



## Review

## An overview of second generation biofuel technologies

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## ABSTRACT

The recently identified limitations of 1st-generation biofuels produced from food crops (with perhaps the exception of sugarcane ethanol) have caused greater emphasis to be placed on 2nd-generation biofuels produced from ligno-cellulosic feedstocks. Although significant progress continues to be made to overcome the technical and economic challenges, 2nd-generation biofuels production will continue to face major constraints to full commercial deployment. The logistics of providing a competitive, all-year-round, supply of biomass feedstock to a commercial-scale plant is challenging, as is improving the performance of the conversion process to reduce costs. The biochemical route, being less mature, probably has a greater cost reduction potential than the thermo-chemical route, but here a wider range of synthetic fuels can be produced to better suit heavy truck, aviation and marine applications. Continued investment in research and demonstration by both public and private sectors, coupled with appropriate policy support mechanisms, are essential if full commercialisation is to be achieved within the next decade. After that, the biofuel industry will grow only at a steady rate and encompass both 1st- and 2nd-generation technologies that meet agreed environmental, sustainability and economic policy goals.

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## 1. Introduction

The production of 1st-generation liquid biofuels (produced primarily from food crops such as cereals, sugar crops and oil seeds) is well understood. Mature commercial markets for their use in road transport applications are in place. Corn ethanol in US, sugarcane ethanol in Brazil, and other biofuels elsewhere, have been produced to meet the increasing total global demand which more than quadrupled between 2000 and 2008 (Fig. 1). Future targets and investment plans suggest growth of biofuel ethanol will continue in the near future, rising to around 100 000 Ml in 2014, 45% more than produced in 2008 (IEA, 2009). Total plant capacity could exceed 120 000 Ml/year by that time, given an analysis of the number of plants presently under construction and those planned. However, recent plant closures as a result of lower oil prices, the global financial situation, and changing government support policies, could reduce this estimate.

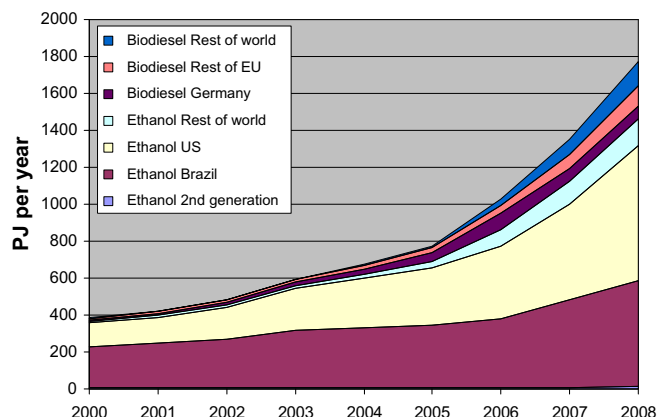
The sustainable and economic production of 1st-generation biofuels has however come under close scrutiny. Their potential to meet liquid transport fuel targets being set by governments to help achieve the goals of oil-product substitution, economic growth, and climate change mitigation is limited by:

- competition for land and water used for food and fibre production (Fargione et al., 2008; Searchinger et al., 2008)
- high production and processing costs that often require government subsidies in order for them to compete with petroleum products (Doornbusch and Steenblik, 2007); and
- widely varying assessments of the net greenhouse gas (GHG) reductions once land-use change is taken into account (OECD, 2008).

Ethanol produced from sugar cane is a possible exception that appears to meet many of the acceptable sustainability criteria as outlined in the sustainable biofuels consensus (GBEP, 2008).

Even though crops grown for biomass feedstocks take up less than 2% of world's arable land (WWI, 2007) many authorities agree that selected 1st-generation biofuels have contributed to past increases in world commodity prices for food and animal feeds, at least in part. However, much uncertainty exists in this regard and estimates of the biofuels contribution in the literature and the media range from 15% to 25% of the total food price increase, with a few assessments at virtually zero and others as high as 75% (Chakraborty, 2008). In the past year or two, many basic food commodity prices have significantly declined without there being any reduction in biofuel production. This tends to reinforce the view that biofuels were not the major reason for food price rises. Regardless of the degree of culpability, competition with food

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**Fig. 1.** Bio-ethanol production in Brazil, United States and rest of world from 2000 to 2008 compared with biodiesel production (based on IEA data and IEA, 2009).

crops will remain an issue as long as 1st-generation biofuels produced from food crops dominate total biofuel production.

### 1.1. Second generation biofuel developments

The cumulative impacts of these various concerns have stimulated the interest in developing 2nd-generation biofuels produced from non-food biomass, a research topic that has continued over three decades. Such ligno-cellulosic feedstock materials include by-products (cereal straw, sugar cane bagasse, forest residues), wastes (organic components of municipal solid wastes), and dedicated feedstocks (purpose-grown vegetative grasses, short rotation forests and other energy crops). These specialist energy crops will still probably be grown on land in competition with food and fibre production, although energy yields (in terms of GJ/ha) are likely to be higher than if crops grown to produce 1st-generation biofuels (together with their co-products) are produced on the same land. In addition poorer quality land could possibly be utilised, but any crop grown without adequate water and nutrient replenishment cannot maintain high oil yields over the longer term (Luoma, 2009; Mang, 2008). Hence production costs are likely to be relatively high and revenue low.

This review paper is based on a detailed report of 2nd-generation biofuel produced by the authors (IEA, 2008a). The objectives are to examine the current state of technological development with emphasis on bio-ethanol, evaluate and compare the production costs, outline the policies necessary to best overcome constraints and support development and deployment; and determine the future challenges to be reached if full commercialisation is to occur. The potential for production of other advanced biofuels is also considered.

## 2. Supply, markets and technologies

Although significant progress continues to be made to overcome the technical and economic challenges, 2nd-generation biofuels still face major constraints to their commercial deployment (IEA Bioenergy, 2009). The processing technologies are relatively immature with pilot plants supplying less than 0.1% of world biofuel production (Mabee and Saddler, 2007). So there could be good potential for further cost reductions and increased production efficiency levels as more experience is gained. Depending partly on future oil prices, 2nd-generation biofuels are therefore likely to become a part of the solution to the challenge of shifting the transport sector towards more sustainable energy sources than petroleum products at some stage in the medium-term. However,

major technical and economic hurdles are still to be faced before they can be widely deployed on a fully commercial scale.

To address these issues, significant investment in RD&D funding by both public and private sources is occurring. At present producing biofuels from ligno-cellulosic feedstocks remains at the late RD&D stage with several new demonstration plants under construction. During 2007, in the United States alone, funding of USD 385 M was provided from the US Department of Energy Biomass Program to support six large-scale ethanol demonstration plants being proposed by various companies to produce a total of over 500 Ml/yr. In addition, USD 200 M was provided for demonstration bio-refinery plants that produce a range of products and a further USD 375 M was granted to three specialist biofuel research centres. Canada created a USD 500 M fund to invest in private companies developing large-scale facilities for producing both ethanol and biodiesel from cellulose. Japan allocated USD 130 M in 2006 for R&D, pilot projects, and market support and in Europe several pilot plants are operating or planned, including the Choren biomass-to-liquid plant in Germany.

The private sector, including several biotechnology companies such as Novozymes, is also investing heavily in major biofuels RD&D programmes. Several oil companies have also invested in research including:

- Chevron – USD 40 M to University of California, Davis and Georgia Tech;
- BP – USD 500 M over 10 years to University of California Berkeley, University of Illinois and Lawrence Berkeley National Laboratory as well as establishing their own BP Biofuels division in the UK with around 60 staff;
- Shell – investments in biofuels companies Iogen and Choren (see below);
- ConocoPhillips – USD 22.5 M over 8 years to Iowa State University; and
- Exxon – invested USD 600 M with Synthetic Genomics in algal oil production.

Given the current investments being made to gain improvements in the process technologies, some expectations have arisen that 2nd-generation biofuel production will reach full commercialisation in the near future. This would enable much greater volumes to be produced at the same time as avoiding many of the drawbacks of 1st-generation biofuels. However, the hypothesis as presented here, is that, at least in the near to medium-term, the biofuel industry will grow only at a steady rate and encompass both 1st- and 2nd-generation technologies that meet agreed environmental, sustainability and economic policy goals (IEA, 2008a).

