits to society.

Part of the excitement about biofuels stems from the fact that they appear at first sight to be carbon-neutral (the carbon they emit to the atmosphere when burned is offset by the carbon that the plants absorb from the atmosphere when growing), renewable (fresh supplies can be re-grown), and that plants can be cultivated in many different environments. The truth, of course, is more complex; one biofuel is not the same as another and each must be considered on its own merits and against sustainability criteria. Indeed, one of the main messages of our analysis is that each biofuel must be assessed individually. This assessment should include a generic set of parameters such as GHG and energy balances as well as wider environmental, socio-economic, political and regulatory issues. These studies are relevant wherever feedstocks for biofuels are produced, whether within the UK or elsewhere globally. Thus our conclusion that biofuels are potentially an important part of the future is tempered with many caveats.

1.1 Wider context

At the national, regional and global levels there are three main drivers for the development of bioenergy and biofuels. These are climate change, energy security and rural development. The political motivation to support biofuels arises from each individual driver or combinations. Policies designed to target one driver can be detrimental to another. For example, policies aimed at ensuring energy security may result in increased GHG emissions where local coal reserves are preferentially exploited at the expense of imported oil or gas. In the context of biofuels, most of the energy used to process biofuels in the US comes from fossil fuels, with coal mainly being used to provide either electricity and/or heat to the conversion plant (Worldwatch Institute 2006). At the local or end user level, similar conflicts may exist

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[c] This approximates to about 11.4 million tonnes of oil per day, where 1 barrel = 0.136 tonnes

[d] Of this aviation contributes a little over 9 million barrels per day (IEA 2006)

between motivations to purchase biofuels, for example, usability, reliability, cost and environment.

This diversity of drivers and potential energy supplies is also reflected in the range of sectors affected by bioenergy and biofuel provision. For example, provision of feedstocks could be the responsibility of three quite distinct sectors – agriculture, forestry and waste disposal – each of which are governed by separate policies, environmental regulations and government departments. As the supply chain develops, an expanding range of obstacles can emerge, from planning of storage and processing facilities for the feedstocks, to transport constraints, and air and water quality issues. Potential problem areas also extend to infrastructure for fuel distribution, availability of appropriate vehicle technologies, appropriateness of fuel standards as well as wider issues of public acceptability and landscape quality. Thus, at the local through to the global level, attempts to promote biofuels from a single perspective are fraught with difficulty, and there are numerous barriers to implementation.

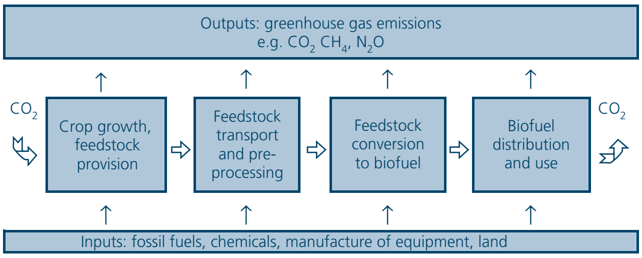
1.1.1 Climate change

Delivering biofuels that contribute to a meaningful reduction in GHG emissions requires the development (*inter alia*) of highly efficient and integrated supply systems. Existing examples of biofuels programmes around the world starkly illustrate the wide range of GHG savings that can be realised. For example, ethanol produced under average Brazilian conditions results in reductions in GHG emissions, on a life-cycle assessment (LCA), of some 80% compared with those of standard petrol (Worldwatch Institute 2006). In contrast, US maize-based ethanol struggles to deliver reductions in GHG emissions of 10% (Farrell *et al* 2006). Within the UK it has been projected that reductions in GHG emissions of anywhere between 10% and 80% could be delivered from wheat to ethanol (Woods & Bauen 2003). This variation in savings is because studies make different assumptions about factors that influence GHG emissions, such as management practices, feedstock used (including crop yield), land-use changes, conversion process efficiencies and end use of the fuel. Nevertheless there exist opportunities for selecting a combination of factors across biofuel supply chains that deliver optimum GHG savings.

Current policy frameworks and subsidies for biofuels are not directed towards reducing GHG emissions, but rather provide incentives for national supply targets. As a result, there is no incentive to invest in the systems that would deliver low GHG biofuels.

GHG emissions arise from each stage in the supply chain from feedstock production and transport to conversion, biofuel distribution and end use (see Figure 1.1). This report considers the potential for science and innovation, at each of these stages, which when integrated could lead to entirely novel options for climate change mitigation.

Figure 1.1 Greenhouse gas emissions from production and utilisation of biofuels.



1.1.2 Energy security

Demand for oil is rising, both from developed and developing countries. As highlighted above, this has implications for energy security and on the oil markets. Thus, interest in biofuels is being driven by the need to find alternatives to fuels derived from fossil oil and due to the current era of high oil prices.

Virtually any degree of energy security can be achieved if countries are willing to pay for it. For example, countries with good coal or gas resources, or with good trading links to countries rich in tar sands and oil shale, can produce a range of synthetic fuels that can be used for transport. However, the costs of producing these synthetic fuels are very high and moreover, their life cycle emissions are much more carbon intensive than for conventional oil fuels. Such developments would compromise objectives to mitigate climate change. Whether this trade-off between energy security and climate change mitigation could be avoided by the production of biofuels will depend on how biofuels are produced and on developments right across the supply chain.

1.1.3 Rural development

The perceived need to maintain indigenous food production capacity (food security), even if the food is much more expensive to produce than imports, along with the benefits of environmental services that are derived by land management, for example soil and watershed protection, biodiversity management, visual amenity (although these are mainly unquantified) have prompted many western governments to subsidise indigenous farming and forestry activities (Steenblik 2007). Although such subsidies have become increasingly controversial, the farming lobby continues to be a powerful political force and subsidised land management remains likely for the foreseeable future (Steenblik 2007). Against this background the costs of storing surpluses, the ‘dumping’ of those surpluses on world markets, and the economic distortions caused by the market protectionism this demands have severely damaged the development of agriculture in many developing countries (IIED 2005). Biofuels could provide a part of the answer to this problem by diverting 'surplus' production to a new market while maintaining productive capacity.

Biofuels must be considered alongside other drivers for prices for food based commodities, such as increasing global demand. In developing countries, particularly those of the tropics and subtropics, rising prices for food-based commodities, such as cereals and vegetable oils, could assist investment in agriculture and forestry which, in turn, could help to improve yields and production efficiencies (De La Torre Ugarte 2006; Rosegrant *et al* 2006). With careful implementation, the rural poor of these countries, who are mainly farmers, could be major beneficiaries of a new biofuel inspired development dynamic. However, it must be accepted that, without specific intervention, the urban poor in developing countries will suffer as a result of increased food prices, unless economic prosperity rises as a whole and a reasonable amount of the value generated by biofuels is retained locally (Woods 2006). We do not assess these issues, but we are aware of the dangers of an overly simplistic food versus fuel debate when synergistic opportunities for food and fuel exist and should be maximised.

1.2 The study

This study was launched in October 2006 and sets out to assess the potential scientific developments that could contribute to greater and more efficient production of biofuels for use in the transport sector. The study therefore focuses on liquid biofuels for transport, including biodiesel, bioethanol, biobutanol, biogas and synthetic biofuels, such as diesel and petrol. Developments across the entire production chain were considered, including feedstocks, processing as well as end use and distribution of the fuels. Although the application of biofuels for aviation and shipping are not assessed in this report, many of the developments that are outlined will also be transferable to these sectors.

The study was informed by an open call for evidence and several evidence gathering workshops and sessions. These involved representatives from environmental and development non-governmental organisations (NGOs), industries related to biofuels, including feedstock producers, fuel producers and the end use and distribution industry. Summaries of the evidence can be found online. Annex 2 lists all those who submitted evidence to the study, including participants at the workshops and those who provided evidence orally.

We also wish to thank all those who have contributed to the study, especially Professor Jacquie Burgess for facilitating the industry workshop and Dr Ausilio Bauen, Dr David Leak, Professor Peter Pearson, Professor Nilay Shah, Professor Richard Templer and Jess who helped during the drafting process.

2 Feedstock

2.1 Overview

This chapter addresses the range of feedstocks that can be used to produce biofuels within the wider context of their environmental, social and economic impacts and the technologies that need to be developed to increase the sustainability of their production.

Several feedstocks can readily be produced in the UK, such as those from arable crops currently grown for food and their co-products, from dedicated energy crops and forestry, or from domestic waste and marine biomass. It is probable that biofuels will also be manufactured in the UK from feedstocks imported from elsewhere within Europe, more distant countries and from developing economies. As international trade in these commodities is likely to expand in coming years, it will be essential to establish a common and accepted set of sustainability criteria by which to assess not only the different biofuels, but also the different feedstocks and their production systems.

Most of the agricultural crops grown globally are optimised for products that enter the food chain or are used as feed for farm animals (OECD & FAO 2007). Many of these same products, such as sugar, starch and oil, are currently being used as feedstocks for biofuels. This raises several concerns about land-use and the security and quality of the food chain.

In the future, biofuels will be produced from more complex materials, particularly lignocellulose which is the major component of cell walls and makes up the bulk of the biomass of energy crops such as trees and the perennial grasses. Lignocellulose feedstocks also include the co-products of agricultural production of food crops, such as straw, the waste parts of the plant not harvested or processed for food and co-products and from the forestry, paper and pulp industrial sectors. There is also the potential to produce fuels such as alkanes which are extracted directly from plants, as well as wax esters, which are formed on the plant surface. Species of aquatic algae that avoid the competition with other land uses may also be cultivated either in large tanks or at sea. However, there will be a need to resolve specific sustainability issues related to exploitation of these new sources.

A significant advantage of developing and using dedicated crops and trees for biofuels is that the plants, particularly perennials and preferably those with long growing seasons, can be bred for purpose. For example, this will include the development of higher carbon to nitrogen ratios, crops with higher yields of biomass or oil, cell-wall lignocellulose characteristics that make the feedstock more amenable for processing. It will also include traits enabling some plant species to be cultivated with minimal external inputs, low nitrogen requirements and capable of growing on marginal land with low biodiversity value or abandoned land not suitable for quality food production. Negative environmental impacts, such as on soil carbon and emissions of nitrous oxide (N_2O) from feedstock production, as discussed in-depth in Chapter 5, can be addressed in these new crop improvement programmes for biofuels. Several technologies are available to improve these traits, including the use of traditional plant breeding, genomic approaches to screen natural variation for incorporation into breeding programmes and the use of genetic modification (GM) to produce transgenic plants.

Much can be accomplished by new fast-track breeding methods for crop improvement that do not involve GM. These can rely on traditional means of introducing genetic variation, such as mutagenesis, but use new and rapid DNA-based technologies to identify potentially useful mutants. Similarly, the understanding gained from genome sequencing programmes of model species provides an important basis for exploring the biodiversity of natural populations for traits of interest. Nevertheless, there are many applications that can only be achieved, or achieved very much more rapidly, if GM technology is used. Box 1 highlights the potential role for GM in biofuel development.

The genomes of several plant species of direct relevance to the development of future biofuel crops, including poplar as a model tree species, rice as a model for temperate grasses, sorghum for tropical grasses and Arabidopsis for oilseed rape, have now been fully sequenced (see International Rice Genome Sequencing Project 2005; Wullschleger *et al* 2002; Ouyang *et al* 2007; Schoof *et al* 2004). A new genetic model for grass crop genomics is also becoming established through research on the temperate wild grass, *Brachypodium distachyon* (Garvin 2007). In the context of marine biomass, sequenced genomes of several phytoplankton species are available (see Palenik *et al* 2007).

Box 1 A potential role for Genetic Modification (GM) in biofuel development

Within Europe, in particular, the use of GM in crop improvement has been a controversial issue for public engagement. GM is a technology that can be applied to many applications. Each application should be considered individually in a holistic analysis, informed by sound science, of its risks, benefits and impacts to determine its relative utility and merit (Royal Society 2002a). Current research is addressing these issues.

(Box 1 *continues*)

(Box 1 *continued*)

There are two main areas for development of field and forestry crops. First, the improvement of dry biomass yield and productivity under low input cultivation systems, where fertiliser inputs are reduced, and the development of crops that have increased tolerance to environmental stresses. Second, the improvement of feedstock characteristics to allow more efficient conversion processes. GM can be a useful tool to aid both of these areas. Indeed GM would be the only means to improve processing qualities through the regulated expression of genes that encode hydrolytic enzymes for starch or lignocellulose breakdown before their further digestion and conversion in the biorefinery. GM can also be used to change the composition of plant cell walls and their structural organisation. This can make it easier to open up the lignocellulose matrix reducing the need for high-energy processes before cell wall digestion.

The use of GM in containment, where organisms are kept in enclosed environments such as fermentation vats, is a far less contentious issue. GM micro-organisms are already widely in use within fermentation systems for food and non-food applications. These developments in industrial biotechnology, and the emerging applications of synthetic biology – where new biological systems are designed and constructed for specific purposes – will become a major focus in coming years. Robust and benign micro-organisms that have been modified to increase their effectiveness for using and converting lignocellulose, sugars and oils into new improved biofuels will increasingly form part of the technologies that underpin integrated biorefineries (see Section 3.6).

As each new crop and feedstock production system for biofuels is proposed for development and use across the world, it will become necessary to analyse in detail its relative strengths, weaknesses, opportunities and threats, using an agreed set of sustainability criteria (Lewandowski & Faaij 2006; Cramer Commission (2005); UN-Energy 2007). A policy framework should be designed to ensure that these different parameters are given appropriate consideration in determining incentivisation; the use of life-cycle assessments is likely to become a routine requirement for decision-making.

2.2 Diversity of feedstocks

2.2.1 Starch and sugar

Plants are capable of making starches and sugars, as temporary or permanent energy stores. Currently, the biofuel industry globally is making extensive use of these two agricultural commodities that are also used in human food and farm animal feed. Thus, sugar from sugar cane (*Saccharum officianarum*) supports, for example, Brazilian bioethanol production. Brazil is the world's largest sugar and ethanol producer, currently accounting for some 40% of world sugar trade and over half of global ethanol trade (Worldwatch Institute 2006). Starch from maize (*Zea mays*) underpins a significant proportion of the US biofuels targets, and similarly, maize currently underpins fuel ethanol production in China (IEA 2004). Attention is also focussing on the potential of sorghums (*Sorghum* spp) to produce bioethanol feedstocks, from either grain sorghums as a replacement for maize, or sweet sorghums to replace sugar cane (Draye *et al* 2001). Drought tolerance is a major feature of sorghum with consequent low water requirements for high yields of either starch or sugar feedstocks (Biopact 2007). Within Europe, other cereals that are domestically grown, principally wheat (*Triticum* spp) and sugar beet (*Beta vulgaris*), currently contribute to ethanol production and many biofuel facilities using the starch or sugar feedstocks are already in operation (IEA 2004).

This use of the same raw materials for both fuel and food/feed can have multiple economic and environmental impacts. As discussed in Section 2.3 and Chapter 5, these impacts produce a growing tension in global decisions for land use and progress towards long-term sustainability.

In terms of these two feedstocks, agriculture in the UK also has the capacity to produce starch and sugar through its widespread cultivation of cereals, particularly wheat grain, and its cultivation of sugar beet. The sugar feedstock is underpinning the first bioethanol plant in the UK in Wissington, Norfolk, with a capacity of 70 million litres (Ml) (NNFCC 2007). About 650,000 tonnes (t) of sugar beet (2006 UK harvest, 7.1 Mt) will be supplied under contract by existing growers (NNFCC 2007). The second UK bioethanol plant, to be based in Hull, Yorkshire, is planned to have a capacity of 420 Ml and use some 1 Mt of locally grown wheat grain (2006 UK harvest, 14.7 Mt) (NNFCC 2007). Additional facilities are under construction or in planning, typically using feedstocks from wheat.

Wheat and sugar beet have been extensively optimised for specific food and animal feed applications and their intensive production systems often rely on multiple inputs to achieve the high yields gained. The use of domestic production of these feedstocks for biofuel manufacture in the UK will depend on cost-competitiveness in the global commodity market, as well as policies directed through incentives. The latter will increasingly involve the use of sustainability criteria which should include an assessment of the full range of impacts of growing the crops and using their feedstocks in biofuels. Direct comparisons of UK crops and production systems with those elsewhere are probable, leading to issues of prioritisation for national land use and food versus fuel security.

2.2.2 Lignocellulose

Lignocellulose, comprising plant cell walls, exists in biomass from agricultural co-products such as cereal straw and cane bagasse to dedicated energy crops and forestry. Lignocellulose is a complex matrix, comprising many different polysaccharides, phenolic polymers and proteins (Möller *et al* 2007). Cellulose, the major component of cell walls of land plants, is a glucan polysaccharide containing large reservoirs of energy that provide real potential for conversion into biofuels. Accessibility of the cellulose microfibrils to biochemical hydrolysis and sugar release is severely limited by the structure of the cell wall and the presence of the highly inert phenolic polymer termed lignin. The specific features of cell walls differ among different sources of lignocellulose, but the problem of accessibility and resistance to bio-based hydrolysis is generic and currently is addressed by energy-intensive chemical and physical pre-treatments to 'open up' the walls for enzymic hydrolysis. Saccharification is the conversion of cellulose and hemicellulose polysaccharides to the hexose and pentose monosaccharides respectively, that can then be converted by microbial fermentation to other products including ethanol.

Biofuel production from lignocellulose holds very considerable potential, given the amount of energy in the biomass and the extent of biomass that is available globally, particularly in residues, co-products and waste from many different sectors such as agriculture, horticulture, forestry, paper and pulp and food processing. When dedicated energy crops and forest trees are added to the sources of lignocellulose, the immensity of the opportunity for conversion to biofuels can be readily recognised. There are major research efforts globally to develop and optimise technologies for producing biofuels from these lignocellulose feedstocks, as discussed in detail in Chapter 3. The world's largest demonstration facility of 'lignocellulose ethanol' (from wheat, barley straw and corn stover), with a capacity of 2.5 Ml, was first established by Iogen Corporation in Ottawa, Canada (NNFCC 2007). Many other processing facilities are now in operation or planning throughout the world.

Co-products of cereal production

It has been calculated that 1.55 billion tonnes of residues, including corn stover, straws from wheat, barley, oats, rice and sorghum, as well as cane bagasse, are produced world-wide. Within the UK, average annual straw yields from wheat alone amounted to 5.9 tonnes per hectare (t/ha) in 2003–2005 (OECD & FAO 2007). Although this source of biomass presents potential, the relative merits of its different uses need to be assessed carefully to determine which contribute most effectively to sustainability, both at a global level and locally to its origin of cultivation. In this context, transportation to the biofuel processing biorefineries will be a significant issue. Cereal production has been highly optimised for grain yield but the crops have not been bred for straw quality in relation to use as biomass. Little work has been done to characterise the molecular organisation of straw cell walls to underpin improved saccharification.

Perennial grasses

In the US, switchgrass (*Panicum virgatum*) was highlighted in the 1980s as a future energy crop; in Europe, three additional species were also selected for further research: miscanthus (*Miscanthus* sp), reed canary grass (*Phalaris arundinacea*) and giant reed (*Arundo donax*) (Lewandowski *et al* 2003).

Today, the major attention focuses on switchgrass and miscanthus, although comparisons have shown that miscanthus produces more than twice the biomass yield of switchgrass (Heaton *et al* 2004). Concerns identified for miscanthus include the narrow gene pool currently available and its characteristics that are typical of those of invasive weeds. Nevertheless, the grass is attracting very considerable attention and research effort, particularly in the US. Within UK agriculture, the sterile triploid hybrid *Miscanthus* × *giganteus*, a cross of *M. sinensis* and *M. sacchariflorus*, is already under cultivation, but is regarded principally as an energy crop for combustion rather than for biofuel production. A range of technologies will need to be developed and applied if the potential of miscanthus as an energy crop is to be realised. The grass can be cultivated with low inputs on marginal land, but biomass yield is linked to inputs and many improvements will be required. As yet, there is little molecular understanding of the crop, its genetics and its agronomy and a number of additional issues, including the optimisation of harvesting processes remain to be resolved.

In contrast to the intensive cultivation of single grass species, feedstock opportunities from mixed perennial prairie grasslands have been highlighted recently in a study showing that greater numbers of species led to greater temporal stability of above-ground plant production (Tilman *et al* 2006).

Wood as feedstock

Forests and short rotation woody crops provide major potential lignocellulose feedstocks for bioenergy and biofuel production. The development of new plantations and agro-forestry systems is expanding throughout the world, with some 125 Mha of industrial plantations in existence: these represent only 3.5% of the total forest area globally (Grace 2005). The forest-based sector has long contributed to society, driving economic growth and wealth creation and providing an indispensable source of shelter and fuel for millions. The forest resource is immense, underpinning a vast complexity of environmental and economic benefits beyond simply the bioenergy sector.

In the past 40 years some 1 Mha of commercial forestry have been planted in the UK. New forest plantations average about 25,000 ha per year, with major expansion occurring in Scotland, northern England and Wales (Milne & Cannell 2005). These plantations are generally 80% Sitka spruce, with additional species of Scots pine (*Pinus sylvestris*), lodgepole pine (*Pinus contorta*), hybrid larch (*Larix* spp), Douglas fir (*Pseudotsuga* spp) and noble fir (*Abies procera*). The forests have been planted to produce timber as the primary product, but they represent an ongoing resource that could be harvested annually to provide lignocellulose feedstocks. If forestry is to become a significant element in the supply of biofuels, the wood resource will eventually need to be increased, either in the area of forests and/or an increase in production on the same area. This raises the issue of inputs. In this context, extensive application of fertiliser to forests in Scandinavia is currently being advocated to increase feedstock supply for biofuels (Linder S, personal communication).

Short rotation coppice (SRC) is a system of semi-intensive cultivation of fast-growing, woody species as coppice, over rotations that are short compared with cultivation of high forest, although lengthy by comparison with the annual cycle of most agricultural crops. SRC is established with different species and hybrids. The most commonly used species in northern Europe are Willow (*Salix* spp) and hybrid poplar (*Populus* spp) – particularly the European-American hybrids of *P. nigra* × *P. deltoides* and North American hybrids of *P. trichocarpa* × *P. deltoides* (Christersson 1987; Lindroh & Bath 1999). Red alder (*Alnus rubra*) and *Eucalyptus* spp are used in southern Europe (Porter *et al* 2007). Poplars are recognised model systems for woody species, with a broad genetic base for breeding, an extensive understanding of genetics, the availability of a sequenced genome and a well-established set of molecular tools that can be used for improvement of tree species.

2.2.3 Plant oils

Oil crops manufacture oils for storage in their seeds as nutritional reserves to support the growth of seedlings when the seed germinates. The type and yield of oils that accumulate vary dependent on crop, but all vegetable oils are made of triacylglycerols, three fatty acids esterified to glycerol. The diversity of crops yielding oil provides in principle a wide range of species for cultivation of biodiesel feedstock. In practice, soybean (*Glycine max*) is the major crop in the US and South America, whereas rapeseed (*Brassica napus*) is the major contributor to European feedstock (Worldwatch Institute 2006). It should be noted that the lowest cost biodiesel is currently produced from recycled cooking oil and waste animal grease.

Interest is increasingly directed towards jatropha (*Jatropha curcas*), which can be grown on marginal land of lesser agricultural value (Worldwatch Institute 2006). The plant is drought tolerant although oil yields increase with irrigation. Jatropha is considered a potentially useful biodiesel crop for more tropical regions, and widespread plantations are currently being established in South East Asia, Southern Africa, Central and South America and India (D1Oils & BP 2007). Jatropha oil can be used to meet local biodiesel requirements as well as for export to markets including Europe, where domestic feedstock produced from rapeseed and waste oil is unlikely to be sufficient to meet anticipated regulatory demand for biodiesel of around 10 Mt per year from 2010[e] (IEA 2004).

Within Europe, rapeseed is the primary feedstock for domestic biodiesel production, but sunflower seed is also used to produce plant oils for biodiesel. Germany is the major global biodiesel producer, accounting for 2499 Ml[f] in 2006 (Worldwatch Institute 2006). Although the UK is not a major supplier of biodiesel feedstocks, there are several production facilities in operation; the largest, with a capacity of 284 Ml per year[g] is at Seal Sands in Middlesbrough, which uses oilseed rape, soybean and palm oils as feedstocks (NNFCC 2007). Another facility, at Northwich, Cheshire, with a capacity of 227 Ml per year[h] uses a mixture of waste oils from the UK's catering and domestic sector in addition to virgin vegetable oils (NNFCC 2007). Additional smaller capacity plants are operational, using a variety of feedstocks and oils.

The current plant oil feedstocks for biodiesel raise several issues, including their competition for food uses and environmental concerns over their production systems, particularly impacts of deforestation from growing palm oil in Indonesia or increased areas of cultivation of soybean in ecologically sensitive regions of Brazil. Some oil crops, such as oilseed rape, are intensively cultivated requiring high fertiliser inputs to produce high oil yields. Some of these issues may be addressed if the development of jatropha and the projected increases in cultivation of this oil crop throughout countries of Asia and Africa prove successful.

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[e] The EU biofuel directive targets a 5.75% incorporation of biofuels incorporation in transportation fuels by energy content by 2010

[f] 1 litre of biodiesel = 0.88kg (2499 Ml = 2.2 Mt)

[g] 250,000t/yr

[h] 200,000t/yr

2.2.4 Marine resources

Marine macroalgae represent good feedstocks for anaerobic digestion for biogas production, in conversion efficiencies and rates, as well as process stability. Within the UK, the use of seaweed as biofuel feedstock is likely to be restricted to those maritime communities that can benefit from off-shore culture of the macroalgae and link this potential to wastewater remediation (see Chynoweth *et al* 1987, Chynoweth *et al* 2001, Horn *et al* 2000 and Schramm & Lehnberg 1984).

Several studies have addressed the potential of high oil ($>$50%) microalgae for biodiesel production (such as the Aquatic Species Program of the US National Renewable Energy Laboratory: see Sheenan *et al* 1998). Although biomass yields can be high, currently there are considerable problems of mass production, harvesting and processing that do not make their use cost-competitive. Nevertheless, the potential is considered great, particularly given projected yields and the lack of competition for agricultural land use.

It will be essential to assess these marine production systems against appropriate sustainability criteria, given the already existing negative impacts on the marine environment from over-exploitation.

2.2.5 Agricultural and forestry waste

Agricultural co-products encompass an extremely diverse range of feedstocks. These include the cereal straw discussed in Section 2.2.2 and many parts of food crops that are excluded from the food chain. Typically these plant tissues have high lignocellulose content and comprise significant amounts of material, particularly from the vegetable crops and the waste from food processing. One option is to use this waste for biofuel production; another is to recycle the waste to land through 'on-farm composting' and replacing nitrogen fertilisers with nitrogen from waste. In the context of the food chain, there are also substantial amounts of waste generated by the food outlet sectors, which is currently going to land-fill (Butterworth 2006). These also represent a large potential feedstock for biofuel production. Waste is very heterogeneous and composition will vary at different times of the year. Separation of 'useful' feedstock from the waste will need development but even after conversion, a considerable fraction of the original waste will remain for disposal.

Lignocellulose forestry waste presents another significant opportunity, with more than 1 Mt of waste from this sector produced annually in the UK, with the 4.7 Mt of municipal waste paper (Defra 2007). These feedstocks could provide useful inputs to maintain robust supply chains of lignocellulose if combined with seasonal production of energy crops. Decisions about using such feedstock will need to consider any resulting implications for other related industries, such as the waste paper recycling industry and newsprint.

2.2.6 Municipal waste

Municipal solid waste (MSW) is a significant resource in every country, which if successfully integrated into feedstock supply systems, could provide year round feedstock supply and address a significant waste disposal problem. About half the content of MSW is organic, from food and packaging. Estimates of the bioenergy potential of these wastes depend strongly upon assumptions about economic development and consumption of materials. However, a city of one million people could provide enough feedstock to produce about 430,000 litres of ethanol per day, enough to meet the needs of 360,000 people (at per capita fuel use similar to current rates in France) (Worldwatch Institute 2006). Efficient utilisation of this resource could be important in a country like the UK, where there is a relatively limited availability of arable land to grow plants.

MSW can be processed in a number of ways that are described in Chapter 3, including gasification, fermentation and digestion to biogas. However, a number of barriers exist that need to be overcome to realise the potential.

- The conversion processes require a significant feed quality specification that is difficult to achieve in practice.
- High levels of contaminants require removal from these systems, which adds to costs.
- The composition of MSW varies according to time of year, location and levels of recycling.
- Moisture content is also an issue that needs to be resolved effectively.
- There are health and safety hazards in its handling.

