INTERNATIONAL ENERGY AGENCY
AGENCE INTERNATIONALE DE L'ENERGIE

FROM 1st- TO 2nd-GENERATION BIOFUEL TECHNOLOGIES

An overview of current industry and RD&D activities

Ralph Sims, Michael Taylor
International Energy Agency

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IEA Bioenergy

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This Report provides a contribution to the Global Bioenergy Partnership (GBEP).

With the support of the
Italian Ministry for the Environment Land and Sea.

Acknowledgements

This report has been produced as a joint effort between the IEA Secretariat and the Implementing Agreement on Bioenergy. It was co-authored by Warren Mabee[1] and Jack Saddler[2], of Task 39 "*Commercialising 1st and 2nd Generation Liquid Biofuels from Biomass*" of the IEA Bioenergy Implementing Agreement, Michael Taylor of the IEA Energy Technology Policy Division (ETP), and Ralph Sims of the IEA Renewable Energy Unit (REU) who also edited it. Paolo Frankl, Head of the REU, provided guidance and input and Pierpaolo Cazzola (ETP) provided some useful data.

This publication has been funded by the Italian Ministry for the Environment, Land and Sea. It enabled the IEA to provide this contribution to the programme of work of the Global Bioenergy Partnership, initiated by the G8 countries at the 2005 Summit at Gleneagles and with its Secretariat based in Rome at the Food and Agriculture Organisation of the United Nations.

Useful review comments were received from several members of the informal group of Biofuels Policy Analysts from within the IEA, particularly Lew Fulton and Antonio Pflueger, as well as from, the Global Bioenergy Partnership Secretariat, IEA Bioenergy Executive Committee members and other specialists from IEA Bioenery Task 39. The IEA Bioenergy publication "*Gaps in the research of 2nd generation transportation biofuels*" (2008) produced by Task 41 (Project 2) was drawn on extensively in Part C.

Advice and assistance in the publication process, including conversion to web format, was gratefully received from Rebecca Gaghen (Director), Bertrand Sadin and Virginie Buschini of the IEA's Communications and Information Office. It is available as a free download from www.iea.org

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Executive Summary

It is increasingly understood that 1st-generation biofuels (produced primarily from food crops such as grains, sugar beet and oil seeds) are limited in their ability to achieve targets for oil-product substitution, climate change mitigation, and economic growth. Their sustainable production is under review, as is the possibility of creating undue competition for land and water used for food and fibre production. A possible exception that appears to meet many of the acceptable criteria is ethanol produced from sugar cane.

The cumulative impacts of these concerns have increased the interest in developing biofuels produced from non-food biomass. Feedstocks from ligno-cellulosic materials include cereal straw, bagasse, forest residues, and purpose-grown energy crops such as vegetative grasses and short rotation forests. These "2nd-generation biofuels" could avoid many of the concerns facing 1st-generation biofuels and potentially offer greater cost reduction potential in the longer term.

This report looks at the technical challenges facing 2nd-generation biofuels, evaluates their costs and examines related current policies to support their development and deployment. The potential for production of more advanced biofuels is also discussed. 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. Policy recommendations are given as to how these constraints might best be overcome in the future.

The key messages arising from the study are as follows.
- Technical barriers remain for 2nd-generation biofuel production.
- Production costs are uncertain and vary with the feedstock available, but are currently thought to be around USD 0.80 – 1.00/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 at high oil prices, 2nd-generation biofuels will probably not become fully commercial nor enter the market for several years to come without significant additional government support.
- Considerably more investment in research, development, demonstration and deployment (RDD&D) 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 but only at the R&D stage, are identified and proven to be viable.
- Once proven, there will be a steady transition from 1st- to 2nd-generation biofuels (with the exception of sugarcane ethanol that will continue to be produced sustainably in several countries).

A) First Generation Biofuels

Current status

The production of 1st-generation biofuels - such as sugarcane ethanol in Brazil, corn ethanol in US, oilseed rape biodiesel in Germany, and palm oil biodiesel in Malaysia - is characterised by mature commercial markets and well understood technologies. The global demand for liquid biofuels more than tripled between 2000 and 2007. Future targets and investment plans suggest strong growth will continue in the near future.

The main drivers behind the policies in OECD countries that have encouraged this growth are:
- energy supply security;
- support for agricultural industries and rural communities;
- reduction of oil imports, and
- the potential for greenhouse gas (GHG) mitigation.

Recent fluctuating oil prices and future supply constraints have emphasised the need for non-petroleum alternatives. Several non-OECD countries have developed their own biofuel industries to produce fuels for local use, as well as for export, in order to aid their economic development. Many others are considering replicating this model. Driven by supportive policy actions of national governments, biofuels now account for over 1.5% of global transport fuels (around 34 Mtoe in 2007).

Constraints and concerns

While most analyses continue to indicate that 1st-generation biofuels show a net benefit in terms of GHG emissions reduction and energy balance, they also have several drawbacks. Current concerns for many, but not all, of the 1st-generation biofuels are that they:

- contribute to higher food prices due to competition with food crops;
- are an expensive option for energy security taking into account total production costs excluding government grants and subsidies;
- provide only limited GHG reduction benefits (with the exception of sugarcane ethanol and at relatively high costs in terms of $ /tonne of carbon dioxide ($ /t CO_2) avoided;
- do not meet their claimed environmental benefits because the biomass feedstock may not always be produced sustainably;
- are accelerating deforestation (with other potentially indirect land use effects also to be accounted for);
- potentially have a negative impact on biodiversity; and
- compete for scarce water resources in some regions.

Additional uncertainty has also recently been raised about GHG savings if indirect land use change is taken into account. Certification of biofuels and their feedstocks is being examined, and could help to ensure biofuels production 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.

Most authorities agree that selected 1st-generation biofuels have contributed to the recent increases in world prices for food and animal feeds. However, much uncertainty exists in this regard and estimates of the biofuels contribution in the literature range from 15-25% of the total price increase (with a few at virtually zero or up to 75%). Regardless of the culpability, competition with food crops will remain an issue so long as 1st-generation biofuels produced from food crops dominate total biofuel production.