Production of 1st-generation biofuels, particularly sugarcane ethanol, will continue to improve and therefore these fuels will play a continuing role to meet future transport fuel demand. A transition to an integrated 1st- and 2nd-generation biofuel landscape is therefore most likely to encompass the next one to two decades as the infrastructure and experiences gained from deploying and using 1st-generation biofuels are transferred to support and guide 2nd-generation biofuel development. Once 2nd-generation biofuel technologies are fully commercialised, it is likely they will be favoured over many 1st-generation alternatives by policies designed to reward national objectives such as environmental performance or security of supply. In the mid- to long-term, this may translate into lower levels of investment into 1st-generation production plants, other than for sugarcane ethanol production.

The main drivers behind the policies in OECD countries that have encouraged the growth in biofuel production and use to date are:

- energy supply security;
- support for agricultural industries and rural communities;
- reduction of dependence on oil imports, and
- the potential for greenhouse gas (GHG) mitigation.

Recent fluctuating oil prices and the concerns over possible future supply constraints (see for example, [IEA, 2008b](#)) have emphasised the need for non-petroleum alternatives. Several non-OECD countries have begun to develop their own biofuel industries to produce fuels for local use ([Lee et al., 2008](#)), as well as for export to earn revenue should biofuel surpluses arise, in order to aid their economic development. Many other countries are considering replicating this model. Driven by supportive policy actions of national governments, biofuels now account for over 1.5% of global road transport fuels on an energy basis. In 2008, around 69.3 million litres of ethanol with an energy content (low heat value) of around 1460 PJ ([Fig. 1](#)), were produced, as well as 14.8 million litres (500 PJ) of biodiesel ([IEA, 2009](#)).

### 2.1. Greenhouse gas mitigation

Biofuels can be an expensive option for reducing GHG emissions and improving energy security. Estimates in the literature for GHG mitigation from corn ethanol (and biodiesel) vary depending on the country and pathway, but mostly exceed USD 250/tonne of carbon dioxide (\$/t CO<sub>2</sub>) avoided ([Doornbusch and Steenblik, 2007](#)). Most analyses continue to indicate that 1st-generation biofuels show at least some net benefit in terms of GHG emissions reduction and energy balances. However, with the exception of sugarcane ethanol ([Fig. 2](#)), given the relatively limited scope for cost reductions and the increasing global demand for food and fibre, little improvement in these mitigation potentials can be expected in the short term.

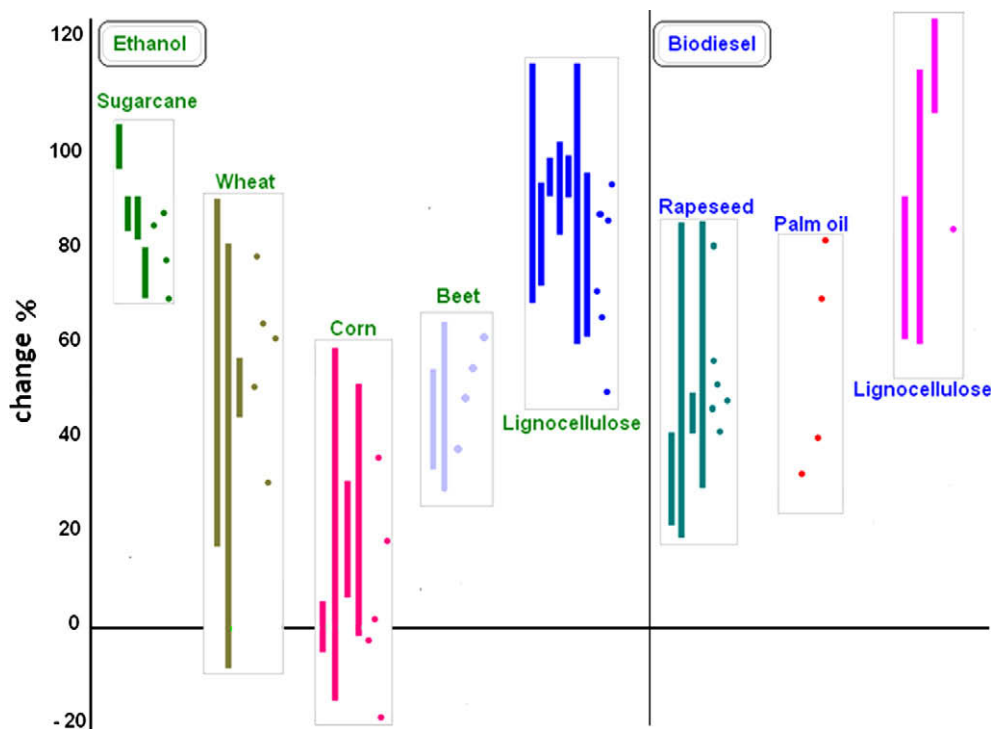
Additional uncertainty has also recently been raised about GHG savings if direct and indirect land-use change is taken into account

([Searchinger et al., 2008](#)). Certification of biofuels and their feedstocks is being examined ([GBEP, 2008, 2009](#)), and could help to ensure that the future production of biofuels meets sustainability criteria, although some uncertainty over indirect land-use impacts is likely to remain. Additional concerns over the impact of biofuels on biodiversity and scarce water resources in some countries also need further evaluation.

### 2.2. Ligno-cellulosic feedstocks

Low-cost crop and forest residues, wood process wastes, and the organic fraction of municipal solid wastes can all be used as ligno-cellulosic feedstocks. Where these biomass materials are available, it should be possible to produce biofuels from them with virtually no additional land requirements or impacts on food and fibre crop production. The technical potential from available annual supplies of residues and wastes has been estimated in energy terms at over 100 EJ/yr at delivered costs in the range of USD 2–3/GJ ([IEA Bioenergy, 2007](#)). However, in many regions there are only limited supplies of these biomass feedstocks, so the growing of vegetative grasses or short rotation forest crops could be necessary as supplements to meet the demand for biofuels. Local field trials to determine the levels of productivity under a range of growing conditions in various localities will be needed. Where potential energy crops can be grown on marginal and degraded land, these would not compete directly with growing food and fibre crops which require better quality arable land. For example, growing eucalyptus mallee crops in strips on the millions of hectares of soils with increasing salinity levels in Australia could help to drive down the water table and reduce the surface salt concentrations that prohibit cereal crop production ([Wu et al., 2005](#)).

Relatively high annual energy yields from dedicated energy crops, in terms of GJ/ha/yr, can be achieved from these crops compared with many of the traditional food crops currently grown for 1st-generation biofuels ([Schemer, 2008; NRDC, 2006](#)). Also energy



**Fig. 2.** Well-to-wheel emission avoidance ranges (shown by the bars) or specific data (shown by the dots) for a range of 1st- and 2nd-generation biofuels (excluding emissions from direct and indirect land-use change) compared with gasoline or mineral diesel.

crop yields could increase significantly over time since breeding research (including genetic modification) is at an early phase compared with the breeding of varieties of food crops. New varieties of energy crops may lead to increased yields, reduced water demand, and lower dependency on agri-chemical inputs. In some regions where low intensity farming is currently practised, improved management of existing crops grown on arable land could result in higher yields per hectare. This would enable energy crops to also be grown without the need for increased deforestation or reduction in food and fibre supplies.