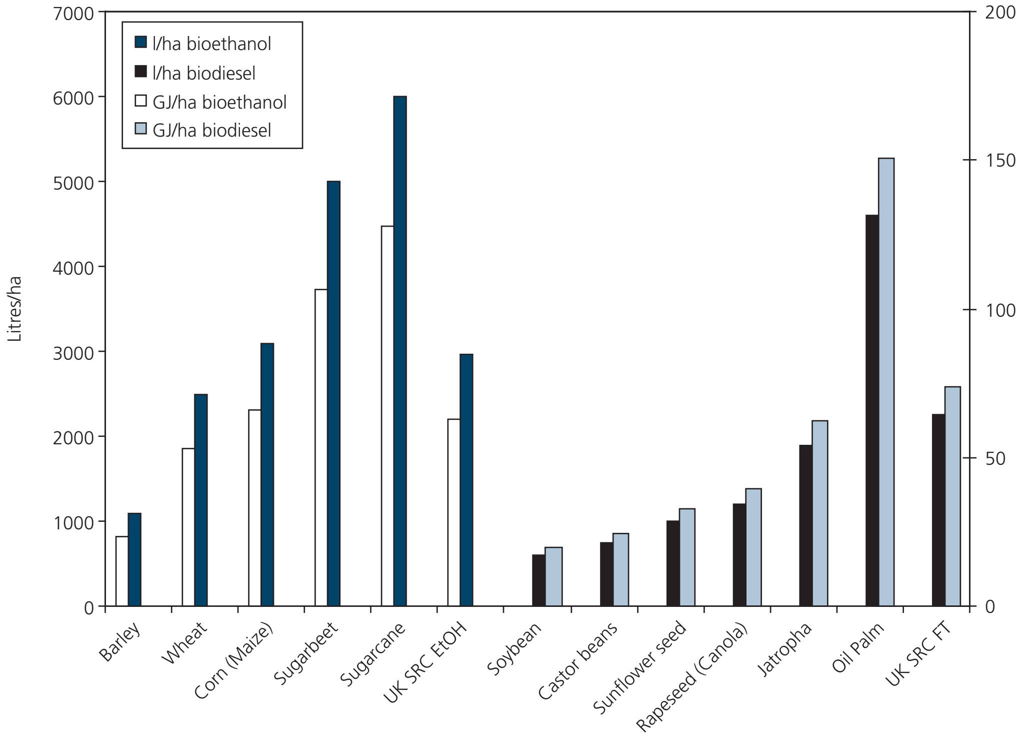
2.2.7 Future sources

Synthetic biology is a rapidly progressing area of science with the potential to produce novel chemicals, on a large scale, through the redesign of biological pathways or organisms. There is considerable interest in the possibility of engineering micro-organisms to manufacture hydrocarbons (Ladygina *et al* 2006). Similarly, the ability of plants to produce complex wax layers on their leaves, as a protective barrier against environmental stresses, also provides the potential for the design of new sustainable production systems of alkanes.

2.3 Land use and ecosystem issues

Increasing demand for agricultural products as feedstocks for bioenergy and biofuels, largely from sugar, maize,

Figure 2.1 Biofuel yields in terms of volume and energy per hectare for selected ethanol and biodiesel feedstock. The data are based on currently available sugar, starch and oil feedstocks converted into liquid fuels using conventional technology and show basic gross output (ie without energy costs for production). For comparison, data have been included for lignocellulose feedstocks: short rotation coppice (SRC) converted to bioethanol (UK SRC EtOH) and also to synthetic diesel converted by Fischer-Tropsch (UK SRC FT) (see Section 3.5.2 for details of process). (Adapted from IEA 2004).



plant oils and wheat, constitutes a significant change for the commodity markets. This is illustrated in the unprecedented demand for maize arising from the expanding bioethanol production in the USA, which is transforming the coarse grain markets (IEA 2004). One impact is likely to be an increase in land area planted in cereals either from reallocation of land from other crops, land taken out of set-aside (within Europe) or from cultivation of new land in many developing countries, particularly South and Latin America (IEA 2004). In this way, biofuel development can have major consequences on land use and food/feed prices, while contributing only a relatively small proportion to global energy demand.

Over the next two decades it has been projected that existing starch, sugar and oilseed crop varieties will continue to provide the bulk of feedstocks for biofuel production (IEA 2004). However, there is some scepticism about this projection, particularly in relation to feedstocks beyond the next ten years. It is likely that lignocellulose will become increasingly important, whether from dedicated energy crops or used in combination with crops that produce other feedstocks, such as sugar cane. Agricultural raw materials from crops grown in tropical areas are likely to be economically cheaper and displace a larger share of petroleum than biofuels produced using feedstocks from temperate climates (IEA 2004). This applies to lignocellulose feedstocks as much as to starch, sugar and oil, and presents major new opportunities as well as potential risks for many developing countries.

2.3.1 Social issues

As areas of high biomass productivity are often also areas of low wealth and earnings, socio-economic benefits could be significant. It will be important to facilitate technology transfer to developing countries, particularly for key technologies such as those that increase feedstock yield or processing qualities of biomass. There is already attention focused on the diversifying of the energy matrix in many countries, looking to increase the number and variety of crops that can be cultivated for bioenergy (DG Energy 2007). Programmes are underway to ensure the rural and regional economies benefit from the domestic production and use of feedstocks as well as their export. For example in Brazil policies for social and regional development, mean biodiesel, particularly from castor oil and palm oil, can gain 'social fuel' certification with associated tax incentives, if raw materials are bought from family agriculture and small farmers (DG Energy 2007). Significantly, if market conditions are appropriate, biofuel crops will always start to be cultivated on the most productive land to gain maximum earnings. Policy decisions will be needed to increasingly shift that cultivation to low biodiversity value marginal land or abandoned land.

2.3.2 Environmental issues

Using different types of land to grow crops raises a wide range of environmental issues, presenting both benefits and risks, as discussed in detail in Chapter 5. These issues are the same whether the crops are cultivated for food or industrial and fuel applications. Monocultures of forestry or field crops can pose considerable risks to biodiversity. The risks can be accentuated in the early stages of development of new crops that have not been extensively characterised, such as for their invasiveness or susceptibility to pests and pathogens. Whereas changing from one monoculture to another is unlikely to worsen the impact on biodiversity, the use of mixed species, such as perennial grasses or trees could be used in preference to enhance biodiversity, without compromising yield (Tilman *et al* 2006).

Certain land types, such as peatlands and tropical forests, will represent large carbon sinks and their conversion to the cultivation of crops will result in greater emissions of soil carbon. In addition some perennial species, such as those developed in SRC, produce considerable root systems that increase the amount of carbon in the soils. Deep ploughing and removal of root systems typically leads to the release of carbon (Cannell *et al* 1993).

The input of artificial fertiliser to increase yield must be carefully regulated or reduced to prevent emissions of N_2O, another potent GHG, either directly from the area of application or from drainage waters downstream. Evidence suggests that the use of perennial crops and trees may reduce N_2O emissions and provide large yields without the addition of nitrogen (Lewandowski & Schmidt 2005). Improved agronomic practices will undoubtedly play a key role in mitigating negative environmental impacts, not least in this context through the timing of application of fertilisers and pesticides that is essential to reduce run-off. In parallel, a greater understanding of the microbial diversity of soils, interactions within the rhizosphere and beneficial impacts of symbionts on nutrient uptake by plants will be important to underpin more sustainable cropping systems.

Opportunities may also exist for the using the cultivation of energy crops such as willow or miscanthus, to treat water that is high in nitrogen, for example from sewage plants, animal waste or even from drainage ditches. This would benefit both the plant growth but also reduce nitrogen emissions from the water treatment, although these and any other environmental impacts that might arise would need to be carefully assessed.

Feedstock development can also pose wider pollution risks that need to be assessed and resolved. For example, volatile organic compounds (VOCs) are released in substantial volumes by some plant species (see Arneth *et al* 2007). As yet little is known of why and how plants produce VOCs such as isoprene, nor how volatile production could be regulated or harvested for use in applications.

Consideration of environmental issues such as these will impact on choices of feedstock for biofuels as well as agronomic and harvesting practises. Developments in crop improvement will help to manage these risks (see Section 2.4), and as further understanding of ecosystems develop, this can be applied to new breeding programmes.

2.4 Research and development for feedstock improvement: current strategies

2.4.1 Germplasm and cultivation characteristics

The use of edible crops to produce starch, sugar and oil for biofuels relies on plant varieties optimised already for the production of human food and farm animal feed. Breeding programmes for new crops to manufacture industrial feedstocks are at a relatively early stage. The completion of genome sequencing programmes of model species of relevance to biofuel development, such as poplar and sorghum, are increasingly informing these programmes. There is also a research need to help improve understanding of the interactions between fertilisers and the rhizosphere and their uptake and utilisation by plants.

There is a general issue with the low level of genetic diversity in several grass cultivars which are now increasingly used as biofuel feedstocks. For example, only a few clones from *Saccharum spontaneum* were used to produce the modern sugar cane varieties. Molecular markers are now in development for use as a more efficient selection of traits of interest, including increased sugar synthesis under non-optimal environmental conditions (Ming *et al* 2006).

Miscanthus has a different set of problems, given that *M.* × *giganteus*, currently grown widely in Europe and increasingly within the USA, is a sterile variety, generated from the hybridisation of *M. sinensis* and *M. sacchariflori*s. Existing lines of *M.* × *giganteus* show little or no genetic diversity, with a single genotype accounting for nearly all of the current acreage. Projects are underway to produce new hybrids; the possibility of polyploid miscanthus, given chromosome doubling, has been shown to be associated with increased rates of biomass accumulation in maize and sugar cane (Jørgensen & Muhs 2001). As yet, miscanthus has not been developed for commercial levels of production and much of the knowledge-base and breeding tools for improvement need to be established. Interestingly, miscanthus belongs to the same group of grasses as maize, sorghum and sugar cane. Opportunities for the development of miscanthus × sugar cane hybrids are already being explored and this strategy for the development of future biofuel feedstocks from grasses is likely to expand greatly in coming years.

In the context of breeding programmes for new varieties of the temperate grasses, the development of *Brachypodium distachyon* as a model for grass crop genomics is likely to lead rapidly to new understanding and progress. Brachypodium has many attributes that make it an ideal genetic model: its genome is small – in contrast to that of cereals such as wheat – and a variety of molecular tools, together with a robust transformation system, are already established (Garvin 2007). Considerable research investment in this model, particularly in the USA, will underpin future optimisation of lignocellulose feedstocks, whether from energy grass crops or from agricultural co-products. In this context public sector support for the development of perennial crops will be important, given perennial germplasm will yield less commercial returns for seed companies than that of annual crops and this may limit private sector investment in research and development.

The discovery and development of new germplasm, which can include new seed collections and tree nurseries, relevant to biofuel feedstocks and their improvement is a high priority, both for land-based crops and marine organisms. There are many reviews of these areas available, for example in relation to India and China (GTZ 2006a, b).

Agricultural production is projected to continue to expand over coming years, with rates in developing countries outpacing those in developed countries (Pinstrup-Andersen *et al* 1999). Current high yields of many agricultural commodities reflect both the success in plant breeding objectives and an intensive high-input arable agriculture on productive land. Research targets are already in place to develop crops that will have improved nitrogen use efficiency and produce good yields under conditions of worsening environmental stress, such as water scarcity, salt stress and elevated temperatures, as well as improved disease resistance. The use of crops capable of growing well on abandoned arable land and set-aside within Europe is also of major emerging interest.

These parameters will become of increasing importance in the design of arable annual and perennial crops that are specifically optimised for the production of biofuel feedstocks. High agricultural water productivity ('kilogram per drop'), low inputs of fertilisers and herbicides/pesticides, and the ability to be cultivated on marginal lands that are incapable of food production, will all contribute to the sustainability requirements for acceptance of new biofuel crops and feedstocks. Importantly, the issue of yield as dry weight of biomass per hectare will continue to be a major trait determining the relative economics of production, particularly in relation to harvesting, collection, storage and transport costs to the biorefinery.

2.4.2 Harvesting and processing characteristics

Forest and crop management for biomass harvesting are research areas in their own right, given the need often to develop new specialised equipment to improve the efficiency of large-scale harvesting of energy crops such as SRC. In this context, the potential of transferring knowledge gained in fundamental plant science is illustrated through studies to explore the utility of genes that control branching in the model plants (Sorefan *et al* 2003), to improve the biomass and harvesting efficiency of willow as an energy feedstock.

In terms of gaining maximum value and energy from the biochemical processing of lignocellulose, such as from forestry and the perennial grasses, it is generally accepted that a far greater understanding of the plant cell wall is urgently required. The composition and molecular organisation of plant cell walls vary between feedstocks, and are responsive to environmental change. Current research is developing new molecular and analytical tools to characterise the diverse range of lignocellulose feedstocks and in parallel, design novel high throughput assays for their digestibility (Möller 2006). The search for features of the plant cell wall that affect processing typically use a genetic approach to identify useful mutants, characterise their properties and transfer that understanding into crop improvement programmes.

The increasing knowledge of plant metabolism and information gained from post-genomic technologies and systems biology has also provided new insights into flux control along pathways of primary and secondary metabolism (Möller 2006). For example, changing the level of expression of genes encoding enzymes such as those catalysing phenylpropanoid metabolism, can affect the composition of the lignin and the extent of lignification, as well as the extent of cross-linking cell wall polysaccharides (Chen & Dixon 2007). In this way the relative impacts of lignin content versus composition on saccharification efficiency can be explored. As yet, relatively few studies have linked these molecular changes directly to changes in digestibility of relevance to biofuel production. However, this research area will undoubtedly expand and provide the basis for the design of new biofuel crops and forest species bred for purpose. A key feature will be to maintain overall fitness of the plants while modifying their principal defensive barrier – the cell wall.

Linking the feedstock breeding programmes to the development of new processing tools is essential to gain rapid progress. The search for novel enzymes and proteins that can aid lignocellulose processing often include a metagenomic strategy, such as those applied to micro-organisms inhabiting the termite hindgut or cow rumen. Studies have focused on the identification of microbial hydrolases and associated carbohydrate-binding domains, as well as other proteins that may increase the efficiency of those enzymes to aid the opening of the plant cell walls to hydrolysis (Gray 2007). The rationale is that the genes encoding these proteins have evolved to digest plant cell walls during the course of a pathogen attack, or when the micro-organisms are using biomass as nutrients for their growth. However, plants also modify their own cell walls during differentiation and during responses to abiotic and biotic environmental challenges. The cell wall is a dynamic system, involving synthesis and deposition, followed by limited hydrolysis and remodelling. Plant enzymes are therefore also starting to attract attention as novel tools for the saccharification process as well as targets for feedstock breeding programmes.

As the optimisation of non-food crop platforms for biofuel production becomes an urgent issue, the need to understand the control of carbon partitioning is increasingly recognised. Research projects are underway to shift the ratio of starch to nitrogen in cereals, tailor plant cell wall composition to its new industrial use and redirect yield from products of relevance to food applications to those that will impact on biofuel production (Möller *et al* 2007).

3 Conversion and biorefineries

This chapter describes the biological and chemical conversion processes that can be used to convert feedstocks into biofuels. The ways in which these different processes can be optimised to ensure more efficient biofuel production are presented together with key challenges.

3.1 Overview

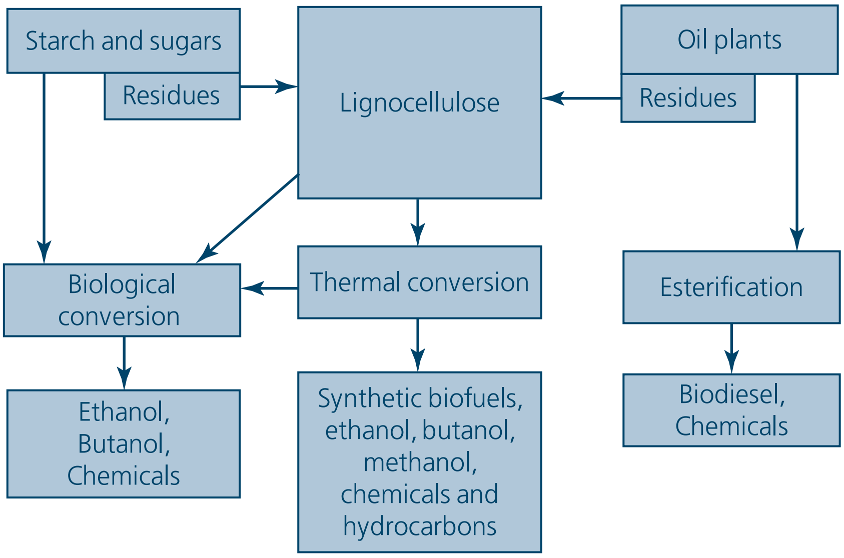
Plant material has the potential to be converted into a wide range of renewable liquid transport fuels. Huge progress has been made in the efficiency and environmental performance in some biofuels chains (for example sugar cane to ethanol) and substantial room for improvement exists in nascent ones (for example the processing of lignocellulose biomass). A consensus long-term vision is that of the 'biorefinery', a facility that converts biomass into several product streams including fuels, chemicals, high-value materials and heat and power. Large public and private interdisciplinary research programmes are being established both nationally and internationally in this area (see EPSRC Supergen programme[i], EC Directorate-General for Research programmes[j] and Dalton 2007).

Depending on the feedstock and the fuel that is to be produced, conversion can be done through several different routes using a range of biological, chemical and thermal conversion processes. In general, biological processes are relatively slow but can deliver a well defined product, which is readily purified, although it may have substantial energy or capital costs; while thermal processes are rapid but generally deliver a mixed product that is more difficult to purify and refine to a useful product. The overall energetic efficiency of the conversion process is also affected by the amount of pre-treatment or transportation that is required before conversion.

As identified in Chapter 2, plant material can be divided into three primary feedstocks: plant oils, sugars/starches and lignocellulose. An important part of the supply chain is transporting and preparing the material for conversion. The first two groups are readily accessible and require little processing before conversion to biofuel. Lignocellulose is more complex and can either be broken down by a combination of physical, chemical and/or enzymic steps to sugars which may subsequently be fermented to produce biofuels, or it can be it can be converted to biofuels by thermochemical routes. In addition to producing biofuels, these processes also produce wastes. Some wastes, for example lignin, can be burnt to produce heat and power; others, such as wastewater from fermentation, need to be treated to extract valuable processing catalysts or other chemicals, or to reduce its toxicity before disposal.

For electrical energy, plant material is just one possible source and it will have to compete with other sources such as solar, tidal and nuclear. However, for chemical production plant material is the only viable alternative source of carbon to conventional fossil oil, and as the price of oil rises there will be increasing incentive to

Figure 3.1 Thermal, biological and chemical routes to biofuel and chemical production.



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[i] www.epsrc.ac.uk/ResearchFunding/Programmes/Energy/Funding/SUPERGEN/default.htm
[j] http://cordis.europa.eu/fp6/projects.htm

develop new processes. Economically this can be beneficial as the revenue from chemical manufacture, which requires only 5–10% of total oil production, is comparable to that generated by the 90–95% used for fuel and energy (Kamm *et al* 2006). This interplay of the fuel and chemicals sectors introduces resilience and flexibility into the oil market. Thus, there is a clear economic advantage in building a similar flexibility into the biofuels market by devoting part of the biomass production to the manufacture of chemicals. Therefore, it will become increasingly attractive to produce chemicals, including biofuels, from plant material.

Increasing the efficiency of biofuel production both in terms of environmental impact and economics is leading to the development of biorefineries (Kamm *et al* 2006). These integrate various conversion processes and make better use of waste products to produce a range of products including fuels, industrial chemicals, heat and electricity.

Current investment and technology choice is largely driven by policy targets aided by high oil prices. This is leading to different regions promoting different technologies, based on the economics as well as the available feedstocks. In addition, the fuel produced needs to be compatible with existing vehicle engines and supply infrastructure. However, developments in end use, which are discussed in Chapter 4, will also have implications for which technologies are viable. Synthetic hydrocarbon fuels can be made by converting plant material into a gas (known as syngas) or liquid such as fast pyrolysis bio-oil and then further processing these primary products into transport fuels by Fischer Tropsch synthesis from syngas or hydrogen related processes for pyrolysis liquid. These synthetic hydrocarbons are entirely compatible with conventional fuels in all proportions, but have much lower levels of sulphur (in the parts per million range) compared to conventional hydrocarbon fuels resulting from the need for ultra-clean syngas to avoid catalyst poisoning. Although these are easy to assimilate into the current infrastructure and engine design, they are currently far from the market in significant quantities when considering biomass derived fuels (DTI 2006 and Rudloff 2007). However the synthesis technology is becoming increasingly used for processing natural gas and natural gas liquids into transports fuels in the Middle East and in Malaysia (van Wechem & Senden 1993).

Although commercial interests will ultimately determine the conversion and associated processes used to make biofuels, they will need to be judged against several sustainability metrics. These include:

- the net GHG emissions over the life cycle;
- the carbon efficiency (how much carbon appears in the products as fraction of the carbon in the feed biomass);
- the energy efficiency (the amount of energy embodied in the products as a fraction of that embodied in the feed biomass);
- the fossil energy ratio (the amount of renewable energy produced per unit of fossil energy used over the lifecycle);
- cost per unit of energy;
- other environmental impact assessments such as local air pollution, eutrophication, acidification etc.

Indeed, the early development of an agreed and consistent set of metrics is critical in informing and adjusting large-scale research programmes. These metrics also allow insights into the properties of 'efficient' biofuels chains, for example low nutrient intensiveness, mild processing conditions, minimal additional reagents, optimising selectivity and minimising bond breaking, making use of all the biomass etc.

The role of LCA will be crucial in determining the values of the various metrics and emissions along the entire chain of biofuel production and as such must be applied to different processing techniques available now and those that might become available after research, development and demonstration (see Chapter 5 for details of LCA). In addition, fiscal and regulatory incentives will be required to ensure that a policy framework is in place which ensures that industry can choose production routes that offer the best environmental and economic benefits.

3.2 Supply, preparation and pre-treatment of raw materials

An important stage in the biofuel supply chain is the provision of a consistent and regular supply of feedstock. Initial processing may be required to increase its energy density to reduce transport, handling and storage costs. Further preparation or pre-treatment may be required to convert it into a form more suitable for the conversion process. How these stages are managed will have implications for the benefits that the biofuel produced can offer. For example, greater fossil energy input for pre-processing may have implications for the overall amount of GHG emissions that arise from producing the biofuels.

3.2.1 Supply of raw materials

A conversion facility will require a year round supply of feedstock to minimise costs (Toft *et al* 1995). Fundamentally there are three options for providing year round supply of feedstock.

- Provide long-term storage of feedstock at source and/or at the conversion site. This can be either as raw feedstock or can be processed into a more stable form.

- Design the conversion process to be sufficiently flexible to handle a range of different feedstocks.
- Import feedstock to provide material when it is not available locally.

Processes and technologies could potentially be developed to allow solid wastes, such as from municipal and commercial sources, to be integrated into the supply chain as a potential year round supply of raw materials, as well as contributing to more effective use of such materials.

Storing plant material can lead to loss of material by biological degradation or pest infestations (Jirjis 1994; Mitchell *et al* 1990; Giølsjø 1994; Gislerud 1990). Feedstocks such as wheat grain can be stored easily and provide a year round supply, whereas sugar beet is much harder to maintain quality as it degrades rapidly (Mitchell & Bridgwater 1994). In addition, leaching of materials can cause problems requiring wastewater treatment, and fungi growing on the material can release spores, which can cause health problems. On the other hand, storage opens up possibilities for slower pre-treatment processes or deliberately introduced process agents such as modified fungal strains that gradually decompose parts of the cell wall exposing cellulose for hydrolysis and fermentation and reducing the need for mechanical or thermal/chemical pre-treatment.

3.2.2 Biomass quality

Processing is required to convert the plant material to a form suitable for conversion, for example to reduce the water content and/or break the material into small particles. Fresh wood can have a moisture content of about 50% by weight. Although storage may reduce this to about 40%, energy is needed to reduce this to levels such as 25% for gasification or 10% for fast pyrolysis (Bridgwater & Maniatis 2004). The feedstock characteristics for biological conversion are often much more specific than for thermal conversion, although drying is not usually an issue.

Plant material contains several 'impurities' that disrupt thermo-chemical conversion processes, for example by poisoning catalysts (Bridgwater 1996). The presence and concentration in the plant material is dependent on the plant species, whereas others are derived from agronomic and agricultural practices as well as geographical factors. In some cases developments that increase the biomass yield may lead to increases in contaminants. Two of the main contaminants are as follows (see Bridgwater 1996; Fahmi *et al* 2007):

- Alkali metal salts, which occur naturally in plants, can sinter or melt and cause blockage, erosion and/or corrosion on equipment surfaces in gasification; in fast pyrolysis they are catalytically active leading to lower yields and lower-quality liquid. The concentration in the feedstock can be controlled by crop selection and breeding, timing of harvest and harvest practice and by washing during pre-processing.
- Although sulphur and chlorine occur naturally in plants, they require removal from syngas by cleaning systems. Sulphur can poison catalysts used in the processing and reduce their efficiency. Sulphur is derived from fertilisers and additives and its concentration in the feedstock can be controlled by varying the application and timing of harvest. Chlorine may be added as part of fertiliser use or from deposits from sea spray in coastal areas, but it can be washed off the plants by rain or during pre-processing.

For marine-based feedstock the main problem is the removal of surplus salt. Although drying may not be necessary as some conversion processes are tolerant of the high water content, salt can be a major contaminant and its efficient removal presents a significant challenge.

3.2.3 Pre-treatment and decentralised processing

Pre-treatment includes making the plant material denser and therefore more efficient to transport, and turning it into a form that makes it more amenable to processing and reduces conversion costs. Some pre-treatment processes are energy intensive and produce significant waste, such as current chemical technologies for recovery of sugar monomers from lignocelluloses. On the other hand, the history of the starch processing industry has shown that it is possible to economically replace chemical hydrolysis with enzymic (amylase) hydrolysis processes. Such developments are expected to occur for the development of enzymes, such as cellulases and hemicellulases, which are required to improve sugar recovery from lignocellulose (Himmel *et al* 2007).

Fast pyrolysis and torrefaction

One option that is in development, which could reduce transport costs by up to 87% is to use fast-pyrolysis to convert the low density (100 kg/m^3) lignocellulose plant material to liquid bio-oil, which has a density of 1200 kg/m^3 (Bridgwater 2007). This process rapidly heats the solid plant material in the absence of air to temperatures of 400–600 °C, decomposing it to a liquid, containing various hydrocarbons, gases and charcoal ('char') (Bridgwater 2007). The gases can be burnt to provide heat and power. The resulting liquid has an oxygen content of 35–40%, which is about the same as the original biomass/plant material. This gives the liquid some unique characteristics such as miscibility with water, but it requires chemical removal of oxygen for production of hydrocarbons. Owing to lack of familiarity with the liquid, it is considered more difficult to handle than conventional fuels because it contains a mix of biochemicals and oils some of which are toxic. The process gives a 75% weight yield of bio-oil, with the chemical content being dependent on the feedstock and the modifications to the conversion process (Bridgwater 2007). The energy content of the bio-oil can be enhanced by adding the pyrolysis by-product charcoal to form a slurry. However this char, which is largely formed of carbon, may also have value either by being burnt to provide a source of energy for the pyrolysis, or it can be buried as a soil improver, thus sequestering the carbon.

Using bio-oil as a feedstock for the production of biofuels can reduce the costs of gasification compared with feeding solid biomass directly into the gasifier. Pre-treatment by fast pyrolysis close to source could lead to a network of small decentralised fast pyrolysis plants (of 100,000 to 300,000 tonnes per year (t/yr)) feeding into a much larger centralised gasification plant coupled to a biofuel synthesis process (Bridgwater 2007). The advantages and disadvantages are summarised in Table 3.1. They require research, development and demonstration, particularly to investigate small-scale pyrolysis and the scaling up of gasification plants.

Particle size of the plant material is also important for fast pyrolysis, requiring the material to ground to about 5mm, which is easier after drying (Bridgwater 2007). An alternative process is torrefaction, which is effectively low-temperature (250–350 °C) slow pyrolysis which drives off all water and some volatile compounds, making the material brittle and easier to grind into smaller components (Bergman & Kiel 2005). However, more needs to be known about the effects of the various emissions from the process and the associated energy and financial costs and whether these justify the benefits it provides.

Lignocellulose feedstock

As described in Section 2.2.2, lignocellulose material is a valuable source of energy, but for biological processes access to these carbon compounds requires pre-treatment. For thermal processes this is less of an issue as they can use the raw feedstock after mechanical processes to break up the material into smaller pieces (Bridgwater & Maniatis 2004). However, for biological fermentation and certain chemical processes, pre-treatment is required before sugars can be released from the waste material or from dedicated crops. The optimal pre-treatment will be feedstock specific. Until recently (Wyman *et al* 2005) there has been little truly comparative information available. Mild acid hydrolysis at elevated temperature and pressure can selectively hydrolyse hemicellulose, which not only releases the predominantly pentose components, but also opens up access to the cellulose. Steam explosion and high-pressure hot water treatments achieve similar goals but exploit the natural acidity of hemicelluloses. These treatments do not significantly depolymerise lignin, allowing it to be extracted for further processing. Alkaline treatments break down the polymeric lignin and partly hydrolyse hemicellulose. Although this can be particularly useful for subsequent enzymic hydrolysis of the hemicellulose and cellulose, extensive washing is usually required to remove lignin monomers which can inhibit the subsequent fermentation (Mosier *et al* 2005). Hydrolysis of cellulose can be achieved with strong acid, but the current trend is towards enzymic hydrolysis to avoid costly recovery and wastewater treatment requirements associated with the use of acid. Harsher conditions are required because of the partial crystallinity of cellulose, which is also an impediment to conversion by enzymes. Chemical methods may be justified with a mixed feedstock, but require efficient methods for acid recovery (von Sivers & Zacchi 1996). Milder enzymic methods should gradually supplant chemical hydrolysis of cellulose and hemicellulose (depending on the initial pre-treatment method), but require development to maximise processivity and to reduce the cost of enzyme production. The isolation and development of new fermentation organisms is moving towards biocatalysts that can carry out both saccharification and fermentation (Lynd *et al* 2005).

Lignin and its by-products need to be removed before fermentation as they are often toxic to micro-organisms and the enzymes used for hydrolysis, which can reduce the conversion efficiency. This could be partly addressed by using low lignin crops or developing new strains of lignin tolerant micro-organisms. Lignin can be burnt to provide a source of heat and power for the conversion process. Alternatively new developments may make it valuable as a chemical feedstock.

Table 3.1 Comparison of solid biomass gasification with pyrolysis liquid gasification (Bridgwater 2007).

