

Biofuels and the biorefinery concept[☆]

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ABSTRACT

Liquid fuels can be made by refining a range of biomass materials, including oil-rich and sugar-rich crops such as oil-seed rape and sugar beet, biomass that consists mainly of plant cell walls (second generation lignocellulosics), macro- and micro-alga, or material that would now be discarded as waste. This can include animal bi-products as well as waste wood and other resources. In the medium-term, plant cell (lignocellulosic) material is likely to be favoured as the feedstock for biorefineries because of its availability. The UK may make use of a number of these options because of its complex agricultural landscape. There are now a range of targets for biofuel use in the UK, although their environmental effects are disputed.

The technology of refining these materials is well known. Possible outputs include biodiesel and bioethanol, both of which can be used as transport fuel. Other potential products include hydrogen, polymers and a wide range of value-added chemicals, making this technology important in a post-petrochemical world. Biorefineries could use cogeneration to produce electricity. The paper identifies a range of research and development priorities which must be met if this opportunity is to be exploited fully.

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1. Background

Liquid biofuels provide one of the few options for fossil fuel replacement in the short to medium-term. They have the potential to offer both greenhouse gas savings and energy security. However, at the time of writing in mid-2008, rising food prices and reportedly poor energy balances, particularly from first generation biofuel crops have led to their use being questioned widely at both global (United Nations Biofuel Initiative: www.unfoundation.org/files/2006/biofuels_factsheet.pdf); Global Bioenergy Partnership: www.globalbioenergy.org/) and local levels (Renewable Fuels Agency, Gallagher Review (<http://www.dft.gov.uk/rfa/reportsandpublications/reviewoftheindirecteffectsofbiofuels.cfm>)). Further concerns over land displacement have also been identified (Searchinger et al., 2008) and have resulted in a pull-back for UK and EU policy of biofuel deployment (EU, 2008).

Liquid biofuels may be made from a variety of biomass sources through a number of conversion routes. Several types of product suitable for road and other forms of transportation fuel can be produced including, in the future, aviation fuel, perhaps using micro-algae for feedstock supply (Carlsson et al., EPOBIO, 2007). Current products include bioethanol, biodiesel and other bio-

based products such as biobutanol. Feedstocks are oil-based crops such as oil-seed rape, used for the production of biodiesel, and sugar- and starch-based crops such as sugar beet and sugar cane, which are used for the production of bioethanol. Such crops which have a food use are often referred to as 'first generation' bioenergy crops. All lignocellulosic biomass (biomass that is mostly plant cell walls which have a high carbon content) can be converted to liquid fuels through biological processes (esterification and fermentation) or through thermochemical routes such as pyrolysis. Such dedicated bioenergy crops with no food use are often referred to as 'second generation' bioenergy crops. Hydrogen may also be produced from biomass, but this is still at the research stage. The complexity of these supply chains may hinder the development of biofuel, but may also be advantageous to the UK as many niche products could emerge from the complex and small UK agricultural landscape.

As part of a wide range of measures in response to international agreements to reduce greenhouse gas emissions, the European Commission has introduced the biofuels directive, to which the UK has committed: the Renewable Transport Fuel Obligation (RTFO) <http://www.dft.gov.uk/pgr/roads/environment/rftfo/>). The UK is moving towards the development of transport biofuels with a target of replacing 5.75 per cent by volume of petroleum-based fuels (as at April 2008) by 2010 (United Nations Biofuel Initiative: www.unfoundation.org/files/2006/biofuels_factsheet.pdf); Global Bioenergy Partnership: www.globalbioenergy.org/), but recent concerns over sustainability have resulted in a re-analysis and assessment of this target which is now considered

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Table 1
Summary of feedstock availability in the UK, processing routes—meeting the 2010 biofuel directive? (Turley et al., 2004)