### 2.3. Supply chain issues

Harvesting, treating, transporting, storing, and delivering large volumes of biomass feedstock, at a desired quality, all-year-round, to a biofuel processing plant requires careful logistical analysis prior to plant investment and construction. Supplies need to be contracted and guaranteed by the growers in advance over a prolonged period in order to reduce the project investment risks for the developer. Crop and forest residues are often widely distributed. If not collected at the time of harvest using integrated systems, then they will need to be collected as a separate operation and brought to a central location. Where road transport cannot be avoided, due to the relatively low energy density of many solid and liquid forms of biomass compared with their fossil fuel equivalents, numerous vehicle movements are inevitable (Table 1). Typically, ethanol yields from the bio-conversion of ligno-cellulose feedstocks range from 110 to 270 l/t dry matter from agricultural residues and 125 to 300 l/t dry matter from forest residues (ORNL, 2006; Mabee et al., 2006). Collectable yields of 3–5 t/ha for cereal straw, or 4–6 t/ha for corn stover, result in ethanol yields varying between 350 and 1600 l/ha/yr.

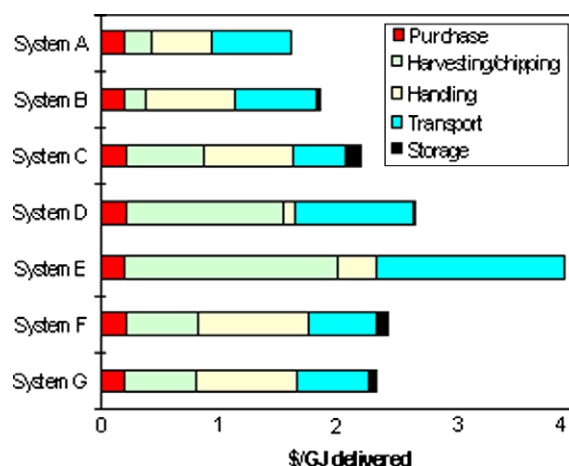
The collection and delivery method will vary with the type of residue, terrain, available machinery, location, soil, seasonal access etc. and the relative costs of collection (Fig. 3). Careful development and selection of a system from the range available is needed to minimise machinery use, human effort, transport efficiency and energy inputs. The choice can have a considerable impact on the cost of the biomass delivered to the processing plant gate (IEA, 2007). The aims should be to minimise the production, harvest and transport costs and thereby ensure the economic viability of the overall project. The supply chain issue is often inadequately taken into account when 2nd-generation opportunities are being considered. Supply logistics will become more important as development accelerates and competition for biomass feedstocks arises. Reducing feedstock delivery and storage costs should be a major goal since feedstock costs are a significant component of the total biofuel costs.

**Table 1**

Typical scale of operation for various 2nd-generation biofuel plants using energy crop-based ligno-cellulosic feedstocks.

Type of plant	Plant capacity ranges, and assumed annual hours of operation	Biomass fuel required. (oven dry tonnes/year)	Truck vehicle movements for delivery to the plant	Land area required to produce the biomass (% of total land within a given radius)
Small pilot	15 000–25 000 l/yr 2000 h	40–60	3–5/yr	1–3% within 1 km radius
Demonstration	40 000–500 000 l/yr 3000 h	100–1200	10–140/yr	5–10% within 2 km radius
Pre-commercial	1–4 Ml/yr 4000 h	2000–10 000	25–100/month	1–3% within 10 km radius
Commercial	25–50 Ml/yr 5000 h	60 000–120 000	10–20/day	5–10% within 20 km radius
Large commercial	150–250 Ml/yr 7000 h	350 000–600 000	100–200/day and night	1–2% within 100 km radius

Note: The land area requirement would be reduced where crop and forest residue feedstocks are available.



**Fig. 3.** Delivered costs of forest arising over a transport distance of 80 km can vary with the choice of system: System A (based on transport to a centralised chipper with no intermediate storage), having around half the delivered cost of System E (based on a mobile, in-forest chipper/forwarder system) (Sims, 2002).

### 2.4. Conversion routes

The production of biofuels from ligno-cellulosic feedstocks can be achieved through two very different processing routes:

- biochemical – in which enzymes and other micro-organisms are used to convert cellulose and hemicellulose components of the feedstocks to sugars prior to their fermentation to produce ethanol;
- thermo-chemical – (also known as biomass-to-liquids, BTL), where pyrolysis/gasification technologies produce a synthesis gas ( $\text{CO} + \text{H}_2$ ) from which a wide range of long carbon chain bio-fuels, such as synthetic diesel, aviation fuel, or ethanol, can be reformed, based on the Fischer–Tropsch conversion.

These are not the only 2nd-generation biofuels pathways, and several variations and alternatives are under evaluation in research laboratories and pilot plants. They can produce biofuel products either similar to those produced from the two main routes or other chemical fuels including dimethyl ether, methanol, and synthetic methane. However, at this stage these alternatives do not represent the main thrust of RD&D investment so are not considered further.

There is currently no clear commercial or technical advantage between the biochemical and thermo-chemical pathways, even after many years of RD&D and the development of near-commercial demonstrations. Both technologies remain unproven at the



fully commercial scale, are under continual development and evaluation, and have significant technical and environmental barriers yet to be overcome.

For the biochemical route, much remains to be done in terms of improving feedstock characteristics: reducing the costs by perfecting the pre-treatment process (Eggeman and Elander, 2005; Weil et al., 2002); improving the efficacy of enzymes (Galbe et al., 2005; Mosier et al., 2005); lowering production costs (Gregg et al., 1998); and improving overall process integration (Sheehan et al., 2004).

The pre-treatment process to expose the cellulose and hemicellulose for subsequent enzymatic hydrolysis is a critical process step. Options can be classified into biological, physical, chemical or a combination, each with variations having different temperatures and reaction times (Wyman et al., 2007). The pre-treatment process is a major cost component of the overall process. No “best” option exists and R&D continues to improve cost and performance goals, though steam explosion and dilute acid are probably closest to commercialisation. The potential advantage of the biochemical route is that cost reductions have proved reasonably successful to date (such as enzyme recycling (Tu et al., 2006)), so the option could possibly provide cheaper biofuels in the longer term than via the thermo-chemical route.

Conversely, as a broad generalisation, there are less technical hurdles to the BTL route since many of the technological components of the system are already proven and have been in operation for decades, focusing on coal-to-liquids and more recently natural gas-to-liquids. Therefore, with this more mature technology, perhaps there is less opportunity for cost reductions (although several untested novel approaches are under evaluation). One specific problem concerns securing a large enough quantity of feedstock for a reasonable delivered cost at the plant gate in order to meet the demands of a large commercial-scale plant that is required for BTL to become economic.

Perfecting the gasification of biomass reliably and at reasonable cost has yet to be achieved, although recent progress has been made after several demonstration plant failures, such as the 10 MW Yorkshire Arbore project. For example, a biomass-fuelled, steam blown, fluidised bed gasification plant operating in Güssing, Austria since 2001 has a fuel capacity of 8 MW and an electrical output of 2 MW<sub>e</sub> with 4.5 MW<sub>th</sub>. The plant, designed at Vienna Technical University, initially had reliability problems but is now running successfully for around 8000 h a year at 90% availability (Hofbauer, 2007). Also the volatile tar component that has acted as a technical barrier to the large-scale deployment of gasifiers has now been exploited as a separate feedstock to produce value-added chemicals by biofuel companies including Choren, Ensyn and Enerkem (Branca and Di Blasi, 2006).

One key difference between the biochemical and BTL routes is that the lignin component of the biomass is a residue of the biochemical enzymatic hydrolysis process and hence can be used for heat and power generation. In the BTL process the lignin is converted into synthesis gas along with the cellulose and hemicellu-

lose biomass components. In spite of this difference, both processes can potentially convert 1 dry tonne of biomass (~20 GJ/t) to around 6.5 GJ/t of energy carrier in the form of biofuels, thereby giving an overall biomass to biofuel conversion efficiency of around 35% (Mabee et al., 2006). The similar overall yield in energy terms (around 6.5 GJ/t biofuels being the top of the range), is because synthetic diesel has a higher energy density by volume than ethanol. Although this efficiency appears relatively low, overall efficiencies of the process can be improved when surplus heat, power and co-product generation are included in the total system. Improving efficiency is vital to the extent that it reduces the final product cost and improves environmental performance, but it should not be a goal in itself.

