Biofuels Review

MANCHESTER
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Biofuels Review

Report for Government Office for Science

Prepared by Dr Patricia Thornley, Tyndall Centre for Climate Change Research
and Sustainable Consumption Institute, University of Manchester

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Executive Summary

Biofuels are a key part of the UK's medium and long term strategies for achieving greenhouse gas reductions. However, biofuels require land resources which are also required for food production and carbon sequestration functions. Therefore it is important to ensure that technology developments are facilitated which will improve resource and land-use efficiency, but it is also important to realize that maximizing the conversion of raw material to biofuel does not necessarily improve the greenhouse gas balance or other overall system attributes. So, there is a need to develop policy frameworks that will facilitate sustainable land use that can satisfy multiple objectives (for food, fuel, carbon sequestration and other ecosystem services).

Such frameworks would facilitate the development of sustainable biofuel systems, which would reduce land conflict by

- Increasing the carbon savings associated with bioenergy implementation.
- Improving the resource efficiency of converting raw material to energy product
- Improving land-use efficiency.
- Increasing the available pool of biomass resource that can be sustainably converted

In addition these systems would deliver wider sustainability benefits, including social, economic and environmental objectives along the supply chain. Clearly it is not possible to deliver systems which maximize all of these parameters and so there is a need to prioritize certain ones. That prioritization could vary with feedstock, location and development context, but also be underpinned by a value prioritization, which is also likely to vary between stakeholders.

Performance of the whole biofuel system is not determined by the technology conversion efficiencies, but by the cumulative impact of all steps in the chain. Therefore achieving these system objectives requires not just efficient technology development, but broad consideration of all stages of the biofuel chain. However, system development would be dependent upon technology development that

1 ***Is feedstock-flexible i.e. that can tolerate a wide variety of feedstock variations, trace components and contaminants***. This could include, for example, development of catalytic processes that are robust to different trace elements or development of pre-processing technologies such as torrefaction that standardize material properties
2 ***Can make best use of the whole crop*** e.g. pre-processing technologies to deconstruct lingo-cellulose
3 ***Can service multiple end-use demands*** i.e. "no regrets options" that provide flexibility for future energy system development. These could include: gasification which provides a platform to electricity, heat, liquid fuels and renewable chemicals

Achieving this technology development would be supported by some advances in scientific understanding e.g.

- reducing the energy and carbon intensity of biomass production and processing
- better understanding how feedstock characteristics influence conversion

- improved understanding of production of high yielding species, and
- improved understanding of the dynamics of the main greenhouse gases (CO_2, CH_4, N_2O etc.) for a wider range of land-use types, agro-ecological zones

These need to be allied to improved understandings of the growing, logistics and handlings of feedstocks.

Current trajectories for biofuel system development would suggest that future sustainable biofuel systems are more likely to rely on high yielding lingo-cellulosic feedstocks, rather than the current oily, starchy or sugary feedstocks. This should ease the tension created by direct use of foodstuffs, improve land use efficiency (particularly as these can be supported on lower grade land) and add flexibility of end-use options. However, this requires judgements on the best use of biomass, since the same material would be suitable for conversion to heat, electricity, transport fuel or renewable chemicals. It is likely that the optimal choices will be variable and context specific and policy frameworks will be required that can guide such decisions, but adapt to local circumstances.

If current dietary trends continue, major increases in the consumption of meat will result in substantially increased future agricultural land requirements, while climate change impacts will result in drastic deterioration of staple cereal yields in parts of Asia and Africa. This will increase global land pressures and imported biofuels could be viewed as effectively exporting greenhouse gas reduction targets in the form of land –use and other (related) impacts. Therefore it is important that the true extent of the land-use impacts of biofuels (direct and indirect) are appreciated, but these often involve complex interactions where causality may be contested. Consequently ascribing generic iLUC factors can be subjective, context dependent and imprecise. It is also difficult to justify management and certification efforts related to supply chain greenhouse gas emissions and land-use change for biofuels, but not for food and other imported goods.

In terms of appropriate policy frameworks it should be noted that the application of national greenhouse gas caps (such as in the existing UNFCC framework) does not generally result in globally GHG efficient production of food or biofuels and does not extend to all producer countries. Supply chain carbon accounting could be applied to encourage reductions in biofuel greenhouse gas emissions, but will have no impact on less regulated markets and cannot on its own, optimize or even necessarily improve land use patterns. Ultimately if land-use change is of ecological concern it would seem to make sense to explicitly discourage this by policy mechanisms that apply to both food and fuel.

However, minimizing land-use change is only part of the “land-use” issue. Other policy challenges revolve around the prioritizing different land functions i.e. answering the question “What is land for?” (food, fuel, settlement, ecosystem services etc.) Whether or not it is possible to construct frameworks that would incentivise appropriate behaviour, it certainly is important to be aware of the alternative uses and their impacts. Additionally it is important to remember that preservation of ecosystem functionality also confers global benefits but with no economic recognition at present. Balancing these objectives is challenging and requires a more substantial evidence base.

While it is necessary to address these uncertainties and improve understanding of biofuel impacts, it is also necessary to deliver substantial greenhouse gas reductions in the near term in order to avoid “dangerous” climate change. This requires a policy framework that moves deployment forward, while addressing the uncertainties and working to develop more sustainable biofuels.

Key Messages

1. Biofuels can deliver greenhouse gas (GHG) reductions and other sustainability benefits, but they require land, which is also in demand for food, carbon sequestration and eco-system service provision. Sustainable biofuel development is therefore dependent upon sustainable land-use patterns, which could be encouraged by developing appropriate policy frameworks.
2. Maximizing the efficiency of biofuel production systems does not necessarily maximize the greenhouse gas savings or land-use efficiency. These must be considered separately.
3. The performance of a biofuel system is cumulatively affected by all steps in the process chain, not just the conversion technology. In some chains, “upstream” factors such as the choice of a relatively low yielding oil seed plant may be the key reasons for low levels of greenhouse gas reductions or land-use efficiency and it may not be possible to compensate for this by focusing on downstream “technology” steps in isolation.
4. Future biofuels are more likely to use “woody” lingo-cellulosic material, which should improve land-use efficiency and greenhouse gas reductions.
5. Climate change, population growth and dietary trends are predicted to increase land requirements for food production. It is therefore important to understand the direct and indirect land impacts of biofuels and the food system, but also to realize that there is substantial uncertainty associated with current assessments.
6. Applying national greenhouse gas caps (as in the existing UNFCC framework) does not encourage GHG efficient production of food or biofuels, though supply chain greenhouse gas assessments may help.
7. Land-use policy needs to go beyond minimizing land-use or land-use change and consider the multi-functional nature of land, including ecosystem service benefits.
8. While there are substantial uncertainties there is also an urgency to accelerate deployment to deliver much-needed greenhouse gas reductions.

1. Introduction

This report has been commissioned by Government Office for Science to: review the implications of biofuel production for food production; consider the interactions between the energy and agricultural systems, particularly around land-use and food availability; and identify key policy and research challenges.

Section 1 outlines the structure of the report.

Section 2 provides background on the rationale for UK biofuel development.

Section 3 outlines the main available and developing biofuel production technologies, including consideration of bioenergy development objectives and barriers.

The feedstock requirements associated with the various technologies are then examined **in Section 4**, including consideration of how technology development may change future feedstock demand. The relevant interfaces this presents with other consumption sectors are discussed, with a particular focus on agriculture.

Having explored the future bioenergy feedstock demand the report then moves on in **Section 5** to present available information on the future food demand, considering different projections made by different organisations and summarizing the key anticipated climate change impacts, the key food demand drivers and links to food security, consumer choice and trade.

Section 6 then brings together the analysis of biofuel and food demand growth to consider the interfaces between the two, with a particular focus on the implications for land use and agriculture. This includes discussion of the greenhouse gas emission associated with direct and indirect land-use change.

Section 7 then focuses on trade, outlining the potential for biofuel trade to reduce global greenhouse gas emissions, contribute to national emission reductions plans and deliver wider benefits. It also describes the costs associated with biofuel trade, the challenges associated with balancing these and how they may be affected by uncertainty and knowledge gaps. Ultimately this raises a number of ethical issues which are identified.

Finally in **section 8** the technical and policy challenges for sustainable biofuel development are outlined.

2. Background

In recent years it has become increasingly widely accepted that greenhouse gas emissions are influencing the global climate. This presents society with two major challenges:

1. The challenge of mitigating more severe impacts and avoiding "dangerous climate change" by drastically reducing global greenhouse gas emissions, and
2. The challenge of adapting to living in a different climate

Maintaining "quality of life", including mobility, sustenance, comfort, choice, affordability, food accessibility and security, while addressing these challenges, demands strategic technology deployment based on a thorough understanding of the underpinning science, appreciation of the wider impacts of that deployment and recognition of the interfaces between fuel, food, energy, land-use and water.