Crop type	Harvest fraction	Feedstock area grown in 2004 (100 ha)	Percentage of current crop area	Fuel proposed (million tonnes)	Biofuel
Oil-seed rape	Seed oil	459	+102	0.7	Crushing and esterification of the oil to biodiesel
Wheat	Straw		Currently not used for biofuel		Breakdown, hydrolysis and fermentation of lignocellulose to bioethanol
Wheat	Grain	346	+21	0.8	Breakdown, hydrolysis and fermentation of starch to bioethanol
Sugar beet	Sugar	202	+202	0.83	Breakdown, hydrolysis and fermentation of sugar to bioethanol. A recent suggestion is the formation of biobutanol from this route
Waste oil/fat	–		Currently not used for biofuel	0.1	

appropriate for 2014, with further analysis of the 2020 target of 10% liquid biofuels at that time. Future targets for biofuel supply will also depend on the development of a sustainability framework with the likelihood that greenhouse gas (GHG) mitigation rather than volume supply may be used as the accepted metric and that a 45% reduction in GHG emissions relative to fossil fuel will be necessary in future second generation liquid biofuels. It has been estimated that liquid fuel demand in the UK in 2010 will be 44.5 million tonnes, requiring 2.56 million tonnes of biofuel at that time to meet the RTFO and providing a carbon saving of approximately 2 million tonnes. Such targets however depend on net GHG savings and this is questionable.

In the international market, biodiesel (derived commercially from vegetable or other plant oils) and bioethanol (derived from the fermentation of starch or sugar crops) dominate as the most technically feasible and commercialised alternative renewable fuel sources. Biodiesel can also be derived from animal fats, grease and tallow, which would otherwise be disposed of as waste.

The UK has seen considerable industry 'pull' in the area of biofuels in the last year or so, following the introduction of the biofuels directive. A summary of some of this activity as at May 2007 is shown in the UKERC Bioenergy Research Landscape (ukerc.rl.ac.uk/ERL0304.html) and the planned bioethanol deployments in 2008 are listed in the NNFC report (Black and Vetch, 2008, http://www.nnfc.co.uk/metadot/index.pl?id=7607;isa=DBRow;op=show;dbview_id=2539). It is also apparent that the current high price of oil (at the time of writing in 2008) and the perceived likelihood of its continuing are having a marked effect on the development of a biofuel industry. Bauen (2005) showed that biofuels begin to become financially competitive over \$65 per barrel of oil, even without considering additional environmental benefits. One analysis of the UK biomass resource suitable for liquid bioenergy production is given in Table 1. It reveals that it is unlikely that any single supply stream will be adequate to meet the UK commitment to biofuels for 2010.

Current agricultural practices in the UK suggest that the main sources of liquid biofuels in the near future will be bioethanol derived from wheat grain and sugar beet, combined with biodiesel from oil-seed rape and oil waste products. For dedicated cropping systems, this analysis reveals that approximately a million hectares of agricultural land would be required to meet the 2010 biofuel target for the UK, more than doubling the area dedicated to oil-seed rape production, and doubling the recovery of wheat for bioethanol. Table 1 shows that the equivalent of 800,000 tonnes of fuel produced from wheat grain is currently exported from the UK in most years. Using this material for bioethanol production instead of exporting it would be worth-

while. It is probably not feasible to more than double production of oil-seed rape, the expansion of which has implications for a loss of biodiversity and further intensification.

2. Sustainability

The Royal Society (2008) has published an overview of the issues concerning the sustainability of biofuel supply, as has The House of Commons Audit Committee (2008), to address causal relationships between rising food prices, ecosystem destruction, and claims that the carbon balance of bioethanol from maize can be worse than in the use of fossil fuel (Searchinger et al., 2008) once indirect effects on land displacement are considered. In the UK, the Renewable Fuels Agency commissioned the Gallagher Review, which reported in June 2008. (www.dft.gov.uk/rfa/reportsandpublications/reviewoftheindirecteffectsofbiofuels.cfm).