Although both routes have similar potential yields in energy terms, different yields, in terms of litres per tonne of feedstock, occur in practice. Major variations between the various processes under development, together with variations between biofuel yields from different feedstocks, give a complex picture with wide ranges being quoted in the literature. Typically the enzyme hydrolysis process could be expected to produce up to 300 l ethanol (6 GJ)/dry tonne of biomass whereas the BTL route could yield up to 200 l (4 GJ) of synthetic diesel per dry tonne (Table 2).

A second major difference between the two conversion paths is that the various biochemical routes all produce ethanol whereas the thermo-chemical routes can be employed to produce a range of longer-chain hydrocarbons from the synthesis gas. These include biofuels better suited for aviation and marine purposes. The synthesis gas can also be converted to methanol as well as to higher alcohols for transport fuel application using modified catalysts to provide better yields (Putsche, 1999). Only time will tell which of these various conversion routes will be preferred, but whereas there may be alternative technologies becoming available for powering light vehicles in future (including hybrids, electric plug-ins and fuel cells), such alternatives for aeroplanes, boats and heavy trucks are less likely and liquid fuels will continue to dominate these markets (IEA, 2008c).

Following substantial government and private company investments made to help reduce the commercial and financial risks from deploying unproven technology and fluctuating oil prices, both the biochemical enzyme hydrolysis process and the BTL process have reached the demonstration stage. Several plants in US and Europe are either operating, planned or under construction (details are available at IEA Bioenergy Task 39; Bacovsky et al., 2007; IEA, 2008a). As more partly government-funded demonstration plants come on-line over the next 2–3 years, they will be closely monitored. Significant data on the performance of different conversion routes will then finally become available, allowing governments to be better informed when making strategic policy decisions for future 2nd-generation development and deployment.

The first fully commercial-scale plants could possibly be seen operating as early as 2012 (Biofuels Digest, 2008), although the successful demonstration of a conversion technology will be required first in order to meet this target. Therefore given the com-

**Table 2**  
Indicative biofuel yield ranges per dry tonne of feedstock from biochemical and thermo-chemical process routes.

Process	Biofuel yield (l/dry t)		Energy content (MJ/l) Low heat value	Energy yields (GJ/t)	
	Low	High		Low	High
<i>Biochemical</i>					
Enzymatic hydrolysis ethanol	110	300	21.1	2.3	6.3
<i>Thermo-chemical</i>					
Syngas-to-Fischer Tropsch diesel	75	200	34.4	2.6	6.9
Syngas-to-ethanol	120	160	21.1	2.5	3.4

Source: Mabee et al. (2006), Putsche (1999).

plexity of the technical and economic challenges involved in the current demonstration plants, it could be argued that in reality, the first commercial plants are unlikely to be widely deployed before 2015 or 2020 (IEA, 2008a).

### 3. Production costs

The full biofuel production costs associated with both the biochemical and thermo-chemical pathways remain uncertain and are treated by the various companies producing biofuels with a high degree of commercial propriety. Comparisons between the alternative routes have therefore proven to be very contentious within the industry, with the lack of any real published cost data to date being a major issue for the industry.

The IEA (2008c) has developed a set of projections on the potential market penetration of 2nd-generation biofuels out to 2050. The rate of anticipated cost reductions will depend on feedstock prices, economies of scale from large plants, integration of new technologies and benefits of experience and learning (USDOE, 2008). Using data extrapolated from various sources, future costs were assessed to range from USD 0.80 to 0.90/litre of gasoline equivalent (lge) for ethanol (Table 3). The assumptions underlying these evaluations are for a very ambitious, global energy scenario, whereby global annual CO<sub>2</sub> emissions have to be reduced 50% by 2050. This in-

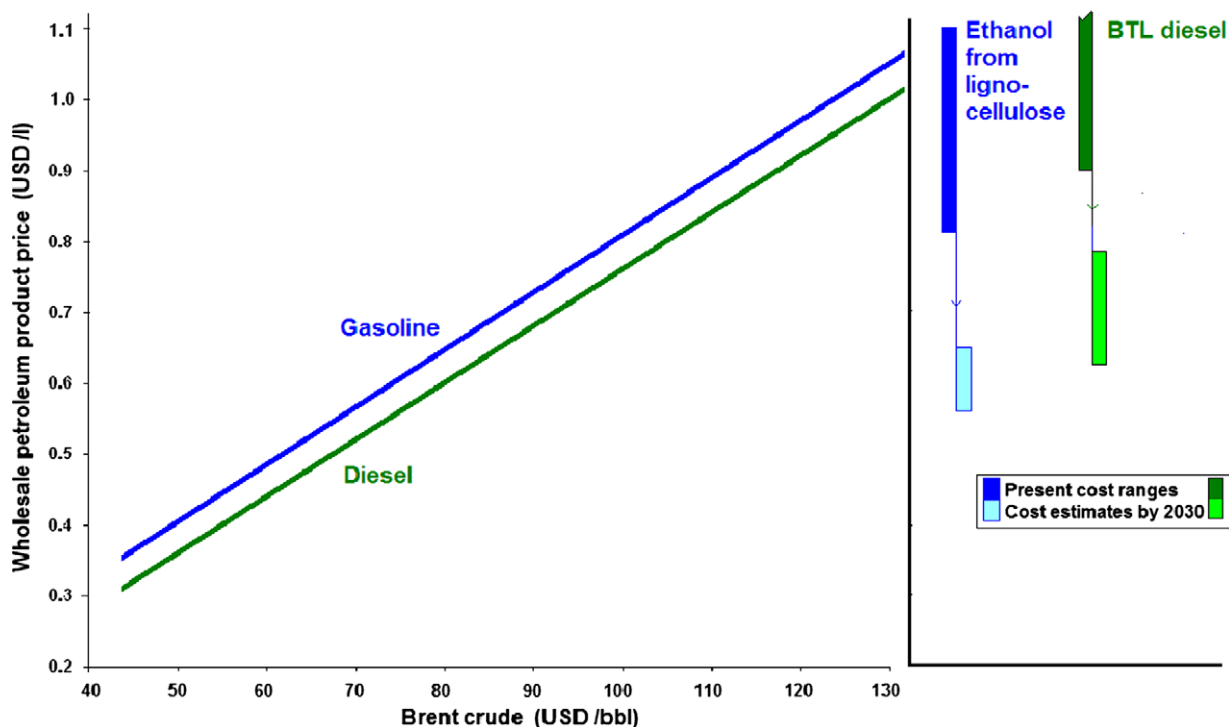
cludes a dramatic acceleration of 2nd-generation biofuels production after 2030 to meet 26% of transport fuel demand in 2050. Less rapid deployment would imply higher costs than those presented.

Competing production costs of ethanol biofuels (free of subsidies) can be compared to the costs per unit of energy of daily free-on-board wholesale gasoline prices. These were correlated with the crude oil price over a 16 month period (IEA, 2006). The current cost range for 2nd-generation biofuels broadly relates to gasoline wholesale prices (measured in USD/lge) when the crude oil price is between USD 100 and 130 per barrel (\$/bbl) (Fig. 4). Since undertaking this detailed analysis, the costs of producing some 1st-generation biofuels have risen due to significant feedstock and energy input price increases, as well as higher costs for steel and other materials for plant construction. The oil price has also fluctuated widely. A simplified version of the analysis using the 2nd-generation biofuel cost ranges as extracted from the literature at the time, excluding any subsidies, indicated that ethanol production costs would need to be reduced to around USD 0.80/lge before ethanol could compete with wholesale gasoline prices achieved when crude oil is around USD 100/bbl.