Advantages	Disadvantages
Capital cost reduction of about 10% due to lower raw material handling costs	Capital cost increase of about 10% due to economies of scale in small pyrolysis plants
Capital cost reduction of about 10% due to lower gasification costs in feeding a liquid at pressure compared with solid biomass	Efficiency loss of about 6–7% due to additional processing step
Product gas requires less cleaning giving capital cost reduction of about 5%	

3.3 Bioethanol and biobutanol production

Bioethanol and biobutanol can be made by biological, chemical and thermal processes. Biobutanol has several properties, such as its higher energy density and ease of blending with conventional fuels that make it more attractive than bioethanol (BP & DuPont 2007).

Bioethanol can be produced by three basic routes (see Figure 3.2). These are: (1) biological fermentation; (2) thermal gasification followed by ethanol synthesis; and (3) thermal gasification followed by biological fermentation. All forms of feedstock can be used in these three routes, although sugars and starches from foodstuffs are likely to use a biological route as it is a well-established and mature technology. The production of ethanol from lignocellulose is less well established but several alternatives are under demonstration internationally (for example in Sweden, Spain, Canada, USA, Japan and Denmark) to identify their feasibility and economic viability and establish priorities for further research. Developments will improve efficiency and reduce costs. Studies indicate that long-term efficiencies and costs may be similar to those associated with sugar cane-ethanol fuel chains (Sims *et al* 2006).

Chemical and thermal routes for butanol production are already established, but are dependent on a clean source of syngas from biomass gasification. Biological production of butanol is based on the well-established acetone – butanol with *Clostridium acetobutylicum*, which converts starch to acetone, butanol and ethanol in the approximate ratio 3:6:1, along with hydrogen and several other by-products. Although this has a long history in the context of acetone production, several problems need to be solved for an efficient biobutanol process, particularly the higher toxicity of butanol (compared with ethanol) to the producing organism. Although butanol is an attractive fuel to use, its production from sugar is three fold less efficient than for ethanol production. Du Pont has apparently developed an improved biobutanol process, but little information is currently available. The ultimate objective needs to be for better stoichiometry, with reactions delivering more moles of alcohol per mole of sugar (Ezeji *et al* 2007).

3.3.1 Biological conversion

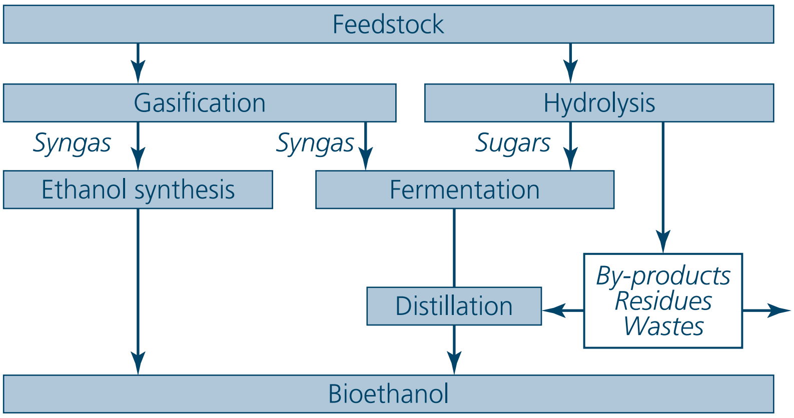
Hydrolysis

Sugars produced directly by plants such as sugar cane and sugar beet can be fed directly into the fermentation process. Starches from foodstuffs, such as corn or grain, require a hydrolysis reaction, known as saccharification, to convert the starch into sugars before fermentation. This is normally done with an enzyme mixture, collectively known as amylases. Although several strains are able to hydrolyse starch, the current efficiency and cost of separate saccharification and fermentation processes suggest that this is unlikely to change in the near future (Shigechi *et al* 2004). However, as outlined above, there is still some way to go before cellulases and hemicellases, which are also enzyme mixtures, reach the same level of efficiency and cost.

Fermentation

Ethanolic fermentation of sucrose or glucose derived from starch typically uses the yeast *Saccharomyces cerevisiae*, although the bacterium *Zymomonas mobilis* offers certain process advantages, such as higher specific productivity, ethanol yield (grams per gram) and high alcohol tolerance. However, neither of these organisms can naturally ferment the pentose (C5) sugars derived from hemicellulose, which is a vital step towards increasing lignocellulose ethanol yield (Huber *et al* 2006). Two approaches have been adopted to solve this: (1) the engineering of pentose fermentation pathways into *S. cerevisiae* (Jeffries 2006) and *Z. mobilis* (Aden *et al* 2002; Deanda *et al* 1996; Joachimsthal & Rogers 2000), (2) engineering of ethanol fermentation pathways in natural pentose utilisers (for example see Altherum & Ingram 1989; Bothast *et al* 1994). Although these strains can be used in separate or simultaneous saccharification and fermentation regimes, with added enzymes,

Figure 3.2 Thermal and biological routes to bioethanol.



analogous strategies are now being taken to produce strains which can produce their own complement of cellulases and hemicellulases (Lynd *et al* 2005).

Separation of the ethanol from the dilute solution is a particularly energy intensive step. It involves distillation followed by either further distillation or by using molecular sieves. Increasing the concentration of ethanol before distillation would improve the efficiency. However, a major constraint in the process is the concentration of alcohol that the micro-organisms currently can tolerate. For ethanol this is about 18% solution, although some under development can tolerate 24% solutions (REF). A demonstrated process that avoids this problem is the integration of thermophilic fermentation at elevated temperatures with nitrogen stripping. This continually removes the ethanol from the fermenter and therefore keeps its concentration well below toxic levels. Condensation of the overhead vapour results in an ethanol rich liquid that is much cheaper to purify than a standard fermenter broth (Hild *et al* 2003).

Particular issues that need to be resolved include the following:

- Improving tolerance of the fermentation micro-organisms to ethanol and particularly butanol.
- Improving the fermentation process to increase the stoichiometric return of ethanol (particularly for strains in which the fermentation pathway has been engineered) and butanol per molecule of sugar.
- Improving the ability of the organism to utilise lignocellulose derived polymers. Some members of the *Clostridium* genus are naturally cellulolytic, so this may be simpler for biobutanol than bioethanol.

Wastewater from both the fermentation processes and hydrolysis can be recycled back into the process once treated to recover the chemical or biological catalysts and remove other impurities.

3.3.2 Thermo-chemical and thermal–biological conversion

Thermal gasification reduces the organic material to syngas, which is a mixture of hydrogen and carbon monoxide. Ethanol can be synthesised directly from the syngas by a chemical process.

Alternatively, following thermal gasification, the syngas could be fed into a biological fermentation process, where microorganisms would then produce ethanol (van Kasteren *et al* 2005). However substantial issues need to be overcome. Fermentation is done in an aqueous solution, which makes it difficult to deliver the hydrogen and carbon monoxide gases efficiently to the micro-organisms. Syngas is normally produced at high pressure of at least 50 bars[k], which could be used to increase aqueous phase solubility in the fermenter, but might affect the physiology and viability of the fermentation micro-organisms. There is therefore a need to design and develop a high pressure 'bioreactor' that facilitates the delivery of syngas, through an aqueous medium, to the micro-organism. This may include the use of extremophile micro-organisms that can withstand the high pressures.

3.4 Biodiesel

Although usable in conventional diesel engines without major modification, the chemical composition of biodiesel is distinctly different to conventional diesel. Current production of biodiesel comprises of a mixture of methyl esters, which is made from the 'transesterification' of plant oils such as from rapeseed, soy bean or palm oil, using methanol, usually derived from fossil fuels. The process used reduces the viscosity of the oil, improves its consistency and miscibility with diesel, as well as improving other properties, such as its viscosity when cold (AMEC 2007). As the chemical composition of the oils from each plant species are slightly different, the properties of the final product also differ, and blends of the various oils maybe needed to produce an acceptable product. In addition to producing monoglycerides the process also produces glycerine as a by-product, which is largely used for cosmetics (AMEC 2007). A better fuel could be produced using bioethanol for the transesterification to produce ethyl esters which are less viscous, particularly when cold (Kleinov *et al* 2007).

A possible longer-term route to biodiesel under active investigation involves the direct production of fatty acid ethyl esters from lignocellulose by engineered organisms such as Actinomycetes and also via production of wax esters in plants (see Chapter 2) (Kalscheuer *et al* 2006).

Although there are now European standards for biodiesel, there is still some variability in the quality, owing to minor levels of contaminants and from the performance of different processes. This is more pronounced when waste oils and fats are used as the raw material, where the fatty acid content needs to be completely neutralised and either removed or converted to ensure complete reaction and a clean product. Biodiesel is currently limited to 5% in diesel in Europe due to concerns over engine warranties, materials, cold weather performance and compatibility.

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[k] 1 bar = 100,000 Pascals

3.5 Synthetic biofuels

Synthetic biofuels are here defined as fuels that are synthesised from synthesis gas produced by cleaned and modified gas from thermal gasification (such as partial oxidation) of biomass. As well as producing bio-based alcohols and biodiesel, feedstock can also be used to create synthetic hydrocarbons, such as diesel[I], petrol and in principle aviation fuel, all of which can have exactly the same properties as fossil fuel derived fuels. Similar processes are currently widely used to produce synthetic fuels from coal or gas (DTI 2006; Huber *et al* 2006). Synthetic fuels have several advantages because they can be used without modification in existing engines and fuel supply. In addition synthetic biofuels are necessarily cleaner than traditional fuels owing to the removal of all contaminants to avoid poisoning the catalysts used in the processing (Spath & Dayton 2003).

There are several thermal and chemical processes that can be used to produce synthetic hydrocarbons (Figure 3.3). The main routes are as follows:

- Thermal gasification to syngas (a mixture of hydrogen and carbon monoxide) followed by upgrading by Fischer-Tropsch (FT) synthesis, as currently under development by Choren in Germany using Shell's proprietary SMDS process (DTI 2006; Rudloff 2007). The gasification and gas cleaning steps require large-scale demonstration.

- Thermal gasification followed by methanol synthesis followed by upgrading with methanol to gasoline (MTG) or methanol to olefins, gasoline and diesel (MOGD) processes. The gasification and gas cleaning steps require large scale demonstration, methanol synthesis and MTG are available commercially.

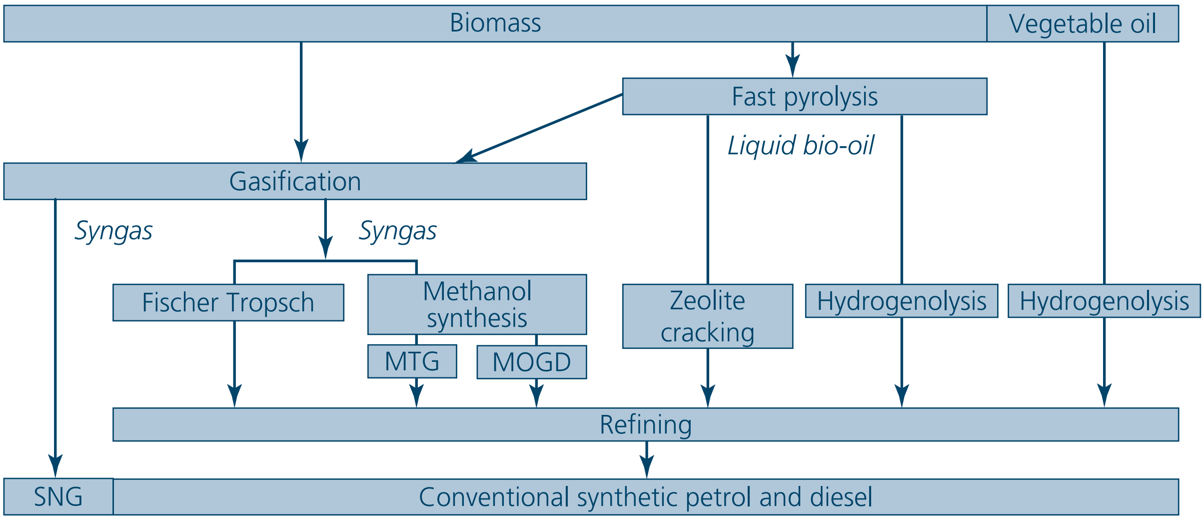
- Fast pyrolysis for gasification and subsequent upgrading of the syngas as above. Fast pyrolysis has limited commercial availability; pyrolysis liquid gasification has not been demonstrated, but is unlikely to present significant technical problems and synthesis processes are available.

- Fast pyrolysis followed by upgrading by hydro-processing or zeolites. Both routes have limited knowledge or experience and require significant research, development and demonstration (RD&D).

- Hydro-processing, which uses hydrogen to remove oxygen and other contaminants such as sulphur and nitrogen from the vegetable oil. This is commercially available, for example from Neste (DTI 2006).

At present, they all have potential and there is no single process that offers clear advantages over another: all of these routes have different economic, environmental and technological advantages and disadvantages. The commercial viability of some processes varies according to the scale at which they are deployed. Savings in greenhouse gases also vary depending on the type of process and how it is performed. Some of the processes also require a range of technical breakthroughs and need to be demonstrated at both large and small scales to show that they can produce biofuels viably. Nevertheless the processes can offer significant efficiency gains for biofuel production and need to be considered in an overall biofuels strategy. The concept of 'polygeneration', also actively being studied for coal utilisation may be a

Figure 3.3 Thermal and biomass gasification routes to hydrocarbons.



[I] It is important to note that the chemical composition of synthetic diesel, which is a product of synthesising carbon monoxide and hydrogen, is distinctly different to biodiesel, which is conventionally used to describe the fatty acid ester of vegetable oil promising route for biomass conversion (see Section 3.6). This involves designing a flexible facility that allows for fluctuating production across a product slate (gaseous fuels, liquid fuels, chemicals such as methanol, heat and power).

3.5.1 Gasification processes

Using either the raw biomass or bio-oil as a feedstock, gasification involves the partial combustion of the feedstock to produce syngas, which is a mixture of hydrogen and carbon monoxide (Huber *et al* 2006). In addition to the syngas gasification produces several contaminants including tars and sulphur and nitrogen compounds, which require removal and further processing. The composition of the output varies according to the feedstock and the gasification process. Before further processing the syngas needs to be cleaned of impurities, such as sulphur and nitrogen, which could disrupt the subsequent catalytic conversion processes. Build up of tar can also reduce the efficiency of the gasification (Huber *et al* 2006). Gas clean up is technically complex and the processes required are very dependent on the feedstock. Feedstock with high contaminants and impurities, or the use of mixed feedstocks increases the range of processes required. Currently there is no experience of large-scale gas cleaning (Hamelinck *et al* 2003; Spath & Dayton 2003).

Economic size and energy input for clean-up of wastes

One of the challenges of biomass gasification is gas clean up to the standards of subsequent process catalysts, some of which are sensitive to contaminants in the parts per billion range. Development of more tolerant catalysts to impurities in biomass-derived syngas would offer significant cost savings and could accelerate implementation of the technology by reducing uncertainties. Concerns with gas cleaning increase as lower cost and more contaminated feedstock is used. Delivery of clean and consistent feedstock may not be sustainable technically or economically as the bio-economy and associated various uses of bio-based feedstock increases. There is a clear need to develop effective gas cleaning systems.

There is also the potential for co-processing with coal, which has been explored for power generation (Perry & Rosilo-Calle 2006). Co-processing would allow smaller quantities of plant material to be gasified, using economies of scale that might otherwise be difficult to achieve. This again will require demonstration to ensure any associated issues are resolved.

3.5.2 Fischer-Tropsch

The FT process is a well established technology that uses a chemical catalyst to produce a range of hydrocarbons from C1 to C50. This is a synthesis reaction from a mixture of carbon monoxide and hydrogen that always gives a wide range of hydrocarbons. Some control over the range and distribution of products is achievable by control of temperature, pressure, catalyst and reactor configuration. Products that are not used can be regasified or used for generating heat and power. Selectivity of the catalyst to produce the required chemicals is important and affects the economics of the process. Contaminants in the syngas can poison the catalysts reducing its efficiency and altering the products that can be produced (Hamelinck *et al* 2003; Huber *et al* 2006; Spath & Dayton 2003). A key research target is the development of catalysts that are more tolerant to impurities. There is also an urgent need for sustainable methods of catalyst regeneration and recycle because the large scale of FT plants means that there is a real possibility of their operation being compromised by shortages of one or more metals that make up the catalysts.

The minimum economic size of a FT process is currently about 1 Mt per year of biofuels. This would require gasification of about 5 Mt per year of biomass feedstock, through, for example, seven gasifiers converting 100 tonnes per hour (t/h) (DTI 2006). However, experience of biomass gasification and gas cleaning, at present, is only small scale although a two- to threefold increase in throughput (up to 30 t/h, 250,000 t/yr) from the largest current gasification plants should be easily achieved. A similar situation exists for alcohol synthesis which is most efficient at large scale. Delivering a viable system will therefore require either:

- developing and demonstrating large-scale gasification and gas cleaning; this can then feed into the currently viable conversion processes; or
- downscaling and optimising the upgrading processes, fed by multiple small-scale gasification processes.

3.5.3 Methanol to Gasoline and Diesel

An alternative to FT is to synthesise methanol and then use the MTG or MOGD process. This has been demonstrated on a small scale by Sustech at Schwartze Pumpe, Germany and is more selective than FT, giving higher yields of fuels; however, it requires an additional processing step which currently reduces the economic viability of the process (DTI 2006). New catalysts could improve the yield and reduce waste products such as aromatic compounds which would reduce costs.

3.5.4 Fast pyrolysis and upgrading

As discussed in Section 3.2.3, fast pyrolysis can be used to produce bio-oil from the biomass. This can then be converted to synthetic biofuels by hydroprocessing (Maggi & Elliot 1997), as described above, or by zeolitic cracking (Diebold *et al* 1994; Huber *et al* 2006). This latter process has only been studied at a basic level but produces an aromatic product that can then be converted in a conventional refinery. However, depending on the type of zeolite catalyst, this process can yield aromatics with high toxicity, which in turn results in more harmful emissions when the fuels are burnt in a vehicles engine. Specific research targets include the development of catalysts that can produce aromatics with lower toxicity and a greater understanding of the entire process to increase the production efficiency.

3.5.5 Pressure liquefaction

Pressure liquefaction is a similar process to fast pyrolysis, using heat and pressure to reduce plant material to a liquid with 15–20% oxygen content (Elliot & Baker 1986) (compared with 35–40% with pyrolysis). Its main advantage is that the process operates in a liquid phase, including water and so wet biomass can be directly used. However there are substantial engineering challenges to delivering the feedstock as a slurry, as well as for adding the catalysts to the process. Separation of the desired product also requires more processing and therefore energy input.

3.5.6 Hydroprocessing[m]

Gasification and subsequent upgrading to a biofuel is energy intensive. An alternative may be the use of hydroprocessing processes to convert plant oils or bio-oil to a product that can then be refined in a conventional refinery. Although the process of using hydrogen to remove oxygen and other impurities such as sulphur and nitrogen from oils is an established process used to upgrade petrochemicals, it has not been on large scale biomass conversion. Neste Oil is building a plant in Finland that will use hydroprocessing to convert 100,000 t/yr of palm oil and other plant oils to synthetic diesel (DTI 2006). There remain specific issues that require further R&D including the following:

- Whether fuels produced are consistent across different feedstocks. Feedstocks will have variable carbon chain lengths, which when converted could produce fuels of differing grades. This relationship between feedstock input and fuel output thus requires further investigation as well as the compatibility of the fuel with existing fuels.

- Investigation of the costs and benefits of further refining the carbon chain molecules by ‘recracking’ or polymerisation.

3.5.7 Production of synthetic natural gas

Methane as synthetic natural gas (SNG) can be synthesised from syngas from thermal gasification of solid biomass or bio-oil by a variation of FT synthesis. SNG can also be produced as a by-product of FT for biofuel production (Huber *et al* 2006; Spath & Dayton 2003).

Anaerobic digestion can also be used to make SNG after removal of carbon dioxide from the biogas. Sources of biogas include landfill sites and large-scale digesters for municipal solid waste or marine biomass. Biogas from all sources typically contains about 50–55% methane by volume, with the balance being mostly carbon dioxide (IEA Bioenergy 2000). This carbon dioxide has to be removed to produce SNG for which there are several well-established processes available, all of which require large scales of operation to be economic. Thus, farm-scale digesters are not big enough to support a carbon dioxide removal system. The carbon efficiency of anaerobic digestion is thus not very high. Landfill gas also contains contaminants that require removal, particularly sulphur- and chlorine-containing compounds from the nature of the materials being biologically degraded.

One of the attractions of SNG as an energy product is that it can be easily distributed by the natural gas grid, in the same way as electricity can be distributed by the power grid.

SNG can be used as a transport fuel by itself as a pressurised gas of a liquefied gas with high utilisation efficiency in engines. However, there are infrastructural problems in distribution storage and by consumers who lack familiarity in its use.

3.5.8 Synthetic ethers

A range of ethers can be produced from synthesis gas by thermal gasification of solid plant material or pyrolysis liquid (Huber *et al* 2006). In the case of ethyl tetrabutyl ether (ETBE) it can be produced from biologically produced ethanol. The interest in methyl tetrabutyl ether (MTBE) and ETBE is as additives to petrol. Dimethyl ether (DME) has also been developed and is promoted as a fuel in its own right with a dedicated infrastructure (Spath & Dayton 2003).

- DME can be produced by dehydrating methanol or directly from syngas. DME has a boiling point below 0 °C and can either be stored as a liquid under normal pressure at low temperature or under a low positive pressure. Engines have been developed for its use, particularly by Volvo in Sweden. DME would require a dedicated distribution system.

- MTBE can be made from methanol by reaction with isobutylene. MTBE use has been banned in USA as it degrades slowly.

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[m] Hydroprocessing is a common process technology name for hydrogenolysis

- ETBE can be made from bio- or synthetic ethanol. It overcomes vapour pressure and materials problems of direct ethanol use but it costs more and some efficiency is lost in its production.

3.6 Biorefineries

The objective of biorefineries is to optimise the use of resources, and minimise wastes, thereby maximising benefits and profitability. The term biorefinery covers the concept of integrating production of biofuels with higher value chemicals and commodities, as well as energy. Unlike the term 'oil refinery', which almost invariably describes very large plants, biorefineries will most probably encompass a whole range of different-sized installations (Kamm *et al* 2006). In its simplest form a biorefinery could be a paper mill, which burns the waste lignin to provide heat and power (which can be used for its own processes). Similarly a sugar refinery creates value from all parts of sugar beet; even the dirt from the beet can be recovered and sold.

Several processes, biological, chemical and thermal can be integrated and optimised in a biorefinery to extract maximum value. Figure 3.4 shows how this might be achieved; however, at present, there are no biorefineries that completely fulfil this vision. Current biorefineries produce ethanol from sugars and starches, plus useful by-products, such as a pure carbon dioxide stream from the fermentation processes, which can be used in industrial processes or the drinks industry, as well as animal feed from dry milling the waste plant material[n].

A biorefinery that sequesters some or all of its carbon dioxide emissions might result in a fuel chain with a negative overall GHG metric. Carbon sequestration may take several forms including geological storage or possibly use in algal bioreactors.

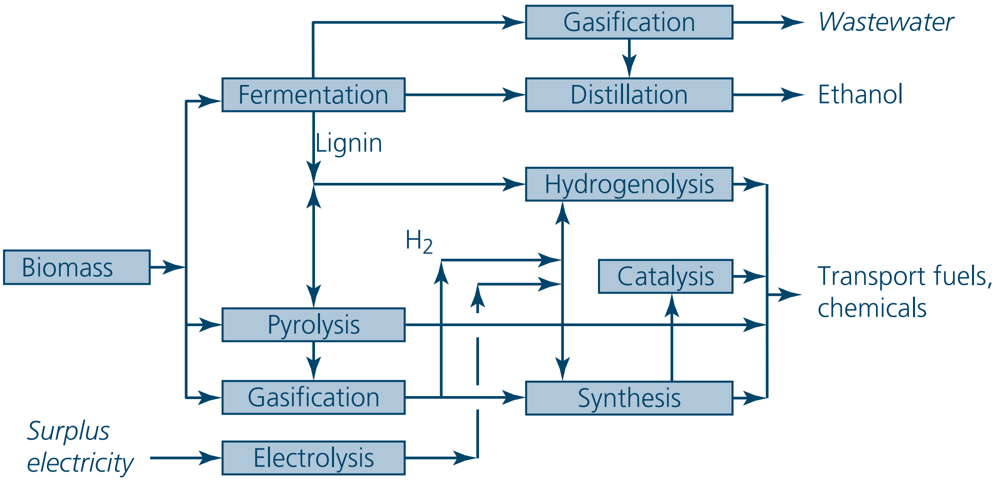
Developments in biorefineries will lead to the use of lignocellulose as a feedstock with increasingly efficient conversion processes and use of wastes. Further developments will lead to the breeding and growing of dedicated crops to optimise the production of energy and other materials.

3.6.1 Co-products: industrial and fine chemicals, fuels and power

Plant material is chemically more heterogeneous than conventional oil, so the range of primary chemicals that can be easily derived from it will be different. Currently, it is envisaged that biorefineries should be producing about a dozen platform chemicals apart from syngas (Corma *et al* 2007). Also as plants can be used to produce a range of chemicals, there is an opportunity to separate these out of the feedstock in biorefineries before biofuel production. There is also an opportunity that feedstocks, such as those from energy crops, may be modified to increase further the value of potential co-products from the biorefinery process. In this context, it is important to note that ultimately the market value for the final product will determine which product, whether fuel or chemical is produced and the quality of the feedstock used and the amount of processing required to produce it.

Any plant-based chemical industry will therefore be constructed on a different selection of simple 'platform' chemicals than those currently used in the petrochemical industry. Given the chemical complexity of biomass, there is some choice of which platform chemicals to produce

Figure 3.4 A biorefinery concept based on integrated biological and thermal processing for transport fuels and chemicals.



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[n] Some of this animal feed produced can be high protein and therefore can be sold as a valuable product; alternatively the waste maybe burnt to produce heat and power, which can be used to provide process energy

since, within limits, different processing strategies of the same material can lead to different breakdown products (Huber *et al* 2006; Corma *et al* 2007). Although biorefineries may only produce about a dozen platform chemicals, given the difficulty in predicting the future demands and prices for different chemicals, emphasis should be placed on the development of capabilities such as sugar chemistry, carbohydrate chemistry, a new catalysis for oxygenated and polyaromatic compounds, extractive processes for high value materials etc.

The production of chemicals will be an important part of the economics of a biorefinery. The empirical chemical composition of plant material (approximately $(CH_2O)_n$) means that the primary chemicals that can be easily derived from it are quite different from that of oil $(CH_2)_n$. As a consequence, any bio-based chemical industry will necessarily be constructed on quite a different selection of simple 'platform' chemicals than those currently used in the petrochemical industry. Although there is a choice of possible platform chemicals, once a set has been chosen for bio-based chemical production and the appropriate network of production plants is established, without flexibility in the conversion processes, it could become increasingly difficult to change that choice without disrupting the whole manufacturing infrastructure. Biorefineries that are designed to be flexible and modular will be able to take a wider range of feedstock or adapt to changes in the demand for specific chemicals, without huge capital costs.

The chemicals that can be produced are dependent on the feedstock crops that are used and the processing strategies that are applied. Flexibility will also mean that the biorefinery can cope with a variety of feedstocks, which mature at different times of the year. A modular installation will also be able to change its processing technologies as new feedstocks are developed. The dependence of the chemicals produced on the feedstock will inevitably be major regional differences in chemical production. It is therefore quite possible that the choice of platform chemicals derived will show much more geographical variation, globally, than in petrochemical production. This could have important consequences for the developing world and may lead to the development of different processing technologies globally.

From a research perspective, the emphasis must be on the development of a set of capabilities that are independent of the exact chemicals that may be produced.

Carbon dioxide is often a by-product or waste stream from conversion processes, notably fermentation, although it always arises from inefficiencies in all conversion processes. Ultimately all biofuels will result in emissions of carbon dioxide when they are used to release their energy and the challenge is the optimum exploitation of the chemical energy in the originating biomass or plant material. Carbon dioxide has several potential uses such as a supercritical solvent for selective extraction of high value products from the biomass or for non-toxic treatment of refinery products intended for food or nutraceutical applications (compounds that have human health benefits such as antioxidants). Carbon dioxide may also be valuable as a feedstock in its own right as a source of carbon, although current technologies are relatively unsophisticated chemically compared with natural photosynthesis (McHugh & Krukonis 1994; Clifford 1999; Kamm *et al* 2006).

3.7 Developments

Developments in conversion technologies and biorefineries will lead to more of the plant being used to produce a wider range of products and with greater flexibility in what is produced. Much of this development is technology dependent and will lead to improvements in environmental and economic performance of the processes and the supply chain. The conversion processes and the biofuel and other end-products that can be produced, are dependent on the feedstocks available and how they are developed. Optimising the efficiency of the supply chain will require feedstocks to be developed with characteristics that increase the efficiency of the conversion process and have the necessary characteristics to produce the end-products. For example, improved understanding of a particular plant species' cell wall could allow that species to be bred so it is easier to break down and its sugars released.

The development of biorefineries and the conversion processes used will be dependent on the feedstocks that are available and the opportunities for their development, either for growth in the UK or as imports. Any realistic research on biorefineries therefore needs to consider the whole systems and supply chains; research projects need to be evaluated in this context. Coordination is also needed nationally across research projects to establish feasible improvement parameters/targets for specific feedstocks and processes that can be translated across technology and discipline boundaries.

There are existing technologies available for improving the crops that produce feedstocks for biorefineries. These include fast-track breeding (non-GM) and the use of GM to increase yield and to facilitate conversion of lignocellulose (Ragauskas *et al* 2006). Although multiple products can already be gained from a single feedstock, an interesting development is the ability to vastly increase the diversity of these products using a GM strategy for the development of new crops. For example, the combined production of biomass and designer chemicals in a single crop holds great economic potential because co-products can add value to biofuel production (Ragauskas *et al* 2006). There are existing examples of this strategy in use to add value to switchgrass and sugar cane. Also, research is already in progress in which genes encoding hydrolytic enzymes are expressed in an inducible way in the transgenic crop to enable the start of hydrolytic digestion in the field and/or post-harvest. Closest to market are the amylases in maize kernels for starch digestion, but as new hydrolase compilations are discovered for lignocellulose digestion, the same strategy can be readily used in biomass crops.