In order to reduce global greenhouse gas (GHG) emissions and avoid dangerous climate change we must either reduce our consumption of GHG intensive products and resources to replace them with lower GHG intensity alternatives. In electricity and other demand sectors solar, wind and marine technologies will have a significant role to play. However, options in the transport sector are much more limited and biofuel production has been accelerated by the desire of developed nations to satisfy their transport and mobility desires while remaining within their greenhouse gas budgets. Electric vehicles and hydrogen fuel cells will play a role, but those technologies are not yet widely available and there will remain a substantial demand for transport fuel in areas where these technologies are less appropriate e.g. aviation, agricultural vehicles and shipping. It is acknowledged that biofuels offer advantages over conventional fuels and can offer a low carbon transport option in the short to medium term (up to 2030), supporting transition to a more comprehensive decarbonisation of the transport sector when the relevant technologies are available [1]. In the long term (up to 2050), biofuels are not sufficient to deliver the necessary carbon reductions in the transport sector, but there will still be some demand for low carbon biofuels, particularly in aviation and shipping and this demand will be higher if Carbon Capture and Storage (CCS) technology is not commercially deployed [2].

Biomass is the only renewable source of fixed carbon and so is the only direct source of low GHG intensity replacements for liquid hydrocarbon fuels. If society continues to demand substantial levels of liquid fuels, biomass will be a key resource for these. However, it is also the main renewable and low-carbon raw material for other products (e.g. chemicals) that are today provided from petroleum synthesis.

The term "***biofuels***" commonly describes liquid fuels derived from biomass normally intended for use in the transport sector, and the impact of these "biofuels" has given significant cause for concern in recent years. However, when considering the impacts of biofuels it is impossible to separate the analysis from a wider consideration of "bioenergy" (which also includes the use of biomass to service the energy demands of the electricity and heat sectors). This is primarily because there is some resource overlap, so that biomass which is useful for heating may also potentially be used for electricity or for transport fuels. As outlined in section 3 this is expected to become increasingly so as technology develops and if biofuel and bioenergy developments are using the same feedstock it is essential to consider both simultaneously. Even where the feedstock differs, biofuels and bioenergy ultimately share the same (constrained) land resource and so this report does not consider biofuels in isolation but examines biofuel development within a wider bioenergy context.

Biomass takes many different forms, which will be discussed further in section 4, but essentially biomass is any organic matter of recent biogenic origin that is used to provide energy or material needs. It is essential that the material is of recent biogenic origin to ensure that the carbon embodied in the material has been recently sequestered from the atmosphere. If that is the case then the carbon dioxide released when the biomass is used for energy effectively "replaces" the carbon dioxide that was sequestered during growth so that there is no long term increase in atmospheric carbon dioxide concentration, attributable to the biomass feedstock (although there may be other associated greenhouse gas releases e.g. from crop biomass cultivation, processing or transport). Therefore most primary forests should not be considered for bioenergy purposes, since the carbon content has not been recently sequestered, but the biodegradable component of wastes could, for example, be included.

Mitigation of climate change is often framed as a quest to reduce greenhouse gas emissions, particularly carbon dioxide. However, carbon exists in the atmosphere, in soils and in the oceans in different forms. The key issue therefore is actually "reducing the ***net*** greenhouse gas transferred to the atmosphere". Therefore it is important to consider the extent to which carbon is sequestered as well as GHG emissions. An efficient response to climate change therefore would minimize the net transfer of greenhouse gas emission to atmosphere, while making best use of land resources to enhance the level of mitigation achieved. Therefore climate change responses should consider the best use of land as well as the most effective way of reducing greenhouse gas emissions. This effectively results in a "carbon hierarchy" for land use, which prioritizes the highest amount of carbon sequestered per unit area of land and can be thought of as one dimension of sustainable land-use. Within that hierarchy preservation of forests would be prioritized above cultivation of perennial crops, which increase long term soil carbon, at the expense of annual crops. However, as outlined in section 6 greenhouse gas mitigation is only one objective of sustainable land use and there are contexts in which other priorities must be taken into account, including the need to provide adequate nutritional sustenance, to preserve or enhance biodiversity and to support sustainable livelihoods.

Biofuel development therefore is part of a wider strategy to replace high carbon intensity energy sources with lower carbon alternatives. These efforts are a response to global targets for reductions in greenhouse gas emissions. In Europe this is currently driven by a European Union target of a 20% reduction in European greenhouse gas emissions below 1990 levels by 2020 and associated policy measures which require increases in the share of renewable energy. The European strategy for achieving these targets involves greenhouse gas reductions for individual member states, renewable energy targets and biofuels targets. So, a key objective of biofuel development is to achieve greenhouse gas reduction targets, but there are also other objectives. For example biofuels may provide a more secure and resilient alternative to dependence on petroleum derived transport fuels. They also have trade and commercial potential. Substantial sums of European funding have been invested in biorefinery development with an expectation that biorefineries will replace petroleum refineries in the future and will grow a future European technology and industrial base.

Finally it is important to realize that, just as the UK is attempting to reduce its greenhouse gas emissions by adopting technologies such as biofuels, other countries are also seeking similar greenhouse gas reductions by similar means. Therefore it is imperative to consider the UK's position, but within the context of international development, which may increase resource pressures.

3. Biofuel production technologies

3.1 Status of biofuel technologies

It is possible to operate internal combustion engines in the transport sector using pure plant oil, extracted from biomass. However, conversion of the biomass or biomass components to a more refined form has many advantages in terms of improved fuel and performance characteristics and so the term "biofuel" is usually reserved for liquid hydrocarbons that are derived from biomass but have been processed so that their properties more closely resemble those of the diesel and petrol fuels they seek to replace. Many different technologies are available for conversion of biomass to bioenergy, but broadly speaking they can be thought of as either thermal, chemical or biological, characterized by the conversion mechanisms. Strictly speaking all involve chemical transformation and some degree of associated thermal energy conversion, but the groupings are helpful in defining the primary conversion mechanism and products, which are summarized in Figure 1.

Figure 1: Key conversion technologies for biofuel development

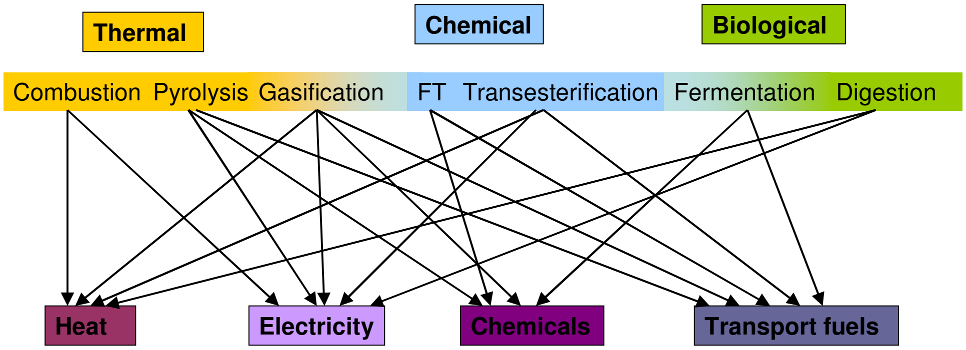


Figure 1 is not a comprehensive catalogue of all conversion technologies/products, rather it shows the main practical routes across the thermo-chemical and biological sectors through which biomass can be readily converted into energy and chemical products, of which transport fuels is one. In reality conversion often involves more than one technology and there may be more than one product, depending on the specific application/configuration.

3.1.1 Thermal conversion

Combustion is perhaps the most familiar of the thermal technologies. It simply involves combusting (or burning) biomass in oxygen (present in air). Biomass fuels present distinct engineering challenges from fossil fuel combustion. However, understanding of these issues has progressed to facilitate substantial commercial experience with the technology at all scales. While combustion is useful for applications which require heat, it is not useful for routes to transport fuels.

Pyrolysis involves heating biomass in the absence of air to convert it to solid (char), liquid (oil) and gas fractions. The oil is unsuitable for direct use as a transport fuel, but could provide a chemical/material base for upgrading to biofuels. Many small-scale pyrolysis facilities exist worldwide, some with commercial application, but efficient upgrading to a consistent product standard remains a significant research and development activity.

Gasification involves reacting biomass with insufficient oxygen for complete combustion so that solid biomass is converted to a gas. The composition of the gas varies with the process conditions and gasifier technology choice. This technology may be used to improve the performance of heat and electricity systems, but also provides a chemical base for synthesis of a wide range of chemicals. There are some examples globally of proven biomass gasification technologies, but there are many technology variations and significant research and development challenges remain in integration of biomass gasification into functioning systems, particularly at larger scales.

Many variations on the above technologies exist e.g. slow, fast and intermediate pyrolysis, oxy combustion, entrained flow and hydrothermal gasification. These offer different processing variants which may have benefits for different feedstocks or objectives. However, if the ultimate objective is liquid transport fuels the main **thermochemical** routes available are to gasify and then catalytically upgrade by a process such as Fischer Tropsch (FT) or to pyrolyze and upgrade to a liquid biofuel. FT conversion is discussed in the section on chemical conversion techniques below.

3.1.2 Chemical Conversion

Fischer-Tropsch (FT) conversion is an important chemical process step in the route to liquid biofuels. It involves catalytic reactions that convert carbon monoxide and hydrogen to a liquid hydrocarbon and can be quite energy (and GHG) intensive. The reactions are well understood and established within the fossil-fuel based chemical industry, but there are particular challenges associated with adapting these processes for the composition of a biomass derived syngas. This has not been successfully demonstrated as a full scale, commercial process incorporating all elements of the chain. In addition conventional FT techniques are often very energy intensive, potentially resulting in significant additional greenhouse gas emissions.