The present widely fluctuating oil and gas prices therefore make investment in 2nd-generation biofuels at current production costs a high risk venture, particularly when other alternatives to conventional oil such as heavy oils, tar sands, gas-to-liquids and coal-to-liquids can compete with crude oil around USD 65/bbl. These com-

**Table 3**  
IEA 2nd-generation biofuel cost assumptions for 2010, 2030 and 2050.

Ligno-cellulosic conversion technology	Assumptions	Production costs – by 2010 USD/lge	By 2030 USD/lge	By 2050 USD/lge
Bio-chemical ethanol	Optimistic	0.80	0.55	0.55
	Pessimistic	0.90	0.65	0.60
BTL diesel	Optimistic	1.00	0.60	0.55
	Pessimistic	1.20	0.70	0.65



**Fig. 4.** Production cost ranges for 2nd-generation biofuels in 2006 (USD/litre gasoline equivalent) compared with wholesale petroleum fuel prices correlated with the crude oil price over a 16 month period, and 2030 projections assuming significant investment in RD&D. Source: IPCC, 2007.

parative costs take into account infrastructural requirements, environmental best practices and an acceptable return on capital but exclude any future penalty imposed for higher CO<sub>2</sub> emissions per kilometre travelled when calculated on a life cycle basis, which would be relatively high for non-conventional oils.

Production costs for 2nd-generation biofuels in the literature range between USD 0.60 and 1.30/l. The main reasons for the wide range between published cost predictions relate to the varying assumptions made for feedstock supply costs, pre-treatment costs, operating life of the plant, performance efficiencies, and future timing of the commercial availability of both the feedstock supply chain and conversion technologies. Given that 2nd-generation biofuels have remained at the pre-commercial stage for two to three decades, eventual widespread deployment is expected to lead to the improvement of the efficiencies of the technologies, reduced costs from plant construction and operating experience, and other “learning-by-doing” effects. The potential for cost reductions is likely to be greater for ethanol produced via the biochemical route than for other liquid fuels produced by the thermo-chemical route, because many of the technological components for a BTL plant are already mature.

If commercialisation succeeds in the 2012–2015 time frame and rapid deployment occurs world-wide beyond 2020, then IEA analysis based on estimates gleaned from the literature (IEA, 2008a), shows that costs could decline to between USD 0.55 and 0.75/lge for ethanol by 2030 (Fig. 4). This is due to cost reductions from large-scale production, improved efficiency of the conversion process, cheaper and more effective enzymes, and improvements throughout the supply chain (Perlack et al., 2005). Ethanol would then become competitive with crude oil at around USD 70/bbl (2008 dollars) and with synthetic diesel and aviation fuel at around USD 80/bbl. Other projections for future cost reductions of biofuels in the literature reach as low as USD 0.25 to 0.35/l. If this proves feasible, then by 2050 biofuels will become competitive well below USD 70/bbl (IEA, 2008a).

#### 4. Technology development challenges

Success in the commercial development and deployment of 2nd-generation biofuel technologies will require significant progress in a number of areas if the technological and cost barriers they currently face are to be overcome. Areas that need particular research and policy attention are outlined below.

##### 4.1. Improved understanding of feedstocks and reduction in costs

A better understanding of currently available feedstocks, their geographic distribution and production, transport, storage and processing costs, is required. Further experience in the production of various dedicated energy crop feedstocks (e.g. switchgrass, miscanthus, poplar, eucalyptus and willow) in different regions needs to be undertaken to better understand the yield potentials, biomass characteristics and production costs. The ideal characteristics for specific feedstocks need to be identified in order to maximise their conversion efficiencies to liquid biofuels. The differences between the characteristics of wood, straw, stover and vegetative grasses can create particular challenges for bio-conversion in multi-feedstock plants (Berlin et al., 2006). Hemicellulose in softwoods has a lower xylose content but higher mannose/galactose than in hardwood species. Softwoods also have only two principal phenyl propane units (coumaryl and guaiacyl) that form the basic building blocks of lignin, while hardwoods and herbaceous plants have additional syringyl units. This chemical structure increases the difficulty of delignification due to the enhanced stability of the lignin in condensed form when exposed

to acidic conditions (Shimada et al., 1997) making ligno-cellulosic materials from woody biomass a challenge for biochemical conversions. The potential for improving these characteristics over time, and the rate of improvement, could be maximised through appropriate levels of R&D investment that need assessment.

On a micro-scale, the implementation of energy crop production could be assessed to ascertain the percentage of total area within a given collection radius needed to supply sufficient biomass all-year-round to a commercial-scale plant. Although in some regions there may be enough agricultural and forest residues available to support several processing plants, it is likely that in many more regions, large-scale production will require dedicated energy crops either as a supplement or as the sole feedstock. The optimal size of production facility should be identified for a variety of situations, after trading off transport costs and economies of scale of the plant against using local, reliable and cost-effective feedstock supplies that support the local rural industry.

##### 4.2. Technology improvements for the biochemical route

Feedstock pre-treatment technologies are inefficient and costly. Improvements in the various pre-treatment options need to be achieved to maximise the efficacy of pre-treatment in opening up the cellular structure of the feedstock for subsequent hydrolysis (Chandra et al., 2007). Dilute and concentrated acid processes are both close to commercialisation and the AFEX process based around steam explosion but using ammonia, could provide significant benefits (Wyman et al., 2007).

New and/or improved enzymes continue to be developed. The effective hydrolysis of the inter-connected matrix of cellulose, hemicellulose and lignin requires a number of cellulases to be employed. Those most commonly used are produced by wood-rotting fungi such as *Trichoderma*, *Penicillium*, and *Aspergillus*, however, their production costs remain high. The presence of product inhibitors also needs to be minimised. Recycling of enzymes is potentially one avenue to help reduce the costs. Whether separate or simultaneous processes for saccharification and fermentation represent the least cost route for different feedstocks is yet to be determined.

A key goal for the efficient production of ligno-cellulosic ethanol is that all C5 (pentose) and C6 (hexose) sugars released during the pre-treatment and hydrolysis steps are fermented into ethanol. Currently, there are no known natural organisms that have the ability to convert both C5 and C6 sugars to produce high ethanol yields (Ragauskas et al., 2006), although major progress has been made in engineering micro-organisms for the co-fermentation of these pentose and glucose sugars. The conversion of glucose to ethanol during fermentation of the enzymatic hydrolysate is not difficult provided there is an absence of inhibitory substances such as furfural, hydroxyl methyl furfural, or natural wood-derived inhibitors such as resin acids. The need to accommodate the variability in biomass feedstocks and to manipulate ethanol and sugar tolerance to potential inhibitors generated in the pre-saccharification treatment remains a scientific challenge. While pentose fermentation has been achieved on ideal substrates (such as laboratory preparations of sugars designed to imitate a perfectly pre-treated feedstock), significant work remains to apply this process to actual ligno-cellulosic feedstocks.

Due to the large number of individual processes in the overall conversion of ligno-cellulosic biomass into ethanol, there remains considerable potential for process integration. This approach could have benefits in terms of lower capital and operating costs, as well as ensuring the optimum production of valuable co-products. Given that 2nd-generation process development is still at the pre-commercial stage, it may take some time to determine the most efficient process pathway and system.

#### 4.3. Technology improvements for the thermo-chemical route

BTL faces the challenge of developing a gasification process for the biomass at commercial-scale to produce synthesis gas to the exacting standards required for a range of ethanol and other bio-fuel synthesis technologies such as Fischer–Tropsch (FT). In spite of many years of research and commercial endeavours and recent progress, cost effective and reliable methods of large-scale biomass gasification remain fairly elusive. The goal should be to develop reliable technologies that have high availability and produce clean gas that does not poison the FT catalysts, or that can be cleaned up to meet these standards without significant additional cost.

Improving the efficiency and lowering the costs of the biofuel synthesis process are important RD&D goals, although improvements are likely to be incremental given the relatively mature nature of the technologies. Developing new catalysts that are less susceptible to impurities and have longer lifetimes would help reduce these costs.

#### 4.4. Co-products and process integration

The production of valuable co-products during the production of 2nd-generation biofuels offers the potential to increase the overall revenue from the process and improve the economics of the process accordingly. Optimisation of the conversion process to maximise the value of co-products produced (heat, electricity, various chemicals etc.) needs to be pursued for different feedstocks and conversion pathways. Flexibility to vary the shares of co-product output within a “bio-refinery” process (Werpy et al., 2004) is likely to be a useful hedge against market price risk for these co-products.

Market assessments of the biofuels and all co-products associated with biofuel production need to take into account all the dis-benefits, costs and co-benefits, including rural development, employment, energy security, carbon sequestration etc. if a fair assessment of project deployment is to be made.