Production and use of some biofuels can be an expensive option for reducing GHG emissions and improving energy security. Estimates in the literature for GHG mitigation from biodiesel and corn ethanol vary depending on the country and pathway, but mostly exceed USD 250 /t CO_2 avoided. Given the relatively limited scope for cost reductions and growing global demand for food, little improvement in these mitigation costs can be expected in the short term.

B) Second Generation Biofuels

Many of the problems associated with 1st-generation biofuels can be addressed by the production of biofuels manufactured from agricultural and forest residues and from non-food crop feedstocks. Where the ligno-cellulosic feedstock is to be produced from specialist energy crops grown on arable land, several concerns remain over competing land use, although energy yields (in terms of GJ/ha) are likely to be higher than if crops grown for 1st-generation biofuels (and co-products) are produced on the same land. In addition poorer quality land could possibly be utilised.

These 2nd-generation biofuels are relatively immature so they should have good potential for cost reductions and increased production efficiency levels as more experience is gained. Depending partly on future oil prices, they are therefore likely to become a part of the solution to the challenge of shifting the transport sector towards more sustainable energy sources at some stage in the medium-term. However, major technical and economic hurdles are still to be faced before they can be widely deployed.

To address these issues, significant investment in RD&D funding by both public and private sources is occurring. In addition, there has been significant investment in pilot and demonstration facilities, but more is likely to be required in the near future if rapid commercial deployment of these technologies is to be supported.

Given the current investments being made to gain improvements in technology, some expectations have arisen that, in the near future, these biofuels will reach full commercialisation. This would allow much greater volumes to be produced at the same time as avoiding many of the drawbacks of 1st-generation biofuels. However, from this IEA analysis, it is expected 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.

Production of 1st-generation biofuels, particularly sugarcane ethanol, will continue to improve and therefore they will play a continuing role in future biofuel demand. The 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 is 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.

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 materials are available, it should be possible to produce biofuels with virtually no additional land requirements or impacts on food and fibre crop production. However in many regions these residue and waste feedstocks may have limited supplies, so the growing of vegetative grasses or short rotation forest crops will be necessary as supplements. 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.

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. Also their 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.

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 logisitical analysis prior to plant investment and construction. Supplies need to be contracted and guaranteed by the growers in advance for a prolonged period in order to reduce the project investment risks. The aims should be to minimise production, harvest and transport costs and thereby ensure the economic viability of the project. This issue is often inadequately taken into account when 2nd-generation opportunities are 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 goal since feedstock costs are an important component of total biofuel costs.

Conversion routes

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

- 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 - where pyrolysis/gasification technologies produce a synthesis gas ($CO + H_2$) from which a wide range of long carbon chain biofuels, such as synthetic diesel or aviation fuel, can be reformed.

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 several other types including dimethyl ether, methanol, or synthetic natural gas. However, at this stage these alternatives do not represent the main thrust of RD&D investment.

Following substantial government grants recently made to help reduce the commercial and financial risks from unproven technology and fluctuating oil prices, both the biochemical enzyme hydrolysis process and the thermo-chemical biomass-to-liquid (BTL) process have reached the demonstration stage. Several plants in US and Europe are either operating, planned or under construction. A number of large multi-national companies and financial investors are closely involved in the various projects and considerable public and private investments have been made in recent years. As more of these 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 become available, allowing governments to be better informed when making strategic policy decisions for 2nd-generation development and deployment.

Based on the announced plans of companies developing 2nd-generation biofuel facilities, the first fully commercial-scale operations could possibly be seen as early as 2012. However, the successful demonstration of a conversion technology will be required first in order to meet this target. Therefore given the complexity of the technical and economic challenges involved, it could be argued that in reality, the first commercial plants are unlikely to be widely deployed before 2015 or 2020. Therefore to what degree 2nd-generation biofuels can significantly contribute by 2030 to meeting the global transport fuel demand remains debatable.

Preferred technology route

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 sets of 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 pretreatment; improving the efficacity of enzymes and lowering their production costs; and improving overall process integration. The potential advantage of the biochemical route is that cost reductions have proved reasonably successful to date, so it could possibly provide cheaper biofuels than via the thermo-chemical route.

Conversely, as a broad generalisation, there are less technical hurdles to the thermo-chemical route since much of the technology is already proven. One problem concerns securing a large enough quantity of feedstock for a reasonable delivered cost at the plant gate in order to meet the large commercial-scale required to become economic. Also perfecting the gasification of biomass reliably and at reasonable cost has yet to be achieved, although good progress is being made. An additional drawback is that there is perhaps less opportunity for cost reductions (excluding several untested novel approaches under evaluation).

One key difference between the biochemical and thermo-chemical routes is that the lignin component is a residue of the enzymatic hydrolysis process and hence can be used for heat and power generation. In the BTL process it is converted into synthesis gas along with the cellulose and hemicellulose biomass components. Both processes can potentially convert 1 dry tonne of biomass (~20GJ/t) to around 6.5 GJ/t of energy carrier in the form of biofuels giving an overall biomass to biofuel conversion efficiency of around 35%. 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, gives a complex picture with wide ranges quoted in the literature. Typically enzyme hydrolysis could be expected to produce up to 300 l ethanol / dry tonne of biomass whereas the BTL route could yield up to 200 l of synthetic diesel per tonne (Table 1). The similar overall yield in energy terms (around 6.5 GJ/t biofuels at the top of the range), is because synthetic diesel has a higher energy density by volume than ethanol.

Table 1. Indicative biofuel yield ranges per dry tonne of feedstock from biochemical and thermo-chemical process routes.

	Biofuel yield (litres/ dry t)		Energy content (MJ/l)	Energy yields (GJ/t)	
Process	**Low**	**High**	**Low heat value**	**Low**	**High**
Biochemical					
Enzymatic hydrolysis ethanol	110	300	21.1	2.3	6.3
Thermo-chemical					
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, ORNL, 2006, Putsche, 1999

A second major difference is that biochemical routes produce ethanol whereas the thermo-chemical routes can also be used to produce a range of longer-chain hydrocarbons from the synthesis gas. These include biofuels better suited for aviation and marine purposes. Only time will tell which conversion route will be preferred, but whereas there may be alternative drives becoming available for 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.