How the various processes in the conversion stage are combined in an integrated biorefinery will have significant impacts on the sustainability of biofuels. Throughout the biorefinery, there is the opportunity for improved recycle of heat/energy or reuse (for example for district heating) which will have an impact on the carbon footprint of the overall process. Integration and optimisation of the processes does not mean that they all need to take place on the same site. Pre-treatments can lead to increased efficiencies in the conversion process, such as by the elimination of water or other impurities that could disrupt the catalysts. Preliminary solvent extraction may also take place locally, producing a mixture of 'higher value' plant chemicals that could be processed at another location, or low value extracts that are best exploited locally (for example to spray on fields). Understanding the total energy and GHG emissions that are emitted from the various options and structures will be vital in determining where these processes are located.

Nature may already be able to provide the characteristics required for bacteria to perform advanced processes, such as breaking down lignocellulose in the guts of ruminants or termites, or to survive potentially extreme conditions, such as in geothermal springs or the deep ocean. A huge resource of microbial and fungal species is already available, for example in the Natural History Museum and Kew Gardens, which could be examined for potentially useful characteristics. These characteristics may be transferable to other bacteria. Developments in synthetic biology could lead to the development of entirely new bacteria that are designed for specific purposes and which can withstand the process conditions.

Specific research needs

The different conversion processes all have specific research needs. In the case of fermentation, new microbial strains are needed to convert hemicellulose and cellulose directly, which will increase the efficiency of the conversion process reducing the need for a separate process. Developments may lead to a single process, using either a single microbe or a mixture, can break down lignocellulose material and ferment C5 and C6 sugars to alcohol. The *Clostridium* genus includes species that are cellulolytic; the genome sequence of *C. acetobutylicum*, which can produce biobutanol, shows evidence for a primitive cellulase (Nölling *et al* 2001).

Microbial tolerance to alcohols needs to be improved particularly to higher alcohols such as butanol. This will increase the efficiency of energy-intensive processes for extracting the alcohols. Opportunities exist for combining chemical, biochemical and thermal processes informed by a new branch of catalysis and even emerging disciplines such as synthetic biology with the fermentation process, which may allow higher alcohols to be produced without poisoning bacteria. The integration of chemistry, biology and process engineering is required to intensify processing and improve performance across a range of metrics.

Catalyst development is required across several processes. For the trans-esterification of plant oils to biodiesel, solid catalysts, such as enzymes or nano-materials, could be easily recovered and reused, which compared to using sodium hydroxide as a catalyst would reduce the amount of wastewater treatment required. Developing new oil crops that produce waxy esters that do not need transesterification will also be important. Improved catalysts would also increase the efficiency of hydroprocessing lignocellulose material to synthetic diesel (Huber *et al* 2006; Spath & Dayton 2003). In the FT conversion, there are real drivers for improved catalysis such as developing catalysts with improved sulphur tolerance, regeneration and recycling (Huber *et al* 2006; Spath & Dayton 2003). Longer term developments that replace FT conversion are also needed and these would need to produce fuels with higher oxygen contents to match the plants from which they are derived.

4 End use and distribution

This chapter will discuss how biofuels are distributed and used in vehicles. It details how different fuels will result in different developments in engines and infrastructure, the implications of fuel specifications and standards on different biofuels that can be produced, the emissions that arise as a result of burning biofuels, and how different biofuels differ in their emissions profile.

4.1 Overview

Use of biofuels has several implications for the end use and distribution chain, including on fuel quality, fuel vapour pressure, viscosity, engines and their fuel supply lines etc. Specific biofuels and the different blends offer advantages and disadvantages in each of these aspects, all of which need to be carefully considered when deciding the policy framework and objectives of a biofuels market.

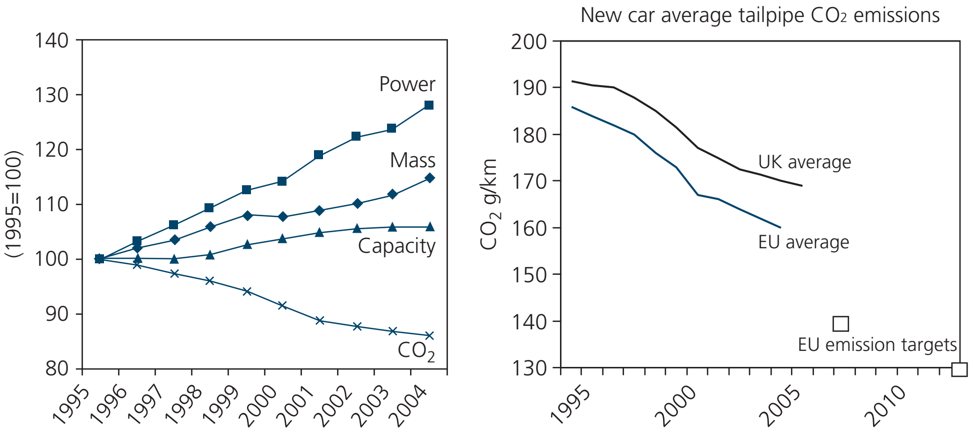
There are several policy drivers involved here, including the need to reduce GHG emissions, improve air quality and improve fuel quality. The issues are intimately related and developments in each part of the biofuel production and supply chain will have implications for another. Any specific changes that arise as a result of policies to encourage biofuel use (for example the UK's Renewable Transport Fuel Obligation (RTFO) or the European Union (EU) Biofuels Directive), will have implications further up the supply chain, in terms of what feedstock is produced, how it is converted and what specific fuel type is produced and blended.

The implications, opportunities and threats for increased usage of biofuels also need to be assessed within the context of existing trends in engine and fuel technologies and regulations that are already decreasing vehicle carbon dioxide and pollutant emissions, particularly in Europe (LCVP 2007; Derwent 2006). Demands for increased power and safety have led to increased weight and engine capacity which require more fuel. However, improvements in fuel efficiency have so far slightly outweighed the impacts of these demands as highlighted by Figure 4.1. Conventional biofuels with their lower energy density and higher oxygen content could help to raise power but decrease volumetric fuel efficiency and have complex positive and negative impacts on air quality as discussed below.

Use of synthetic biofuels (made from plant material), can mean that many of the issues discussed in this chapter can be avoided. As these fuels are almost identical to conventional transport fuels, they can be delivered and used in the existing distribution and end use infrastructure without the need for any modifications to engines and fuel supply lines (Joseph 2007). Where the synthetic biofuels are finished in existing oil refineries, consumers will be familiar with the quality and performance of the product as they will have to meet the quality and standards of oil derived fuels and so reduce the risk of consumer resistance. Synthetic biofuels are also cleaner than conventional oil based fuels, as many of the contaminants have been removed to avoid poisoning the catalysts used in processing (Lemon 2007). There remain issues that need to be resolved such as the variation between the carbon-chain of the fuels that are produced and the costs associated with re-cracking molecules to produce more of the desired fuel.

Nevertheless, as the biofuels market is at an early stage of development, it is reasonable to assume that there will be a mix of different biofuels including synthetic biofuels, bioethanol, biodiesel and biogas. All these fuels will have implications for the distribution and end use sector. For example, low blends of ethanol and biodiesel

Figure 4.1 New car CO_2 emissions are declining in Europe but targets will be missed due to growth in vehicle power and size. (Source: based on data from SMMT(2006), LCVP (2006) and EC (2007)).



(for example Ethanol 5% (referred to as E5), 10% (E10) and Biodiesel 5% (B5), 10% (B10)) can be distributed and used through the existing infrastructure, with some caveats. However this also means that GHG savings per litre of fuel used (rather than per litre of biofuel) or per kilometre driven would be less with low blends than those achieved through using higher blends, even assuming GHG-efficient biofuel production. Using higher blends however requires modifications in the engine technologies deployed and the fuel delivery infrastructure (Lemon 2007), implying a significant lead-time to wide-scale deployment and the need for public support to kick-start market development.

Problems specific to individual biofuel types cannot be applied generally to all biofuels: for example, difficulties with cold starting (high blend bioethanol and biodiesel) and vaporisation of fuel in the fuel line when the ambient temperature is hot (bioethanol). Biodiesel also suffers from issues to do with viscosity at low temperatures and gum formation in the engine (Lemon 2007). There are also biofuel-specific impacts on air quality where use of biofuels can lead to increased production of ozone precursors, carcinogens and respiratory irritants (for example NO_x, carbon monoxide, particulates, aldehydes, etc.) (Jackobson 2007).

Public perception issues will also have an important role and will need to be dealt with openly. These include the potential positive initial reaction to use of biofuels, through to issues related to ambiguous engine warranties and engine damage due to biofuel usage and potentially increasing scepticism of consumers about whether biofuels can offer real environmental benefits or if there is sufficient land available to make a material difference. However, there are potential solutions to these issues raised above, but they will require a policy decision, which must also take into account any tradeoffs in performance or quality of the fuel. For example, the use of flexi-fuel vehicles can help the transition to increased biofuel usage. Use of cetane enhancers with ethanol can help replace diesel usage in trucks and overcome biodiesel gumming problems (Hofstedt 2007). Altering catalysts may help reduce aldehyde emissions and therefore reduce production of this ozone precursor (Joseph 2007). Any policy decision to address the tradeoffs will need to be made based on the best available evidence while also considering the upstream implications (ie on feedstock production and conversion). These decisions also need to be made bearing in mind the history of improvements in engine efficiency and reductions in emissions which are also expected to continue into the future.

At present, there is a lack of real alternatives to help reduce GHG emissions or over-dependence on oil in the transport sector, which makes it essential to develop biofuels in as sustainable a way as possible. It is important therefore that the policy framework allows suitable flexibility for the market to develop different combinations and not exclude one: for example incentivising the purchase of different fuel blends would help to create demand for biofuels in the market, which would drive through changes in feedstock production and conversion sectors. Developing national biofuel markets is not unprecedented and the experience in Brazil (with ethanol from sugar cane), Sweden (ethanol) and Germany (biodiesel) all offer useful examples of how this can be achieved (Goldemberg *et al* 2001; Tipper *et al* 2006), the incentives needed to overcome the technical and non-technical barriers and the proven technological options that already exist to help deliver policies.

4.2 Relative differences between different fuels and their usage

From the perspective of end use and distribution, bioethanol and biodiesel are attractive, because they have the closest physical and chemical characteristics to the mineral diesel and petrol fuels that dominate the supply of energy in the global transport sector. Biogas is also an alternative to CNG in vehicles that are able to use a gaseous fuel, but this currently represents a very small fraction of the EU or global market outside niches such as urban bus fleets.

Neither bioethanol nor biodiesel are exact analogues for petrol or diesel respectively. Ethanol has substantially lower volumetric energy content and the longer carbon chains in the biodiesel cause problems because of its higher viscosity (Lemon 2007). Other issues with ethanol include vapour pressure, oxygen content and its hydrophilic nature, which will lead to an increase in the corrosion of the supply infrastructure (Bennett 2005). For biodiesel production, the simple nature of the transesterification process lends itself to smaller-scale production that does not require major capital, which in turn makes it more difficult to enforce uniform high standards in quality. As a result, neither of these biofuels meets current EU fuel standards (Lemon 2007) if blended in existing conventional fuels at levels of greater than 5% by volume (see Section 4.3).

To meet maximum emissions levels and to improve the combustion of fuels, a minimum (and maximum) oxygenate level is specified. A higher oxygen content of biofuels, in particular ethanol (and its derivative ETBE), means that it can be used as a fuel additive, originally to replace lead as a so-called ‘anti-knock agent’ in petrol and now to replace MTBE (its methanol-based equivalent). There is still a debate occurring about the relative GHG efficiency of ethanol compared with ETBE, with ETBE proving to be an efficient option when produced in large-scale plants (evidence from Lyondell and analysis by Edwards *et al* 2007).

The limitations of biofuels mentioned above are leading to a search for new chemical and biological routes to the production of novel biofuels with properties that are closer to petrol and diesel but without losing the advantages of biofuels (see Chapter 3). Specifically, molecules that have higher energy density, are less hydrophilic and have similar vapour pressure profiles to petrol, rather than ethanol, are being pursued such as alkanes (Huber 2007). Issues about vapour pressure have implications for fuel standards and are discussed further in Section 4.3.1. Options for diesel replacement require similar cetane and viscosity properties.

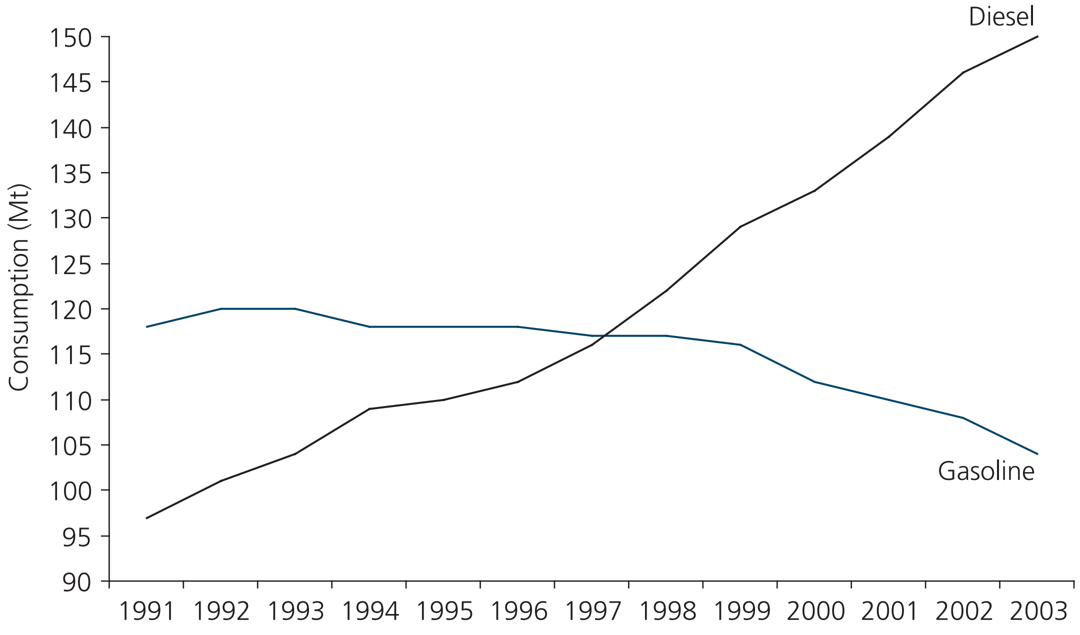
Much of the rise in diesel consumption in the EU (see Figure 4.2) is a result of the greater efficiency of compression ignition engines and the slightly higher volumetric energy density of diesel compared with petrol. In the USA, where fuels are much cheaper, there has not been the same pressure to gain in fuel efficiency and so petrol has remained the dominant fuel in the transport sector.

4.3 Fuel standards and specifications

There is a need for robust and clear systems for fuel standards and specifications which create consumer confidence in biofuels. This goes beyond providing fuel specifications that are technically acceptable to fuel companies and car manufacturers. Consumers need to know and trust the safety of biofuels for engine effects and warranties. However, a situation in which car manufacturers simply say that no biofuels can be used in their engines, thereby avoiding warranty issues is creating and maintaining a barrier to biofuel use (see also comments of consumer confidence in Chapter 3). Fuel standards play a major role in defining the opportunities for biofuels and in some circumstances stipulate the maximum amount of biofuel that can be blended with the base fossil fuel stock. In the EU fuel standards are dictated by the EU Fuel Quality Directive, which has very different implications for bioethanol and biodiesel, effectively limiting the maximum amount of bioethanol that can be blended with petrol to less than 5% per volume (EU 2003). Also, the role of anti-knock agents that prevent premature ignition by maintaining a high oxygenate concentration is important. For biodiesel this stipulation does not exist although parameters such as 'cold filter plugging points' are important. Relevant EU fuel standards for diesel / biodiesel are EN14214 (FAME; UK EN590, all EU diesel) and for petrol/ethanol EN 228 (Unleaded petrol; EU Auto Oil Directive). In January 2007, the European Commission proposed a revision of the standards in the revised EU Fuel Quality Directive (98/70/EC) (EC 2007). For ethanol, the standards have limited the volume that can be blended with petrol to a maximum of 5% per volume in order not to exceed the maximum oxygenate content, although this can be exceeded for 'demonstration' purposes.

There are similar restrictions for biodiesel, limiting it to blends of up to 5% per volume with mineral diesel as long as it meets the EU FAME standard 14214 (CEN 2003). Several vehicle manufacturers have been willing to warranty their vehicles if the fuel used meets the EU FAME standard. However, recently, some manufacturers have reported problems with higher blends of biodiesel and have withdrawn their warranties (*Personal communication* von Buch F, Volkswagen 2007). This

Figure 4.2 EU trends in diesel and petrol consumption (1990–2004) (Source: based on data provided by Blondy J, Total, 2007).



NB: Gasoline: –2.6% per year Diesel: +4% per year appears to be mainly a problem with inconsistent fuel quality arising out of the much-increased range of producers and also some more fundamental problems arising from the greater carbon chain length of biodiesel than mineral diesel. This greater chain length is reported to result in a lower share of the biodiesel being re-volatised when it passes the piston rings and enters the lubricant oil, requiring temperatures in excess of 300 °C for this to happen (*Personal communication* von Buch F, Volkswagen 2007). Mineral diesel on the other hand has a much more variable chain length and the shorter chain components are volatised from the oil at the prevailing engine operating temperature. As a result the lubricity of the oil is compromised over much shorter operating times with biodiesel blends than with mineral blends.

For EU member states to meet the EU Biofuels Directive target of 5.75% displacement of fossil fuel on an energy basis, significantly greater blends than the current 5% per volume threshold will be needed. However, ten percent blends of bioethanol and biodiesel do not currently conform to European fuel standards EN590 or EN228. These issues and conflicts are driving the review of the EU Fuel Quality Directive.

4.3.1 Vapour pressure and bioethanol

A key problem with ethanol blends is maintaining a standard vapour pressure. In petrol, this is generally achieved by the removal of the more volatile substances during summer (eg. butane), which is sufficient to stop the fuel volatising in the fuel delivery system (Bennett 2005). This also allows enough vapour pressure for the fuel to vaporise and spark the ignition during cold periods in winter. Ethanol has a lower reed vapour pressure than petrol. When the two fuels are blended, it forms azeotropic mixtures with some components of the petrol and is also sensitive to the nature of the base petrol used. The result is an asymmetric relation between the vapour pressure of the blended fuel and the volumetric blend rate of the ethanol (Figure 4.3). When the vapour pressure drops below 45 kPa fuel ignition cannot be guaranteed on cold winter days, effectively limiting the maximum ethanol blend percentage during the winter months to E75 (Bennett 2005).

4.4 Engine modifications and performance

Developments in engines will be required if they are to burn larger blends of ethanol because it is corrosive and degrades a range of the materials found in specific components of the engine and fuel supply systems (Joseph 2007). In theory, at least, if biodiesel meets the EU standard set by the Fuel Quality Directive, then no modifications to diesel engines are required. However, several issues have been reported by vehicle manufacturers.

There is an urgent need for official benchmarks on engine performance and emissions when using different biofuels. Existing data are confusing and contradictory, and various claims and assumptions are made about megajoules per kilometre (MJ/km) or miles per gallon (mpg), and GHG emissions per kilometre (especially methane (CH_4) and nitrous oxide (N_2O)) (TNO Automotive 2004). There is also an almost complete lack of agreed data from official and independent tests and trials. Often CH_4 and N_2O are not measured specifically as these emissions are 'buried' with the data on VOCs and NO_x. However, CH_4 and N_2O emissions are needed to evaluate net GHG emissions properly.

4.4.1 Flex-fuel engines

Flex-fuel, or flexible fuel, vehicles (FFVs) have engines that can alternate between two sources of fuel, including petrol and bioethanol or petrol and natural gas. The petrol and bioethanol FFVs offer several advantages and have been used extensively in Brazil and to a lesser extent in the USA and Sweden (Joseph 2007). They allow the 'chicken

Figure 4.3 Relation between ethanol content and vapour pressure for petrol-ethanol mixtures (Source: based on data provided by Bennett J, Ford Motor Company 2007).

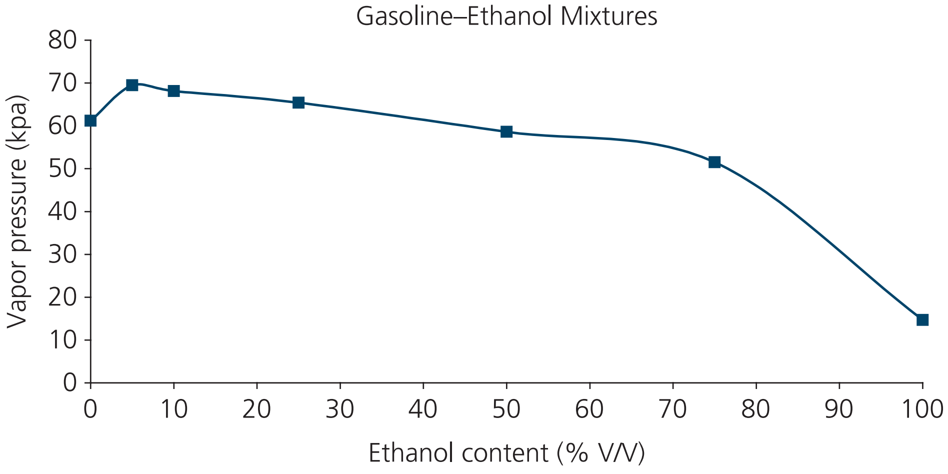
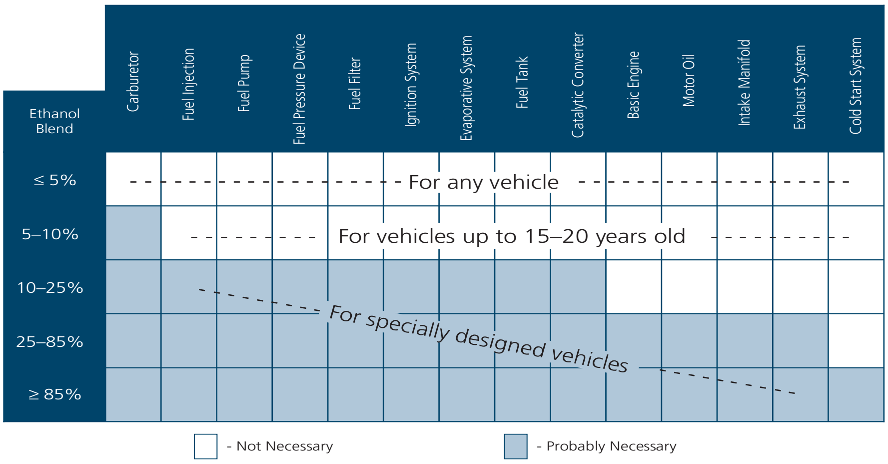


Table 4.1. Necessary modifications to engines to cope with increasing ethanol/petrol blends. This figure is based on necessary modifications introduced by the Brazilian automobile industry (mainly Volkswagen) since the beginning of the ethanol programme in Brazil in 1979. (Source: Joseph 2007).



Ethanol Blend	Carburetor	Fuel Injection	Fuel Pump	Fuel Pressure Device	Fuel Filter	Ignition System	Evaporative System	Fuel Tank	Catalytic Converter	Basic Engine	Motor Oil	Intake Manifold	Exhaust System	Cold Start System
≤ 5%	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5–10%	▨	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10–25%	▨	▨	▨	▨	▨	▨	▨	▨	▨	☐	☐	☐	☐	☐
25–85%	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	☐
≥ 85%	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

☐ - Not Necessary

▨ - Probably Necessary

and egg cycle' to be broken, whereby fuel suppliers do not want to supply biofuels until the market is big enough and vehicle manufacturers do not want to supply new biofuel capable vehicles until the fuel can be supplied in sufficient quantities. The development of appropriate market incentives to encourage development and supply of FFVs could offer more flexibility to increase biofuel usage.

New generations of engines designed to work with higher biofuel blends allow the engines to be modified to maximise the benefits of the higher oxygen content and so improve fuel efficiency and reduce emissions (Joseph 2007). Table 4.2 shows differences between different generations of FFVs in Brazil: the first adopted standard engine compression ratios and so paid the full cost of the lower energy density of ethanol. Engines are being developed with higher compression ratios resulting in improved fuel efficiency as confidence increases that ethanol fuel will continue to be available and in higher blends (Table 4.1). It is important to note that on a volumetric basis, mileage with ethanol is lower than with conventional gasoline, but on a kilometre per mega joule fuel (km/MJ_{fuel}) basis, gains in efficiency can be realised (Joseph 2007).

4.4.2 *Other implications*

Developing alternative biofuels (such as synthetic biofuels), as described in Chapter 3, can open up the potential to deliver tailor-made biofuels to specifically designed engine technologies. For example, Volkswagen has developed a combined combustion system coupled to fuel derived from the Fischer-Tropsch process. Opportunities also exist to use biofuels in electric-hybrid vehicles. The key issue here is whether these biofuels can be used to deliver the European Union's Euro 5 and 6 vehicle emissions standards, which require much greater reductions in air pollutants such as NO_x and particulate matter from petrol and diesel vehicles (EU 2006).

4.5 Atmospheric emissions from the use of biofuels

As with GHG emissions, there are large differences in the exhaust emissions of pollutants between different biofuels, arising from their different physical and chemical characteristics (TNO Automotive 2004). Chapter 5 discusses the implications of these emissions and how they are evaluated. Further uncertainty results from the use of regulated drive cycles versus actual data from real-world tests. Because biofuels are relatively new to the modern vehicle set many of the emission factors taken for granted with fossil-fuel powered vehicles need careful analysis when testing biofuels.

Based on data from VTT (Technical Research Centre, Finland) emissions from ethanol-fuelled (E85) vehicles are similar compared with standard EU2000 petrol (slightly higher for CO and HC, almost identical for 1,3-butadiene and BTEX and slightly lower for PM and NO_x). But the formaldehyde and acetaldehyde emissions are significantly higher, and this confirms other data sources looking at ethanol emissions (for example Nylund & Aakko 2005).

Although formaldehyde and acetaldehyde are naturally occurring and are frequently found in the wider environment, additional emissions may be important because of their role in smog formation (UN-Energy 2007; Leong *et al* 2002) and at higher concentrations, direct effects on health (USEPA 1994). It remains unclear whether the atmospheric concentrations that might result from a major shift in urban fuel use towards ethanol would be sufficient to cause health worries but more research is required on this topic. It also appears possible that, should the health concerns prove serious, alterations to catalytic converters could help reduce acetaldehyde emissions (Leong *et al* 2002). A second area requiring further study is the emissions of ozone-forming precursors, but this topic is not discussed here.

Table 4.2. Comparison of performance of different generations of flexible fuel vehicles using bioethanol as the fuel. Percentages show change in performance compared with using petrol (Source: Joseph 2007).

Year	Engine compression ratio	Engine power	Engine torque	Fuel efficiency improvement	Petrol injection cold start system
2003	9.0:1 to 10.5:1	+3%	+2%	–25 to –35%	Yes
2006	11.0:1 to 12.5:1	+7%	+5%	–25 to –30%	Yes
2008	12.0:1 to 13.5:1	+9%	+7%	–20 to –25%	No

4.6 Conclusions and recommendations

Biofuels offer opportunities as well as threats to future developments in engine technologies designed to improve energy efficiency (km/MJ) and decrease emissions of regulated and non-regulated pollutants. The sustained increase in the use of biofuels urgently requires the parallel and compatible development of engine technologies and biofuel feedstock and conversion technological R&D. Major synergies and gains in efficiencies are possible if such cooperation emerges.

Biofuels will initially be blended with their fossil-fuel analogues at pervasive low blend rates, which is approximately 5–10% by volume for bioethanol and biodiesel. This should provide an incentive to optimise engine development that maximise the advantages and minimise the disadvantages of the biofuels at these blending levels. National, regional and global policies should signal that this is not a short term phenomenon so as to give confidence to vehicle manufacturers and fuel distributors to invest in pro-biofuel engine developments and to adapt existing engine developments to the needs of biofuels. Synthetic biofuels offer an attractive route as they can be used in the existing transport infrastructure and therefore do not require engine or supply-line modifications or even conflict with fuel standards.

In order to develop a regulatory framework and to set standards to allow the whole biofuel supply and use chain to be optimised there is a need for those involved in their development to:

- provide clear information on the types of fuels that future engine technologies will require to be energy and environmentally efficient;
- provide clear information about the physical and chemical characteristics that are possible to provide in future biofuels (energy density, oxygenate levels, cetane number, hydrophilic/hydrophobic etc);
- adapt and optimise for higher blend biofuels.

During the development and assessment of biofuels, careful attention should be paid to ensure that:

- Specific hydrocarbon emissions are controlled, particularly those that are either carcinogenic, cause respiratory problems, or are precursors to ozone production (which impact on humans, animals and vegetation). The links between exhaust emissions and health impacts are not sufficiently well understood and further work is required.
- Particulate matter emissions are considered in engine developments. Spark ignition engines, and therefore petrol type fuels (for example ethanol) have a clear advantage here. More work is required to transfer these advantages to compression ignition engines or future hybrids. Current and future biofuels need to be considered in the development of these novel engine cycles.
- NOx emissions are considered in fuel and engine developments. More work is required to modify biofuel properties and engine technologies and exhaust after-treatment technologies to abate these emissions.
- They have the correct characteristics: increased energy densities, less hydrophilicity, correct carbon chains lengths (shorter in the case of petrol substitutes and longer in the case of diesel substitutes) and better lubricity properties.