### 5. Implications for policies

Promotion of 2nd-generation biofuels can help provide solutions to multiple policy drivers including energy security and diversification, rural economic development, and GHG mitigation. It can also assist with the reduction of other environmental impacts, at least those relative to the use of other transport fuels. Policies designed to specifically support the promotion of 2nd-generation biofuels must be carefully developed if they are to avoid unwanted consequences and potentially delay commercialisation. Lessons learned from policies instigated to support 1st-generation biofuels can be applied, such as ensuring the full environmental ramifications of deploying 2nd-generation biofuels is thoroughly understood. This could be of particular relevance to developing countries where corporate investment could be at the risk of exploitation of the local people which continues to be a concern (GBEP, 2008).

Government policies that currently support many 1st-generation biofuels and their relatively high costs (with the notable exception of sugarcane in Brazil) could be viewed as an impediment to the development of 2nd-generation biofuels. For example, the goals of some current policies that support the industry with capital grants and agricultural subsidies are not always in alignment with policies that foster innovation to further develop the production and process technologies. The opposite view is that the present support for 1st-generation biofuels will eventually benefit 2nd-generation biofuels. For example, where well designed support policies are already in place, then the fledgling industry for

2nd-generation would have the opportunity to grow alongside that of 1st-generation using the infrastructure already developed and thereby reducing the overall costs. Advances in technology should then enable 2nd-generation biofuels to build on the infrastructure and markets established by 1st-generation biofuels and hence, in the longer term, provide a cheaper and more sustainable alternative (IEA, 2008a). This assumes that future policy support will be carefully designed in order to foster the transition to 2nd-generation and take into account the specificities of both 1st- and 2nd-generation biofuels, the production of sustainable feedstocks, and other related policy goals under consideration.

Policies to support either 1st- or 2nd-generation biofuels ideally should be part of a comprehensive strategy to also reduce GHG emissions. A first step that could help produce a more competitive market for biofuels is to ensure that there is a national carbon price or other CO<sub>2</sub> reduction incentive in place. Taking into account the environmental impacts of CO<sub>2</sub> emissions derived from petroleum products would mean biofuels that have a proven mitigation potential could compete on a more equal footing. This is also important to ensure that bioenergy feedstocks are put to their highest value use, allowing for competition for the limited biomass resource between heat, power, bio-material applications etc. In addition, the harmonisation of policies across sectors – including energy, transport, health, climate change, local pollution, trade etc. – is necessary to avoid policies working at cross purposes.

The instigation of some form of carbon charge is in itself unlikely to be enough to ensure the commercialisation of 2nd-generation biofuels in a timely manner. In addition to systems placing a value on CO<sub>2</sub> savings, an integrated package of policy measures will be needed to ensure commercialisation occurs, including continued support for R&D; addressing the financial risks of developing demonstration plants; and providing for the deployment of 2nd-generation biofuels. This integrated policy approach, while not entirely removing financial risk for developers, will provide the greater certainty needed to invest with confidence in an emerging sector.

#### 5.1. Enhanced RD&D investment in 2nd-generation biofuels

Continued investment in RD&D is essential if 2nd-generation biofuels are to be brought to market in the near to medium-term. Topics needing support include evaluating sustainable biomass production, improving energy crop yields, reducing supply chain costs, as well as improving the conversion processes via further basic research. Such investments ultimately should lead to deployment of commercial-scale production and processing facilities and competitive market deployment of the biofuels.

The goals of both public and private RD&D investments related to 2nd-generation biofuel production, use, as well as trade, should include:

- increasing crop productivity and improvement of ecosystem health through management techniques, improved mechanisation, water management, precision farming to avoid wasting fertilisers and agro-chemicals, and plant breeding and selection (including genetic modification);
- evaluating land-use change impacts on GHG emissions, minimising the loss of soil carbon through the careful selection and growing of energy crops, and assessing the potential benefits of increasing the soil carbon content;
- cost effective production, processing, blending and distribution;
- enabling sustainability lessons learned from 1st-generation biofuels to be applied; and
- increasing the performance of the various conversion technologies.



A broad, international collaborative approach ideally should be taken in order to complement the various RD&D efforts in different countries; to reduce the risk to investors; and to create a positive environment for the participation of financial institutions. Continued analysis of co-benefits including energy security, GHG mitigation, potential local advantages particularly for rural communities and sustainable development, and the value of co-products, should be undertaken. International collaboration on assessing the benefits and impacts of 2nd-generation biofuels and their sustainability monitoring should be continued through such organisations as the Global Bioenergy Partnership ([www.globalbioenergy.org](http://www.globalbioenergy.org)) and IEA Bioenergy, Task 39 ([www.task39.org](http://www.task39.org)). However, the unwillingness for commercial companies to be involved due to the constraints of protecting intellectual property rights for commercial investments must be recognised. Agreement on sustainability principles and criteria that include effective and attainable systems achieved via certification, and that are consistent with World Trade Organization (WTO) rules, would be a significant step forward.

### 5.2. Accelerating the demonstration of 2nd-generation biofuels

Before commercial production can begin, multi-million dollar government grants are currently required to encourage the private sector to take the risk of developing a commercial scale processing plant, even during periods when high oil prices make biofuels a more competitive option. Risk sharing between the public and private sector is essential to accelerate deployment of 2nd-generation biofuels. Funding for 2nd-generation biofuel demonstration plants is needed from both the public and private sectors. Developing links between industry, universities, research organisations and governments, has already been shown to be a successful approach in some instances (see for example, Shell, 2008).

Present support to provide risk sharing for demonstration projects does not match the ambitious plans for 2nd-generation biofuels of some governments and regions, although there are exceptions. Additional support policies need to be urgently put in place. Funding to support the pre-commercial testing of 2nd-generation biofuels technologies should be encouraged in order to reduce the risk to investors. Support for the necessary infrastructure and demonstration plants could be delivered through mechanisms similar to the US “*Program for Construction of Demonstration Technologies*”, funded by the US Department of Energy.

Where feasible, funding for 2nd-generation biofuels and/or biorefinery demonstration plants should be harmonised with national and regional renewable energy programmes which incorporate the production and utilisation of biomass. Links with other synergistic policies should be made where feasible in order to maximise support for development of infrastructure. Integration and better coordination of policy frameworks requires coordinating national and international action among the key sectors involved in the development and use of biofuels.

### 5.3. Deployment policies for 2nd-generation biofuels

Deployment policies generally fall into two categories of either blending targets (which can be mandatory or voluntary) or tax credits. Mandatory targets give certainty over outcomes, but not over the potential costs, while it is the inverse for tax credits. What pathway individual countries choose will depend on their policy goals and the related risks that they perceive. Deployment policies are essential if rapid scale-up of the industry is required to reduce costs through learning-by-doing. Otherwise deployment and cost reductions are likely to be slow since initial commercial deployment will only focus on niche opportunities where costs and risks are low. Continued support for development of 2nd-generation

biofuels by governments is essential, but it should not necessarily be at the expense of reducing current programmes designed to support 1st-generation developments. Where obtaining a smooth transition from 1st- to 2nd-generation over time where this is deemed desirable (for reasons of cost savings, supply security or GHG mitigation for example), the biochemical and BTL routes for biofuels should be considered in a complementary but distinct fashion, possibly requiring different policies due to their distinct levels of maturity.

### 5.4. Environmental performance and certification schemes

Continued progress needs to be made in addressing and characterising the environmental performance of biofuels. Approaches to standardisation and assessment methods need to be agreed, as well as harmonising potential sustainable biomass certification methods. These will need to cover the production of the biomass feedstock and potential impacts from land-use change. Policies designed to utilise these measures could work as a fixed arrangement between national governments and industrial producers, or could be designed to work as a market-based tool by linking to regional and international emission trading schemes such as the one in place between member states of the European Union.