Production costs

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

The commercial-scale production costs of 2nd-generation biofuels have been estimated by the IEA to be in the range of USD 0.80 - 1.00/litre of gasoline equivalent (lge) for ethanol and at least USD 1/litre of diesel equivalent for synthetic diesel. This range broadly relates to gasoline or diesel wholesale prices (measured in USD /lge) when the crude oil price is between USD 100-130 /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 new heavy oil, tar sands, gas-to-liquids and coal-to-liquids can compete with oil when around USD 65/bbl taking into account infrastructural requirements, environmental best practices and an acceptable return on capital but excluding any future penalty imposed for higher CO_2 emissions per kilometre travelled when calculated on a life cycle basis.

The main reasons for the major discrepancies between various published cost predictions relate to varying assumptions for feedstock costs and future timing of the commercial availability of both the feedstock supply chain and conversion technologies. Given that 2nd-generation biofuels are still at the pre-commercial stage, widespread deployment is expected to lead to the improvement of technologies, reduced costs from plant construction and operation 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 liquid fuels produced by the thermo-chemical route, because much of the technology for BTL plants (based on Fischer-Tropsch conversion) is mature and the process mainly involves linking several proven components together. So there is limited scope for further cost reductions. However if commercialisation succeeds in the 2012-2015 time frame and rapid deployment occurs world-wide beyond 2020, then costs could decline to between USD 0.55 and

0.60/lge for both ethanol and synthetic diesel by 2030. Ethanol would then be competitive at around USD 70/bbl (2008 dollars) and synthetic diesel and aviation fuel at around USD 80/bbl. By 2050, costs might be further reduced for biofuels to become competitive below USD 70/bbl. `

Successful development - technology and knowledge 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 attention are outlined below.

Improved understanding of feedstocks, reduction in feedstock costs and development of energy crops

- A better understanding of currently available feedstocks, their geographic distribution and costs is required. Experience in the production of various dedicated feedstocks (e.g. switchgrass, miscanthus, poplar, eucalyptus and willow) in different regions should be undertaken to understand their yields, characteristics and costs.
- The ideal characteristics of specific feedstocks to maximise their conversion efficiencies to liquid biofuels need to be identified, as well as the potential for improving feedstocks over time. Rates of improvement could then be maximised through R&D investment.
- On a micro-scale, the implementation of energy crop production needs to be assessed to ascertain the area within a given collection radius sufficient to supply 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 large-scale production will require dedicated energy crops either as a supplement or in some regions as the sole feedstock. The optimal size of production facility, after trading off economies of scale against using local, reliable and cost-effective feedstock supplies, should be identified for a variety of situations.

Technology improvements for the biochemical route, in terms of feedstock pre-treatment, enzymes and efficiency improvement and cost reduction

- Feedstock pre-treatment technologies are inefficient and costly. Improvements in physical, chemical and combinations of these pre-treatments need to be achieved to maximise the efficacy of pre-treatment in opening up the cellular structure of the feedstock for subsequent hydrolysis. Dilute and concentrated acid processes are both close to commercialisation, although steam explosion is considered as state-of-the-art.
- New and/or improved enzymes are being developed. The effective hydrolysis of the interconnected matrix of cellulose, hemicellulose and lignin requires a number of cellulases, those most commonly used being produced by wood-rot fungi such as *Trichoderma, Penicillum*, 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 costs. Whether separate or simultaneous saccharification and fermentation processes represent the least cost route for different feedstocks is yet to be determined.
- A key goal for the commercialisation of ligno-cellulosic ethanol is that all sugars (C5 pentoses and C6 hexoses) 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 at high yields, although major progress has been made in engineering micro-organisms for the co-fermentation of 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 understand and manipulate process tolerance to ethanol and sugar concentrations and resistance to potential inhibitors generated in pre-saccharification treatments, remains a scientific goal. Solutions to these issues will also need to accommodate the variability within biomass feedstocks. While pentose fermentation has been achieved on ideal substrates (such as laboratory preparations of sugars designed to imitate a perfectly-pretreated feedstock), significant work remains to apply this to actual ligno-cellulosic feedstocks.
- Due to the large number of individual processes in the overall conversion of ligno-cellulosic biomass into bioethanol, there remains considerable potential for process integration. This could have benefits in terms of lower capital and operating costs, as well as ensuring the optimum production of valuable co-products. Given that development is still at the pre-

commercial stage, it may take some time to arrive at the most efficient process pathways and systems.

Technology improvements for the thermo-chemical route, in terms of feedstock pre-treatment, gasification and efficiency improvement and cost reductions

- 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 biofuel 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 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. Given the constraints on scalability and the level of impurities in the desired syngas, pressurised, oxygen-blown, direct entrained flow gasifiers appear to be the most suitable concept for BTL.
- 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 catalysts that are less susceptible to impurities and have longer lifetimes would help reduce costs.

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. 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. The flexibility to vary co-product output shares is likely to be a useful hedge against price risk for these co-products.
- Market assessments of the biofuels and co-products associated with biofuel production need to take into account all the disbenefits, costs and co-benefits, including rural development, employment, energy security, carbon sequestration etc. if a fair assessment of their deployment is to be made.

C) Implications for Policies

Promotion of 2nd-generation biofuels can help provide solutions to multiple issues including energy security and diversification, rural economic development, GHG mitigation and help reduce other environmental impacts (at least relative to those from the use of other transport fuels). Policies designed to support the promotion of 2nd-generation biofuels must be carefully developed if they are to avoid unwanted consequences and potentially delay commercialisation.

One related view is that the relatively high cost of support currently offered for many 1st-generation biofuels is an impediment to the development of 2nd-generation biofuels, as the goals of some current policies that support the industry (with grants and subsidies for example) are not always in alignment with policies that foster innovation. Another view is that 2nd-generation biofuels will eventually benefit from the present support for 1st-generation biofuels. With well designed support policies for both, the fledgling industry for 2nd generation will grow alongside that of 1st-generation using the infrastructure already developed and thereby reducing overall costs. This report leans more towards the latter position that advances in technology will enable 2nd-generation biofuels to build on the infrastructure and markets established by 1st-generation biofuels to provide a cheaper and more sustainable alternative. This assumes that future policy support will be carefully designed in order to foster the transition from 1st- to 2nd- generation and take into account the specificities of 1st- and 2nd- generation biofuels, the production of sustainable feedstocks, and other related policy goals being considered. Other views also exist and only time will tell which view will eventuate. -

Policies to support 1st- or 2nd-generation biofuels should be part of a comprehensive strategy to reduce CO_2 emissions.