Transesterification is a chemical reaction in which a group of chemicals (triglycerides or fatty acids) present in plant fat and oils are reacted with an alkanol (most commonly methanol) to produce fatty acid methyl esters (FAME) and glycerol. This reaction generally takes place with a chemical catalyst such as sodium hydroxide. The FAME produced can be purified and used as biodiesel and transesterification is a commonly used process today.

3.1.3 Biological Conversion

Anaerobic digestion is a biological process where micro-organisms break down organic material under anaerobic conditions i.e. in the absence of oxygen. The result is a gas that contains a high proportion of methane, the main constituent of natural gas and so would often be used as a natural gas substitute. Alternatively it could be used as a base for transport fuel production, particularly if the end product were compressed liquid natural gas (LNG), which can be used for vehicle applications, rather than as a liquid biofuel.

In **fermentation** micro-organisms feed on sugars to produce alcohols (currently ethanol and butanol) which can be distilled, dehydrated and used as a transport fuel. Biomass feedstocks such as sugar cane and sugar beet provide a direct source of sugar for this process. Starchy feedstocks (such as corn) can also be fermented once the starch has been hydrolyzed by enzymes to release sugars. The major constituent of most biomass is lingo-cellulose and to convert whole biomass plants to ethanol it is necessary to first hydrolyse the lignocellulose to release the sugars for conversion to ethanol. This generally requires a pretreatment stage, such as acid hydrolysis or steam explosion prior to enzymatic hydrolysis. Development of successful pretreatment and hydrolysis technologies for different biomass feedstocks is a key research challenge.

3.1.4 Biorefinery technologies

The terms “biorefinery” and “biorefinery technologies” are also frequently encountered. Biorefining is the chemical processing of biomass feedstocks to obtain multiple chemical products, often including fuels such as bioethanol. This incorporates, not one, but several technologies combined in a single process plant designed to suit particular feedstocks and chemical demands. An important point to realize is that the efficiency of conversion of biomass to biofuel in a biorefinery plant may actually be quite low, but this is offset by the production of other material products, which introduce a distinct additional set of greenhouse gas savings and revenue streams.

3.2 Biofuel System Performance

As discussed above bioenergy technologies are at different stages in their development trajectories. Therefore the current focus of technology research and development varies between technologies.

However, in all cases, if biofuels are to be successful in reducing greenhouse gas emissions we need to develop technologies that minimize the carbon emissions associated with the supply chain and processing steps. Therefore R&D efforts should be focused particularly on reducing the energy and carbon intensity of biomass production and progressing technologies that offer the best long term scope for low energy and low carbon intensity fuels.

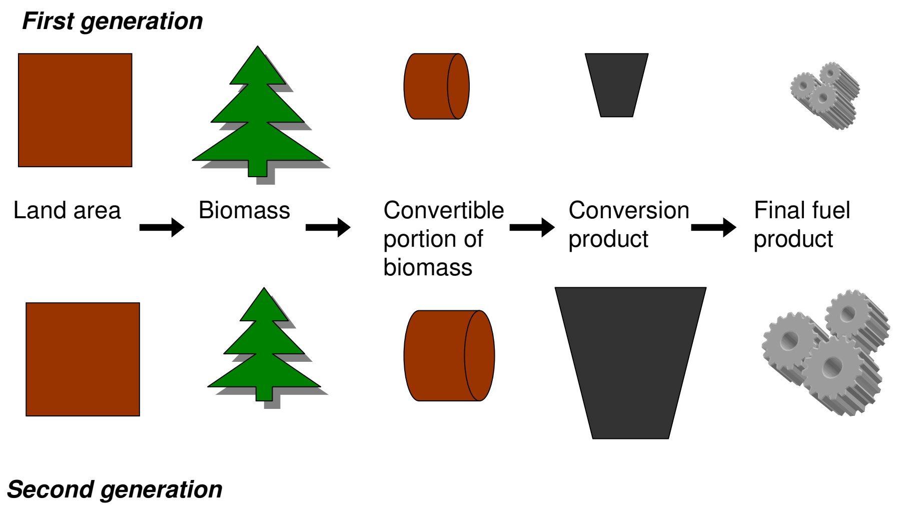
In addition if we are to make best use of natural resources (the biomass resource, our land resource etc.) then it is necessary to design biofuel production systems that are efficient i.e. that maximize the amount of biofuel produced per unit of available resource. From the above description of technologies it is clear that some technologies access only a part of the plant e.g. transesterification makes use only of the oily fraction; fermentation only the sugar components. Therefore it is important to understand how feedstock characteristics affect the suitability for conversion by different methods and the ultimate efficiencies obtained. This is discussed in further detail in section 4 and is one of the key rationales for developing more omnivorous technologies, including third generation biofuel schemes.

It should also be a key objective of bioenergy research to make more efficient use of the available resource. Figure 2 summarizes how the efficiency and resource availability at each stage of 2 typical biofuel chains (one first generation and one advanced second generation) affect the final amount of biofuel that is delivered for the same area of land. At each step in the process chain the area of the icon displayed is proportional to the quantity of material involved. So, we start with the same area of land, which delivers a certain quantity of biomass, of which a certain proportion is convertible to biofuel, which yields an intermediate conversion product and then a finished fuel. The extent to which a particular chain outperforms another will vary with specific process decisions, but the important point is the general observation that the final output of biofuel per unit area of land is not primarily determined by the technology conversion efficiency, but by the cumulative impact of all steps in the chain. In this case maximizing the proportion of the crop which is actually utilized in the conversion process is particularly important. For other process schemes other steps may be more significant. However processes that only use the oils or sugar component are unlikely to give high levels of resource efficiency unless these components form a very large proportion of that crop.

Increasing the amount of biofuel available from a constrained land resource therefore requires not just efficient technology development, but also maximizing the proportion of the crop that is actually utilized in the conversion process, broad consideration of all stages of the biofuel chain and how changes in one step may influence the performance of others and ultimately the net system efficiency.

The greenhouse gas intensity of biofuels is also related to the resource efficiency in so far as producing a certain amount of a particular biomass requires inputs that correspond to a certain amount of greenhouse gas emissions. If more biofuel can be produced from the same amount of biomass, this effectively decreases the greenhouse gas emissions per unit of biofuel. However, if this is achieved by introducing new steps that increase the energy or greenhouse gas burden of the overall biofuel chain this can reduce the greenhouse gas efficiency of the biofuel itself, even if its resource efficiency has increased.

Figure 2: Diagram showing comparison of the performance of first and second generation biofuel technologies



Therefore maximizing the conversion of raw material to biofuel does not necessarily improve the greenhouse gas balance of a biofuel. For example in figure 2 if energy is required to step from "biomass" to "convertible portion of biomass" or chemicals are consumed in moving from "convertible portion of biomass" to "conversion product" these entail greenhouse gas emissions which would increase the overall greenhouse gas intensity of the final product. This often results in a balancing act, where higher efficiencies may be facilitated by additional inputs and the extent to which this is justified needs to be considered case by case. As technology develops this balance may shift and so there is a need to persist with R&D that may improve efficiency or reduce inputs even if current GHG balances are not attractive.

3.3 Objectives of biofuel systems development

The future bioenergy industry will comprise biofuel, bioelectricity, bioheat and biochemical sectors, which may develop separately or within a more integrated industrial biotechnology context. The biofuel sector will likely encompass a number of different biofuel technology systems, which have been technical and commercially successful. It is important that the performance of future biofuel systems is closely aligned with energy and other policy objectives and the following should therefore be key biofuel technology development objectives:

1. **Increase the available pool of biomass resource that can be sustainably converted.** This could be done by improving the tolerance of conversion technologies to different feedstock characteristics and may incorporate development of appropriate intermediate or pre-processing technologies, such as torrefaction.

2. **Improve the resource efficiency of conversion of the raw material to energy product** – remembering that to do this it is necessary to obtain higher efficiency across the whole of the bioenergy chain (not just the conversion technology) and that one key way of achieving this improvement is to develop technologies that can utilize a larger proportion of the feedstock. In principle this would suggest a move away from options such as oil extraction/transesterification for biodiesel production and production of ethanol from wheat or beet, and a move towards technologies such as gasification, which can efficiently convert feedstocks to a usable energy form.

3. **Increase the carbon savings associated with bioenergy implementation.** Improving resource efficiency can contribute to increased carbon savings, but sometimes there is a trade-off, where improved resource efficiency results in additional carbon emissions.

4. **Improve land-use efficiency.** Maximizing the energy output per unit area of land can be achieved by improving the resource efficiency (2) and by focusing on higher yielding crops per unit area of land. These tend to be the lingo-cellulosic materials and developing second generation technologies that can convert lingo-cellulose efficiently is a key route to increasing the amount of bioenergy that can be delivered per unit area of land used.

5. **Develop overall systems with wider sustainability benefits.** The development of bioenergy systems has many interfaces with land systems, agricultural systems, energy systems and affected communities. It is important that the potential for ecologic, social and economic impacts at all stages in the chain are recognized. These can be both positive and negative and so it is important that they are managed to deliver appropriate benefits to different stakeholders.

In parallel with these it is necessary to develop operational knowledge with regard to growing, harvesting, logistics etc. and the policies and forms of contract that are required if these are to be successfully implemented with all the associated benefits to the rural economy.