Spark ignition (petrol-fuelled) engines currently emit substantially less pollutants than compression ignition (diesel-fuelled) engines per kilometre driven. However, compression ignition engines are substantially more energy efficient. The lower energy density of ethanol (primarily a petrol substitute) exacerbates this situation of pollutant emissions and vehicle energy efficiency. As ethanol has a higher octane number than petrol, it allows for the use of higher engine compression ratios, which in turn will partly redress these issues.

5 Evaluating the impact of biofuels

This chapter discusses key environmental issues associated with production of biofuels and ways in which they can be addressed. These concepts have already been referred to in Chapters 1–4 and are referred to in Chapters 6–8. The issues include energy consumption, GHG emissions, land use, water consumption, eutrophication, biodiversity and air quality. It is vital that these impacts are evaluated and quantified in order to provide a rational basis for assessing the long-term viability and acceptability of individual biofuel supply-chain options. Tools such as LCA, environmental impact assessment (EIA), strategic environmental assessment (SEA) and sustainability assessment (SA) provide important frameworks for such evaluations. This chapter focuses on the use of LCA to provide such a framework for cross-comparison between the supply-chain options and the wider direct and indirect impacts.

5.1 Overview

Expansion in the use of biofuels for transport will entail both positive and negative environmental impacts. The extent and nature of these impacts will vary according to developments throughout the entire production chain from feedstock production, conversion and end use. If biofuels are to be genuinely sustainable, then the developments that offer the greatest environmental benefits will need to be given priority. However, there will also be trade-offs between the different impacts because some developments might offer benefits for one environmental issue while negatively impacting another. The potential impacts of widespread cultivation of biofuel crops and feedstock developments range across GHG emissions, changes in land use, water use and the impacts of increased nutrient and pesticide applications. Similarly, conversion into biofuels and subsequent end use of the fuel will also have wider environmental impacts including water usage and contamination and air quality. It is also important to consider the indirect environmental impacts that might arise as a result of the interactions between different land uses, such as land used for biofuels, food and material production. All these interactions will have impacts including those listed above; it will be important to ensure that impacts are not unfairly related to one use if they are also relevant to other uses. Ideally, all direct and indirect impacts need to be evaluated and applied in consistent assessment of biofuels. This would help to compare the overall benefits of different biofuels and indicate to what extent they are environmentally sustainable. The assessments would also help to identify practices and developments that offer the maximum benefits. Opportunities exist for how these issues can be assessed such as through use of tools like LCA. However, substantial knowledge and gaps in the data also exist in evaluation of impacts on biodiversity, water and eutrophication, so that tools such as LCA can at present only provide a partial picture of the real impacts of biofuels.

The analytical techniques and issues presented in this chapter will also have policy implications in the UK, EU and globally, such as on the UK RTFO and EU Biofuels Directive.

5.1.1 Sustainability of biofuels

Any assessment of the environmental impact of biofuels must also occur in the context of sustainability which incorporates other aspects, especially related economic and social issues. Inherently, the term 'sustainable' cannot be captured using a single simple metric. Instead, definitions tend to capture the concept by using diffuse but intuitive terms or a sub-set of quantifiable/semi-quantified targets such as the Millennium Development Goals (Brundtland 1987, UN 2007).

As with any new development, evaluating the economic and social impact of biofuels and their potential can be difficult. A robust economic assessment needs to incorporate changes such as removal or application of financial incentives, subsidies, taxes, and the emergence of new products and services. Without such assessments, investments which are very risky and wasteful may be made, and may not achieve the claimed economic benefits.

The development of biofuels has both direct and indirect social impacts, including job creation (quality and permanence), social responsibility and social equity, including issues such as wealth distribution to rural communities. For example, the 'food versus fuel' debate is a serious issue as the rapidly increasing demand for biofuels can substantially distort global food markets (UN-Energy 2007). Whereas the rural poor in developing countries, who are mainly farmers or are involved with agricultural production and are likely to gain from increased agricultural commodity prices, the urban poor will be vulnerable to the price increases. Potential inequalities such as these have to be addressed within social sustainability and through more cautious use of policies to promote biofuels.

5.2 Life-cycle assessment

LCA is an established technique for evaluating the natural resource requirements and environmental impacts from the whole life cycle of a product or service (ISO 2006). In theory, LCA can be used to provide a complete evaluation of all the natural resource and environmental impact of a product or service. However, this requires a large amount of data on the life cycle of the product or service as well as the complete network of products and services used for its provision, use and, where relevant, re-use, recycling and eventual disposal. Although there are numerous software packages and supporting databases to accomplish this, (see Mortimer *et al* 2007) in practice, many LCA studies concentrate on the most prominent natural resource and environmental impacts of a given product or service.

In practice LCA usually focuses on land use, primary energy and GHG emissions, and it provides a highly effective means of estimating total GHG emissions and energy resource depletion associated with the production and utilisation of biofuels. These estimates are calculated relative to the conventional oil-based transport fuels that biofuels potentially replace. Some combinations of options for producing biofuels could result in only small net GHG savings, and in the worst circumstances, total GHG emissions could be higher than those of fossil-based petrol and diesel. Conversely, if favourable combinations of options are chosen, then biofuels can be truly 'carbon neutral' (zero total GHG emissions or 100% net savings) or perhaps even 'carbon negative' (potential GHG emissions savings exceed those of fossil-based diesel and petrol) (see Larson 2005 and references in Table 5.2).Therefore, deriving such estimates will mean that LCA can be used as a tool to help decide on the combinations of options for producing and using biofuels that result in the largest reductions in GHG emissions. As biofuels and feedstocks can be imported, the technical and geographical scope will affect LCA results, which makes it important to ensure that such differences are also incorporated into assessments.

Other potentially important issues that have received less attention in LCAs include water consumption, eutrophication, biodiversity and air pollution (Rowe *et al* 2007). Where data on these other impacts are available, they need to be incorporated into LCA. In the absence of such data, these wider impacts also need to be analysed using techniques such as SEA and EIA. These assessments are enshrined by EU directives and provide a more qualitative assessment of the wider impacts of products and services, such as biofuels (EU 1997, 2001). The assessments are especially important where quantitative data do not exist on specific environmental impacts. These assessments do not replace LCA but can add balance by providing a more holistic picture of environmental impacts. Decision makers need to ensure that assessments of biofuels are based on both quantitative LCA and qualitative assessments. Decisions on the choice of biofuels and production processes must also ensure that the influence of quantitative and qualitative data is balanced objectively so far as possible.

5.3 Limitations and opportunities in life-cycle assessment

Some LCA studies show a range of fundamentally different results for net savings in GHG emissions savings. This is potentially confusing and misleading for policy-makers and the public. Ensuring that all LCA studies are transparent provides a simple way of addressing this problem. Transparency means that all calculations, assumptions and sources of data are documented and accessible to the subsequent audience. Only through transparency in LCA studies can the differences in results be identified and resolved satisfactorily. This, in turn, would increase confidence in the meaning and suitability of LCA. It is expected that the methodology for assessing biofuels through the UK RTFO and elsewhere will adopt this approach (DfT 2007).

The Global Bioenergy Partnership (GBEP) was launched in July 2005. It involves all G8 countries, China and Mexico plus FAO, IEA, UNDP, UNCTAD, UNEP, UNIDO, UNDESA, UNF, WCRE and EUBIA, with Brazil, Tanzania and the World Bank as observers. Part of the current work of GBEP is to harmonise the methodologies used to conduct LCA of biofuels. Work is on-going and is expected to be complete during 2008.

Even with full transparency, there still remain several fundamental issues for the practical application of LCA for biofuels, including the choice of reference systems, especially for alternative land use, the selection of allocation procedures for joint products and missing data.

Both geographical and technological scope can also have a significant influence on LCA results. In the LCA results presented in this section, the focus is on biofuels that could be produced under current circumstances in the UK. However biofuels and feedstock can also be imported from other countries (see Section 2.3). Additionally, new feedstocks and processing technologies are being developed that might replace those which are currently available. Hence, LCA studies are needed on all the current and likely future major biofuel options for the UK in order to have a realistic policy debate.

5.3.1 Establishing reference systems

Reference systems are used in LCA when the activity under consideration displaces an existing activity, particularly in cases involving fixed resources such as land. In the case of land used to grow crops for biofuel production, the question arises 'what was the land used for before the new crop was grown?' This is an important question because land availability and use cause real changes in GHG emissions associated with the biofuel(s) in question. LCA has to address the GHG emission of the previous land use; this emission becomes a 'credit' for the biofuel in subsequent calculations. Typically, it is assumed that 'maintained set-aside' will be used to produce biofuels in the EU. Hence, 'maintained set-aside' becomes the reference system in LCA calculations.

As biofuel use expands, it will probably become necessary to use other land which normally produces a tangible product, such as a food crop. The fact that a crop has been displaced and will presumably have to be cultivated elsewhere has to be taken into account in the LCA calculation. Consequently, an LCA study would now have to examine such alternative cultivation by establishing so-called 'comparative reference systems'. This involves identifying all the critical resource inputs and key desired outputs before and after the biofuel is produced. For biofuels, the critical resource input is land. For example, before biofuel production, if land is used to grow a food crop and crude oil provides transport fuel and then the land is used for biofuel production, some other land will be required to grow the food and crude oil is no longer needed for road transport. The critical resource inputs and key desired outputs in these 'before' and 'after' situations must balance and the change in net GHG emissions can also be determined by their comparison. In this case, there must be some unused land somewhere that can be used to grow the displaced food production. However, important questions remain concerning which current food growing land will be used to grow biofuels and which land will be used to grow the displaced food crop. One way of resolving this could be by LCA coupled with market analysis. This is where assessing the market can help affirm what land has been used to grow the displaced crop and the GHG emissions that have arisen as a result.

5.3.2 Joint product allocation

The production of many biofuels involves the generation of other products, such as agricultural residues (straw, bagasse, corn stover, etc.) and process by-products (rape meal and glycerine, distillers' dark grains and solubles, sugar beet pulp, etc.). It is necessary to divide total GHG emissions between such joint products in a meaningful and justifiable manner. Comparative reference systems also find application in the issue of the allocation of GHG emissions between joint products (Mortimer 2006). There exist several possible allocation procedures and this can lead to the conclusion that the choice and subsequent LCA results are arbitrary and, potentially, subjective, which is not a sound basis for the evaluation of biofuels. There is a need to develop an agreed, practical and realistic approach to joint product allocation.

5.3.3 Missing data

There is also a need for accurate and complete quantification of all the main sources of GHG emissions associated with biofuel production. There are several prominent considerations where fundamental scientific data are incomplete or uncertain for biofuels such as the emission of N_2O from soils and changes in the carbon content of certain soils, both of which are major issues (see Section 5.4). Missing data on wider environmental impacts such as water use, biodiversity, eutrophication and air quality (such as ozone precursor formation from ethanol evaporation – Chapter 4) also need to be incorporated into LCA. In many instances, surrogate or approximate data on such considerations are available for LCA calculations. However, such proxies have sometimes been based on political expediency and compromise rather than established science and observed data. As discussions and negotiations over the possible successor to the Kyoto Treaty intensify, new understanding and data will emerge on these topics. However, the process of data gathering needs to be accelerated and coordinated to ensure that a comprehensive and coherent database is available as quickly as possible to support LCA in assisting the policy debate.

While such databases are being developed, it will also be important to use qualitative techniques such as SEA and EIA along with LCA to ensure that the wider suite of impacts can be assessed and fed into the decision-making process.

5.4 Biofuels and greenhouse gas emissions

Greenhouse gases, such as methane, carbon dioxide and nitrous oxide (N_2O), are emitted along the entire supply chain and are affected by various practices and processes, including fertiliser use, agronomy, harvesting, conversion and distribution. In addition, plants also emit volatile organic compounds (VOCs) such as isoprene, which not only affect air quality, but in the presence of NO_x can lead to the formation of the GHG ozone (see Section 5.7.1) (Arneth *et al* 2007). LCA can incorporate some of the main sources of GHG emissions into calculations (see Section 5.3). However, as discussed in Chapter 2 there is a need for substantial research to provide better assessments of land use change, soil carbon and N_2O emissions and how these might be reduced.

5.4.1 Soil carbon and carbon sinks

Chapter 2 highlighted that the CO_2 emissions from converting land types, particularly those that are large carbon sinks need to be evaluated. Studies estimate that the net land carbon sink, including soils and vegetation, is approximately 1.5 gigatonnes of carbon per year (GtC/yr), and takes up some 20% of current human CO_2 emissions (Royal Society 2001). However there are uncertainties in quantifying the size of land carbon sinks at a local scale that requires research (Royal Society 2001). Globally, peatlands contain about 528 Gt of carbon, of which 42000 Mt is contained in forested tropical peatlands of SE Asia (Hooijer *et al* 2006). Drainage of the peatlands in SE Asia can lead to emissions of CO_2 of up to 100 t/ha/yr or 3kg/m^2/day, but if the land is subsequently burnt this figure could double or treble. Between 1997 and 2006, CO_2 emissions from the drainage and burning of peatlands in SE Asia averaged about 2000 Mt/yr, equivalent to 8% of global emissions from fossil fuel burning (Hooijer *et al* 2006). These emissions of soil carbon apply regardless of the cause of the land change to the cultivation of crops, whether for food or fuel applications. The causes of peatland degradation are multifold including deforestation by logging, and drainage and burning for development of timber plantations, agriculture and oil palm (some of which is used for biodiesel production in Europe). Thus the cause of this problem cannot solely be attributed to biofuel demand as other industries are intricately involved.

5.4.2 Emissions of N_2O from biofuels

The GHG nitrous oxide (N_2O) has a global warming potential 296 times greater than CO_2 (IPCC 2007a). It is produced in the soil from nitrogenous fertilisers and from natural mineralisation of nitrogen, by the parallel processes of bacterial nitrification and denitrification. The largest single global source of atmospheric N_2O today is use of industrial fertilisers[o] for agricultural production.

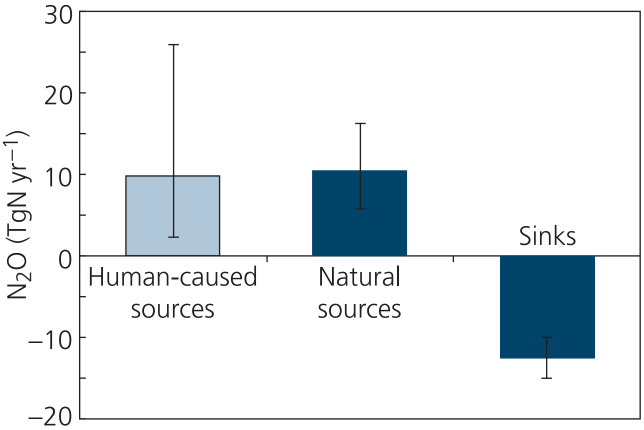
To maintain high rates of annual production, arable crops are generally fertilised at rates of up to 350kg/ha/yr of nitrogen. If new land is brought into cultivation for biofuels, as seems necessary to meet policy requirements, after the first year or two sustained production will require regular fertiliser applications, which in turn will lead to an increase in emissions of N_2O. The IPCC estimates that 1% of added nitrogen is returned to the atmosphere through activities that result in the mineralisation of soil organic matter (IPCC 2006). However, a recent paper by Crutzen *et al* (2007), which considers N_2O release from rivers, estuaries and coastal zones, animal husbandry and the atmospheric deposition of ammonia and NO_x, highlights that it is more likely that the amount of nitrogen returned to the atmosphere as N_2O is in the range 3–5%. Using this larger range of N_2O emissions could significantly reduce the currently assumed GHG emission gains from replacing conventional fossils fuels with biofuels such as biodiesel from rapeseed and bioethanol from maize.

There is a need to improve our understanding of the scientific basis for N_2O release from different biofuel crop production systems and land types. This also needs to be coupled with better understanding of the nitrogen cycle and the interactions of these systems. Such improved knowledge would help when comparing which plants and production systems produce lower N_2O emissions and, in turn, would help decide upon those systems that provide the best GHG savings. Feedstock developments can help in this regard (see Chapter 2). Investigating the potential of 'win-win' opportunities such a wastewater remediation and crops growth could be useful here (see Section 2.3).

5.5 Land use

There are many competing demands for land: to grow food, for conservation, urban development and recreation. The larger the amount of productive land diverted away from food production to grow biofuel crops, the larger the implications for food availability and prices. Thus there is considerable interest in the use of less productive land for cultivation of biofuel feedstock, such as marginal lands. Also, opportunities for gaining the maximum use from the crops grown and combining food and non-food applications need to be developed. This development is likely to involve providing incentives for the growers of the feedstocks and should involve consideration of the full range of parameters, including environmental and socio-economic impacts. As discussed above, the use of LCA should help to provide an objective assessment of the relative merits of different feedstocks and the production systems. There are however limitations that need to be overcome and other factors involved in land use assessment also need to be accounted for such as land quality (including nutrient and water content) and soil carbon changes.

Figure 5.1 Estimate of human and natural induced increase in atmospheric N_2O emissions.



Note: human sources of N_2O include the transformation of fertiliser nitrogen into N_2O and its subsequent emission from agricultural soils, biomass burning, cattle and some industrial activities. Although understanding of the human impact has improved, the data and error bars highlight that there is still a need to improve quantification of human sources of N_2O. (Adapted from IPCC (2007a).

5.5.1 How much land to meet UK policy targets?

Estimates for the amount of UK land that will be required to produce enough biofuels to replace 5% (by volume, as proposed by the RTFO) of current usage of oil-based transport fuel vary widely. Calculating such a figure can be difficult as it depends on a range of interacting factors

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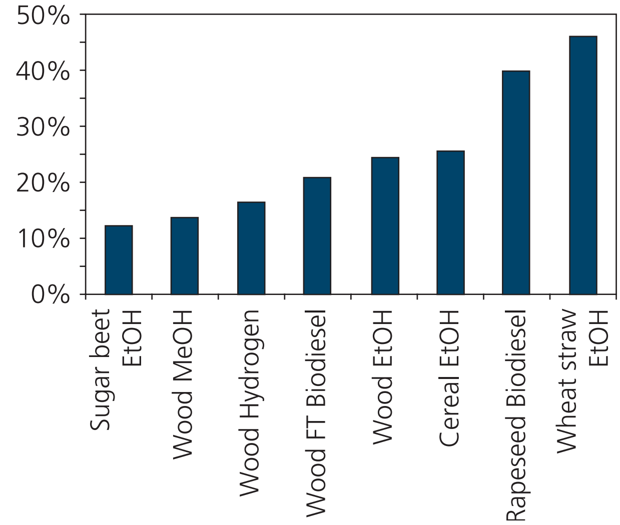
[o] Using fertiliser can also result in eutrophication of water courses, which is discussed in Section 5.7

that will have implications on how the UK meets its policy targets. These include among others:

- the type or mix of biofuels produced;
- the feedstock from which the biofuels are derived, including their energy content and yield per hectare;
- the cultivation practices;
- the type of conversion process;
- the sources of heat and electricity used in the conversion of the biomass feedstock into finished biofuel;
- the use of by-products and the allocation procedures applied to their evaluation.

Figure 5.2 (taken from Woods & Bauen 2003) shows the range can be anywhere between about 10% of UK arable land (for ethanol from sugar beet) up to about 45% land use for wheat straw to ethanol; of the UK's total land area of 24.25 Mha, 6 Mha is arable land and 2.4 Mha is forest (Defra 2005). These figures do not take into account the net energy balance of the system, so although some of the feedstocks use less land, the overall energy balance can be poor. In reality, a range of crops will probably be used to meet biofuels policy directives, so the actual land use figure will also depend on the proportions of this mix. In addition, technological developments along the supply chain will also impact on land use. For example, improving crop yield per hectare and improving conversion efficiency will provide a greater final yield of biofuel, which will use less land to meet policy directives. However, these estimates make it clear that there is no realistic prospect of the UK becoming self-sufficient in biofuels for transport for anything more than low replacement levels of use. Finally economic and social factors will also have an impact on how much land is used, including the level of importation of biofuels to meet policy targets as well as other land-use objectives for rural communities.

Figure 5.2 Percentage of UK arable land area needed to supply 5% of energy demand by transport in 2001, on an energy content basis.



Note: These figures show the mid-point for each option and do not show the possible range, which would depend on factors such as the cultivation practice, crop yield, conversion and process efficiency. (Source: Woods & Bauen 2003).

5.5.2 How to compare land use

Land use can be compared in a variety of ways, most of which are based on calculating the overall energy balance. The most convenient way to compare the land used by different biofuels and other sources of biomass is in terms of delivered energy per unit land area (in units of millions of joules per hectare per year (MJ/ha/yr)). Delivered energy is the energy contained in fuels and electricity which consumers access for their subsequent use. It is derived from primary energy[p], which is a measure of the amount of energy contained in depletable natural resources including fossil fuels and nuclear fuel. Delivered energy can be converted into 'useful energy', which is the energy needed as heating, cooling, light, motive power, etc. A clear distinction must be made between primary energy and other forms of energy. These different forms of energy are not interchangeable and cannot be equated with each other. As a consequence of inevitable inefficiencies and losses, a greater amount of primary energy is needed to provide a given amount of delivered energy, which in turn is greater than the amount of useful energy that can eventually be supplied. Often in the assessment of energy technologies, deceptively simple indicators can be derived such as the ratio of primary energy input to delivered energy output. Given the definition of primary energy, this ratio is greater than one for energy technologies based on entirely depletable resources such as fossil and nuclear fuels. For renewable energy technologies, including biofuels, it can be less than one (see Table 5.2).

Tables 5.1a to c provide average estimates of delivered energy available from various UK feedstocks under particular conditions and specified assumptions. These estimates do not account for delivered energy required in the provision and conversion of the feedstock into biofuels; this can be achieved by evaluating these processes using estimates of the primary energy needed. It should be noted that only forestry residues are included in Table 5.1b, c, and that no quantification has been made of the amount of delivered energy that could be gained from currently available forestry timber, which

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[p] In this definition, primary energy does not include renewable energy (such as biomass energy)

potentially could provide significant benefits in terms of delivered energy. The tables show that certain combinations of options can result in real efficiency gains in land use.

Table 5.1a illustrates the estimated delivered energy available from specific liquid biofuels that could be produced in the UK from major feedstocks. Two types of estimate are presented: the first only considers the delivered energy available from the liquid biofuel, as the main product of each process under investigation; the second takes into account all the delivered energy that could be available from the main product and all co-products that could be used as fuels, on the assumption that these co-products would be converted into heat by conventional combustion. The estimates will change by adopting other conversion technologies, such as gasification or pyrolysis, or if the co-products were used in electricity generation or Combined Heat and Power (CHP) production. The delivered energy available also varies considerably depending on whether feedstock is regarded as a source of liquid biofuels only or as an integrated source of delivered energy. The estimates in both Table 5.1b, c would also alter if potentially more efficient technologies were applied or if CHP generation was adopted. Overall these tables imply several key points:

- That more efficient land use is possible by using existing feedstock and by using co-products more efficiently. For example, using wheat grain to produce bioethanol and the straw to generate process heat and electricity results in delivered energy that is much greater than for other combinations shown in Table 5.1a.
- Feedstock converted into liquid biofuels can be a more efficient use of land than using feedstock to generate electricity, and in some circumstances, it can also be more efficient than for heat generation. For example, bioethanol produced from wheat grain with the straw used for heat is more efficient than all electricity production processes and heat production processes (except for heat from miscanthus pellets).
- Policies supporting biofuel development need to incentivise those processes that are the most efficient use of land.

5.5.3 Comparison of energy resource depletion and GHG emissions savings

The evaluation of total GHG emissions and the ratios of primary energy inputs to delivered energy outputs associated with the production and utilisation of biofuels needs to be set in context of the fossil-based transport fuels that they are intended to replace. This helps to compare the relative benefits of different biofuels and is done by comparing the GHG emissions and energy ratios from biofuels with those of petrol and diesel. The baselines adopted here are represented by the estimates summarised in Table 5.2. Total GHG emission estimates in Table 5.2 are based on IPCC (2001) values of global warming potential and assume that all net savings exceeding 100% are due to credits from the displacement of a UK mix of electricity generation. There are significant differences in total GHG emissions and net savings for some biofuels. Whilst net savings can be low (less than 50%) if unfavourable combinations of production options are chosen, it is also possible to achieve very high net savings. Indeed, it is even possible to obtain net savings exceeding 100%. This is due to the avoided GHG emissions when surplus electricity is generated from by-products. These calculations depend on the factors outlined in Section 5.5.1.

By way of illustration, some typical estimates of total GHG emissions and net savings for biodiesel production from plant oils (oilseed rape), bioethanol production from sugar (sugar beet) and bioethanol production from starch (wheat grain) are presented in Table 5.2. Apart from a brief summary of the production details, the major assumptions incorporated into these estimates are recorded in the attached notes (a–r). To provide meaningful comparative estimates, published studies have been used; these have sufficient transparency to enable basic assumptions to be applied consistently. In particular, such consistency applies to the assumed values of global warming potentials for CH_4 and N_2O, GHG emission factors, especially for the manufacture of nitrogen fertiliser, the production of natural gas and the generation of electricity, N_2O emissions from soils, and the allocation procedures for by-products.

Overall Table 5.2 makes the following key points:

- There is a great deal of variation in greenhouse gas emissions savings between different biofuels. Savings depend on how co-products are used, the type of agriculture and how the conversion processes are powered.
- A lot of potential exists to improve the efficiencies of existing feedstocks including wheat, sugar beet and oilseed rape. For example for bioethanol production from sugar beet, if the beet pulp is used as animal feed, under conventional agriculture and there is a straw fired CHP process, then net greenhouse gas savings can amount to 215% compared to petrol.
- Policies are required that incentivise combinations of production processes that deliver the greatest greenhouse gas savings.

5.6 Water consumption

In some locations, including the UK, the availability of water can be a fundamental consideration for the practical

Table 5.1. Estimated delivered energy available from liquid biofuels and energy available from electricity and heat from lignocellulose feedstock.

(a) Estimated delivered energy available from liquid biofuels in the UK

Liquid biofuel and process	Unit delivered energy available[a] (MJ/ha/yr)
Biodiesel only from oilseed rape (plant oil)[b][n]	40,335
Biodiesel and co-products from oilseed rape (plant oil for fuel[b] and rest of plant for heat[c][m])[n]	99,849
Bioethanol only from wheat grain (starch)[d][o]	67,085
Bioethanol and co-products from wheat (wheat grain (starch)[d] for fuel and wheat straw for heat[e][m])[o]	148,825
Bioethanol only from sugar beet (sugar)[f][o]	117,105

(b) Estimated delivered energy available as electricity from lignocellulose feedstocks in the UK

Feedstock and method of combustion	Unit delivered electricity available (MJ/ha/yr)
Forestry residue pellets for co-firing[g][k][p]	2,146
Forestry residue chips for dedicated combustion power plant[g][l][p]	2,152
Forestry timber	Not available
Straw for dedicated combustion power plant[h][l][p]	11,803
Short rotation coppice pellets for co-firing[i][k][p]	32,087
Short rotation coppice chips for dedicated combustion power plant[i][l][p]	36,178
Miscanthus for dedicated combustion power plant[j][l][p]	65,999
Miscanthus for co-firing[j][k][p]	90,549

c) Estimated delivered energy available as heat from lignocellulose feedstocks in the UK

Feedstock and method of combustion	Unit delivered heat available (MJ/ha/yr)
Forestry residue pellets for combustion[g][m][p]	4,903
Forestry residue chips for combustion[g][m][p]	5,029
Forestry timber	Not available
Straw for combustion[h][m][p]	37,768
Short rotation coppice pellets for combustion[i][m][p]	73,339
Short rotation coppice chips for combustion[i][m][p]	73,472
Miscanthus pellets for combustion[j][m][p]	206,967

(a) Delivered energy measured in terms of net calorific value (lower heating value (LHV)).
(b) Assuming oilseed yield of 3.1 t/ha/yr at 15% moisture content.
(c) Combustion of rape straw assuming a yield of 2.81 t/ha/yr, rape meal assuming an effective yield of 1.70 t/ha/yr and glycerine assuming a yield of 0.11 t/ha/yr.
(d) Assuming wheat grain yield of 8.6 t/ha/yr at 20% moisture content.
(e) Combustion of wheat straw with a yield of 3.78 t/ha/yr and 15% moisture content, and distillers' dark grains and solubles (DDGS) with an effective yield of 2.87 t/ha/yr.
(f) Assuming sugar beet yield of 52.1 t/ha/yr.
(g) Assuming forestry residues yield of 0.50 t/ha/yr at 25% moisture content.
(h) Assuming straw yield of 3.78 t/ha/yr at 15% moisture content.
(i) Assuming short rotation coppice yield of 12.1 t/ha/yr at 50% moisture content.
(j) Assuming miscanthus yield of 28 t/ha/yr at 50% moisture content.
(k) Co-firing in a coal-fired power plant with a thermal efficiency of 35%.
(l) Combustion in a dedicated power plant with a thermal efficiency of 25%.
(m) Combustion in a heating plant with a thermal efficiency of 80%.
(n) Mortimer *et al* (2003a).
(o) Mortimer *et al* (2004).
(p) Elsayed *et al* (2003).

Notes: (1) Figures do not account for the amount of energy required for the provision and conversion of the feedstock. (2) b, c do not include lignocellulose from forestry timber, which would provide a much greater delivered energy value than that provided by using residues. (3) Other lignocellulose feedstocks, such as switchgrass, are not included. (4) b, c are based on energy from combustion: more efficient conversion technologies would increase the delivered energy available.