- A first step that would help produce a more level playing field for biofuels is to ensure that there is a carbon price or other CO_2 reduction incentives in place. Taking into account the environmental impacts of CO_2 emissions from liquid fuels derived from fossil fuels would mean biofuels could compete on a more equal footing. This is also important to ensure that bioenergy feedstocks are put to their highest value use, due to competition for the limited biomass resource for 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.

- However, the levelling of the playing field for biofuels 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_2 savings, an integrated package of policy measures will be needed to ensure commercialisation, 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 certainty they need to invest with confidence in an emerging sector.

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 future. This includes evaluating sustainable biomass production, improving energy crop yields, reducing supply chain costs, as well as improving the conversion processes via further basic RD&D and demonstration. This ultimately will lead to deployment of commercial scale facilities. The goals of public and private RD&D investments related to biofuel trade, use and production should include:
  - producing cost effective 2nd-generation biofuels;
  - enabling sustainability lessons learned from 1st-generation biofuels to be used for 2nd-generation;
  - increasing conversion technology performance;
  - evaluating the costs and benefits of increasing soil carbon content and minimising loss of soil carbon via land use change; and
  - 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.
- A broad, collaborative approach 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 trade, their use and production, and sustainability monitoring should be continued. Agreement on sustainability principles and criteria that include effective, mutually agreed and attainable systems via means such as certification, and that are consistent with World Trade Organization (WTO) rules, would be a significant step forward.

Accelerating the demonstration of commercial-scale 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 when high oil prices make biofuels a more competitive option. This risk sharing between the public and private sector will be essential to accelerate deployment of 2nd-generation biofuels.
- Funding for demonstration and deployment around 2nd-generation biofuels 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. Present support to provide risk sharing for demonstration projects does not match the ambitious plans for 2nd-generation biofuels of some governments, although there are some exceptions. Additional support policies need to be urgently put in place. Funding to support demonstration and 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 bio-refinery demonstration plants should be harmonised with national and regional renewable energy programmes which

incorporate biomass production and utilisation. 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 key sectors involved in the development and use of biofuels.

Deployment policies for 2nd-generation biofuels

- Deployment policies generally fall into two categories: blending targets (which can be mandatory or voluntary) and tax credits. Mandatory targets give certainty over outcomes, but not over the potential costs, while it is the inverse for tax credits. What pathways individual countries choose will depend critically on their policy goals and the risks 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 focuses 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. To obtain a smooth transition from 1st- to 2nd-generation over time where this is deemed desirable (for reasons of cost savings, supply security or greenhouse gas mitigation for example), the two classes of biofuels should be considered in a complementary but distinct fashion, possibly requiring different policies due to their distinct levels of maturity.

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 EU.
- 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 well over USD 100 / bbl. Therefore a long-term view should be taken but without delaying the necessary investment needed to bring these biofuels closer to market. International co-operation is paramount, although the constraints of intellectual property rights for commercial investments must be recognised. Collaboration through international organisations such as the Global Bioenergy Partnership should be enhanced with both public and private organisations playing active roles to develop and sustain the 2nd-generation biofuels industry for the long term.

1 Introduction

Biofuels offer a potentially attractive solution to reducing the carbon intensity of the transport sector and addressing energy security concerns. Demand for *1st-generation biofuels* continues to grow strongly. However some biofuels have received considerable criticism recently as a result of:

- rising food prices;
- relatively low greenhouse gas (GHG) abatement, or even net increases for some biofuels, based on full life-cycle assessments;
- high marginal carbon abatement costs ($/t C avoided);
- the continuing need for significant government support and subsidies to ensure that biofuels are economically viable ; and
- direct and indirect impacts on land use change and the related greenhouse gas emissions.

Directly linking these issues to all 1st-generation biofuels can certainly be challenged. Sugarcane ethanol is the exception. It is already being successfully produced in several African and South American countries based on the Brazilian model. This 1st-generation biofuel presents few of the problems identified for others and, at least where good conditions and suitable available land exist, can be cost competitive with gasoline without needing any government subsidies. Several developing countries are therefore proceeding to produce their own ethanol, driven by high oil prices and the promise of sustainable development. They do not need to wait for 2nd-generation biofuels to become commercially viable, but could benefit further when they do.

The biofuels debate has pushed *2nd-generation biofuels* using non-food feedstocks firmly under the spotlight with the hope commonly expressed that they will soon become fully commercialised at the large production scale; be cost competitive with 1st-generation and petroleum-based fuels; and resolve many of the other issues often raised concerning some 1st-generation.

In order to move away from sole dependence on food crops towards the conversion of ligno-cellulosic feedstocks to bioethanol, synthetic diesel and aviation fuels, the necessary transition from 1st- to 2nd-generation biofuels will require major steps forward - but the pathways and timelines are unclear. It is recognized that 2nd-generation biofuels generally have several advantages over both fossil fuels and many 1st-generation biofuels. These include reduced GHG emissions, a more positive energy balance, and better access to sustainable biomass feedstocks all-year-round in order to keep the conversion plant operating and hence spread the annual overhead costs over a greater number of litres of biofuel produced. The challenge for a project developer is to procure sufficient feedstock from within a reasonable transport radius of the plant over the long term.

The commercialisation of 2nd-generation biofuels will have implications for many developing countries that are actual or potential biofuel producers, consumers and exporters. If carefully managed, development of these technologies offers the promise of sustainable development, rural revenue generation, and mitigation of the impacts of environmental changes worldwide.

Whilst 2nd-generation biofuels are being demonstrated, other concepts are being tested at the R&D and pilot scales. These advanced systems include algal oil production and novel conversion technologies. It is also recognized that in a situation analogous to the refining of crude oil to produce multiple, higher value chemicals and plastics, that in the medium- to long-term biofuels will likely be produced not only in conjunction with heat and power, but also with other bio-materials and chemicals to enable the 'bio-refining' of biomass to serve multiple purposes. Once successfully developed in OECD countries currently investing in bio-refinery RD&D, technology transfer will enable many other countries to also benefit.