## 6. Conclusions

The production of 1st-generation biofuels, mainly from traditional food crops, has increased rapidly over the past few years in response to concerns about energy supply security, rising oil prices and climate change. Due to an improved understanding of total GHG emissions as a result of detailed life cycle analyses, and related direct and indirect land-use change issues, the perceived environmental benefits of 1st-generation fuels have recently been brought into question.

It has become evident that some “good” 1st-generation biofuels such as sugarcane ethanol, have GHG emission avoidance potential; are produced sustainably; can be cost effective without government support mechanisms; provide useful and valuable co-products; and, if carefully managed with due regard given to sustainable land use, can support the drive for sustainable development in many developing countries.

Other “less good” 1st-generation biofuels are being criticised with regard to their relatively low GHG emissions avoidance; unsustainable production relating to deforestation, water use, and land management; competition for food crop feedstocks pushing up food commodity prices; and the need for generous government support schemes to remain competitive even after the technologies have become mature. As a result a lot of hope has been placed on 2nd-generation biofuels.

Where these rely on crop and forest residues, or high yielding, non-food energy crops grown specifically for feedstocks, they are considered to be produced more sustainably than some 1st-generation fuels, and with better land use opportunities, including potential production on marginal lands.

However, full commercialisation of either biochemical or thermo-chemical conversion routes for producing 2nd-generation biofuels appears to remain some years away. This is in spite of several decades of research and development, and more recent investment in several pilot-scale and demonstration plants in US, Europe and elsewhere. Even with generous government subsidies, the commercial risks remain high, especially with recent widely fluctuating oil prices and global financial turmoil adding to the investment uncertainty.

There is no doubt that good progress with bio-ethanol production has been made during the past three decades following

increasing public and private investments in RD&D. Successful outcomes include development of improved micro-organisms and the evaluation of innovative conversion technologies with improved performance and efficiencies. There is also a better understanding by the industry of the overall feedstock supply chain (whether from crop and forest residues or from purpose grown crops), necessary to provide consistent quality feedstock delivered all-year-round to the conversion plant gate. There has also been successful developments relating to the construction of pilot-scale bio-refineries to produce a range of co-products, some being *small-volume, high-value* products, and others, like biofuels, being *high-volume, low-value*.

Overall, unless there is a technical breakthrough in either the biochemical or thermo-chemical routes that will significantly lower the production costs and accelerate investment and deployment, it is expected that successful commercialisation of 2nd-generation bio-ethanol and other biofuels will take another decade or so. During this period, demonstration and industrial-scale 2nd-generation plants will be continually improved in order that the products become competitive with petroleum fuels as well as with 1st-generation biofuels. Emphasis for biofuel application will need to be given to aviation, marine and heavy vehicle applications which will have limited alternatives. After 2020 or thereabouts, 2nd-generation bio-ethanol could become a much more significant player in a global biofuels market characterised by a balance between 1st- and 2nd-generation technologies.

Policies designed to reward environmental performance and sustainability of biofuels, as well as to encourage provision of a more abundant and geographically extensive feedstock supply, could see 2nd-generation products begin to eclipse 1st-generation alternatives in the medium to longer-term.

The key messages arising from this study are as follows.

- Technical barriers remain for 2nd-generation biofuel production.
- Production costs are uncertain and vary with the feedstock available and conversion process, but are currently thought to be above USD 0.80/litre of gasoline equivalent.
- There is no clear candidate for “best technology pathway” between the competing biochemical and thermo-chemical routes. The development and monitoring of several large-scale demonstration projects is essential to provide accurate comparative data.
- Even with oil prices remaining above USD 80/bbl, 2nd-generation biofuels will probably not become fully commercial nor enter the market for several years without significant additional government support.
- Considerably more investment in research, development, demonstration and deployment is needed to ensure that future production of the various biomass feedstocks can be undertaken sustainably and that the preferred conversion technologies, including those more advanced and those still only at the R&D stage, are identified and assessed whether or not they are economically viable.
- Once proven, there will be a steady transition from 1st- to 2nd-generation bio-ethanol, (with the exception of sugarcane ethanol that will continue to be produced sustainably in several countries).

Overall, it is considered that 2nd-generation technologies to produce liquid transport biofuels will not become commercially competitive with oil products in the near future unless the oil price remains consistently over USD 100/bbl. Therefore a long-term view for the potential of biofuels should be taken but without delaying the necessary investment needed to bring these technologies closer to market. International co-operation is paramount and collab-

oration through international organisations should be enhanced with both public and private sectors playing active roles to develop and sustain the 2nd-generation biofuels industry for the long-term.

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## References

- Bacovsky, D., Körbitz, W., Mittelbach, M., Wörgetter, M., 2007. Biodiesel production-technologies and European providers. Report to IEA Bioenergy Task 39, Biofuels, T39-B6, 104pp. Available from: <[www.task39.org](http://www.task39.org)>.
- Berlin, A., Balakshin, M., Gilkes, N., Kadla, J., Maximenko, V., Kubo, S., Saddler, J.N., 2006. Inhibition of cellulase, xylanase and  $\beta$ -glucosidase activities by softwood lignin preparations. *J. Biotechnol.* 125, 198–209.
- Biofuels Digest, 2008. Mossi and Ghisolf to build 66 Mgy ethanol plant in Piedmont, Italy. 6 February. <http://www.biofuelsdigest.com>.
- Branca, C., Di Blasi, C., 2006. Multistep mechanism for the devolatilization of biomass fast pyrolysis oils. *Indust. Eng. Chem. Res.* 45 (17), 5891–5899.
- Chakraborty, A., 2008. Internal World Bank study – biomass caused food crisis. <http://www.guardian.co.uk/environment/2008/jul/03/biofuels.renewableenergy>.
- Chandra, R., Bura, R., Mabee, W.E., Berlin, A., Pan, X., Saddler, J.N., 2007. Substrate pretreatment: the key to effective enzymatic hydrolysis of lignocellulosics. In: Lisbeth, O. (Ed.), *Advances in Biochemical Engineering/Biotechnology–Biofuels*, vol. 108. Springer, p. 368. ISBN: 978-3-540-73650-9.
- Doornbusch, R., Steenblik, R., 2007. Biofuels: is the cure worse than the disease? Paper prepared for the Round Table on Sustainable Development, Organisation for Economic Co-operation and Development (OECD), Paris. 11–12 September, SG/SO/RT(2007)3/REV1. <http://www.oecd.org/dataoecd/9/3/39411732.pdf>.
- Eggeman, T., Elander, R.T., 2005. Process and economic analysis of pretreatment technologies. *Bioresour. Technol.* 96 (18), 2019–2025.
- Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel carbon debt. *Science Express* 7 February. [www.sciencexpress.org](http://www.sciencexpress.org) Science 1152747.
- Galbe, M., Liden, G., Zacchi, G., 2005. Production of ethanol from biomass – research in Sweden. *J. Sci. Ind. Res.* 64 (11), 905–919.
- GBEP, 2008. A sustainable biofuels consensus. Global Bioenergy Partnership, March. <http://www.globalbioenergy.org/bioenergyinfo/global-initiativesbrbr/detail/en/news/4587/jicode/1/>.
- GBEP, 2009. Task Force on Greenhouse Gas Methodology, Global Bioenergy Partnership, Rome. <http://www.globalbioenergy.org/>.
- Gregg, D.J., Boussaid, A., Saddler, J.N., 1998. Techno-economic evaluations of a generic wood-to-ethanol process: effect of increased cellulose yields and enzyme recycle. *Bioresour. Technol.* 63 (1), 7–12.
- Hofbauer, H., 2007. Polygeneration based on biomass gasification – experiences from Güssing. 3rd Euroheat and Power RTD seminar. <http://www.euroheat.org/documents/RTD2008/Hermann%20Hofbauer.pdf>.
- IEA, 2006. World Energy Outlook 2006, International Energy Agency, IEA/OECD, Paris. [www.iea.org](http://www.iea.org).
- IEA, 2007. Bioenergy project development and biomass supply – good practice guidelines. 61pp, International Energy Agency, IEA/OECD, Paris. [www.iea.org](http://www.iea.org).
- IEA, 2008a. From 1st - to 2nd-generation biofuel technologies – an overview of current industry and RD&D activities. International Energy Agency, IEA/OECD, Paris, p. 120. [www.iea.org](http://www.iea.org).
- IEA, 2008b. World Energy Outlook 2008, Chapter 11, International Energy Agency, IEA/OECD, Paris. [www.iea.org](http://www.iea.org).
- IEA, 2008c. Energy Technology Perspectives. International Energy Agency, IEA/OECD, Paris. [www.iea.org](http://www.iea.org).
- IEA, 2009. Medium term oil-market report. International Energy Agency, IEA/OECD, Paris, p. 120. [www.iea.org](http://www.iea.org).