All of these studies have highlighted the benefits of second generation fuels relative to first generation and also suggest that both good and bad biofuels exist, depending on energy balance as well as economical and social sustainability and future deployments must focus on these issues. In addition, The Gallagher Review suggests that no future bioenergy crops should be cultivated on agricultural land since this may displace food crops to pristine environments where other ecosystem services could be threatened. Biofuel supply to the UK is regulated by the RFA and minimum standards of reporting on greenhouse gas mitigation are required. More than 80 per cent of the current 2.5 per cent by volume liquid transport fuel from biological sources is imported (Department for Environment, Food and Rural Affairs, 2007), with the RFA first monthly data revealing that over 50% of this was from USA corn and Brazilian sugar cane. As yet, the sustainability of this supply is reported but largely unregulated. Both the UK and EU will address this issue in the near future, with sustainability criteria emerging (EU Sustainability Criteria for Biofuels: www.foeeurope.org/agrofuels/documents/Proposal_sustainability_criteria_biofuels_27Mar08.pdf).

The evidence suggests that the use of second-generation non-food-dedicated energy crops such as trees and grasses is likely to increase in the future, since they have a better energy balance than food crops. They can be grown on land not required for food, although displacement may still be an issue. Their impact has been examined by analysis of the whole-life-cycle from field to fuel, which provides powerful tools for determining the relative benefits of one biofuel chain over another, although some uncertainties still exist in these approaches (Rowe et al., 2008).

3. Current status of research

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

3.1. Fundamental plant biology and crop science

Any technology available to increase crop yield per unit land area and inputs, (particularly fertiliser and water) in current and future climates should be of value to the future development of the biofuel industry. More importantly, improving plant quality—for example, by increasing sugar content or starch content and decreasing protein content—will enable efficient processing and extraction for biofuel:

- The UK has good expertise in crop science and fundamental plant biology, but it is only being applied in a limited way to bioenergy cropping systems.
- GM technologies and non-GM biotechnology may provide the step change necessary for future improvements, but public acceptance of these technologies is still uncertain.
- There is considerable interest in the use of micro- and macro-algae (seaweed) as feedstock for biofuel, but scaling and commercialization of these systems remains challenging. No widescale consideration of the environmental impacts of such deployment has currently been undertaken.

3.2. Industrial microbiology

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

3.3. Environmental impacts

In the UK and Europe, one of the key drivers for investment in biofuels is environmental. Meeting our commitment to the Kyoto Protocol, and developing a low carbon economy are key to Government targets (Biofuels Research Advisory Council, 2006). Given this, considerable emphasis is needed on assessing the whole-life-cycle carbon costs of all the technologies considered above. Different studies disagree on the greenhouse gas balance of a variety of bioenergy cropping systems. The greenhouse gas or carbon costs are very dependent on what the bioenergy crop might be replacing. Again, if conversion and production are considered, life-cycle assessment may give contrasting results. Research tools are now available to ensure correct full-life-cycle analysis and these must be linked to policy developments to ensure that environmental as well as economic drivers are considered in any regulatory framework.

3.4. Conversion technologies

Engineering technologies for bioethanol and biodiesel are more or less available off the shelf. However, inefficient and expensive enzymes and chemicals are involved in these processes, and improving on them forms the challenge for future research.

4. The challenge for 2050 and beyond

4.1. Future developments and the necessity for 'step-change' research discovery—making the biorefinery work

Although it is technically possible to meet the 2010 biofuel directive target from domestic feedstock resources, it is unlikely