The aims of this report therefore are presented in three separate parts:

- **Part A**) - to assess the status and markets of 1st -generation biofuels and the opportunities and barriers to future expansion. A general introduction reviews the current markets, drivers and future projections. A broad assessment of 1st-generation biofuels is then made, including the latest technology developments to reduce costs and the barriers to increasing their deployment and future growth.

- **Part B)** - to outline the state-of-the-art of the technologies and costs relating to feedstock production, supply chain logistics including storage, and the various conversion processes employed for 2nd-generation biofuels. Detailed analysis of the status of 2nd-generation technologies has been undertaken and the transition from the more mature 1st-generation technologies evaluated.

  Following a review of new crops that could provide 2nd-generation feedstocks, a basic introduction to ligno-cellulosic feedstocks is then provided, including those sourced from agricultural crop residues, forest arisings, wood process residues, and specialist energy crops. This leads on to a detailed exploration of the two major pathways[3] for 2nd-generation conversion technologies:
  - *biochemical* processes that utilise enzymes (or acids) to isolate the building-block chemicals from ligno-cellulosic feedstocks to produce ethanol; and
  - *thermo-chemical* processes that either initially reduce the ligno-cellulosic feedstocks to their most basic gaseous components through gasification before re-constituting them into a range of liquid biofuels, or pyrolyse the solid biomass into liquid "bio-oil" before refining it into useful biofuels and chemicals.

- **Part C)** – to present the research status of *advanced biofuels*, for example, feedstock produced from algae, conversion by hydrogenation and bio-refineries. The concept of a bio-refinery that produces biofuels together with multiple co-products such as materials, chemicals, and heat and power is explored. Also considered are advanced bio-refining platforms that could link elements of both biochemical and thermo-chemical systems in order to optimise the use of limited biomass feedstocks from both the economic and environmental perspectives. Recommendations for future policies to support and encourage biofuels are given.

It is hoped that the knowledge gained from this overview study could be used to feed into assumptions made for future scenario models, and to assist in the development of supporting policies for IEA-member and non-member governments. The study concentrates on technology development and the necessary changes to current infrastructure for transport fuels, though it does not exclude other related issues such as sustainable biomass supply, life cycle analysis results, land use changes, agricultural management practices, crop rotations, integrated cropping for co-products, soil carbon, nutrient cycling and soil fertility.

It is evident that there are now many stakeholders involved in the rapidly developing biofuel industry, including for 2nd-generation development and demonstration. So close collaborations, where practical, have been adopted. It is also evident that much of the knowledge being gleaned has future commercial value. Confidentiality has been respected throughout the report, which does mean that its value to many readers will be less than they might have anticipated. However there have been many recent international conferences and meetings on biofuels held by a wide range of organizations and targeting diverse audiences from producers to equipment manufacturers and investors to decision makers. Several of these recent meetings have been attended by the co-authors and the relevant information, being in the public domain, has been included in the report as appropriate.

Overall, the detailed objectives of the study were to:
- review 1st-generation systems and technologies exploring the barriers and impacts;
- provide an overview of new and developing 2nd-generation biomass feedstock production and biofuel conversion technologies;
- evaluate the difficulties of supplying feedstock supplies to large-scale plants for all-year-round processing;
- ascertain how close to market existing demonstration plants might be after commercial scale-up;
- discuss implications of the potential rate of replication of commercial biofuel production plants; and
- provide suitable information for use by investors, policy makers and scenario modelers.

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[3] Whereas biochemical processes produce ethanol, thermo-chemical processes can produce longer chain hydrocarbons more suitable for aviation and marine purposes. However recent laboratory research (Dumesic, 2008; www.RenewableEnergyWorld.com September 24, 2008), has shown the potential to convert sugars and carbohydrates into synthetic gasoline, synthetic diesel, aviation fuel etc.

PART A) First Generation Biofuels

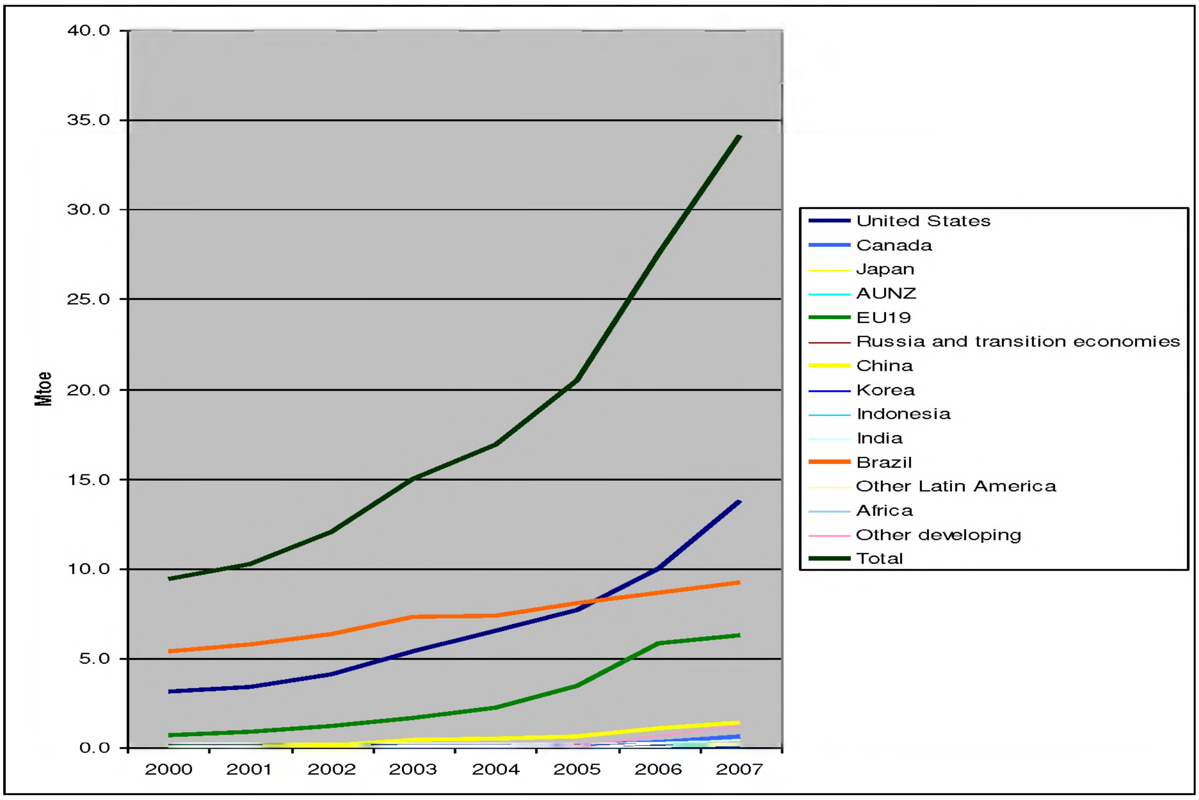
2 Markets and Technologies

The demand for 1st-generation biofuels, produced mainly from agricultural crops traditionally grown for food and animal feed purposes, has continued to increase significantly during the past few years. The main liquid and gaseous biofuels on the market today are:

- bioethanol - produced from sugar-containing plants or cereal (grain) crops used as a gasoline substitute mainly as blends in spark ignition engines and providing 2% of total gasoline fuel supply (although research continues on also using ethanol in compression ignition engines);
- biodiesel - produced from vegetable oils or animal fats, usually after conversion into a range of fatty acid methyl (or ethyl) esters, although at times consumed as untreated raw oils, which when used as a mineral diesel fuel substitute in compression ignition engines provides around 0.2% of total diesel fuel supply; and
- biomethane - as landfill gas or biogas, produced by the anaerobic fermentation of organic wastes including animal manures. The raw gases can be scrubbed (cleaned and purified) to produce a high quality methane-rich fuel, similar to commercial natural gas. This can then be compressed and used in vehicle engines using technology proven when fuelling with compressed natural gas (CNG). Due to a lack of compatible vehicles and infrastructrue, gaseous biofuels are far less popular than liquid biofuels.

All together, biofuels currently provide over 1.5% of the world total transport fuels (34 Mtoe in 2007 on an energy basis; Fig 1) and the crops grown for biomass feedstock take up less than 2% of the world's arable land (WWI, 2007). The US has become the largest producer, having recently overtaken Brazil. Since it also imports large volumes, mainly ethanol from Brazil, it is also the largest consumer. Europe is the third largest producer, remaining well above China, although consumption has dipped recently due to a lower demand for biodiesel after a change in policy by a number of European governments.

Figure 1. Global trends in biofuels production by region



Source: IEA data

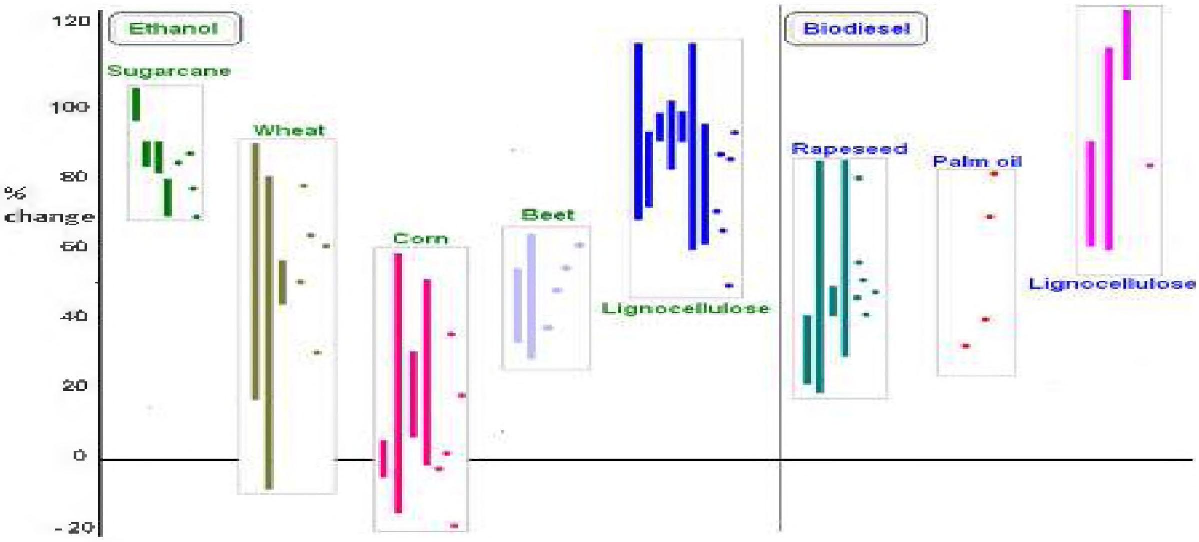
Demand for transport fuels accounts for the majority of oil consumption in many countries, and has risen faster than total energy demand during the past few decades. There has been little sign of this trend declining (although there is some evidence that the recent very high oil price has had some effect). Biofuels are particularly important because, as demand for oil increases and supplies become scarcer and more difficult to extract, few other options exist that can provide transport fuels in the short- to medium-term. Electric vehicles are being developed by several automobile manufacturers and hydrogen fuel cells have been deomonstrated, but it will be many years before either of these technologies could surpass the internal combustion engine. Between 2008 and 2013 biofuels are projected to account for half of the growth in incremental liquid fuel supply (IEA, 2008b).

2.1 Impacts of 1st-generation biofuels

1st-generation biofuels have played an important role in establishing the infrastructure and policy drivers required to support renewable transport fuels in the international market place. However, when all the emissions are included using a life-cycle analysis (LCA) methodology, their GHG-mitigation benefits are quite variable, and not always as good as has been claimed. LCA of biofuels usually encompasses the inputs of fossil fuels and fertilisers needed for the production of the biomass, the energy use and emissions from the industrial conversion processes, emissions from the final combustion of the liquid fuel and allocation on an equitable basis to any-co-products. GHG emissions from land use change, both direct and indirect, should also be included but this is not always possible due to lack of data.

Related emissions include nitrous oxide (N_2O), produced during manufacture and after application of nitrogenous fertilisers, and carbon dioxide (CO_2) produced when using fossil fuels for transport and processing of biofuels and when carbon stocks in the soil and the covering vegetation are depleted as a result of land use change. Significant uncertainty surrounds the life-cycle GHG savings of biofuels, in part because direct and indirect land-use change effects are generally not adequately covered, if at all, in current LCAs (Renewable Fuels Agency, 2008). A review of around 60 recent life-cycle analysis studies was conducted by the IEA and the UN Environmental Programme and published in an OECD report on biofuel policies (OECD, 2008). It confirmed that there are wide ranges of GHG balances for any given biofuel (Fig. 2). This reflects the range of feedstocks, process choices, heat supplies from coal, natural gas or crop residues, and whether simple boilers or combined heat and power (CHP) systems are used on-site.