Table 5.2. *Comparison of energy and greenhouse gas savings for different crops and production systems.*

Feedstock	Co-product use	Agriculture practice	Process inputs: heat and power	Energy		Greenhouse gas emissions	
				Ratio of primary energy inputs: delivered energy output MJ/MJ net	Net Primary energy savings%	Total greenhouse gas emissions (j) g CO_2eq./MJ net	Net greenhouse gas emissions savings% (j)
Ultra-low-sulphur diesel (a)(l)(m)				1.26		87.6	
Unleaded petrol (b)(l)(o)				1.19		81.5	
Bioethanol							
Starch (wheat grain) (d)(o)	Distillers' dark grains and solubles (DDGS) use as animal feed	Conventional (e)(q)	Natural gas-fired process heat, grid electricity	0.64	46	63.5	22
	DDGS use as animal feed	Conventional (e)(q)	Natural gas-fired process CHP	0.60	59	52.1	36
	DDGS use as animal feed	Conventional (e)(q)	Straw-fired process CHP	−0.07	106 (k)	36.7	55
	DDGS use as co-firing (p)	Conventional (e)(q)	Straw/coal-fired process CHP	−0.63	153 (k)	11.6	86
Sugar (Sugar beet) (o)	Beet pulp used as animal feed	Conventional (q)	Natural gas-fired process heat, grid electricity	0.83	30	48.6	40
	Beet pulp used as animal feed	Conventional (q)	Natural gas-fired process CHP	0.68	43	41.1	50
	Beet pulp used as animal feed	Conventional (q)	Straw fired process CHP	−0.52	144 (k)	−93.4	215 (k)
Biodiesel							
Plant oils (oilseed rape)	Rape meal used as animal feed (f)(m)	Conventional (h)(q)	Natural gas-fired process heat, grid electricity	0.44	65	46.3	47
	Rape meal used as animal feed (g)(m)	Low-nitrogen (i)(q)	Natural gas-fired process heat, grid electricity	0.33	74	29.9	66
	Rape meal used as animal feed and co-firing (g)(n)	Low-nitrogen (i)(q)	Rape straw/coal-fired process CHP	0.21	83	26.2	70
	Rape meal used only for co-firing (g)(n)(r)	Low-nitrogen (i)(q)	Rape straw/coal-fired process CHP	−0.35	128 (k)	−5.6	106 (k)

(a) Ultra low sulphur diesel produced in the UK with a net calorific value of 42.38 MJ/kg.
(b) Unleaded petrol produced in the UK with a net calorific value of 43.99 MJ/kg.
(c) 103kg N/ha/yr application during cultivation and a sugar beet yield of 52.1 t/ha/yr Average EU-15 soil emissions of 2.79kg N_2O/ha/yr for sugar beet cultivation.
(d) Wheat yield of 8.60 t/ha/yr at 20% moisture content.
(e) 185kg N/ha/yr application during cultivation. Average EU-15 soil emissions of 2.23kg N_2O/ha.a for wheat cultivation.
(f) Oilseed rape yield of 3.07 t/ha/yr at 15% moisture content.
(g) Oilseed rape yield of 2.92 t/ha/yr at 15% moisture content.
(h) 196kg N/ha/yr application during cultivation. Average EU-15 soil emissions of 3.12kg N_2O/ha/yr for oilseed rape cultivation.
(i) 81kg N/ha/yr application during cultivation. Average EU-15 soil emissions of 3.12kg N_2O/ha/yr for oilseed rape cultivation.
(j) Assumed Global Warming Potentials of 23kg eq. CO_2/kg CH_4 and 296kg eq. CO_2/kg N_2O (IPCC 2001).
(k) Net savings exceed 100% due to credits from the displacement of a UK mix of electricity generation.
(l) Excluding vehicle combustion CH_4 and N_2O emissions.
(m) Mortimer *et al* 2003a.
(n) Mortimer *et al* 2003b.
(o) Mortimer *et al* 2004.
(p) Punter *et al* 2003.
(q) Edwards *et al* 2006.
(r) Mortimer & Elsayed 2006.

cultivation of crops for biofuel production. Water is required through the entire biofuel supply chain, and is best documented for feedstock production. Distribution of water resources varies greatly according to location and time. Globally, pressures on water supply are increasing from a growing population, per capita usage and the impacts of climate change (UNESCO-WWAP 2006). Consequently, water for all uses is becoming scarce. Developments in the agricultural sector for food and non-food crops will have important implications for water usage and availability. Increased usage of biofuels will raise demand for water, which could, in turn, negatively impact on water availability for other uses. These issues require careful consideration by decision-makers when deciding upon the potential role for biofuels and in any sustainability assessments of biofuels.

Although there are some data available about water use efficiencies of crops, which can be placed into LCA calculations, water requirements through the rest of the biofuel supply chain (processing and end use) are unknown. This is a generic issue that not only applies to biofuels but also to other industries such as conventional oil and gas and food. There is a clear need for R&D to establish water use requirements across the entire biofuel production chain.

Growing any crop will require water and specific crops will need more than others but there is not an extensive database of this information, and some of data does not always account for differences in the factors that impact water use efficiency (WUE). WUE depends on several factors including precipitation, evaporation, transpiration, which in turn, are dependent on climatic variables, including elevated CO_2 levels, solar radiation absorption and windspeed (see McNaughton & Jarvis 1991 and FACE CO_2 experiments). There is a need to assess these factors for different crops at different locations. It must also be noted that even if crops have high WUE, their impact on water availability is a separate issue that will also need to be evaluated. Water availability will also be affected by interactions and competition with other crops and land use change. The likely choice and dynamic changes in crop production and the species/varieties chosen for biofuels will inevitably have an effect on the flows of water through the landscape. Hydrological studies, such as those being funded by Natural Environment Research Council and the Centre for Ecology and Hydrology, will need to focus on the extent to which roots from new crops extract water from the ground and therefore calculate any resulting impact on water availability. Such studies could also help inform agricultural practices so crops can be planted at times of the year where they will have a lower impact on the ground water resource. Water catchment management will also be of importance here to ensure the resource is secured.

We recommend the development of datasets to account for water use efficiency across the entire biofuel supply chain. These datasets need to account for variations between crops and the conditions at specific locations that affect water use. In addition, the results from hydrological studies will also need to be integrated into these datasets to assess the overall impacts of biofuel use on water availability. LCA calculations could provide a useful way of assessing many of these issues.

5.7 Wider pollution issues

From feedstock through to conversion and end use, the entire chain of biofuel production has a range of wider pollution impacts. These issues require evaluation in order to get a more accurate picture of the wider impacts of biofuels and to help decide upon combinations of processes that offer optimal benefits across the chain.

5.7.1 Feedstock production

As highlighted in Sections 2 and 5.4, some crops release VOCs, such as isoprene, which can lead to ozone formation. VOCs play a variety of important roles in atmospheric chemistry. Isoprene is emitted by plants and different biofuel plants emit varying amounts of isoprene (Arneth *et al* 2007). Some plants such as conifers also produce other terpenes, which are made up of different numbers of isoprene units. The amount of isoprene released increases in high temperatures and high light conditions, for example during summer heatwaves, and there is evidence that emissions will increase in the future owing to climate change and associated higher temperatures (Sanderson *et al* 2007).

Studies in the UK have shown that most isoprene emissions arise from coniferous forests in Scotland and areas with large numbers of poplars in eastern England (Stewart & Hewitt 2003). Using forestry as feedstock to produce biofuels could potentially increase isoprene emissions. However, the dataset does not exist for many plants that emit isoprene. Therefore, research is needed to quantify the amount of isoprene that could be emitted by a range of different plants used for biofuel production. This applies just as much to the UK as elsewhere as the quantity of VOC emissions varies according to geographical location and environmental conditions. Scientific understanding of why plants emit isoprene and what plant-based mechanisms lead to their emission is incomplete. Thus there is a need to develop this knowledge base as it would help to guide developments that could mitigate isoprene emissions.

As highlighted in Chapter 2, agricultural practices for production and cultivation of biofuel feedstocks such as use of artificial fertilisers and pesticides have several pollution impacts. One such impact is eutrophication, where run off of nutrients such as nitrogen and phosphorous from fertilisers adversely affect the aquatic environment (Smith *et al* 1999). Such nutrient enrichment can cause rapid growth of algal blooms. As these blooms are broken down by bacteria, the oxygen content of the water diminishes to the point where no other life can be sustained. Agricultural activities, especially those that involve intensive techniques based on significant inputs of artificial fertilisers, are often associated with the process of eutrophication. There are many different and complex pathways in which initial emissions, in gaseous, liquid or solid form, can cause eutrophication and this presents a significant challenge for eventual quantification in LCA. In addition, eutrophication also has impacts on biodiversity of the affected areas (Pykala 2000). Although considerable work has been performed on this problem, LCA studies can be restricted by the lack of adequate databases for the eutrophication effects of the various activities and inputs associated with biomass cultivation and harvesting.

Although the scientific basis for eutrophication is well established, the precise pathways through which different compounds impact eutrophication are yet to be fully traced and quantified. This applies to potential biofuel crops and other agricultural crops. There might be potential compounds during the rest of the production chain that also cause eutrophication. The extent of eutrophication also varies according to soil type and environmental conditions. For example, greater amounts of N_2O emissions occur in wetter conditions than in an arid environment, which in turn causes there to be different eutrophication impacts in these environments. The suite of data to determine the extent of eutrophication does not exist at present and there is a need for R&D to establish such datasets. Establishing such R&D programmes would help to target appropriate policies and management practices to ensure potential impacts can be minimised.

5.7.2 Storage and conversion

Storage of feedstock, preparation and conversion can result in dust formation due to processes that prepare solid material and also result in noise pollution issues (Toft *et al* 1995). Biological, chemical and thermal conversion processes also have wider pollution impacts that require evaluation. For biological processes, there is a need to dispose of fermentation waste streams and micro-organisms, waste gases and reagents used to purify alcohols. Acids and residues from chemical reactions such as hydrolysis also need to be managed and disposed of. Thermal processes that rely on gasification also have problems related to noise, odour, wastewater, tar, ash and exhaust gases such as carbon monoxide, all of which requires effective management and evaluation (Bridgwater & Maniatis 2004).

5.7.3 End use

As highlighted in Chapter 4, use of biofuels in vehicles also leads to emissions of pollutants, such as formaldehyde, acetaldehyde and others. The relative proportion of these pollutants in exhaust emissions will vary between different biofuels. As biofuels are developed and used there will therefore be a need to develop pollutant profiles for each type in order to compare them and therefore provide more accurate evaluation.

5.8 Biodiversity

Biodiversity provides an important role in ecosystem functioning and the provision of services that are essential for human wellbeing (for example human health, food etc) (MEA 2005). However, over the past few centuries human activity has resulted in fundamental and irreversible losses of biodiversity. This loss is accelerating with changes most rapid over the past 50 years (MEA 2005). Globally, habitat conversion for agriculture and forestry has been a major driver of this loss; for example, more land was converted to cropland between 1950 and 1980 than between 1700 and 1850 (MEA 2005). The situation is different in the UK because of the long history of humans changing the natural environment through agriculture and forestry, which has resulted in the production of 'semi-natural' managed landscapes, some of which are nevertheless highly valued for their amenity value.

Chapter 2 highlighted that any form of agriculture can pose risks to biodiversity and there are opportunities to improve biodiversity by using specific crops and land management systems. As with any new agro-ecosystem, growing a biofuel crop will alter local habitats and resources in a way that will affect native species distribution and abundance. These effects will depend on the crop, its density, duration and distribution on the landscape, and any regular inputs, including water and agrochemicals. Given the range of potential crops, from trees to dense grasses, impacts to biodiversity will vary.

Several other impacts also need to be evaluated both within the UK and also globally. These include impacts such as those arising from direct effect of change in land use; from just changing the crops being grown in an agricultural landscape, to going from a diverse crop system to monocultures, through to large-scale conversion of biodiverse systems, such as peatlands and tropical forest. If using UK set-aside land to grow biofuel crops, then consideration any resulting impacts on biodiversity will also need to be evaluated because some of these areas are very biodiverse relative to farmland (Critchley & Fowbert 2000).

As the cultivation of new crops intensifies then new impacts, such as pests and diseases, will also occur and will need to be addressed. There is a risk that pests and diseases could lead to increased use of pesticides/herbicides. This in turn could lead to changes in pest and disease resistance and subsequent impacts on crop yield, as was experienced in the 20th Century with oilseed crops in the UK.

The characteristics of biofuel crops may also be important in determining their potential impact on biodiversity. Characteristics that make them appealing for crop use, such as fast/vegetative growth and high yield, may also enable them to become invasive under the right environmental conditions. Introducing new species into an area can raise the risk of infestation by new pathogens and pests. If crops spread into surrounding habitats, particularly natural ecosystems they may also displace local biodiversity and/or disrupt ecosystem processes, including for example water and nutrient cycles. There is a precedent for introduced, fast growing tree crops becoming invasive in this way, particularly in the warmer regions, such as *Eucalyptus*. There is also some evidence that grasses such as sweet sorghum, giant reed and reed canary grass are invasive in specific environments in the USA (Raghu *et al* 2006). In addition, miscanthus and switchgrass are being assessed for invasiveness in the USA. Miscanthus species that exhibit vegetative propagation, an ability to resprout from below ground, efficient photosynthetic mechanisms and rapid growth rates could be invasive. Switchgrass, a seed-producing species, shares many of these invasive traits.

Any evaluation of these risks needs to be balanced with the potential benefits to biodiversity. There is evidence showing that biodiversity could benefit under certain circumstances (Anderson & Fergusson 2006; Rowe *et al* 2007). Large-scale SRC willow can provide benefits for some bird species, butterflies and flowering plants. The impacts of perennial grasses are less well known and require further research. However, in mixed compositions some perennial grasses may also provide some wildlife benefits compared with conventional, intensively managed farmland. It will be important to identify and support such 'win–win' situations.

It is clear that the overall risks and benefits for biodiversity need to be appropriately evaluated for any potential bioenergy crop. We recommend that potential bioenergy crops be evaluated by using a risk assessment framework that covers the following:

- the full life-cycle of biofuel production;
- the invasiveness potential of the crop;
- takes into account the potential interactive effects of the biofuel crop with other pressures in the area (such as for example, drought stress);
- the impacts to ecosystems;
- changes in these risks under a future climate.

Application of existing tools to measure impacts of agricultural practices on key biodiversity indicators may be useful for developing methods to assess biodiversity impacts on pilot plantings. The non-native species risk assessment methodology, developed for Defra, for assessing the environmental threats posed by introduced species is one such example; there are others. In addition, current and ongoing UK projects on biodiversity impacts of energy crops, such as that underway on willows in the Rural Economy and Land Use (RELU) programme of ESRC, NERC and BBSRC, will help develop relevant methodology. Risk assessments of crops will also need to occur with ongoing monitoring of locations where crops are grown to help provide an evidence base for future decisions. This would help to ensure that any unintended impacts (positive and negative) can be identified and appropriate actions can be targeted to deal with such impacts. Given that biofuel feedstocks will be produced globally, appropriate measures need to be taken to ensure that barriers to undertaking risk assessments, such as poor knowledge of biodiversity and lack of access to monitoring tools, are addressed. Addressing biodiversity in LCA is constrained by the lack of data as crops and regions that are growing feedstocks have not yet been assessed for their impacts on biodiversity. Establishing this knowledge base would also help to address biodiversity impacts in LCA calculations.

5.9 Conclusions and recommendations

Throughout the entire supply chain, biofuels have a range of environmental impacts that need to be evaluated. The extent of impacts such as GHG emissions, water consumption, biodiversity, eutrophication and air pollution vary according to how the feedstock is produced, converted and how efficiently it is eventually distributed and used. Quantification of these impacts can provide a powerful means of comparing the overall environmental benefits offered by different biofuels and therefore enable stakeholders to make decisions that are more informed.

LCA can provide a useful way of comparing the land-use impacts through calculation of energy resource use and GHG emissions. However, the application of LCA in any policy sphere must reflect changes that occur in the real world. Thus, LCAs must be capable of estimating for example, the real changes in GHG emissions that occur when biofuels are produced and used to replace conventional transport fuels. There is a large research and development need for LCA, and the calculations need to be able to incorporate the emergence of new evidence and data, including new understanding of soil carbon dynamics, nitrous oxide emissions, water consumption, biodiversity and wider pollution issues. LCAs must also be conducted with a full appreciation of the limitations: the need for transparency, establishment of comparative reference systems, incorporation of missing data and allocation of joint products. We recommend conducting completely consistent LCA studies that address the specific policy question under consideration.

There are opportunities to increase the effectiveness of LCA to provide a better picture of the wider environmental impacts. Many of these impacts are crucial environmental issues that need to be evaluated and reflected in LCA calculations, so that any developments that exacerbate these impacts can be avoided. There is a need to improve quantification of water use across the biofuel production chain. For some areas this will be especially important in the future as the effects of climate change put pressure on water supply and availability. Similarly the biodiversity impacts of biofuel production need to be understood and quantified. There is also a need to establish to what extent biofuels affect eutrophication and air quality. We recognise that establishing the evidence base for many of these issues could take considerable time and research effort. Until such datasets are developed and incorporated into LCA, there will be a need to conduct qualitative assessments of wider impacts, using techniques such as SEAs and EIAs.

There is also a need to incorporate social and economic assessments of biofuels to ensure that overall sustainability can be addressed. When decisions need to be made about the sustainability of different biofuels and their production pathways, quantitative data provided by LCA and more qualitative data provided by other assessments need to be carefully and transparently balanced.

We recommend that sustainability criteria are developed by DEFRA, DBERR, DfT, DIUS, DfID, HMT, the Sustainable Development Commission and the devolved administrations.

The use of multi-criteria decision analysis (MCDA) could provide a valuable mechanism for assessing the sustainability of biofuels that brings together evaluations of the environmental, economic and social impacts. However, the output of an MCDA needs to be used carefully as variations in the quality of the assessments and data that are used to inform it, mean that it can only provide a profile of the impacts, thereby adding to the understanding of the issues and should not be used to provide a definitive answer.

Decisions are currently being made about biofuel policies, such as the RTFO and more generally globally that will need to incorporate such assessments. Unless biofuel evaluations can command confidence, then serious doubts will remain and be exploited about the claimed environmental benefits or costs of biofuels. It is crucial to develop, implement and monitor the necessary assurance schemes that underpin basic confidence in the environmental impacts of biofuels, especially among the public. This is a challenging agenda which cannot be ignored nor treated as a trivial exercise. In a world where carbon accounting and subsequent market mechanisms will become commonplace in response to the threat of global climate change, the way in which these issues are addressed for biofuels should set the precedent for how all products and services will have to be treated in the future.

6 Policy

This chapter outlines the key policy issues that relate to the development of biofuels. It includes aspects related to innovation policy, policies designed to mitigate climate change, increase energy security, prioritise land use, incentives for research and development (R&D) and also other policies that are required to help reduce emissions from transport. There is also a discussion about the role of public perception.

6.1 Wider policy context

The long-anticipated surge in demand for oil from developing regions (China, India and Latin America in particular) has begun to exert a large effect on world markets, as has the continued high level of demand from Europe and the USA. Partly for these reasons, and with the growing dependence of world supplies on OPEC, it seems that the world may have entered a new era of sustained high oil prices, in the US$50–80 per barrel range or more.

With the exception of ethanol from sugar cane in the tropics and sub-tropics, the costs of producing biofuels are currently higher than the costs of fuels derived from conventional mineral oil. Hence, outside the tropics, unless major cost reductions or large rises in oil prices occur, the future of biofuels both as a low carbon fuel and as a contributor to energy security will depend on the incentives offered by government tax and regulatory policies. The environmental benefits gained from increased biofuel usage, both local and global, will likewise depend directly on tax and regulatory policies. Their potential in both respects is appreciable but not guaranteed. It will depend on cropping and afforestation practices and whether alternative crops and biofuels can be developed.

Land use adds a new dimension to energy policy. It will require the integration of current and new policies and practices that aim at a continuing reduction in environmental impacts and which must be sufficiently flexible to reward changes in practices as new knowledge emerges on the environmental, economic and social impacts of biofuels. This chapter outlines the possible development of a set of flexible policies aimed at delivering sustainable biofuels in the near and medium term. Over the longer term, technological developments, for example in hydrogen fuelled vehicles, could make biofuels for surface transport obsolete; policy will need to be open to and should encourage these options.

6.2 Commercial motivations and innovation

Estimates of the costs of biofuels are shown in Table 6.1. Estimates vary between countries and even between studies, making the uncertainties large. Nevertheless the scale of the uncertainties does not obscure three general points. (1) Higher oil prices are beginning to make current biofuels commercially more attractive. (2) The possibilities for cost reductions through economies of scale and innovation are appreciable for all biofuels, with lignocellulose technologies (row 8) anticipated to fall into the same range as foodstuff-based technologies (see rows 4–7 and 9–10). (3) The post-tax prices of petrol and diesel fuels in Europe (row 3) (though less so in the USA) are

Table 6.1. Estimated costs of biofuels compared with the prices of oil and oil products (biofuels exclusive of taxes).

Biofuel	2006 (US cents/litre)	Long-term about 2030 (US cents/litre)
1 Price of oil, US$/barrel	50–80	
2 Corresponding pre-tax price of petroleum products US cents/litre	35–60[a]	
3 Corresponding price of petroleum products with taxes included, US cents/litre (retail price)	150–200 in Europe[b] About 80 in USA	
4 Ethanol from sugar cane	25–50	25–35
5 Ethanol from corn	60–80	35–55
6 Ethanol from beet	60–80	40–60
7 Ethanol from wheat	70–95	45–65
8 Ethanol from lignocellulose	80–110	25–65
9 Bio-diesel from animal fats	40–55	40–50
10 Bio-diesel from vegetable oils	70–100	40–75
11 Fischer-Tropsch synthesis liquids	90–110	70–85

Note: the estimates for the biofuels and Fischer-Tropsch liquids are rounded (adapted from IEA 2006).
(a) note range differs from row 1, for several factors such as refinery costs.
(b) Excluding a few outliers above and below this range.

universally higher than the pre-tax costs of biofuels, often appreciably higher; hence tax credits or other incentives, for example in the form of reductions in excise taxes on biofuels, would have a large effect on substitution.

Such estimates do not allow for changes in prices and land values that may arise from competing demands from agriculture. As with oil and gas, the prices of the product cannot be disconnected from pressures on the available resources, primarily on the availability of land for agriculture, most of all in developing regions. Since the early 1960s, pressures on land resources have been eased in developing regions by, among other things, the growth of yields associated with the green revolution and improvements in husbandry. Yields roughly doubled on average over the 40–50 year period. The economic prospects of biofuels will likewise depend on improvements in yields both in the growth of the crops and in the efficiency of the conversion processes. Detailed assessments of the potential for feedstock production and conversion systems are given in Chapters 2 and 3 respectively.

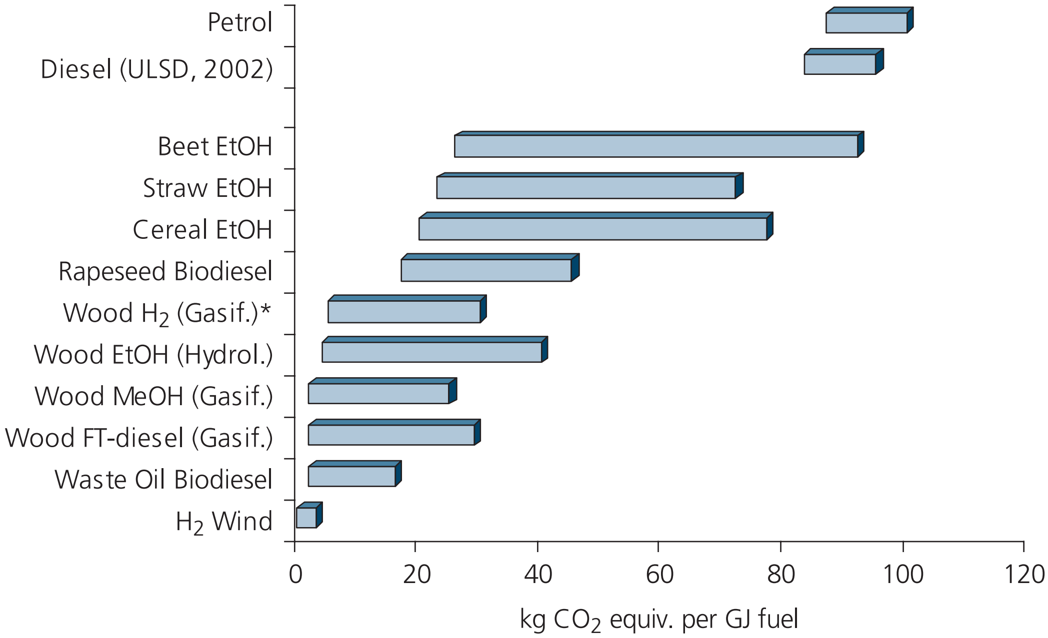
There are also possibilities, noted again below, for producing biofuels in ways that would improve the productivity of agriculture itself: for example agro-forestry practices and the restoration of degraded agricultural lands, woodlands and watersheds. In other words there are environmental and economic co-benefits associated with particular sets of land management practices that need to be taken into account when assessing the costs and benefits; they range from serious dis-benefits–as might arise for example through the aggressive expansion of monocultures–to major benefits of improving the quality of poor soils, the availability of surface and ground water resources and the reduction of flooding risks.

6.3 Energy security and mitigation of climate change

For countries with good coal or gas resources, or with good trading links to countries rich in tar sands and oil shale, virtually any degree of energy security can be achieved if they are willing to pay for it. These resources are abundant, but the costs of producing liquid fuels from them are very high; in the case of synthetic biofuels costs are in the range 90–110 US cents per litre, approximately twice the costs of oil fuels at US$50/barrel (see Table 6.1 rows 2 and 11) (IEA 2006). A larger issue, however, is that synthetic fuels are much more carbon intensive than conventional oil fuels; to reduce their emissions to levels comparable to the latter CO_2 capture and storage will be needed, which would add further to costs (estimates are available in IPCC 2005).

Whether the production of biofuels can provide increased ‘energy independence’ without increasing GHG emissions will depend on the crops, the cropping practices and the conversion systems adopted. There is a risk of their being produced in ways that would also diminish or even negate their climate change benefits if driven solely from an energy security perspective. Figure 6.1 shows one set of estimates of the GHG intensities of alternative biofuels, allowing for ‘life cycle’ emissions arising in various stages of production and distribution (see also the estimates in

Figure 6.1 Greenhouse gas emissions from biofuels compared with conventional transport fuels. Note that these ranges are rough estimates and can be wider depending on how feedstock is grown, converted and the biofuel is used and distributed (Source: Woods & Bauen 2003).



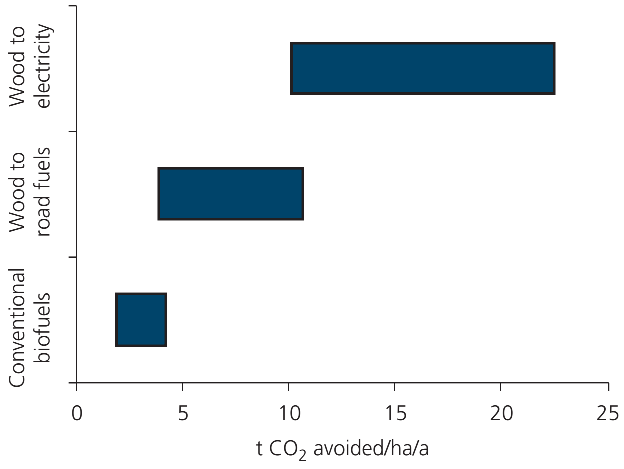
* The range in emissions results from the different modes of hydrogen transport.

Tables 5.1 and 5.2 in Chapter 5). Estimates vary between studies and between locations: the use of fertilisers, the effects of micro-climates on N_2O emissions, fuels used in processing, transport distances, use of co-products and methods for accounting for their use and so forth. However, as with cost estimates, the unquestionably large uncertainties are not such as to obscure the main points: (1) biofuels from cereals, straw, beet and rapeseed are likely to reduce GHG emissions, though the estimated contribution varies over a wide range, from 10 to 80% (averaging about 50%) depending on crop, cropping practice and processing technologies; (2) biofuels from lignocellulose material are likely to show a twofold or more improvement in average abatement potential when compared with biofuels derived from food crops.

6.4 Climate change and land use

GHG savings per hectare of land also point to the crucial importance of developing more efficient biofuels. Figure 6.2 (Larivé 2007) is based on work by CONCAWE and suggests that using wood for electricity generation offers CO_2 savings per hectare in the region of three to five times greater than for biofuels derived from food crops and about twice that of biofuels from lignocellulose. However, as noted above for greenhouse gas emissions per unit of energy, these results are dependent on a range of factors including the yield of the feedstock, the conversion efficiency and process chosen (such as use of co-products), as well as which fuel is being displaced (see Chapter 5 and Larson 2005). For example, the greatest carbon dioxide savings are achieved by displacing coal for electricity production with biomass. However, if biomass replaces gas the CO_2 savings are comparable to the lignocellulose biofuels. Therefore, under certain conditions, biofuels will provide the more effective land use for greenhouse gas mitigation and under other conditions biomass power generation will be favoured. Without specific case comparisons, it is not possible to make unequivocal statements about whether electricity or transport fuel production provides greater greenhouse gas savings.

Figure 6.2 Tonnes of CO_2 equivalent saved per year per hectare of land (Source: Larivé 2007).



Notes:

(a) If the waste heat from electricity generation is used in CHP plant, the yields are roughly twice those shown for wood-to-electricity.

(b) Figures for wood to electricity is for the displacement of state of the art coal fired power station.

(c) Wood to road fuels is used as a proxy for all high yielding energy crops.