<sup>1</sup> The Implementing Agreement on Bioenergy is an international collaborative agreement set up in 1978 by the IEA to improve international co-operation and information exchange between national bioenergy RD&D programmes. IEA Bioenergy aims to accelerate the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, to provide increased security of supply and a substantial contribution to future energy demands. Currently IEA Bioenergy has 22 Members and is operating on the basis of 13 Tasks covering all aspects of the bioenergy chain, from resource to the supply of energy services to the consumer. More information on IEA Bioenergy can be found on the organisation’s homepage [www.ieabioenergy.com](http://www.ieabioenergy.com).

- IEA Bioenergy, 2007. Potential contribution of bioenergy to the world's future energy demand, [www.ieabioenergy.com](http://www.ieabioenergy.com).
- IEA Bioenergy, 2009. Sustainable bioenergy – a reliable energy option. Report prepared for IEA Bioenergy Implementing Agreement, [www.ieabioenergy.org](http://www.ieabioenergy.org).
- IEA Bioenergy Task 39, 2009. Commercialising 1st-and 2nd-generation liquid fuels from biomass, a database showing processing plant details and locations. <http://biofuels.abc-energy.at/demoplants/>.
- IPCC, 2007. Climate Change 4th Assessment Report – Mitigation. Intergovernmental Panel on Climate Change, Working Group III, Chapter 5, Transport. Cambridge Press, UK. [www.ipcc.ch](http://www.ipcc.ch).
- Lee, H., Clark, W.C., Devereux, C., 2008. Biofuels and sustainable development, report of an executive session on the “Grand challenges of a sustainability transition”, San Servolo Island, Venice, 19–20 May. Center for International Development, Harvard University <http://www.cid.harvard.edu/sustsc>.
- Luoma, J.R., 2009. Hailed as a miracle crop, *Jatropha* falls short of hype. *Yale Environment 360*, Guardian Environment Network. <http://www.guardian.co.uk/environment/2009/may/05/jatropha-biofuels-food-crops>.
- Mabee, W.E., Saddler, J., 2007. Deployment of 2nd-generation biofuels. Technology Learning and Deployment Workshop, International Energy Agency, Paris, 11–12 June. <http://www.iea.org/textbase/work/2007/learning/agenda.pdf>.
- Mabee, W.E., Gregg, D.J., Arato, C., Berlin, A., Bura, R., Gilkes, N., Mirochnik, O., Pan, X., Pye, E.K., Saddler, J.N., 2006. Update on softwood-to-ethanol process development. *Appl. Biochem. Biotechnol.* 29, 55–70.
- Mang, H-P., 2008. Perspective of bioenergy and *Jatropha* in China, International Consultation on Pro-poor *Jatropha* Development, International Fund for Agricultural Development, Rome, 10–11 April. [www.ifad.org/events/jatropha/country/HP\\_Mang.ppt](http://www.ifad.org/events/jatropha/country/HP_Mang.ppt).
- Mosier, N., Wyman, C.E., Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M., Ladisch, M., 2005. Features of promising technologies for pretreatment of lignocellulosic biomass. *Bioresour. Technol.* 96 (6), 673–686.
- NRDC, 2006. Ethanol: energy well spent – a survey of studies published since 1990. Natural Resources Defence Council and Climate Solutions, New York, US, p. 8.
- OECD, 2008. Economic assessment of biofuel support policies. Organisation for Economic Co-operation and Development, OECD, Paris. [www.oecd.org/tad/bioenergy](http://www.oecd.org/tad/bioenergy).
- ORNL, 2006. Bioenergy conversion factors. Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee, USA. [www.ornl.gov](http://www.ornl.gov).
- Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., and Erbach, D.C., 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. Department of Energy/GO-102005-2135, April.
- Putsche, V., 1999. Complete Process and Economic Model of Syngas Fermentation to Ethanol. C Milestone Completion Report. National Renewable Energy Laboratory, Golden, Colorado, USA.
- Ragauskas, A.J., Williams, C.K., Davison, B.H., Britovsek, G., Cairney, J., Eckert, C.A., Frederick Jr., W.J., Hallet, J.P., Leak, D.J., Liotta, C.L., Mielenz, J.R., Murphy, R., Templer, R., Tschaplinski, T., 2006. The path forward for biofuels and biomaterials. *Science* 311 (5760), 484–489.
- Schemer, M., 2008. Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences* 105 (2), 464–469.
- Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* 319, 1238–1240 (29 February).
- Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M., Nelson, R., 2004. Energy and environmental aspects of using corn stover for fuel ethanol. *J. Indust. Ecol.* 7 (3–4), 117–146.
- Shell, 2008. Shell announces six new biofuels research agreements. [www.shell.com/home/content/media/news\\_and\\_library/press\\_releases/2008/biofuels\\_research\\_agreements\\_17092008.html](http://www.shell.com/home/content/media/news_and_library/press_releases/2008/biofuels_research_agreements_17092008.html).
- Shimada, K., Hosoya, S., Ikeda, T., 1997. Condensation reactions of softwood and hardwood lignin model compounds under organic acid cooking conditions. *J. Wood Chem. Technol.* 17, 57–72.
- Sims, R.E.H., 2002. The Brilliance of Bioenergy – in Business and in Practice, Earthscan, UK, p. 316. [www.earthscan.co.uk/?tabid=101758](http://www.earthscan.co.uk/?tabid=101758).
- Tu, M., Zhang, X., Kurabi, A., Gilkes, N., Mabee, W.E., Saddler, J.N., 2006. Immobilization of  $\beta$ -glucosidase on Eupergit C for ligno-cellulose hydrolysis. *Biotechnol. Lett.* 28 (3), 151–156.
- USDOE, 2008. Biomass program biofuels initiative. United States Department of Energy. <http://www1.eere.energy.gov/biomass/pdfs/nbap.pdf>.
- Weil, J.R., Dien, B., Bothast, R., Hendrickson, R., Mosier, N.S., Ladisch, M.R., 2002. Removal of fermentation inhibitors formed during pretreatment of biomass by polymeric adsorbents. *Indust. Eng. Chem. Res.* 41 (24), 6132–6138.
- Werpy, T., Petersen, G., Aden, A., Bozell, J., Holladay, J., White, J., Manheim, A., Elliot, D., Lasure, L., Jones, S., Gerber, M., Ibsen, K., Lumberg, L., Kelley, S., 2004. Top value added chemicals from biomass – volume 1: results of screening for potential candidates from sugars and synthesis gas. Pacific Northwest National Laboratory, National Renewable Energy Laboratory and Department of Energy, Washington, DC. 76pp..
- Wu, H., Fu, Q., Bartle, J., Giles, R., 2005. Potential value of mallee (dryland Eucalyptus scrubby perennial crop) for biofuel farming and salinity management. In: *Proceedings, 6th Bioenergy Australia conference*, Melbourne, December.
- WWI, 2007. Biofuels for transport: global potential and implications for agriculture, Worldwatch Institute, Report Prepared for the German Federal Ministry of Food, Agriculture and Consumer Protection.
- Wyman, C.E., Dale, B.E., Elander, R.T., Holtzapple, M.T., Ladisch, M.R., Lee, Y.Y., Mitchinson, C., Saddler, J.N., 2007. Pre-treatment: the key to unlocking low cost cellulosic ethanol. *Cellulosic Ethanol Forum and Technology Roundtable*, Diamond Bar, California, USA. February 15.