Figure 2. ***Well-to-wheel emission changes for a range of biofuels (excluding land use change) compared with gasoline or mineral diesel.***



Source: OECD, 2008 based on IEA and UNEP analysis of 60 published life-cycle analysis studies giving either ranges (shown by the bars) or specific data (shown by the dots).

Ethanol from sugarcane can produce significant net savings in GHGs, particularly when (as is usually the case) the bagasse co-product is used to provide heat and power at the processing plant (Fig. 2). Where surplus electricity is sold off-site or other co-products are allocated a share of the GHG emissions, the total savings can be more than 100% of those produced using gasoline as a vehicle fuel. By contrast, ethanol produced from cereals can, under some circumstances (even excluding land-use change) be negative, producing more GHGs than when using gasoline.

The wide range of results is driven by differing methodologies followed for assessing N2O emissions from fertilisers, and the assumptions for the treatment of by-products in the technology conversion phase. For biodiesel from rapeseed oil, if the IPCC reference values for nitrogen release are used and the energy allocation method applied, a GHG improvement of between 40% and 55% under European conditions seems a reliable and robust result.

Relatively few studies exist for palm oil, with much depending on the land used to grow plantations, and the land-use change implications. Significant GHG savings can occur if the plantation is grown on already cultivated land, but if forest has to be cleared before planting or peatland destroyed, then there can be very significant increases in emissions.

Current LCA approaches for biofuels are still partial in some aspects (Table 1). The review of LCA studies (OECD, 2008) did not include GHGs resulting from land use change. One of the chief concerns is that 1st -generation biofuels demand will shift agricultural production on to areas that are currently not cultivated and will lead to a significant one-time release of CO_2 during land preparation and initial cultivation. Negative impacts on biodiversity and water resources may also occur. Social impacts such as displacement of subsistence farmers is also possible in some cases

Table 1: Main policy issues and suitability of LCA methodology to address them

Main drivers	Issues	Suitability of LCA
Climate change	Emissions from production and use of fossil fuels and fertilisers	Suitable
	Soil carbon stock changes	Method under development
Non-GHG environmental issues	Soil quality preservation	No (no impact indicator)
	Land use, land use change	Partly (generally as land occupation)
	Water management	Partly (as water consumed and depleted)
	Water pollution	Partly (not at local level)
	Air quality	Partly (not at local level)
	Biodiversity	No (no consensus on impact indicator)
Energy security		Partly (consumption of fossil energy)

GHG emissions from new cultivation can occur directly, by growing energy crops after deforestation for example, or indirectly, where an existing crop is converted for use as an energy crop (e.g. corn in the U.S.) and thereby induces new production of that crop elsewhere to meet total demand. The location of new production may be very difficult to determine and track, as it could be far away, perhaps on a different continent, and on land available only after deforestation.

Although it is very difficult to model the very complex interactions in the agricultural market between demand for different crops and land-use change, there is mounting concern that current biofuels policies don't adequately take into account the risk of GHG emissions occurring indirectly. Due to the wide range of uncertainties, particularly relating to soil carbon content changes over time, this subject remains controversial and much research is still needed. A detailed discussion can be found in the Agriculture and Forestry chapters of the IPCC 4th Assessment Mitigation report (IPCC, 2007) which quotes an uncertainty range of ± 50% for related land use CO_2 emissions and sequestration.

Although this is an area that is not well understood, the potential for negative indirect impacts is clear. The studies undertaken by the University of Minnesota and elsewhere suggest that where land-use change occurs, such as by the conversion of forests, scrubland, savannah to croplands, a significant initial release of CO_2 occurs, that is recuperated through the lower GHG profile of using biofuels as a substitute for fossil fuels only after many years (Fargione *et al.*, 2008; Searchinger *et* *al,* 2008). However, much uncertainty exists over modelling the indirect land-use change and the results need to be treated with caution (see ADAS, 2008 for a critique).

The value of biofuels as a GHG reduction option is a function of both their production costs and their full GHG impacts. With high production costs and small net GHG reductions often possible, the marginal abatement cost from using some 1st-generation biofuels has been quoted to be relatively high around USD 200-300 /t CO_2 avoided, or even up to USD 1700 /t (OECD, 2008) or above (see below). However, the uncertainty over the accuracy of the LCA analysis needs to be taken into account. For instance, the allocation of GHG emissions between the co-products arising from biofuel production (such as dried distillers grains with solubles (DDGS) from corn ethanol, and high-protein meals from vegetable oil crops, both widely used as animal feed) has not always been undertaken in life-cycle analyses. The value of these co-products has also been ignored at times in comparative cost/benefit calculations. This is exacerbated by the potentially far greater uncertainty arising from indirect land-use change.

Energy supply security is another strong policy driver for biofuel production, and the significant contribution that biofuels have made to the transport sector in recent years has most likely helped to keep oil prices from going even higher than they have. Quantifying these impacts is difficult but should not be ignored. If oil supplies remain tight in the future, there will be strong incentives for countries to continue to increase production and use of biofuels, both for oil import cost savings and to ensure adequate supplies of liquid fuels, with greater supply diversity. However, greater clarity of the costs of these policies is also needed.

2.2 Ethanol

By far the largest volume of biofuel production comes from ethanol, produced from a wide range of feedstocks but with 80% coming from corn (maize) and sugarcane. Corn ethanol is mainly produced in the US (24.4 bn l in 2007; Fig. 3) with subsidies around USD 0.50/l and sugarcane ethanol in Brazil (18.0 bn l in 2007) now without subsidies following strong supporting policies over 3 decades. Total world production has tripled between 2000 and 2007 to reach over 25.5 Mtoe.