While there are already several options for climate change mitigation in electricity sector – coal with carbon capture and storage, nuclear power, wind, the offshore wave and tidal stream resource, solar energy – there are currently limited options for transport, as many of the possible options face considerable challenges and costs, such as hydrogen with fuel cells, which requires technological developments and a new infrastructure. Even if electricity generation were 100% carbon free, the UK will still need to reduce carbon emissions in the transport sector if its long-term aspiration for a low carbon economy is to be achieved (DTI 2003). For these reasons, where policy stipulates low carbon transport, the economics may still favour the use of lignocellulose-derived fuels for transport, which is closer to being widely deployed than other technologies, rather than for electricity generation and heat. In other words the overall commercial feasibility and value of lignocellulose as a basis for low carbon transport may be higher, and this may offset the higher costs involved.

Given the pressures noted above, that large-scale biofuel production is bound to exert on land resources, the case for raising yields in this way is compelling. The evidence submitted by the Woodland Trust on the dangers of environmental damages arising from an aggressive over-exploitation of biofuels and the need to balance these concerns with an understanding of the possibilities for environmental co-benefits that could be derived from a more enlightened approach to biofuels is persuasive:

> *Where possible, we need to see development of biofuels in a 'win-win' scenario, providing carbon savings and also…positive benefits to biodiversity and improving natural 'ecosystem services' by improving soil and water quality and biodiversity.*

It is not possible to make precise estimates of the potential of biofuels globally because yields vary enormously with region, crop and management practices. The survey by Sims *et al* (2006) shows yields being in the region of 30 gigajoules (10^9 joules) per hectare per year (GJ/ha/yr) (approximately 0.65 t/ha/yr) for biodiesel from oil seed rape, and 15, 40, 110 and 115 GJ/ha/yr for ethanol from wheat, maize, sugarcane and sugar beet respectively. Taking 50 GJ/ha/yr as a very rough average, meeting 10% of the world's demands for transport fuels, which are currently about 170 exajoules (10^{18} joules) per year (EJ/yr) (emitting over 3.5 GtC/yr) would require about 340 Mha, or approximately 7% of land under crops and pasture (amounting to 5 billion hectares). It is relevant to add that degraded agricultural lands, woodlands and watersheds are thought to amount to nearly 2000 Mha, 500 Mha in Africa alone (UNEP 2002). Although such estimates are highly uncertain, the point arises, once again, that there is an opportunity to produce biofuels in ways that would help to restore degraded lands and watersheds, an immense 'win–win' opportunity at the international level. This will need to be taken forward by a number of government departments including DfID, FCO, DEFRA and DBERR.

Such calculations are readily repeated under alternative assumptions. Based on the carbon-wedges methodology of Pacala & Socolow (2004), biofuels could potentially contribute to perhaps 1 Gt of carbon abatement in the long term, and perhaps 2 Gt if more efficient biofuel supply and use chains are rapidly developed. This would imply an energy production from biofuels of roughly 35 EJ/yr rising to 70 EJ/yr. For comparison, the 2 billion people without access to modern energy forms consumed 45 EJ of biofuels each year in the 1990s (mainly firewood and dung for cooking), most of it with very low energy conversion efficiencies of 3–5% (Barnes & Floor 1996; World Bank 1996).

6.5 Policy instruments for biofuels

The Stern Review (Part IV) put forward three groups of instruments for climate change mitigation (Stern 2006):

- Carbon pricing, in the form of carbon taxes, tradable permits, or the imputed prices of restrictions on carbon emissions; (also see Royal Society 2002b).
- Direct support for R&D, demonstration projects and tax incentives or marketable 'obligations' to develop new technologies (such as the UK's Renewables Obligation (RO)).
- Environmental standards and regulations. In transport these can take several forms, including efficiency and emission standards for vehicles, for instance. For biofuels, regulations and standards would also need to be applied to cropping and afforestation practices in the interests of attaining the wider ecological benefits discussed above.

The Stern Review took as self-evident that policies to improve efficiency in transport would also need to be pursued, such as the improvements that would arise from a better balance between public and private transport, congestion pricing, and between the demands of motorised, bicycle and pedestrian traffic. Given that addressing climate change is an international problem for 'collective action', the Stern Review took the widely accepted principle that countries would not export their environmental problems to others. Indeed the original purpose of the Stern Review was to find a way forward for international policies on climate change. Lastly, policies need to be durable given the long-term nature of the problem to be solved.

Fiscal and regulatory policies for biofuel development and use in the UK need to be assessed in this light. They currently have two aspects:

- A biofuel duty differential equivalent to 20 pence per litre less than petrol and diesel. It is valid until March 2009 (DfT 2007).
- A Renewable Transport Fuels Obligation, to be introduced in April 2008. This is an obligation on fuel suppliers to ensure that 5% of all UK fuel sold will be from a renewable source. There will be a 'buy-out price'– a price paid by parties who fail to meet their obligation – of 15 pence per litre for 2008–09 (DfT 2007). Suppliers will also be required to provide a detailed report of the greenhouse gas balance and wider environmental impacts of the fuels they put on the market.

The combination of duty incentive and buy-out price is also guaranteed at 35 pence per litre for 2009–10 but will reduce to 30 pence per litre in 2010–11 (HMT 2006). In practice, if the target set by the RTFO is met then no funds enter the buy-out fund. This raises the barrier-to-entry significantly for those biofuel suppliers that do not have links to the obligated parties and reduces the potential to use the buyout fund to reward innovation and best practice.

The shortcomings of these incentives are similar to those initially experienced with the Renewables Obligation for electricity generation (they have now been addressed in the Energy White Paper, 2007 (DTI 2007)):

1. They are very short-term, when policies to mitigate climate change and derive the environmental co-benefits of biofuels require a long-term strategy with long term incentives. The main effect of current policies will be to encourage the import of fuels from abroad and the domestic production of crops and fuels with low CO_2-equivalent savings (see Figure 6.1 and Tables 5.1 a, b, c and 5.2).
2. There is a risk that the policy will lead to the export of environmental problems to developing countries supplying the fuels, as there is no guarantee that they will be sourced from regions with environmentally sustainable cropping and forestry practices. It remains to be seen how effective the public reporting requirements for GHG performance and broader sustainability assurance will be under the RTFO.

If effective, new GHG and sustainability assurance and certification infrastructure will be developed around the world. A European scheme is currently being developed, but any scheme will require a considerable increase in knowledge and data.

3 There is no 'banding', that is to say no differentials in the incentives structure to recognise that low carbon technologies in their earlier phases of development require a greater incentive than the proven options. One of the lessons learned from the RO for electricity is that, in the absence of banding, investment will flow to the more established near-term options (such as happened with onshore wind, leading to considerable pressures on the countryside) and little to the more promising long-term options, such as the offshore resource.[q]

4 There is no carbon pricing. As the Stern Report and many others have argued, mitigation policies require a combination of incentives. One is a carbon price. The others are incentives to support low carbon innovations directly: R&D, demonstration programmes and long-term 'obligations' or tax incentives for technologies in an earlier stage of development and use.

5 The approach to deriving the sorts of wider environmental co-benefits discussed above is not clear, as is also apparent from the evidence submitted by several parties to the Royal Society in the course of preparing this study.

These shortcomings would not be difficult to address. First, an obvious step forward would be to extend the RTFO or the fuel duty allowance to say 2025 with a commitment to making such adjustments over time as are necessary to improve its effectiveness. The second would be either to 'band' the RTFO or to introduce a fuel duty allowance that offered much greater incentives for the development and use of biofuels from advanced production and conversion systems (including lignocellulose and waste biomass). This would also act to encourage more targeted private research, development and demonstration. Refining policies, so that they are targeted towards reducing the GHG emissions from biofuels, while promoting sustainable development, will help direct investment. The third would be to complement private RD&D through a greater public RD&D effort. Fourth, carbon pricing needs to be extended to transport fuels on a CO_2-equivalent basis, ideally using LCAs to identify the carbon price penalty for the various categories of fuel sources and cropping practices; this of course will require, as with other environmental problems, a monitoring system to be set up. Among other things, this pricing system would provide not only the incentive for use of the already proven biofuels, but would also provide a bigger incentive for those biofuels and cropping practices with the greater GHG abatement potential. (If carbon pricing were introduced, this might best be in the context of using it to replace the RO or fuel duty allowance for biofuels from food crops, which rest on mature technologies.) Fifth, a public policy statement is needed regarding the potential of – and the practices for attaining – the environmental co-benefits of biofuels. For obvious reasons this statement would need to include policies covering the import of biofuels from, and international assistance for sustainable practices, in developing regions.

6.6 Transport fuels and transport policy more generally

The estimates in Section 5.5 indicate that meeting the RTFO target of 5% replacement of oil based transport fuels, without using imports, would require anywhere between 10 and 45% of the UK arable land area. The inclusion of energy production from organic and municipal wastes would raise this contribution and reduce the land requirement. This is a relatively small but nevertheless useful contribution; but it is clear that the transition to a low-carbon transport economy will require a much wider range of policies, and involve several more technologies and practices, than we have been able to pursue in this report. The key ones include:

- Improvements in vehicle fuel efficiency. For example hybrids and plug-in hybrids could potentially double or more the efficiency of passenger vehicles, and thus they could double the effectiveness of the biofuel programmes. The plug-in hybrid also opens up the important possibility of the batteries being recharged through low carbon energy forms for electricity generation, such as renewable energy and nuclear power, which would further reduce the 'carbon footprint' of transport.

- Use of well-to-wheels indicators driven by full LCA of the entire supply chain to provide carbon-abatement cost comparators (Figure 6.3).

- Congestion pricing, which aside from reducing congestion directly would improve vehicle fuel efficiency.

- Alternative fuelled vehicles, such as hydrogen with fuel-cells or fully electric vehicles. This will require significant developments, for example to produce hydrogen with low carbon emissions such as from coal with carbon capture and storage or renewable energy or nuclear power (King Review 2007).

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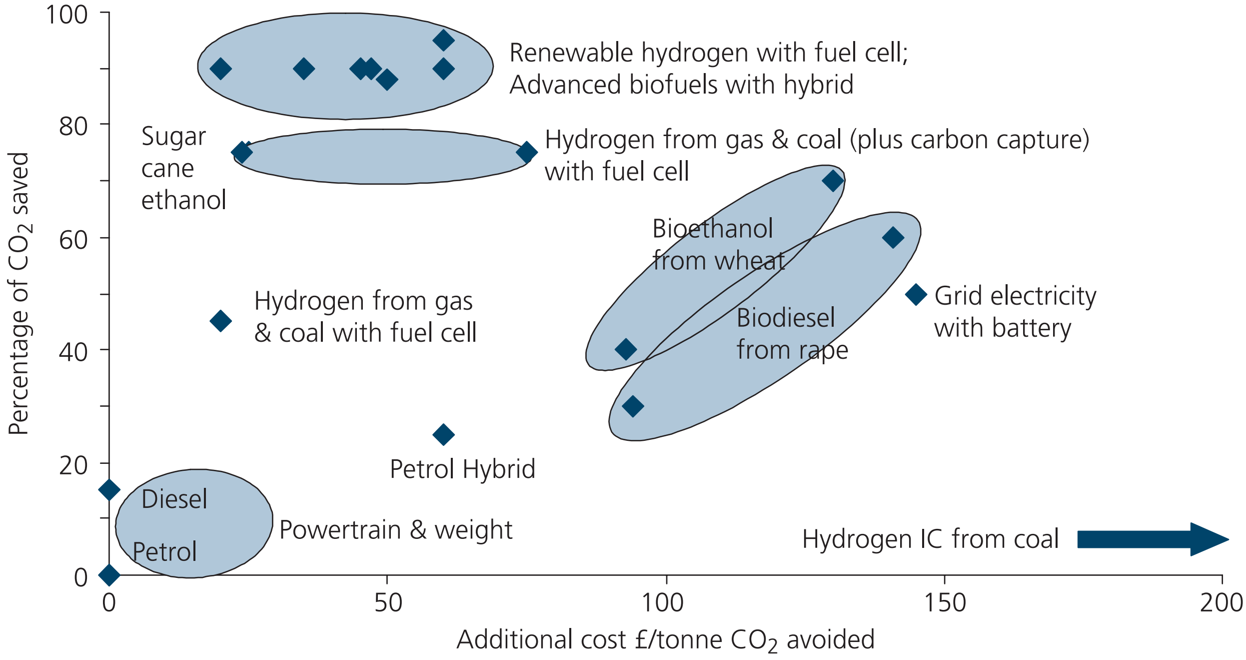
[q] The Government is currently in the process of rectifying this by weighing the options for banding

Figure 6.3 Comparison between additional cost per tonne of CO_2 abated against percentage of CO_2 saved. Alternative fuels and vehicle technologies provide opportunities, but CO_2 savings and cost effectiveness vary widely. Note that this figure does not include lignocellulose biofuels, which offer larger CO_2 savings. Figure for grid electricity with battery is an average figure and is likely to show a greater range of savings and costs depending on electricity source and battery technology. (Source: Adapted from E4Tech (2004).



Many of these concepts have been technologically demonstrated. However, there remain formidable technological challenges to develop them further and reduce costs to commercially compatible levels. Their commercial development will also require the incentives that only public policies can provide. The RTFO would be better defined more broadly to become a Low Carbon Transport Fuel Obligation. In addition, incentives relating to the carbon performance of a vehicle could be applied at the point of sale, such as the Vehicle Excise Duty, which would act as a guide for customers. As with policies for biofuel development, the key will be to have a combination of policies that: (1) extend the principle of carbon pricing to transport; (2) extend the incentives for innovation to the development and use of low carbon/high efficiency vehicles and the use of electricity or hydrogen as a vehicle fuel; and (3) put in place more ambitious proposals for congestion pricing, using the latter as a means of transferring the burden of road-user charges from fuel taxes to pricing road use directly.

6.7 Policy and research

The convergence of risks of supply of fossil fuels for the transport sector, coupled with an increasing global recognition that GHG emissions from industry and the transport sector are largely responsible for climate change, has led to a political consensus that alternative fuel options must be pursued. Of these various fuels, policies to encourage biofuels have been developed most rapidly. A number of policies have been put in place, both at the European level and nationally, based largely on setting ambitious targets for biofuels to supply a proportion of overall transport fuels. Further policy measures can be envisaged if current targets cannot be achieved.

Whilst policy is largely neutral as to the technologies needed to achieve the targets, it is apparent that at present a robust evidence-base is not in place to assure sustainable processes for biofuel development in the timescales required. Essentially, policy requirements are ahead of the research needed to achieve the outcomes proposed. Some biofuels (especially those developed from lignocellulose biomass) have the potential to be sustainable transport fuel in the long term, and can proved a partial replacement for fossil derived fuels. There is an urgent need for investment in the technologies needed to underpin future development in the most sustainable biofuels to achieve policy requirements, rather than rely on the expanded use of less sustainable alternatives.

6.8 Public dialogue and communication

Climate change is starting to become widely recognised by the public through the many references to environmental issues in the media. Society is already looking for ways to mitigate the increasing risks facing the planet, and decreasing our dependence on fossil reserves is seen as one of the key elements in the search for sustainability.

The potential of renewable energy has been highlighted positively in the media. The use of biofuels has recently received some media coverage, drawing attention to several issues regarding sustainability. These issues revolve around perceptions of conflict between use of land, water resources and agricultural production for food or fuel. There is also concern that large-scale cultivation of energy crops will be detrimental to biodiversity and the landscape in the UK, as well as causing harm to the environments and economies in developing countries of the world. Any use of GM technologies, particularly involving large-scale cultivation of monocultures, may also connect with long-standing concern, particularly in Europe, over the use of this technology.

This complex mix of concern and opportunity requires an informed discussion on the take-up of biofuels; informed in the sense that a coherent scientific evidence base is developed and fed into discussion and debate, and in the sense that any deliberation and decision-making includes an understanding of public and stakeholder views as well as relevant socio-economic research. Public attitudes and the actions of stakeholders can play a crucial role in realising the potential of technological advances. It is important therefore to foster a process of iterative dialogue with the public and interested sections of society to help frame, identify and think through the issues.

6.8.1 Holistic analysis and communication

Biofuels development includes a complex interplay of different issues, and decisions taken will impact on many different interests at all stages in the supply chains: from growers, processors and users of feedstocks through to consumers. For example, for agriculture, there are many issues to consider: from choice of crop, the forward investment needed for perennials, learning to cultivate new crops and needing to have the appropriate machinery for harvesting. Increasing reliance on agricultural feedstocks will also impact directly on rural communities, their economic and environmental sustainability and career decisions of young people to maintain farms in preference to moving to the cities.

Due to the interplay of multiple factors, any analysis of the concern and opportunities raised by biofuels will require an integrated or 'holistic' approach that draws on scientific, social science and economic research. This would involve placing scientific evidence in a framework, which includes assessment of specific issues such as the protection of the quality and security of the food chain, climate change and the need to decrease dependence on fossil reserves. It will also involve placing the evidence in a broader framework that brings in an iterative dialogue with the public and other stakeholders to ensure that discussions about the concerns and opportunities posed by biofuels occur with full consideration of all the evidence and implications for society.

6.8.2 The role of the scientific community

Integrated supply chains will be an absolute requirement to achieve the potential offered by the newly emerging bio-economy. The different members of the scientific community will need to work together to develop a shared consensus on what science needs to achieve to deliver sustainable biofuels. Such integration needs to be reflected in communication activities.

One such example is the Science to Support Policy project funded by the European Commission (EPOBIO) developed a process for providing an evidence base to underpin outreach and decision making in the context of future plant-based bio-products (Beilen *et al* 2007; Paschou 2007). After the development of criteria for selection of topics, the science-led issues were analysed in a wider holistic framework of environmental impacts, socio-economics and regulations to determine the relative strengths, weaknesses, opportunities and threats offered by each alternative. Through integrating these very diverse perspectives and including very different communities for information gathering, the EPOBIO process reached both policy makers and the public (Paschou 2007). A similar process in developing holistic and coherent biofuel analysis, communication activities and stakeholder participation could be explored.

6.9 Conclusions

The future contribution of biofuels to energy security and the emergence of a low carbon energy economy in the UK will depend significantly on the incentives offered by government policies. Farmers, the processors and distributors of biofuels, and the motor vehicle industry will all respond if the 'right' incentives are put in place. As outlined above, policies need to:

- be in place for the long-term, out to about 2025, being amended as and when necessary to improve their effectiveness;
- extend carbon-equivalent pricing to transport fuels and vehicles on a CO_2-equivalent basis;
- support innovation directly, with the incentives being greater for more efficient biofuels (this could take the form of a 'banded' RTFO, but there are alternatives such as extended fuel duty allowances);
- provide greater incentive for those fuels produced by cropping practices with a lower 'greenhouse gas footprint' based on LCA;

- complement private R&D by greater public R&D, perhaps financed out of revenues from the RTFO–an approach which would be fully consistent with the economic goals of such ‘obligations’, which are to foster low-carbon innovation;

- support policy-relevant research, for example through the UKERC, on (1) the wider social and economic effects of biofuel production and use, and (2) of the policies for developing low carbon/high efficiency vehicles.

Such policies will need to be developed collaboratively between a number of UK government departments including DfT, DBERR, DIUS, Defra, HMT, the Sustainable Development Commission, the Commission for Integrated Transport and the devolved administrations.

The dangers of producing biofuels in unsustainable ways have been highlighted, and it is taken as given that unsustainable practices will not be ‘exported’ by the UK through its import policies. Using the UK marketplace to incentivise good environmental, economic and social practice abroad will result in complex global policy implications. This is currently most contentious in the World Trade Organisation, where the potential to erect new barriers to trade through sustainability assurance and certification systems is causing concern. Indeed, the current RTFO policy on mandatory reporting on the GHG and broader sustainability performance of biofuels, rather than carbon-equivalent pricing, is a direct result of these concerns. However, there is a unique opportunity internationally, not only to avoid such problems, but to produce biofuels in ways that would help to restore degraded farmlands, woodlands, forests and watersheds. In order to facilitate this, the development of sustainability criteria for biofuels and land use need to be given greater priority and momentum in international negotiations. Furthermore effective mechanisms need to be put in place to facilitate technology transfer. The UK government, including Defra, DfID, FCO, HMT, DBERR and DIUS and HMT are well placed to show world-wide leadership in the development of a sustainable global biofuels industry.

Elsewhere in the report, we also highlight the significant uncertainty in the estimates of the impacts (environmental, social and economic) of biofuels. However, waiting until these uncertainties are overcome is also not an option because a few biofuels are already cost-competitive and are entering the market. Should the UK wish to influence the development of biofuels in a way that encourages innovation, improves efficiencies, and lowers costs and environmental impacts, then enlightened policies are required that target the entire innovation chain from feedstock production through conversion to end use and that range from blue sky research to applied social development theory. These policies should be technology neutral but targeted towards encouraging biofuels that have low GHG emissions, environmental impacts and costs. This will allow them to be sufficiently flexible to encourage innovation and encompass new understanding as it emerges. There is a real risk that without such support many of the technologies that could deliver the greatest benefit will not be developed and the biofuel sector will become locked-in to a system that is sub-optimal, both in terms of efficiency and sustainability.

The policy options outlined above should enable the UK to take a responsible lead in biofuel development and implementation following an integrated pathway that targets climate change mitigation and adaptation, energy security and economic development simultaneously.

7 Research and development

The overall challenge for biofuel development is that although plants offer an immense potential for energy provision, current fuel specifications prevent this potential from being realised. There are real scientific opportunities for using plants to capture the energy from the sun and deliver it for use in vehicles. These opportunities will necessarily involve the development of biofuels that approach the oxygen content of plant biomass and new engine technologies that can accommodate these fuels. The following research and development needs will take us towards meeting this challenge.

Biofuels are part of the bioenergy sector of the bioeconomy. This continuum in itself necessitates an integrated approach to research and development. In addition, the complex nature of the supply and use pathways of biofuels further reinforces this need for integration. We are aware that research needs we highlight for biofuels have wider implications for the entire biological production system. This is because all production systems must eventually move towards meeting the same sustainability standards and there are strong linkages between non-food and food plant products. It is essential that there is a process established for this integration and we recommend that bodies such as the Technology Strategy Board (TSB) and the Energy Technology Institute (ETI) play a coordinating role across all the sectors that are involved in prioritising and delivering the R&D. This process will determine the timeframe for research and development. Rapid progress will only be achieved when effective integration is established.

We now follow the individual steps in the supply and use pathway. Recommendations for research and development are provided together with suggested agencies who should take responsibility for ensuring implementation and delivery. Significantly, progress will strongly depend on close collaboration between the agencies responsible for implementation.

The following tables highlight a range of generic issues with an indication of who needs to fund such work. Each of the recommendations encompasses a broad diversity of research needs that will involve a range of disciplines spanning science, engineering and social science. Research and development needs are given in detail in the chapters of this report and major priorities are outlined here.

7.1 Feedstocks

A diverse range of feedstocks, comprising sugar, starch, plant oil and lignocellulose, can support biofuel development. These feedstocks can be derived from multiple sources including annual food crops, perennial energy crops and forestry, agricultural co-products such as straw and other materials currently regarded as waste. There are also opportunities for developing marine organisms, for example to produce oil. There is also a unique opportunity internationally to produce biofuels in ways that would help to restore degraded farmlands, woodlands, forests and watersheds.

A major target for crop improvement is to increase yield of feedstock while reducing negative environmental impacts. This will include targeting reduced emissions of N_2O and more effective scavenging of phosphorus. The ability to raise yield under the abiotic stresses of drought, salinity and temperature, as well as under biotic stresses caused by pests, pathogens and weeds, is a major research target. The search to provide new genetic material will be all important, including the diversity of germplasm with inherent ability to tolerate these stresses. In total, the genetic base for feedstock development must be broadened to create robust production systems.

In addition, feedstock quality must be improved for more effective processing. This will include, for example, development of higher starch to nitrogen ratios, alterations to plant cell-wall organisation and composition to improve sugar release from lignocellulose, and development of plant oils that are more appropriate as biofuel.

It is essential to provide the research base for both the energy and non-energy bioeconomy, such that co-product development from energy feedstocks can be further exploited within integrated biorefineries.

What needs to be done	Responsibility for funding
Increase yield of feedstock while reducing negative environmental impacts. (Sections 2.1, 2.3, 2.4)	BBSRC, Defra, NERC Agri-business Oil majors Forestry Commission (FC)
Understand water use requirements for biofuel production	BBSRC, Defra, NERC, FC Agri-business
Raise yields under abiotic stresses (Section 2.4)	BBSRC, DfID, Defra, FC agri-businesses
Develop sustainable approaches to withstand biotic stresses (Section 2.4)	BBSRC, Defra, DfID, FC Agri-businesses
Capture from species diversity, genetic resources as new feedstocks (Section 2.4)	BBSRC, NERC, FC Oil majors
Develop improved feedstock qualities for biological, chemical and thermal processing (Section 2.2, 2.4)	BBSRC, agri-business, oil majors

Table (*continues*)

Table (*continued*)	
Develop the potential for co-product development from multipurpose feedstocks (Section 2.2, 2.4)	BBSRC, DBERR (Department of Business Enterprise and Regulatory Reform), Technology Strategy Board (TSB) EPSRC agri-business, food, pharmaceutical and chemical industries, oil majors
Develop crops for year round supply of feedstock to integrate it with the supply chain (Section 3)	BBSRC, Defra
Improve harvesting techniques for energy crops (Section 3)	Defra, DBERR, TSB

7.2 Conversion and biorefineries

There is a considerable range of options for converting the feedstocks into biofuels, whether these are petrol or diesel replacements. These options are constrained by the composition of the feedstock and the quality demands of the fuel. The first stage is preparing the feedstock for conversion, for example breaking it up to improve processability or removing contaminants, which can disrupt conversion processes.

For biological conversion of lignocellulose feedstocks, a major generic constraint is accessibility of hydrolytic enzymes to the energy-rich cellulose material. The feedstock needs to be pre-treated to ‘open up’ the cell wall matrix, which then becomes accessible for saccharification. The sugars released provide the nutrient source for micro-organisms that manufacture biofuels. A major research target must be the acquisition of new bio-molecular tools for processing and use of feedstock. These tools are likely to emerge from analysis of complex biological systems that have evolved the capability to process and degrade lignocellulose to sugars in their natural environments.

The application of synthetic biology to fermentation of sugars will play an increasing role in developing micro-organisms to produce biofuels. This work, together with further searches of natural biodiversity, is needed to provide organisms that more efficiently generate firstly ethanol, with the aim of higher alcohols and even alkanes in the future. For biodiesel from plant oils, the main research target must relate to improvements in processing, which is currently confined to trans-esterification, but needs also to consider hydroprocessing.

Thermo-chemical processing, for example by pyrolysis, can provide more energy dense feedstocks, allowing access to more diffuse and heterogeneous biological resources. These feedstocks can then be upgraded, for example by gasification and Fischer-Tropsch catalysis, to replacements for current transport fuels. However, gasification results in the complete destruction of the organic matrix. New processes are being developed that will involve breaking of fewer carbon bonds that will in turn require new catalysts or biological conversion systems for building up to biofuels with acceptable properties for use with existing and new engine technologies.

Improved efficiencies mean that all processing is likely to move to biorefinery technologies, which provide multiple outputs in addition to biofuels, for example heat, power and fine chemicals. From a research perspective, the emphasis must be on the development of a set of capabilities that are independent of the exact chemicals that may be produced. However, a major research effort is needed to manage the scale of requirements for various components to be refined. Thus, pharmaceuticals, and some nutraceuticals, will be produced on a relatively small scale, whereas some of the derived chemicals could become platforms for major industrial products.

What needs to be done	**Responsibility for funding**
To develop biological processing of lignocellulose to increase accessibility for efficiency of saccharification	BBSRC, FC Agri-business Oil majors
Capture from species diversity, new genetic resources for feedstock processing	BBSRC, DBERR, TSB Agri-business Food and chemical industries Oil majors
Use synthetic biology to develop new micro-organisms for production of biofuels by fermentation	BBSRC Agri-business Oil majors
Improve processing of plant oils for biodiesel production	EPSRC, DBERR, TSB Oil majors
Establish value of pyrolysis in concentrating diffuse feedstocks	EPSRC, DBERR, TSB
Develop new physico-chemical systems for biofuel synthesis	EPSRC, DBERR, TSB Oil majors
Provide the underpinning science and technology for developing and demonstrating integrated biorefineries	DBERR, TSB, BBSRC Food, chemical and pharmaceutical industries Agri-businesses Oil majors
Develop more fuel tolerant and more fuel flexible conversion processes	EPSRC, DBERR, TSB
Improve catalysts for fuel synthesis to be more tolerant of contaminants in thermal gasification and pyrolysis products	EPSRC, DBERR, TSB
Provide demonstration and long term operation of large and small-scale demonstration plants to reduce risks and uncertainties for commercialisation and that account for feedstock production scales	EPSRC, DBERR, TSB Agri-businesses Oil majors

7.3 End use and distribution

Biofuels offer opportunities as well as threats to future developments in engine technologies designed to improve energy efficiency (kilometres per megajoule) and decrease emissions of regulated and non-regulated pollutants. Furthermore future developments are already constrained by existing agreements concerning regulations for emission reductions and safety. Biofuel feedstock and conversion technology development must occur with the end use needs in mind and vice versa. To achieve this, research and development must be integrated across the supply chains linking feedstock to fuel quality specifications.

A principal research area is in defining the characteristics that make an ideal transport fuel. As it takes many years before all the vehicles currently in use are replaced, which for Europe/UK is about 15 years, biofuels need to be compatible with existing fuel standards. Thus as a matter of urgency, biofuels are required that can directly substitute petrol and diesel in existing engines. These biofuels will need to mimic the properties of petrol and diesel such as in octane equivalent, energy density, cetane number and hydrophobicity.