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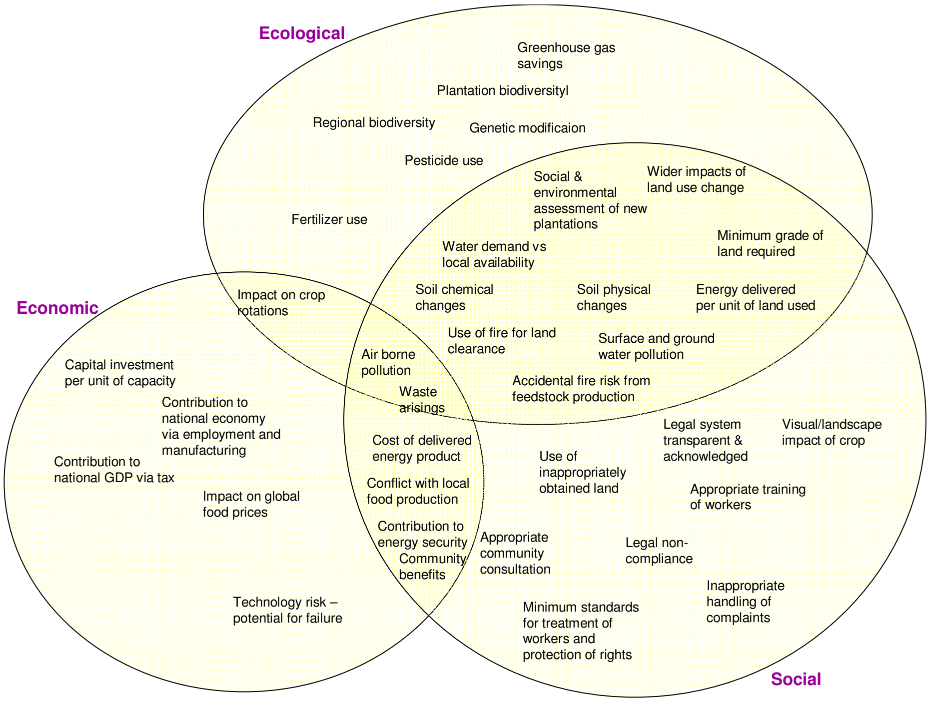
Figure 3 shows a summary of possible wider impacts of bioenergy systems taken from the Supergen Bioenergy project, grouped by their categorisation as social, economic or ecologic. Clearly there are a wide variety of potential impacts, the magnitude of which will vary for different biofuel systems in different development contexts. However, it is important to realize that different stakeholders will also perceive the environmental risks (and benefits) associated with these impacts differently [3].

Figure 3: Possible impacts of bioenergy systems



3.4 Biofuel technology performace

Biofuel production technologies are often categorized as first, second and third generation. While the distinction between these categories is not always clear-cut, a summary of commonly applied categorisations is given in the tables below

Table 1: First generation biofuels

FIRST GENERATION	
Feedstock	**Technology**
Oily feedstocks	Transesterification
Sugary feedstocks e.g. sugar cane	Fermentation
Starchy feedstocks e.g. corn	Fermentation

So, first generation biofuels are traditional biodiesel or bioethanol produced by well-established technologies, but inherently limited by their reliance on only a small part of the overall biomass plant.

Second generation biofuels transcend the obstacle of only using part of the biomass feedstock by focusing on technologies that can convert the lignocellulosic elements of plants.

Table 2: Second generation biofuels

SECOND GENERATION	
Feedstock	**Technology**
All lignocellulosic material e.g. wood, plant fibre, straw	Steam explosion
	Acid hydrolysis
	Enzymatic hydrolysis
	Fermentation

The term third generation biofuels is used less consistently than the distinction between first and second generation technologies. However, in a broad sense it is generally used to describe bioenergy systems that escape the land and resource constraints by making use of algae, waste material or other available by-products.

3.5 Objectives of biofuel technology development

The objectives of biofuel systems development have been outlined in 3.3 and from these the following technology objectives can be prioritized

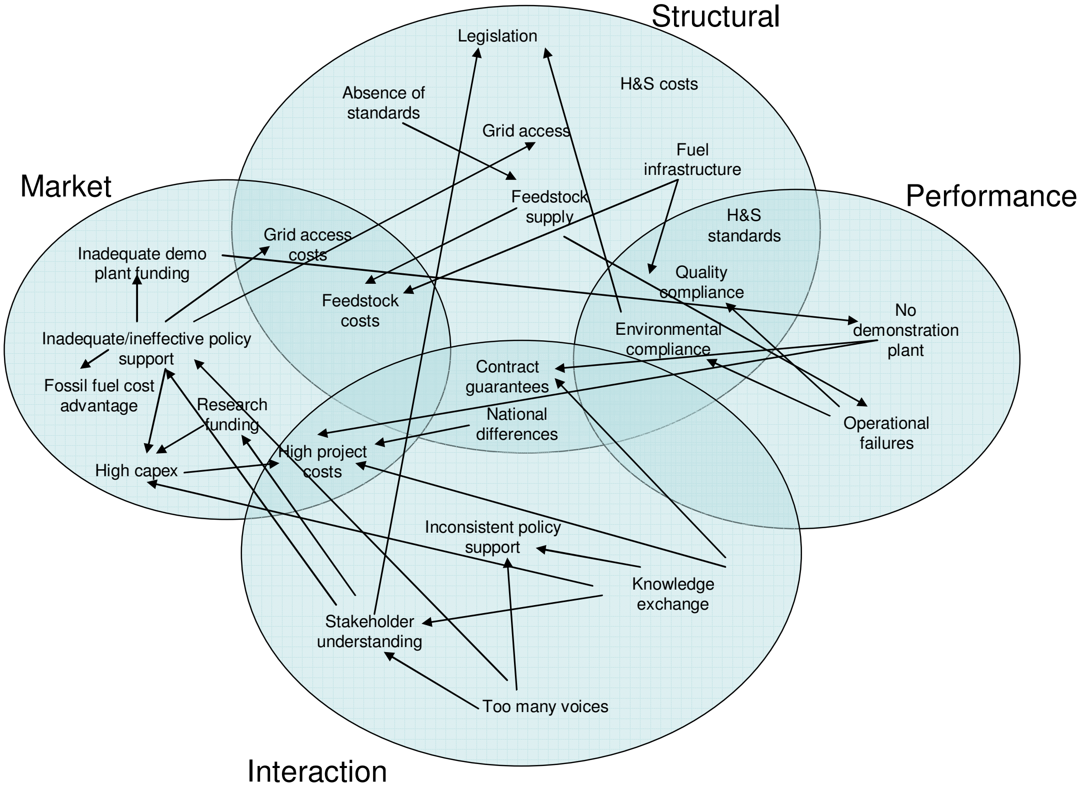
1 Development of technologies that are feedstock-flexible i.e. that can tolerate a wide variety of feedstock variations, trace components and contaminants e.g. development of catalytic processes that are robust to different trace elements, development of pre-processing technologies such as torrefaction that standardize material properties so that best use of the materials can then be made
2 Development of technologies that can make best use of the whole crop e.g. development of pre-processing technologies to deconstruct lingo-cellulose, allowing access to its chemical components for conversion
3 Development of technologies that can service multiple end-use demands i.e. “no regrets options” that provide flexibility for future energy system development e.g. gasification which can then provide a platform to electricity, heat, transport fuels and renewable chemicals

It should be noted that, while advanced technology development facilitates some of the above objectives, these new technologies may also have substantial technical, engineering, economic and other risks. Taking these into account might mean that it does not always make sense to switch to more advanced technologies. This is particularly the case where careful engineering design can be applied to a process scheme to enhance its performance against the above objectives. For example production of biodiesel from palm oil is a first generation technology that has been shown to have limited or no greenhouse gas benefits in some cases. [4]. Some parties might therefore argue that it should be replaced by other options, such as gasification of soft wood and FT synthesis, which might give greater greenhouse gas savings per unit of energy produced. However, there are other, more conventional ways of improving the benefits of this system e.g. utilisation of a larger proportion of the plant by burning residues to provide heat and/or electricity could substantially improve the overall greenhouse gas balance of the system. Therefore it should not be assumed that advanced technologies with higher conversion efficiencies always offer the best option.

3.6 Barriers and research challenges

Barriers to increased bioenergy deployment are a mixture of technical and non-technical issues and often the latter are the most important. Detailed work in 2008-9 with a range of European industrialists and academics in the sector highlighted a number of key barriers, which are shown in figure 4 [5].

Figure 4: Barriers to bioenergy development in Europe



A research workshop in 2011 identified the following issues as key research challenges for bioenergy development in the thermochemical sector [6]:

- Best use of biomass – to deliver maximum benefits and the best energy vector to deliver these
- Feedstock availability – considering the availability and scalability of supply for different applications
- Sustainability of feedstock – confirmation of the sustainable level of feedstock available to the UK, taking into account future trends, land use and resource management
- Policy – including perspectives on the long term best use of biomass in the future energy mix and clarity on the role of imported biomass
- Efficiency – improvement of efficiency in thermochemical conversion applications

- Demonstration – of thermal conversion and biorefinery technologies at different scales
- Costs – ultimately the cost to produce, but with understanding of the importance of the prices of UK/imported feedstocks, how different bioenergy chains add value and an understanding of unintended consequences e.g. competing markets

It was notable throughout this workshop that there was less focus on particular technologies for development than on overall objectives and this reinforces the importance of a systems outlook. However, there are certainly some key enabling technologies which would support these objectives and torrefaction and gasification were particularly highlighted at the workshop as options that would assist in addressing this.