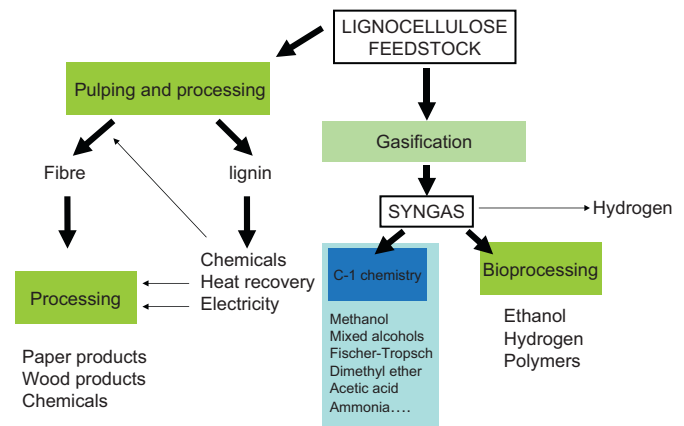


Fig. 1. A conceptual biorefinery with lignocellulose feedstock being used for lignin to energy to combustion through thermochemical process, pulp recovery for paper, gasification for gaseous fuel and biological processing for bioethanol. Other fuels are also possible.

that this target can be achieved with current cropping systems. Part of the problem is that crop rotations determine what crops a particular farm grows. Space is also a limiting factor. For sugar beet, current plans assume an extra million hectares of agricultural land being available, and the same amount of land again is being considered to grow dedicated biomass bioenergy crops for heat and power. This scenario also assumes that no further demand for biofuels will occur, and yet all energy analysis suggests that this is unlikely. Imports of bioethanol and biodiesel will contribute to our net requirement, but in the long term, with full-life-cycle assessment, are not likely to be environmentally sustainable.

In contrast, the UK has a considerable lignocellulosic biomass resource. Lignocellulose is the intimate mix of plant biomass that constitutes the cell wall—a complex material largely consisting of lignin and cellulose. Up to six million tonnes of forest residues may be available in the UK each year, for example, and of this, only approximately a million tonnes is recovered and utilised today (Department for Environment, Food and Rural Affairs, 2007). Other lignocellulosic resources, such as 200,000 tonnes a year of wheat straw, are also available. Dedicated lignocellulosic biomass crops include woody short rotation coppice willow and poplar and miscanthus grass. Unlike conventional crops such as oil-seed rape, these are low-intensity, low-inputs crops with a much improved greenhouse gas balance and other environmental benefits such as enhanced biodiversity. All research analysis suggests that perennial crops will be favoured over annual crops, since they have a greater seasonal capture of solar energy and again produce biomass without the investment into reproductive structures such as grain.

Despite these issues, plants will be used more generally as part of the bio-based economy as we become less dependent on the oil. Plants are the ultimate source of renewable sustainable bioproducts, and this extends way beyond simply using plants for energy. High-quality, low-volume chemicals will be harvested alongside energy crops. Several such conversion routes are possible, but the basic feedstock for all second-generation biofuels will be lignocellulose (UKERC Bioenergy Research Landscape: ukerc.rl.ac.uk/ERL0304.html). Step-wise research challenges linked to this development are inevitable. At the moment it is extremely difficult to extract and process lignocellulosic feedstocks efficiently. Several bottlenecks exist and some are identified in Fig. 1 (UKERC Bioenergy Research Landscape: ukerc.rl.ac.uk/ERL0304.html; Turley et al., 2004; Bauen, 2005).

4.2. Key scientific advances necessary for the biorefinery to work

Challenge: better use of available feedstock.

- Plants cell walls are lignin and cellulose. These complex structures are still far from understood. Fundamental to their utilisation for bioenergy will be research on understanding construction and deconstruction of cell walls (Gomez et al., 2008). Linked to this, a key scientific challenge is to make hydrolysis and fermentation reactions efficient and cost effective at large-scale.

Likely to occur: Could occur over a 5-year timescale.

Challenge: new designer feedstock and microbial processes for breakdown.

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

- *Likely to occur:* Five to 10 years—heavy investment by the US; BP announced its new Bioenergy Centre to be funded either in the UK or the US.

Challenge: better technologies for the assessment of lignocellulose and breakdown processes

- Cross-cutting interdisciplinary approaches and new technologies are required to visualise plant cell walls, microbial systems and their functioning. New computing developments will be necessary to enable the biorefinery concept, at all levels from modelling microbial function, to predictive experiments, systems engineering and pilot-scale and commercial plant.

Likely to occur: more speculative but possibly 10 years plus.

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