An opportunity exists to align the design and development of new engine technologies with future advanced biofuel supply pathways. This alignment will deliver significantly lower GHG emissions, levels of atmospheric pollutants, including VOCs, NO_x, particulates, ozone, with concomitant impacts on land. To reduce, for example, VOCs changes to catalytic converters will be required. **For vehicle manufacturers to make the investments needed, a long-term market for transport fuels containing a high blend of biofuels must be established**.

Existing distribution networks can have problems operating even with low biofuel blends. This derives from biofuels generally being more hydrophilic[r] than conventional fuels, and thereby being potentially more corrosive than them. New investments in the distribution infrastructure for coping with higher biofuel blends will only be made when there is certainty that demand will be assured. This is typical of a situation in which the investment into the infrastructure needed to supply a product will not be made until there is certainty of demand for the product. Conversely, the demand relies on the infrastructure.

What needs to be done	Responsibility for funding
Develop further biofuel-relevant engine technologies (Sections 4.1, 4.4)	EPSRC, DfT Vehicle manufacturers
Develop the understanding of biofuel engine combustion products (Section 4.5)	EPSRC, DfT Vehicle manufacturers
Ensure engine technologies, conversion systems and feed-stock developments are cross-compatible (Section 4.1, 4.6)	BBSRC, Defra, DBERR, TSB, DfID, EPSRC Vehicle manufacturers

7.4 Evaluating environmental impacts

Biofuels are currently considered within the relatively narrow context of GHG emissions arising from the transport sector. However, many of the environmental issues raised about biofuels and their feedstocks are exactly the same as those arising from other plant-based production systems, especially those for food. This results in a distorted perspective that biases the interpretation of potential environmental impacts. For example, palm oil produced for food applications has aggravated deforestation but demand for biodiesel can be met from existing plantations with food production re-directed to newly deforested less sustainable plantations. Only the land for biodiesel is currently accounted. To be effective, new accounting procedures must apply equally to all land use.

Research is urgently required to define the frameworks for the accounting and monitoring procedures of sustainability. This necessitates establishing the research capability to develop robust LCA. There must be transparency and public acceptability in the assumptions and calculation methodologies used in the assessments. If adopted, this research should achieve outcomes that allow greater comparability between assessments of different production, supply and use systems.

What needs to be done	Responsibility for funding
Further develop accounting and monitoring procedures for sustainability using existing work as a foundation (Section 5.1–8)	There is no obvious target for this aspect but it should include, among others, FC, TSB NERC ESRC, DfID, Defra, DBERR, DfT
Provide robust assessments of alternative processes and products to identify the most promising opportunities for development and deployment (Sections 5.2, 5.3)	EPSRC, DBERR, TSB, Defra, industry

7.5 Policy

Experience with energy-environmental policy making over the past 20 years shows there is a continual need for research on the design and performance of the policies themselves. As the evidence on climate change hardens,

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[r] This does not apply to all biofuels

future policies will need to be much more ambitious and much broader in scope than anticipated even a few years ago. There will also be a need for international initiatives and harmonisation of regulations, not least with the sustainable production and use of and trade in biofuels.

Policies need to be flexible to respond to changing circumstances, an improving evidence base, changing public and political perceptions and in response to shortcomings and experiences with previous efforts. It is crucial that they are informed by policy-related social and economic research, as has been recognised by the establishment of the UK Energy Research Centre (UKERC). **We recommend continued and expanded funding for this kind of research by the Research Councils and other public sector bodies. We also recommend expanded public funding for policy as well as technological research into low carbon/high efficiency vehicles more generally (Section 6.6)**.

Research is also required for the impact of biofuel development on a range of social and economic issues including:

- the effects of alternative incentive schemes on cropping and conversion practices;
- the indirect effects of land use for biofuels on the prices of agricultural products, both in the UK and in countries that are significant suppliers of biofuels or feedstocks to the UK;
- the effects of innovation and innovation policies on costs and prices;
- the social, economic and environmental implications of changes in the use of water resources and fertilisers in the production of biofuels.

This list is not comprehensive, but does serve to show that there is a substantial research agenda ahead on biofuels on the social science as on the physical science side if policies are to benefit from the insights of the research community.

What needs to be done	Responsibility for funding
Socio-economic analysis of biofuel systems for effective and efficient policy development (Sections 6.2, 6.3, 6.4, 6.5, 6.8)	ESRC, DBERR, TSB, Defra, EPSRC, NERC
Provide the science to ensure biofuel development is compatible with climate change policy (Sections 6.3, 6.4, 6.5)	ESRC, DBERR, TSB, DfID, Defra
Develop a process for effective public engagement on biofuel issues (Section 6.8)	RCUK, DBERR, TSB, DfT

8 Conclusions and recommendations

Climate change mitigation, energy security, rising oil prices and economic objectives are stimulating strong interest in the development of biofuels for the transport sector. However, many of the biofuels that are currently being supplied are being criticised by different interest groups for their environmental impacts, food security and land use implications. Unless biofuel development is supported by appropriate policies and economic instruments that address these issues, then there is a risk that we may become locked into inefficient – and potentially environmentally harmful – biofuels supply chains and the benefits of alternatives based on new technologies still under development may be lost.

It is widely recognised that there is no simple solution to the problems of climate change and that greenhouse gas emissions need to be reduced across all sectors. Emissions from the transport sector are rising rapidly and compared to those from the power sector, they are difficult to deal with. This is partly because demand is rising so rapidly, but also because fewer mature technologies are available to decarbonise the transport sector in comparison to the power sector. While there are a mix of available sources for power generation (coal, oil, gas, nuclear and renewables), transport is dominated by one source – oil. With suitably targeted policy interventions, energy supply in the transport sector could become more diverse, while also reducing greenhouse gas emissions. Biofuels are already entering the transport market and are, arguably, more mature than other technologies such as hydrogen, fuel cells and fully electric vehicles. While plant material may be able to provide a source of hydrogen or electricity, several challenges need to be overcome for these other technologies to become more prevalent. Although on a greenhouse gas reduction basis the most immediately effective use of plant material, in terms of conversion efficiency, is to generate heat, this is not always true when comparing combustion for electricity with conversion to biofuels. There are real opportunities to develop biofuels that can deliver substantial greenhouse gas savings (Section 6.3). This means that it is also important to consider how liquid biofuels can help tackle much-needed emissions reductions in the transport sector.

Looking further into the future, the emerging biofuels sector is an integral component of the emerging 'bio-economy'. Plant material can be used for more than just energy provision, with the potential to deliver benefits into other sectors including the chemicals industry. There is a major opportunity for R & D and policy communities to direct efforts towards the development of this new future and the UK is well placed to show leadership. Many of the technologies and production systems for biofuels and chemicals are at relatively early stages of conception or development. Their establishment is founded upon the immense scientific progress in understanding biological, thermal and chemical systems. This new knowledge offers a wide diversity of opportunities and pathways for the more efficient and environmentally beneficial exploitation of plant material for biofuels and chemicals. While we focus on the development of biofuels for transport in this report, it is necessary to be mindful of these other potential future applications so that opportunities for the use of bio-based feedstocks beyond transport and energy supply are not forgotten.

The wide diversity and complexity of options for producing biofuels in itself presents a challenge to fully understanding the relative benefits that different biofuels can offer. It is therefore not possible to make simple generalisations about biofuels being 'good' or 'bad'. Each biofuel option needs to be assessed individually, on its own merits. Nevertheless, some general conclusions and recommendations for the sector as a whole can be drawn:

1 Existing policy frameworks and targets for biofuels are sometimes based on scant evidence and may miss important opportunities to deliver greenhouse gas emissions reductions.

Primarily in response to economic and energy security drivers, the European Union, USA and Brazil, have developed policies to increase the use of biofuels. However, provisions such as those contained within the EU Biofuels Directive are currently not directed towards reducing greenhouse gas emissions, even though this is widely perceived as a motivation for their use, but instead set down national supply targets. As a result, there is no direct incentive to invest in the systems that would deliver the lowest greenhouse gas biofuels, or the wider environmental, social and economic benefits. There is a real danger that a policy framework driven solely by supply targets will result in biofuel pathways being developed that miss opportunities to deliver reductions in greenhouse gas emissions. In addition, economic and regulatory incentives are needed to accelerate the technology developments needed to deliver biofuel supply chains that can provide more substantial emissions reductions. The proposed carbon and sustainability reporting aspect of the Renewable Transport Fuels Obligation in the UK offers a potential basis to achieve this.

We recommend that policies designed to increase biofuels usage are refined at national level to include a greenhouse gas reduction target for fuels, while also promoting sustainable development (Section 6.5).

2 Biofuels alone cannot deliver a sustainable transport system. They should be part of an integrated package of measures.

Biofuels have a limited, but potentially useful, ability to replace fossil fuels, largely due to technical and economic constraints. Current policy frameworks need to recognise that there is no 'silver bullet' to deal with transport emissions and that biofuels on their own are not the answer. Without policies that stimulate innovation in a whole range of technologies (including, but extending well beyond, biofuels) it will be extremely difficult to decarbonise the transport sector.

Biofuels are currently the only fuel for the transport sector that is compatible with the existing mix of engine technologies and fuel delivery infrastructure. Alternative fuels such as hydrogen require considerable investment to develop low carbon sources, efficient storage units and the development of a delivery infrastructure. Meeting the rising demand for transport will require combining biofuels with other developments, including vehicle and engine design; the development of hybrid and fuel cell vehicles and supporting infrastructure; public transport; congestion pricing; and urban and rural planning to improve the balance between public and private transport and between motorised and non-motorised and pedestrian traffic. Such changes would be greatly facilitated by extending carbon pricing and incentives for innovations in low carbon technologies and practices for transport. Indeed, the focus should be on providing 'sustainable mobility' rather than transport.

We recommend:

- **Expanded funding for policy as well as technological research into low carbon/ high efficiency vehicles more generally (Section 7.5).**
- **Extending the principle of carbon pricing to transport fuels (Section 6.5).**
- **The provision of direct tax incentives or marketable obligations to promote development of new technologies such as more fuel efficient and low carbon vehicles (Section 6.6).**
    - **The Renewable Fuel Transport Obligation is a step in this direction, but would be better redefined to become a Low Carbon Transport Fuel Obligation, and extended to 2025 (Section 6.5, 6.6).**
    - **In addition, the Vehicle Excise Duty should be used to give a stronger indication of the carbon emissions from the use of the vehicle, which would act as a guide to the environmental performance of a vehicle at the point of sale (Section 6.6).**
    - **Benchmarks on engine performance and emissions when using different biofuels need to be standardised. This needs to cover all GHG emissions; some, such as methane and N_2O are currently not classified as GHG emissions (Section 4.4).**
- **The provision of specific innovation incentives for development and use of low carbon/high efficiency vehicles and alternative energy sources for transport (see Section 6.6).**
- **DfT, in collaboration with the UK Commission for Integrated Transport, lead the development of a UK transport plan (after expiry of the existing one in 2010) that explicitly recognises the need for sustainable, low carbon transport and that combines the policies described above and the mechanisms for implementing them. The case for a more integrated approach is developed in Section 6.6.**

Such policies will need to be developed collaboratively between a number of UK government departments including DfT, DBERR, DIUS, Defra, HMT, the Sustainable Development Commission, the Commission for Integrated Transport and the devolved administrations (Section 6.9).

3 There are a significant number of social, economic and environmental uncertainties associated with biofuels and policy frameworks must ensure that such issues are addressed.

Our conclusion that biofuels are potentially an important part of the future is tempered with many caveats. There exist a number of sustainability issues that need to be resolved. Questions often raised include: 'How much land is required to meet current policy targets?'; 'What volume of biofuels can be produced globally, regionally and nationally?'; and 'What implications will biofuels have on land use and local livelihoods?' Establishing accurate answers to these questions is difficult because they are dependant on a number of interacting scientific, social, environmental and economic factors such as the yield of the feedstock, the conversion efficiency, the location of the end user and the type of end use. Considerably more information is needed to reduce the uncertainties in these assessments.

In order to balance the uncertainties associated with different biofuel options sustainability criteria need to be applied for *all* land use, whether for non-food or food production. This will also provide valuable information on the wider context within which research and development of biofuels must progress (see Section 3.1 and 5.1). In particular, understanding the precise greenhouse gas abatement potential of biofuels must be underpinned by robust science. Significant uncertainties in the estimates of environmental, economic and social impacts of biofuels are likely to remain for some time. Policies to address these cannot wait until the uncertainties are overcome, as some biofuels are already entering the market. The UK Renewable Transport Fuel Obligation (RTFO) carbon reporting and sustainability certification scheme could go some way to resolving these issues. It will also be vital to establish international frameworks for sustainability assessment.

In this context, we have also pointed out the dangers of a policy of importing biofuels leading to the 'export' of environmental problems to developing regions (Chapter 6). There is no reason in principle why such problems cannot be avoided, and indeed we noted, as have many other studies, that there are ways of combining biofuel production in developing regions with the restoration of degraded lands, watersheds and forests-an issue that needs to be pursued in connection with the UK's and the EU's interests in international development.

The development and use of existing tools, such as life cycle assessment, strategic environmental assessment and environmental impact assessment could also make valuable contributions for the assessment of biofuels. These tools can to be used to assess all land use, but they may need to be refined to address biofuels and other specific uses. Responsibility for the development of the criteria will not sit within one government department alone and will require a cross-departmental approach if they are to be effectively developed and implemented. In addition, for the reasons just noted, the development and implementation of the criteria need to be coupled with our responsibilities for the promotion of sustainable development in developing regions, requiring a cooperative effort at the international level through international development organisations and bodies such as the OECD, WTO, CBD and CSD. Attempts at international harmonisation of methodologies to measure the greenhouse gas emissions impacts of biofuels by the Global Bioenergy Partnership (GBEP) are relevant in this regard.

As most of the technologies are likely to be developed in the OECD and rapidly emerging economies, there is a need for mechanisms to facilitate effective technology transfer to and between developing countries. This will be vital to ensure that biofuels develop sustainably irrespective of geography.

Public attitudes and the actions of stakeholders can play a crucial role in realising the full potential of technological advances. Biofuels raise a number of concerns and opportunities, such as the use of GM technology, food security and land use. Addressing these concerns requires an informed discussion based on the scientific evidence, but also an understanding of public and stakeholder values and views. It is important therefore to foster a process of iterative dialogue with the public and interested sections of society to help frame, identify and think through the issues (see Section 6.8).

We recommend:

- **Applying carbon certification and sustainability criteria to the assessment of biofuels, which may require additional criteria specific to biofuels to be developed (see Sections 5.1 to 5.3). These assessments can only become fully effective if applied to all forms of land use, which avoids the need to assess the indirect impacts of biofuels.**
- **That sustainability criteria are developed by DEFRA, DBERR, DfT, DIUS, DfID, HMT, the Sustainable Development Commission and the devolved administrations (Section 5.9).**
- **Establishment of mechanisms to facilitate effective technology transfer to and between developing countries, and also to find approaches to biofuel production that address the problem of restoring degraded lands and watersheds. This will need to be taken forward by a number of departments including DfID, FCO, DEFRA and DBERR (Sections 2.3 and 6.4).**
- **The facilitation of effective public dialogue so an informed discussion on the concerns and opportunities raised by biofuels takes place (Section 6.8).**

4 There is a danger of policy forging ahead of the research and technology needed to achieve the outcomes proposed.

There is evidence that the promotion of biofuels has led to policy getting ahead of the research and technology development needed to achieve the outcomes proposed. There is an urgent need for further formulation and application of policy which fosters the commercialisation of low-carbon biofuels and the successful development of a strong and stable industry. These policies need to encourage research, development and innovation that improve efficiencies, lowers costs and environmental impacts. These must be targeted towards the entire innovation chain, from feedstock production through to conversion and end use, and also incentivise R&D from short- to long-term timescales. There is a real risk that without such support, many of the technologies that could deliver the greatest benefits will not be developed and the biofuels sector will become 'locked-in' to a system that is sub-optimal, both in terms of efficiency and sustainability.

Industry requires clear and coherent policy signals to provide a long-term, favourable framework for progress to be made. There continues to be a lack of policy integration between the various Government departments involved, directly or indirectly, with biofuels in the UK. Without such integration, there is considerable potential for the creation of conflicting or disjointed policies which cause confusion and uncertainty in commercial decision-making, seriously hampering investment.

We recommend:

- **Formulation of policies that target the entire innovation chain to ensure that the development and use of biofuels follow an integrated pathway, which simultaneously targets climate change mitigation and adaptation, energy security and economic development (Sections 6.5 and 6.9).**
- **The development of long-term policy frameworks that are also sufficiently flexible to encourage innovation and to encompass new understanding as it emerges (Sections 6.7 and 7.5).**

5 There is a huge opportunity for the UK research, development and policy-communities to make a significant contribution to the development of a sustainable global biofuels industry

It is recognised that the UK R D & D agenda alone cannot address all the issues associated with the successful development of a global biofuels industry. However, there are many areas where UK science can make a very significant contribution (see Chapter 7). These include R D & D on biofuel crops, feedstocks, processing techniques and end products that are specifically relevant to the UK and parts of the EU. There is also considerable potential for the UK science base to assist the development of existing and new biofuel crops, feedstocks and end products in other areas of the world, especially in developing countries. The UK's agronomy community should be encouraged to apply its well-established but currently-neglected knowledge to increasing understanding and quantification of soil N_2O emissions for biofuel production in the UK and elsewhere. There also exist significant opportunities for the UK R & D community to tackle some of the uncertainties involved with calculating land use figures and biofuel supply potential. Meanwhile, UK policy-makers have the expertise and levers to develop policies for promoting a sustainable global biofuels industry, through international environment, trade and development policy.

We recommend:

- **The UK Government provides support to many of the R D & D niches in this sector, including biotechnology, agronomy, land use assessment and the calculation of biofuel supply potential (Chapters 2–5 and 7).**
- **The UK Government's international departments and HMT show world-wide leadership in the development of a sustainable global biofuels industry. Departments such as Defra, DfID, FCO, HMT, DBERR and DIUS need to ensure that there are effective mechanisms in place to facilitate technology transfer and that the development of sustainability criteria for biofuels and land use is given greater priority and momentum in international negotiations (Section 6.9).**

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Working group membership

This report has been prepared by the Royal Society working group on biofuels. The following members of the working group were invited in their personal capacity rather than as a representative of their organisation:

Chair

Professor John Pickett CBE FRS	Rothamsted Research

Working group

Professor Dennis Anderson	Centre for Environmental Policy, Imperial College London
Professor Dianna Bowles OBE	Centre for Novel Agricultural Products, University of York
Professor Tony Bridgwater	Bioenergy Research Group, Aston University
Professor Paul Jarvis FRS	Atmospheric and Environmental Science, University of Edinburgh
Dr Nigel Mortimer	North Energy Associates
Professor Martyn Poliakoff CBE FRS	School of Chemistry, University of Nottingham
Dr Jeremy Woods	Centre for Environmental Policy, Imperial College London

Secretariat

Richard Heap	Manager, Energy and Climate Change
Tanzeed Alam	Science Policy Officer, Energy and Climate Change
Dr Simon Edwards	Manager, Biosciences and Health (January to April 2007)
Philip Watson	Manager, Biofuels (to June 2006)

This report has been reviewed by an independent panel of experts and also approved by the Council of the Royal Society

Review panel

Sir David Wallace CBE FREng FRS Chair of review panel	Treasurer and Vice President of the Royal Society (to November 2007) and Master, Churchill College, University of Cambridge
Professor Lynn Gladden OBE FRS	Shell Professor of Chemical Engineering, University of Cambridge
Professor Jonathan Jones FRS	Senior Scientist, Sainsbury Laboratory, John Innes Centre
Professor John Shepherd FRS	Professor of Marine Sciences and Director of the Earth School of Ocean and Earth Sciences, University of Southampton
Professor Pete Smith	Professor of Soils and Global Change, University of Aberdeen
Professor Chris Somerville FRS	Director, Department of Plant Biology, Carnegie Institution, Stanford University, USA

Annex 1 Abbreviations and glossary

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
Arabidopsis	Thale cress (*Arabidopsis thaliana*) is one of the model organisms used for studying plant biology. Changes in the plant are easily observed, making it a very useful model, especially when considering ways to increase yields of biofuel crops through crop breeding techniques
BBSRC	Biology and biological sciences research council
Biodiesel	A diesel-equivalent processed fuel that is derived by transesterification of plant oil or animal fats
Bioeconomy	All economic activity derived from the application of our understanding of mechanisms and processes, at the genetic and molecular level, to any industrial process
Biofuel	Any transport fuel that has been derived from biological material
Biogas	Gaseous fuel comprised of methane (approximately 60%) and carbon dioxide, produced by anaerobic digestion (absence of oxygen) of organic material by micro-organisms. Can be used as a transport fuel or, as a replacement for natural gas
Biomass	Any biological material that can be used either directly as a fuel or in industrial production or fibre production
Bio-oil	A carbon-rich liquid produced by pyrolysis of plant material, which can be used to produce chemicals and fuels
Biorefinery	Any facility that produces a variety of products, such as fuels, heat, power and chemicals, from bio-based materials
C_2H_5OH	Ethanol
C_4H_9OH	Butanol
Catalyst	A substance, including enzymes, that increases the rate of a chemical reaction but is not consumed during the process
Catalytic converter	A device that uses catalysts to reduce harmful emissions from an internal combustion engine
Cetane	Cetane number is a measure of the ignition quality of diesel. Cetane enhancers can be added to improve its performance.
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
DBERR	Department for Business, Enterprise and Regulatory Reform
Defra	Department for Environment, Food and Rural Affairs
DfID	Department for International Development
DfT	Department for Transport
DME	Dimethyl ether

EIA	Environmental impact assessment
EPSRC	Engineering and physical sciences research council
ESRC	Economic and social sciences research council
ETBE	Ethyl tetra-butyl ether or 2-ethoxy-2-methyl-propane
EU	European Union
Extremophile	Micro-organisms that live optimally at relatively extreme conditions e.g. of acidity, salinity, temperature or pressures. Enzymes isolated from these organisms are used in some industrial manufacturing processes
FC	Forestry Commission
Feedstock	Any material that can be converted to another form of fuel, chemical or energy product
FFV	Flexible fuel vehicle
FT	Fischer-Tropsch: a catalyzed thermo-chemical reaction where carbon monoxide and hydrogen created by gasification of feedstock, is converted into synthetic transport fuels such as petrol, diesel and kerosene, which have exactly the same properties as fossil fuel derived fuels
Gasification	A process that converts materials, such as coal, petroleum or biomass, into synthesis gas (or 'syngas'), which comprises mainly carbon monoxide and hydrogen
GHG	Greenhouse gas
Glycerol	A compound with the molecular formula $C_3H_5(OH)_3$ which is a by-product of the production of biodiesel via transesterification. Can be used in other industries, e.g. the pharmaceutical, cosmetics etc
GM	Genetic modification
Hydrolysis	A chemical reaction where a compound, such as starch or cellulose, is broken down by reaction with water into smaller components. In the case of biofuels, this can use enzymes or acid
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 [?]
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
Isoprene	A volatile organic compound that is released by plants under high temperature and CO_2, which under certain conditions is an ozone precursor
LCA	Life cycle assessment
Lignocellulose	Plant cell walls are composed of lignin and cellulose, which provide mechanical strength. Can be broken down to lignin and cellulose or used directly as a feedstock.
Litres	Metric unit of volume, where one litre (l) = 1000 cm^3
Mha	Megahectare (millions of hectares), where one hectare = 10,000 m^2
Ml	Megalitre (millions of litres)
MOGD	Methanol to olefins, gasoline and diesel, a catalysed conversion process that uses methanol to produce petrol or diesel

mpg	Miles per gallon
MSW	Municipal solid waste
Mt	Megatonne (millions of tonnes)
MTBE	Methyl tetra-butyl ether or 2-methoxy-2-methylpropane
MTG	Methanol to gasoline, a catalysed conversion process that uses methanol to produce petrol
N_2O	Nitrous oxide
NGO	Non-governmental organisation
NERC	Natural Environment Research Council
Nutraceutical	Compounds that have human health benefits such as antioxidants
OPEC	Organization of the Petroleum Exporting Countries
Pyrolysis	The chemical decomposition of organic materials by heating in the absence of oxygen or any other reagents, except possibly steam. Heating biomass rapidly (fast pyrolysis) can help increase yields of liquid fuels, where the resulting bio-oil can then be transported for conversion into biofuels
RTFO	Renewable transport fuels obligation
RD&D	Research, development and demonstration
SEA	Strategic environmental assessment
SNG	Synthetic natural gas
SRC	Short rotation coppice
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
Synthetic biofuels	Fuels produced via thermochemical conversion of biological material, such as petrol, diesel and kerosene, which have exactly the same properties as fossil fuel derived fuels. These are defined differently to synthetic fuels, because synthetic fuels can also be made from coal, gas and oil
Tonnes	Metric unit of weight, where one tonne (t) = 1000 kg
t/ha	Tonnes per hectare
t/yr	Tonnes per year
Transesterification	A reaction that is catalysed by an acid or a base, where the alkoxy group of an ester compound is replaced by another alcohol. This process can be used to produce biodiesel
TSB	Technology Strategy Board
UKERC	UK Energy Research Centre
Vapour pressure	The pressure at which the gas of a substance is in dynamic equilibrium with its liquid or solid forms, at a given temperature
VOC	Volatile organic compound
WTO	World Trade Organization
WUE	Water use efficiency

Annex 2 Call for evidence response and workshop attendees

To inform the study we issued an open call for evidence in October 2006. We followed this with two workshops one for industry and the other for non-governmental organisations. Three oral evidence sessions were held. We are very grateful to those who responded to this call and to those who provided additional information at the request of the working group.

Industry workshop

Dr Ausilio Bauen	E4Tech
James Beal and Richard Parker	Renewables East
Dr Mairi Black	Home Grown Cereals Authority
Mr Ian Bright	Somerset Council
Jessica Chalmers	Low Carbon Vehicles Partnership
Dr Peter Davidson	D1 Oils Plc
Peter Gaines	Environmental Industries Commission (and Lyondell)
Thomas Gameson	Abengoa Bioenergy
Graham Hilton	Energy Crops Company Limited and Greenspirit fuels
Dr Paul Jefferiss	BP
Prof Graham Jellis	Home Grown Cereals Association
Dr David Lawrence	Syngenta
Dr Julian Little	Bayer Biosciences
Warwick Lywood	Ensus Limited and D1Oils
Dr Richard Miller	Miller Klein Associates Ltd
Mark Paulson	Coppice Resources
John Reynolds	North East Biofuels
Helen Scholey	Shell
Anthony Sidwell	British Sugar and IEA Bioenergy Task 39
Dr John Sime	KTN Bioscience
Peter Smith and John Sutton	Cargill
Sean Sutcliffe	Biofuels Corp
Professor Roger Sylvester-Bradley	ADAS/Green Grain
Jeremy Tomkinson	National Non Food Crops Centre
Graham Tubb	South East England Development Agency
Rob Vierhout	European Bioethanol Fuel Association
Matthew Ware	National Farmers Union
Malcolm Watson	UK Petroleum Industry Association
Claire Wenner	Renewable Energy Association

Oral evidence

Chris Scarrott	Roquette
Peter Gaines	Environmental Industries Commission and Lyondell
Prof Chris Somerville FRS	Stanford University, USA

NGO workshop

Maria Arce	Practical Action
Gundula Azeez	The Soil Association
Abi Bunker	Royal Society for the Protection of Birds
Dr Doug Parr	Greenpeace
Sian Thomas	The Woodland Trust
Ian Woodhurst	Campaign to Protect Rural England

Written evidence

Gundula Azeez	The Soil Association
Dr Ausilio Bauen	E4Tech
James Beal and Richard Parker	Renewables East
Dr P Berry	ADAS
Dr Mairi Black	Home Grown Cereals Authority
Prof Derek Burke	Personal view
Bill Butterworth	Land Network International Ltd
Jessica Chalmers	Low Carbon Vehicles Partnership
Prof Roland Clift	University of Surrey
Prof Brian Collins	Department for Transport
Dr Peter Davidson	D1 Oils Plc
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Dr Dick Glick	Corporation for Future Resources
Dr Jeff Hardy	Royal Society of Chemistry
Merlin Hyman	Environmental Industries Commission
Dr Paul Jefferiss	BP
Prof Graham Jellis	Home Grown Cereals Association
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Dr Jenny Jones	University of Leeds
Peter Jones	Biffa
Dr Henk Joos	D1 Oils Plc
Mr Shafqat Kakakhel	United Nations Environment Programme
Dr Maeve Kelly	Scottish Association for Marine Science
Sir David King FRS	Office of Science and Innovation
Dr David Lawrence	Personal view
Warwick Lywood	Ensus Limited and D1Oils
Prof Malcolm Mackley	University of Cambridge
Jean-Guy Mares	Personal view
Dr Donal Murphy-Bokern	Defra

Dr Cordner Peacocke	Conversion and Resource Evaluation Ltd
Dr John Pidgeon	Broom’s Barn Research Station
Prof David Powlson	Rothamsted Research
David Proudley	National Farmers’ Union
Renton Righelato	World Land Trust
Dr Linda Saunderson	Scottish Executive Environment and Rural Affairs Department
Dr Stuart Shales and Dr Alan Wheals	Society for General Microbiology
Gary Shanahan	Department of Trade and Industry
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Prof Pete Smith	University of Aberdeen
Prof Nick Syred and Prof Antony Griffiths	Cardiff University
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Sian Thomas	The Woodland Trust
Chris Walsh	The Society of Motor Manufacturers and Traders Ltd
Dr David White	Institute of Chemical Engineering
Cedric Wilkins	Scottish Enterprise
Prof Alan Williams	University of Leeds
Dr David Williams	National Non-Food Crops Centre
Dr Paulo Wrobel	Embassy of Brazil, London
Baroness Barbara Young	Environment Agency

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ISBN 978 0 85403 662 2
Issued January 2008 RS1053

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Registered Charity No 207043