In the biological sector similar overall objectives can be identified but the underpinning technologies (on which delivering the improvements depends) are distinctive and these include:

- Improving plant biomass characteristics for efficient, low-energy fermentation (improved saccharification) through understanding plant cell wall recalcitrance to degradation.
- Improve understanding of which species are high yielding, have suitable fuel-production capabilities and can grow well on marginal land and/or with minimal water use.
- Improve plant polymer hydrolysis and fermentation efficiency by enzyme identification/characterisation/modification and identification of microbes for improved fermentation of plant feedstock polymers/sugars.

4. Biofuel feedstocks

4.1 Matching feedstocks to technologies

Section 3.1 has already discussed the availability of different bioenergy technologies and how these may be applied to different feedstocks. Considering things the "opposite way around" bioenergy feedstocks may be broadly divided into the following categories:

- Wet feedstocks e.g. cattle slurry, sewage sludge
- Sugary feedstocks e.g. sugar beet
- Starchy feedstocks e.g. corn
- Oily feedstocks e.g. rape seed oil
- Woody feedstocks e.g. saw mill residues
- Putrescible feedstocks e.g. organic fraction of municipal waste

In section 3.1 it was pointed out that for certain conversion technologies there were preferred feedstocks. In exactly the same way any particular feedstock can be best converted via certain preferred technologies.

Wet feedstocks are often converted via anaerobic digestion. This allows a reasonable efficiency to be achieved despite the high moisture content. It is possible to dewater these feedstocks and combust or gasify them (with support firing as appropriate), but generally the high moisture content severely impedes the achievable efficiency. Methane from AD could be upgraded and compressed for use like LNG in vehicles, but the routes to liquid biofuels are less developed and incur additional efficiency penalties.

Sugary feedstocks generally perform well via fermentation routes. However, this often results in only the sugary portion of the feedstock being accessed, limiting the whole crop efficiency that can be achieved. Recalling figure 1 this is less important if dealing with very high yielding feedstocks e.g. sugar cane production in Brazil. However, it is much more important when dealing with e.g. sugar beet in more temperate climates.

Oily feedstocks can be readily converted directly to biodiesel via transesterification, but the efficiency of this is limited and it only makes use of the oily portion of the crop, which may be only a very small part. Typical yields for different feedstocks are given in Table 3 and are all significantly lower than typical lingo-cellulosic energy crop yields for the UK of 10-15 odt/ha [7].

Table 3: Typical yields of oily feestocks

	Yield (t/ha)	**Notes**
Jatropha	0.1-4.8 [8]	
Oil palm	1.7 – 4.2 t/ha [9, 10]	
Soybean	0.8-3.7 t/ha [11]	Top 10 producer countries
Oilseed rape	2.1-4.4 t/ha [12]	UK yields 2010

The main constraint associated with this conversion route therefore is the low oil yield of the relevant plants. Since only a very small proportion of the plant is actually being converted in each case, making best use of the whole crop is necessary to maximize resource efficiency.

Starchy feedstocks are best converted by fermentation, but it is necessary to first release the sugars from the starch, which requires energy input and, as with oil crops, only a limited part of the crop is actually being accessed. Examples of this are production of ethanol from corn or wheat, which can result in quite limited greenhouse gas savings when the energy associated with pre-processing, the small proportion of the crop being used and the substantial agronomic (especially fertiliser) inputs involved in crop production are all taken into account.

Putrescible feedstocks have high levels of organic plant or animal matter (e.g. food waste) that would soon putrefy or degrade and are most suited to conversion by digestion, as discussed for wet feedstocks.

Woody or fibrous feedstocks such as wood and energy grasses contain high levels of lingo-cellulose. This has a strong cellular structure which impedes breakdown by chemical or biological processes. Therefore at present generally these feedstocks are thermochemically converted. Combustion is well proven, but does not provide routes to biofuels. Alternatively almost all of these materials can be gasified with appropriate feedstock preparation (drying and comminution (size reduction)) and choice of gasifier. The syngas could then be transformed to transport fuel via FT techniques. Looking to the future, plant cell wall science is being developed to better understand how lignin deconstruction might be achieved through biochemical processes.

Algae based feedstocks: There is significant interest in the potential of algae to provide bioenergy feedstocks. The two main options are extraction of oily compounds from high lipid micro-algae, which can then be converted to biodiesel or thermochemical or biological conversion of high-yielding kelp or macro-algae. In principle these feedstocks offer the prospect of escaping land constraints on production and the photo-synthetic limitations on yields of land-based crops. This could result in a significant additional bioenergy resource.

4.2 Current feedstock demand

The main incentive for UK utilisation of biofuels is the RTFO and this also provides the most comprehensive information on current UK biofuel feedstock demand. In the year 2010-2011 used cooking oil dominated the most feedstocks used, forming 30% of biofuels declared [13]. The second largest raw material was soy, at 15% of the total, and wheat at 10% [13]. In total 1,440 million litres of biofuel were supplied, which is 3.1% of the road transport fuel total[13]. At present the European Renewable Electricity Directive sets a target of 10% for 2020 [14]. The RTFO targets have, to date, increased annually and targets have been set up to 5% by 2014, although no further trajectory beyond that is currently specified in legislation [14]. The presently envisaged increases would therefore increase UK biofuels penetration by over 60%.

4.3 Future feedstock demand

However, the type of feedstocks utilized may change in future as legislation is set to demand minimum sustainability standards. For example EU standards already preclude the use of material that was planted on land of particularly high carbon stock and UK legislation is set to require gradually increasing carbon savings levels, which would effectively rule out some fuel-technology combinations.

The net impact is likely to be a shift in feedstock type. As outlined above it is important to take the whole system performance into account. However, one of the most significant factors driving high levels of greenhouse gas emissions is application of high levels of agrochemicals, particularly nitrogen fertilizer. It is generally expected that this will gradually lead to a reduction in demand for agronomically intensive crops such as corn and wheat. A second very significant factor is land-use change (where this is included in the calculation of greenhouse gas intensity) and a third is the plant yield. Therefore the ideal feedstock would have high yield per unit area of land, low levels of agronomic input and minimal land-use change. This would suggest a shift towards woody feedstocks or usage of waste, provided that the conversion technology challenges for both those feedstocks can be overcome.

4.4 Interfaces with other sectors

It is very important to remember that biofuel development interfaces with many other sectors and biofuel constraints may change as these sectors develop. The following are particularly relevant:

4.4.1 Interface with the bioenergy sector

Feedstocks currently used to produce liquid transport biofuels are generally quite distinct from those that tend to be used to deliver heat or electricity. However, development of second and third generation technologies should mean that by 2020-2030 it will be possible to use a unit of woody biomass to produce heat, electricity or transport fuel, with potential resource efficiency and carbon saving advantages. This requires decisions with respect to the best use of biomass. This is a question fraught with difficulty:-

- "Best" incorporates multiple criteria (including those from figure 3) that may be viewed differently by different users
- The benefits conferred from bioenergy solutions are often context specific e.g. the extent to which wood heating delivers greenhouse gas savings depends on the fuel that would otherwise be used
- The goalposts are constantly moving e.g. bioenergy delivers very attractive greenhouse gas savings compared to today's UK grid electricity mix, but if grid carbon intensity continues to decline (more renewables and nuclear in future) the relative savings offered by biomass may become more modest, and
- Development of some technologies is compatible with multiple future options but others are less flexible e.g. gasification has potential for more efficient transport fuel production but also for electricity generation and so gasification technology and infrastructure development has potential for multiple and wide-ranging impacts.

However oxy combustion development is much more tightly linked to a bio-electricity solution in an environment where a CCS infrastructure has been developed. In the first option biomass can deliver substantial benefits, but developments in other sectors might reduce the value of e.g. the greenhouse gas reductions. In the second case the ability of biomass to deliver substantial benefits is dependent upon the development of other technologies and infrastructure, which could not be justified from the biomass potential alone.

All of these factors make it very difficult to prescribe the role that transport biofuels could/should play in the future bioenergy mix.

4.4.2 Interface with the energy sector

As discussed above the extent to which the rest of the energy sector decarbonizes and the extent to which overall energy demand is reduced are both key in determining the amount of biomass that may be required to service the electricity and heating sectors.

4.4.3 Interface with the biomaterials sector

As we move towards a substantially decarbonized industrial sector, the future source of raw materials needs to be considered. Biomass is effectively the only renewable source of fixed carbon on the planet. This makes it extremely useful as a feedstock for production of low carbon chemicals and other products.

4.4.4 Interface with wood markets

There is already a global, established wood industry which utilizes forest and other resources to provide timber, fuel wood and industrial wood requirements. In recent years there has been increasing concern from some sectors that development of a substantial bioenergy sector could increase market prices, impacting on industry performance. While it could be argued that this simply reflects an evolutionary realignment of market forces concerns have been raised because this realignment results from explicit policy initiatives.

4.4.5 Interface with the forestry sector

Existing forests provide very substantial carbon sinks and their ability to absorb carbon dioxide is important in regulating the global greenhouse gas balance. Obviously it is important that primary forests are preserved for these and other reasons e.g. biodiversity and socio-economic. Planting of new forests or changes in forest management regime may also improve long term carbon balances, but this requires careful consideration. Studies to date have been inconclusive [15]; some work demonstrating decreases in the forest carbon pool with removal of forest residues [16]; others showing evidence of soil degradation [17], but no consistent impacts on site productivity or soil C concentrations unless the forest floor is removed; while others have shown that residue removal decreased tree volume and soil top layer carbon content [18, 19], but the impact varied with soil type and tree species. Further evidence is clearly needed to clarify the extent and nature of the effects of forest management on overall carbon sequestration and fertility.

In addition to the ecological impacts of sourcing increased levels of wood from existing forests there are also market impacts, as outlined in section 4.4.4. In theory it should be possible for materials cascading approaches to facilitate provision of different quality of wood products at different prices for different (bioenergy and other) users, optimizing to maximize carbon sequestration [20]. However, in practice fuel suppliers will respond to market signals which may be skewed by local supply-demand balances. Also forest management practices would adapt over time to maximize profit from whichever demand sector that emerged.

4.4.6 Interface with the marine sector

As noted above utilisation of algae as a feedstock has potential to escape some of the land availability and yield constraints applicable to land-based crops. However, there are other significant challenges associated with developing biofuels derived from algae. First of all, achieving high yields generally requires high levels of aqueous nutrients and carbon dioxide, although this can be addressed e.g. by utilisation of waste water, which could have particular environmental benefits near aquaculture sites and/or utilisation of carbon dioxide from point sources, including power stations.

Micro-algae is generally cultivated in either open pond systems or enclosed photo-bioreactors. The latter entails heating and light source provision (increasing costs and reducing greenhouse gas reductions), while the former generally attains lower yields. The result is that the use of micro algae for energy production (including biofuels) is likely to have to be combined with waste water treatment and/or high value chemical production for development of an economically viable system [21].

Macro-algae is perhaps more suitable for open water cultivation, but there are significant challenges associated with maintaining algae cultivation platforms in open sea conditions and the practicalities of harvesting offshore. Also the composition of the macro-algae feedstock with high levels of potassium and chlorine is very challenging for thermochemical conversion; while options such as anaerobic digestion exhibit relatively low efficiencies.

Addressing these issues and allowing for the practicalities of harvesting and processing the feedstock, constrains the areas where algae could be cultivated and the ultimate production level. Therefore while algae could provide an important additional resource which does not compete directly with food production it is, like terrestrial biomass, a constrained resource which should not be over-estimated.

4.4.7 Interface with the food and agricultural sectors

Of course one of the most significant bioenergy interfaces is the interface with the food system. Future food demand is discussed in section 5 and the interfaces between food and fuel production in section 6. While this is a very important interface, it must be remembered it is only one of many interfaces which mould the role and contribution of biofuels.

5 Future food demand

5.1 Future food demand projections

Global population is expected to peak at about 9.2 billion around 2075 (8.9 billion in 2050) [22], with the largest predicted growth in Africa and Asia. At the same time significant urbanisation is ongoing, with the 40% living in urban areas in Africa expected to increase to 62% and from 43% to 67% in Asia. [22]. Generally urban migration affects diets as people substitute starchy foods with energy-rich foods such as livestock products, oils and sugar and switch from traditional staples like roots, tubers and coarse grains to wheat [23].

5.2 Drivers of future food demand

Due to changing lifestyles, diets, and development and improving food supply in food insecure regions, the per capita food consumption is likely to rise from a global average of about 2800 kcal/person/day today to 3100 kcal/person/day by 2050 [23]. Larger increases are expected in developing countries to about 2700 kcal/person/day in 2050[1], along with a rapid change in lifestyle and diet although there will still be a significant level of undernourishment (food consumption under 2500 kcal/person/day) especially in sub-Saharan Africa [24].. This is expected to result in significantly higher demands particularly for cereals, such as wheat, since they are required for direct human consumption and also to provide animal feed for dairy and meat production. If current dietary preference trends continue, major increases in the consumption of meat are expected to result in substantially increased land requirements for agricultural production in future. [25].

5.3 Impacts of Climate Change on Agriculture

In coming decades climate change is expected to increasingly impact on agriculture. As noted above, Africa and Asia are the regions were the highest increases in population growth and urbanisation are expected[23], driving increases in food demand. At the same time agricultural production in these regions is likely to be significantly affected by climate change.

Changing climatic conditions will affect crop growth and livestock performance, while predicted increases in the frequency of extreme weather events will increase food system volatility [25].

5.4 Adaptation to Climate Change

The Foresight Report on the future of food and farming [25] notes that the extent to which adaptation occurs in the food system will critically influence how the food system is affected by climate change. The scope for adaptation varies with crop and location. For example in higher latitudes (northern Europe, including the UK) yield improvement for wheat of 8-25% by 2050 are expected[26], but these are only accessible by

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application of higher levels of nitrogen fertiliser. By contrast in parts of Asia and Africa climatic conditions for growing agricultural products will worsen and production of some cereals, such as wheat will be at best much more inefficient or at worst impossible.

Successfully maintaining sufficient production levels to meet global demand is likely to therefore require additional export by key producing countries. This could provide moral or ethical incentives for exporters to responsibly increase their cereal production to provide sufficient amounts of wheat of a specific quality at a stable and reasonable price [27].

Over the last 40 years intensification of agriculture has delivered huge benefits in terms of increased yields, with a 2 fold increase in global food production during that period [28], largely driven by a 5-7 fold increase in mineral fertiliser application. This has effectively reached the stage of diminishing returns, with the amount of cereal crop produced per unit of fertiliser applied having decreased for many years and now plateauing at a low level [29]. This is partly due to approaching saturation in terms of nutrient benefits and partly due to requirements to plant crops in parts of the world where yields are low and the benefits conferred by fertiliser application are small compared to global performance, but significant within that region. Consequently fertiliser production accounts for 1.2% of global primary energy demand [30].

Breeding programmes and genetic modification may bring some further yield benefits, but other than modifying demand behaviours the other main option for servicing the increased food demand and offsetting reductions in yield from climate change impacts is to expand the area of agricultural production. This extensification approach could make a contribution to helping to meet the future demand challenge, but incurs further land-use change, resulting in associated greenhouse gas emissions.

Taking wheat as an example, about 650 to 685 Mt of wheat is produced worldwide [31] and the EU is the largest producing region [32]. The global demand for wheat is expected to increase to about 900 Mt by 2050 and trade to double to around 240 Mt [23, 33]. It is not possible to meet future projected wheat demand without closing the gap between actual and agro-ecological yields ***and*** expanding cultivated land area in key producer countries such as China [27]. This has potentially very serious implications for global greenhouse gas emissions, since conversion of existing land to agricultural use is a key source of global greenhouse gas emissions.

6. Interfaces between the food and fuel systems

6.1 Scope of food-fuel interfaces

Utilisation of material that could be used as a food to provide energy presents considerable ethical challenges, particularly at times when adequate nutrition and food security are key global concerns. Early biofuel development focused on these feedstocks, largely because they presented a familiar, well developed feedstock with readily accessible chemical components. However, efforts to improve feedstock tolerance, technology flexibility, greenhouse gas balances, resource efficiency etc. are resulting in a trend away from feedstocks that could be used as food and towards more generic lingo-cellulosic feedstocks. Acceleration of this development trajectory may help to ease the food-fuel tension.

The key physical interface here is land, which will be discussed in more detail below. However, it is important to remember that our global land resource is ultimately physically constrained in terms of quantity, but in practice is also constrained by a number of other factors that reflect the ability of a particular piece of land to provide useful outputs. These include soil quality and fertility, water availability and terrain. First generation biofuels are generally competing for agricultural grade land. However, second and third generation feedstocks, focused more on lingo-cellulosic material do not require the same high grade of land and can produce useful yields on much more marginal land. Care is still needed however to ensure that appropriate assessments of suitability are made. High yields in crop trials are sometimes not sustained in commercial application or are constrained e.g. by irrigation/water availability and there is a need to take this into account in yield projections. [34].

6.2 Land Resource

Land has multiple functions. It is required for settlement expansion, for recreational purposes, for rain catchment, carbon sequestration, supporting biodiversity and, in recent years, increasingly production of biofuels, particularly in countries where land resources are abundant. Of course this does not just happen with biofuels – a significant proportion of our food and other requirements is grown on land in other countries and imported. This is part of the global trade network on which our society is based. However, it is important to recognize its impact – when importing these items we are effectively exporting the land-use and other associated impacts.

6.3 Land Constraints

Land constraints are key in determining biomass availability. There is a limited amount of land available globally, which is of varying quality and only some is able to produce adequate crop yields to be worth commercially farming. The productivity threshold varies e.g. average wheat yields in the UK are among the highest in the world and farmers would not consider planting this crop on marginal land even if wheat prices were very high. However, in some parts of the world much lower yields are sufficient to incentivise production. The actual yield achieved depends on a number of factors e.g. variety planted, management regime, climate and water availability. In future climate scenarios projected rainfall, availability of irrigation and the extent to which ground water and aquifers may become depleted could impact on yield in future. Therefore it is important to bear in mind that, while land is a fundamental physical constraint, its attributes may change over time. Hence overproduction, climate change and neglect may all contribute to deterioration of the available land resource.

Unless there are significant behavioural changes, demand for agricultural produce (particularly meat and therefore grain) will increase in future particularly in Asia and Africa. Increases in demand may be met by intensification, likely requiring additional fertiliser application, with significant greenhouse gas increases, or by extensification, requiring additional land for agricultural production. It is therefore important to consider the impact of land-use change.

6.4 Land-use Change

6.4.1 Greenhouse gas emissions and sinks associated with land-use

Plants and trees absorb carbon dioxide during their lifetime, converting it to carbohydrates which are stored in the plant mass or “biomass”. Therefore different land uses are associated with different carbon exchanges with the atmosphere. Primary forests absorb large amounts of greenhouse gases each year as trees grow and emit greenhouse gases as forest material decays. They also act as a carbon reservoir or carbon stock, locking up large amounts of carbon dioxide in the standing stock, roots and soil. Agriculture can sequester carbon in soil, but this is generally released during tillage of the land, so that, in practice annual crops do not provide significant long term carbon sequestration, although perennial plants can. Also various agricultural activities (including fertilizing and manure spreading) cause greenhouse gases to be released from soil and this may more than offset any sequestration incurred via the growing crop.

In general for the direct soil emissions (not taking into account the emissions associated with seed and agrochemical manufacture etc.) agricultural crops are a net source of greenhouse gases per unit area of land (particularly N fertilizer intensive crops), scrubland or waste land is fairly neutral in terms of annual emissions, perennially cropped land is a net sink for carbon emissions and wooded or forest land is a more significant carbon sink [35], which must be preserved or increased if atmospheric greenhouse gas concentrations are to be stabilized in the long term [36].

6.4.2 Greenhouse Gas Impact of Land-Use Change

Direct Land-Use Change

Clearly then land-use change has 2 direct impacts: first of all it may change the rate at which that piece of land can sequester carbon from that point onwards and it may alter the carbon store associated with that land. For example converting waste land to a perennial energy crop will incur initial carbon releases associated with the loss of vegetation and soil disturbance. The land will then absorb carbon dioxide as the perennial plants grow to maturity and we would expect this carbon absorption to be higher than if the land had remained wasteland. When the crop is finally harvested a significant amount of the carbon stored will be released, but a substantial proportion will remain sequestered within the root and soil system.

Some land changes can be clearly seen to be net carbon sinks, others as net sources of additional greenhouse gas emissions. Often the initial change incurs a carbon debt which will be “repaid” within a characteristic period.

There is some understanding of the carbon dynamics of these systems, but not for all relevant land-use types nor for all agro-ecological zones. In addition there is very significant uncertainty attached to our understanding of some of the processes involved e.g. N_2O emissions, soil carbon levels and attendant variability. Superimposed on top of this there is little understanding of how these fluxes and exchanges are likely to be affected by climate change in future e.g. will increased mean temperatures result in elevated N_2O emissions in temperate regions? Co-ordinated research at an international level is required to more fully understand this, including the agro-ecological and climatic variability.

Indirect Land Use Change

Having defined the direct greenhouse gas impact of any land-use change it is also important to think about the indirect impacts. This is primarily about recognizing that land is generally not simply “idle” waiting to be used, but, in reality, if land were not being used for one function it would have been used for something else. Therefore in principle any change in the use of land may displace pre-existing activities which then result in a land-use change elsewhere. So utilisation of land for bioenergy may displace pre-existing activities which then result in a land-use change elsewhere. Equally this argument could be applied to food production, where utilisation of land for agriculture may displace a pre-existing land-use which is then compensated for by a land-use change elsewhere.

It could also be argued that utilisation of land for bioenergy could preclude future cultivation on that land without incurring a land-use change and associated carbon debts. This is particularly relevant for consideration of future food supply and land-use.

In some cases causality and attribution may be fairly clear. For example if carrots are being grown in a field and the farmer switches production to miscanthus then consumers may source their carrots from elsewhere or reduce their consumption of carrots. If sourced elsewhere the increase in demand may be met from increasing productivity on existing land or by increasing the amount of cultivated land. If the latter an indirect land-use change is incurred which will have associated greenhouse gas emissions. If increased productivity there is no indirect land-use change, but if cultivated land is increased there is an indirect land-use change. This would apply even if consumers compensated for reduced carrot supply by consuming an alternative product, produced elsewhere, which might occupy even more land.

Several parties have argued strongly that indirect land-use change should be taken into account when considering biomass production and associated greenhouse gas savings. In some cases, where the casual relationship between the biomass production and indirect land-use change is clear this can be seen to be entirely justified. However, some points of caution are in order:-

1. Causality is not always clear cut – it can be difficult to determine if an indirect land-use change has occurred ***as a result of*** the biomass production
2. Geographical variability is substantial e.g. some countries have limited land resources and are less likely to compensate by cultivating additional land, whereas in other countries this may be a normal response
3. Global trade impacts substantially on the magnitude of the effect e.g. there is no guarantee that locally produced carrots will replace locally produced carrots and if the result is imported food from a country which achieves lower (or higher) yields this could have a much bigger (or much smaller) greenhouse gas impact than might first appear likely.
4. There may be impacts without causality e.g. if a eucalyptus forest is planted in Brazil for biofuel production on waste land that may be a sound ecological decision at this point in time, perhaps increasing carbon sequestration for the next few years, but such a plantation is a long-term commitment and therefore this precludes that land from cultivation for a period of perhaps 20 years or so. During this period rising food demand may require additional cultivated land and it may be that area would have given high yields but is not available.

These issues of causality further complicate assessment of the greenhouse gas impact of indirect land use change (iLUC) and the complex interactions involved mean that ascribing generic iLUC factors can be subjective, context dependent and imprecise.

It is also important to remember that the greenhouse gas emissions associated with land-use change are not exclusively a “bioenergy” issue. This increases the importance of adequately defining policy queries framed around bioenergy and greenhouse gas reductions. Only then can the scope of the system considered and assessment timeframe (both of which can hugely impact results) be tailored to match the question being evaluated and appropriate scientific responses and data be provided.

6.4.3 Policy Issues Related to Land-Use and Land-Use Change

Many of these problems arise because land is required to service multiple demands. Therefore thinking about one land attribute in isolation (carbon sink or biofuel production) cannot deliver an optimal solution for global greenhouse gas reductions, which are affected by the aggregated land-use patterns.

This is further complicated by the differing accounting regimes that have been set up as part of various policy constructs. For example the IPCC framework and Kyoto protocol are based on a territorial approach to greenhouse gas emissions where different countries are allocated different national emissions budgets. By contrast the RTFO and EU RED adopt a supply-chain focused approach, where all carbon emissions along the supply chain are counted, regardless of where they occur. Having two such distinct accounting systems in place can produce some peculiar results. For example UK wheat production is some of the most efficient in the world. It uses substantial fertiliser application, but could be adapted to climate change with little increase in specific greenhouse gas emissions per unit of wheat produced, so, if wheat production is required to increase in future to compensate for demand increases and/or yield declines elsewhere it would make "greenhouse gas" sense to increase production in the UK. However, that would increase the UK's national emissions inventory, which would be undesirable at a time when stringent national emission reductions are sought. Other countries, particularly those with substantial land resource may have much more practical scope for increasing production but this may be at a much higher level of greenhouse gas emission per unit of product. The application of national greenhouse gas caps therefore does not generally encourage globally GHG efficient production of food or biofuels.

Bioenergy is one of the few production systems worldwide where there is any attention paid to the net supply chain GHG emissions. This also gives rise to problems when it comes to decisions over land use. Present legislation focuses on the idea that we should count the greenhouse gases associated with biofuel production, include in that a land factor and filter what is acceptable and not acceptable based on those supply chain emissions. That may remove the most damaging biofuels from the regulated markets and may encourage technological development to facilitate lower GHG biofuels, but it, first of all, will have no impact on less regulated markets and cannot on its own, optimize or even necessarily improve land use patterns. For example in the 2011 OfGEM calculation protocol (modelled on the EU RED) carbon credits are given per unit area of marginal land planted with biomass. The problem with this is that for a fixed crop output the greenhouse gas balance will appear better if a greater area of land is planted and therefore it could incentivize unnecessary land-use change. So minimizing green-house gas emissions which include soil emissions may encourage use of particular land classes, but will not necessarily minimize actual land take.

It also needs to be recognized that there are many interactions between the food and fuel systems. Soy production is a good example where under present market conditions the amount of revenue an Argentinean farmer receives from the oil might roughly equal the revenue from the soy meal, which is a valuable high protein commodity used in animal feed production. Therefore establishing whether demand for food or for fuel has encouraged land-use change and production is practically impossible. Ultimately if land-use change is of ecological concern it would seem to make sense to explicitly discourage this by policy mechanisms that apply to both food and fuel. Calculation protocols could be devised that evaluate integrated measures such as valuing the energy output per unit of land, whether food or fuel. It could be argued that policies to discourage land-use change already exist in the IPCC national inventory reporting framework. However, this does not currently apply to all countries and so cannot effectively discourage land-use change in all producer countries.

Many of these land-use conflict issues revolve around the basic difficulty associated with prioritizing one product or one function over another. It may indeed be that in some circumstances food production is a more valuable use of land than fuel production, but that balance depends on the amount of available land, the food demand, energy demand, land quality, water availability and soil carbon content, without even beginning to think of the social and economic ramifications of food and fuel production.

Location and context may affect the “best” use of land, making application of generic criteria at best challenging and at worst impossible. Whether or not it is possible to identify optimal use or construct frameworks to incentivise appropriate land use, it is nevertheless important to be aware of the alternative uses and their impacts.

7 Biofuel Trade: Costs and Benefits

Global biofuel trade is an example of global environmental interdependency, so that production e.g. of soy oil for biofuels in South America allows developed nations to maintain mobility within carbon budgets and this is recognized and recompensed via economic trade. Biofuels have therefore been successful in creating export markets and trade platforms for many countries, including some developing ones. That trade brings valuable income in exchange for the biofuel commodity. But there are many other levels of transaction going on that it is important to recognize. In one sense the purchasing country could be seen to be effectively exporting their responsibility and duty to reduce emissions – continuing to enjoy the mobility and energy benefits without directly paying the full carbon price under the applicable framework. The exporting country is effectively exporting not only a product but also use or occupancy of their land resource.

Of course this is as true for biofuels as it is for other commodities. Yet, while there is much discussion about the ethics of purchasing bioethanol from Brazil (which may or may not have caused deforestation) there is much less discussion about importing bananas from the Caribbean where production may equally have caused land use change or goods from China, where the manufacturing process may have increased electricity demand, resulting in new hydro-electricity schemes, with significant resultant loss of land.. In that sense there seems little rationale for separating out biofuels for special treatment compared to other imported materials, especially food, which could have equally significant land use change implications and greenhouse gas emission consequences. Additionally it is important to remember that the biofuel trade is in some ways providing compensation for the carbon sequestration function of some ecosystems. In reality preservation of ecosystem functionality also confers many other global benefits but with no commensurate recognition.

7.1 Responsibilities and Ethics

Several reports on future food production have acknowledged the importance of global trade in meeting future food demand, particularly when addressing issues of food security and adapting to climate change e.g. future decreasing yields in some regions may result in local scarcities which will require supplements from traded produce. However, it is important to recognize the full extent and impact of trade in food and fuel. Trade of most products is an exchange of the product for financial revenue. The exporting country has invested capital and resources into production for which a price is paid by the importers that provides net income to the export country. Production of food and biofuel, however, requires the use of land and fully assessing this can be more problematic than for other export products, partly because of the much greater potential for impacts and partly because of notions related to sovereignty and land ownership e.g. is it acceptable for multi-national companies to purchase land in another country solely to produce goods for an export market?

Essentially trade of biofuel is part of a symbiotic relationship between biofuel producer and consumer and can become significant at national levels on both sides. So UK and European imports of biomass can have positive and negative impacts in producer countries. Biofuel trade may therefore offer welcome prospects for regional development and trade benefits in some parts of the world. However, there are also risks associated with biofuel trade and ultimately the challenge faced by the biofuel industry is to balance those risks and rewards in a way that respects social, ecological and economic constraints, but also maximizes development opportunities.

Land is at the centre of this balancing act. In recent years producers in many countries have pursued biofuel or biomass production in order to profit financially from international trade opportunities, which have, in themselves been created by incentive schemes and policy instruments. Criticism has been heaped on unscrupulous producers and focus has shifted to “sustainability and certification schemes” as a means of avoiding some of the more extreme damage that could be wrought.

It is important to realize that what is actually going on here is a market response to increasing the value of land. Biofuel market development has transformed areas of land that were previously perceived to be of minimal value into assets that could now provide high levels of income. Obviously the market response is to develop that land to maximize profit. This is not a new phenomenon – the UK and other EU states have been importing agricultural produce from a wide variety of countries for many years. However, in this case we are not buying “nutrition” or “fibre”. It could be argued that we are not even buying fuel, but actually “greenhouse gas reductions”. Some would argue that it is ethically unacceptable for the UK to continue its high carbon intensity existence while effectively exporting its greenhouse gas reduction targets, but that fails to acknowledge the potential benefits of this symbiotic trade relationship. It can improve land quality, facilitate agricultural investment, provide jobs and trade income to some countries, where these benefits are much needed. Nevertheless there remains a need to be confident that greenhouse gas reductions are actually being achieved by these transactions. This could be supported by development of a globally agreed framework for assessing greenhouse gas reductions, which could draw upon recent advances in scientific understanding of the underpinning processes and be adjusted as the scientific knowledge base improves.

It should also be noted that many of the wider impacts (ecologic, social and economic) of producing biofuels or biomass are not very different from production of other agricultural commodities. But this new biofuels market has, in some parts of the world, increased the role of large multi-national companies at the expense of smaller producers and introduced new trade partners, which brings new risks and uncertainties.

8. Challenges

Modern society demands mobility and increasing levels of material goods, yet, it also wishes to constrain greenhouse gas emissions. Biofuels offer a solution to that dilemma – they provide a way of minimizing greenhouse gas emissions while broadly maintaining the lifestyle status quo. However, as deployment levels increase it is essential that various challenges are addressed to ensure that greenhouse gas reductions are achieved and that we really are maintaining the status quo rather than impacting negatively on unseen producers and our natural resource capital. The following technology and policy challenges have been discussed within this report and are key to achieving sustainable biofuel development alongside sustainable food supply.

8.1 Technology challenges

Addressing biofuel technology challenges requires development of ***biofuel systems*** that connect ***sustainable feedstock production*** with ***efficient conversion technologies*** via appropriate ***interface matching*** of feedstocks with technologies.

Sustainable Feedstock Production Challenges

- Maximizing resource efficiency by improving our understanding of which combinations of high yielding species and high efficiency production methods maximize resource efficiency,

while also

- Minimizing the energy and carbon intensity of biomass production,

which includes,

- Improving understanding of the variability of soil carbon sequestration including the effects of forest management on carbon sequestration and
- Improving understanding of the growth profile of energy crops on "marginal" land, in different climates and under future predicted climate change conditions.

Interface Matching Challenges

- Improving understanding of the impact of feedstock characteristics on conversion efficiency.
- Improving plant biomass characteristics for efficient, low energy fermentation (improved saccharification) through understanding plant cell wall recalcitrance to degradation.
- Developing successful pre-treatment and hydrolysis technologies for different biomass feedstocks.

Efficient conversion technology Challenges

- Improving plant polymer hydrolysis and fermentation efficiency through enzyme identification/characterisation/modification and identification of microbes for improved fermentation of plant feedstock polymers/sugars.
- Developing efficient, feedstock-flexible conversion technologies that can service multiple end-use demands, such as gasification.
- Improving understanding of bioproducts system efficiencies and feedback loops between product demand and scientific possibilities

8.2 Policy challenges

- **Developing an adequate framework to assess the sustainability and impacts of biofuels** – *A balance is needed here between a comprehensive assessment scope (including socio-economic impacts) and focusing time and resource on the issues/feedstocks most likely to give rise to significant concerns and/or which can usefully and practically be assessed.*
- **Improved understanding of the direct and indirect consequences of land-use change –** *Methodologies are emerging but there are very significant uncertainties and validation is required for confident policy development. Assessment frameworks that facilitate a more holistic approach (e.g. across sectors, taking into account competing land-use demands) may offer insights.*
- **Developing robust procedures to ensure the sustainability of biofuels –** *There are many significant activities in this area and the UK has played significant roles, but this is best pursued by international agreement to avoid damaging competitiveness and/or the development of secondary, less-sustainable markets with associated impacts.*
- **Preventing deforestation and maximizing carbon sinks** – *Valuing ecosystem services could make a substantial contribution to this objective.*
- **Protecting food security –** L*ong term vision and planning is required beyond national boundaries and taking into account future climate change impacts. This needs to be connected to practical, financeable measures for producers that facilitate adaptation while incentivising mitigation and land-use efficiency.*
- **Addressing the mismatch between national inventory and supply chain policy incentives for greenhouse gas reductions –** *Development of supply chain accounting methods which focus on the GHG emissions of products (such as biofuels) can play a role in encouraging GHG reductions, but only if: the calculation scope is comprehensive; account is taken of other sectors which compete for the same resources; interactions with existing policy frameworks are adequately considered and GHG limits/thresholds are set at appropriate levels.*
- **Developing appropriate land-use policy and enforcement/incentivisation at an appropriate scale –** *Encouraging appropriate use of land is key to balancing food-fuel demands. This requires development of appropriate frameworks that reconcile high level objectives with contextual development at multiple scales, including global, national, regional and local.*
- **Ensuring that sustainable bioenergy development, which can make a vitally important contribution to greenhouse gas reductions, is not impeded or delayed by developing policy frameworks to address the above issues** – *Near-term reductions in greenhouse gases are more "valuable" in addressing climate change impacts than long term ones. Biofuels can offer real, much-needed, near-term carbon reductions and it makes sense to sustainably exploit these rather than waiting for future solutions which may not deliver as promised. This requires stable, supportive policies to encourage investment.*

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