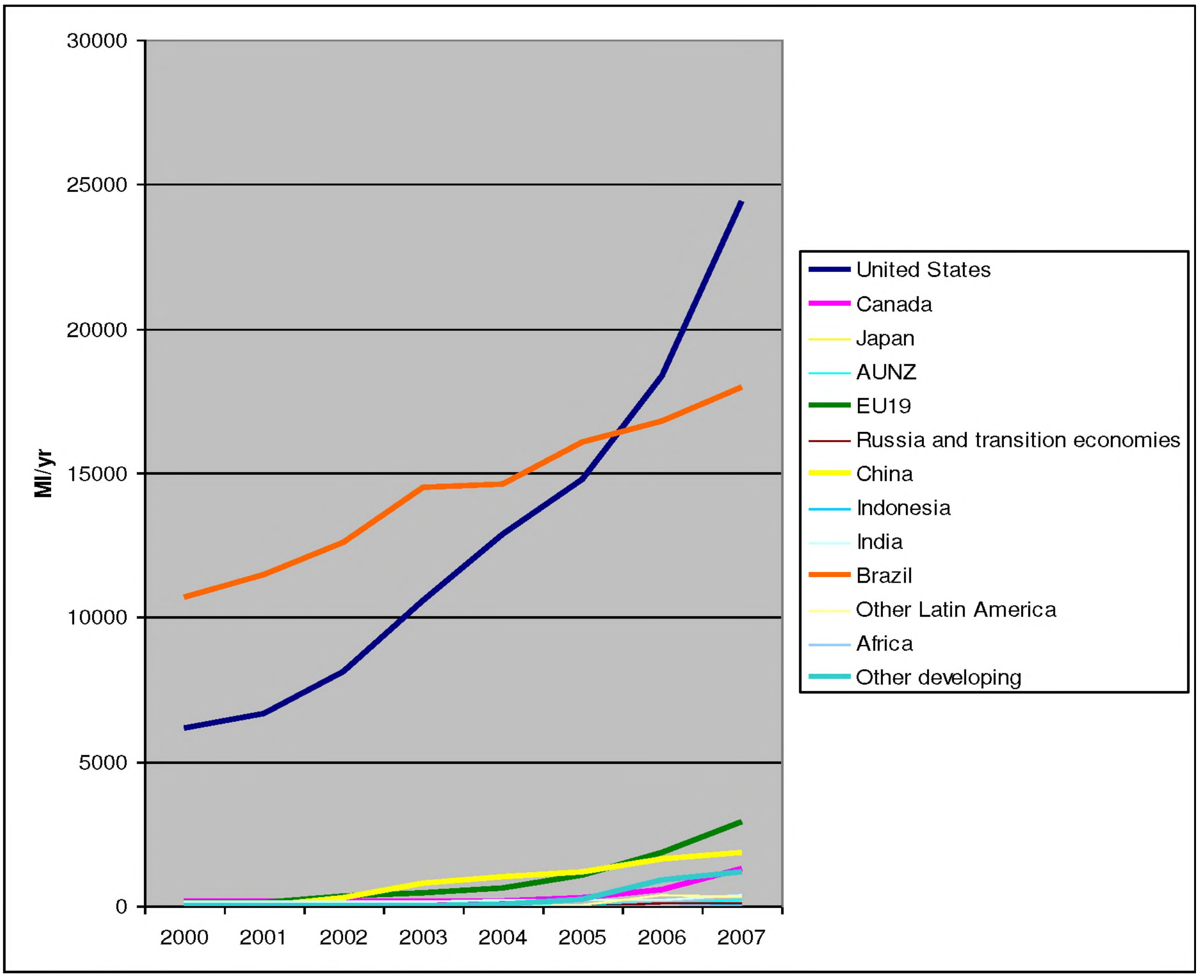
In the US, corn production costs dropped from around USD 300 /t in 1975 to USD 100 /t by 2003. The delivered feedstock cost (including subsidies) was approximately 30% of the total ethanol production cost of USD 0.90 /l in the mid 1980s. By 2007, corn prices had doubled and their share of total production costs had also increased, in part due to economies-of-scale at the processing plant. However corn ethanol production has remained profitable in recent years mainly due to the higher oil price (Fig. 4) as well as from increased subsidies and higher average yields per hectare. However an estimate of profitability (shown as the solid line in Fig. 4, net of subsidies and taking into account the energy value of ethanol, a price premium for octane and oxygen enhancement and the sale of DDGS co-products) shows that without subsidies (dashed line) the higher recent feedstock costs would not have been offset by the competing higher oil price. Even in early 2008, profitability remained marginal, although by mid 2008 the very high oil price aided profitability. Since then the oil price has dropped (to around $70 / bbl at the time of writing).

By late 2007, the US had 130 ethanol plants operating with a total production capacity of over 26 bn l/yr (REN21, 2008) operating at around 94% capacity. Another 84 plants were under construction or expansion, which when completed will double existing production capacity. The better understanding of the true production costs and the growing concerns at environmental issues from corn ethanol appears to be over-ridden by the drive for supply security. In EU by contrast, biofuel policies are being reviewed and new capacity planning has slowed recently.

In Brazil in 1975, when policies were first introduced to encourage sugar-to-ethanol production, just over 90Mt of sugarcane were produced. Thirty years later, in 2005, sugarcane production had increased to over 420 Mt/yr with around half used for ethanol production. Ethanol production costs have dropped from about USD 1.00 /l ethanol in 1975 to USD 0.35 /l in 2005 with cane feedstock costs delivered to the plant remaining about half the total costs over this period (Junginger, 2007). The recent emergence and rapid dominance of flex-fuel vehicle engines has created an incentive for car owners to choose the cheapest fuel at the pump, and in the past three years this has mainly been ethanol. Domestic demand is expected to continue its rapid rise, along with expected ongoing increases in exports to the US and other countries. Brazil's ethanol expansion plan, begun in 2005, is to add 5 bn l/yr of new production capacity by 2009 (a 40% increase) at a cost of USD 2-3 billion.

The low-cost production of sugarcane ethanol in Brazil may not be easy to replicate in Africa and other Latin American countries where sugarcane grows, due to higher costs and lower productivity in factors such as land, labour and conversion facilities. However slight regional growth is starting to become evident (Fig. 3) and the potential for cane-to-ethanol expansion in many countries is good. Outside of the US, ethanol production from corn, beet, small cereals, sorghum, cassava and other crops appears less likely to rapidly increase due to cost and sustainability issues.

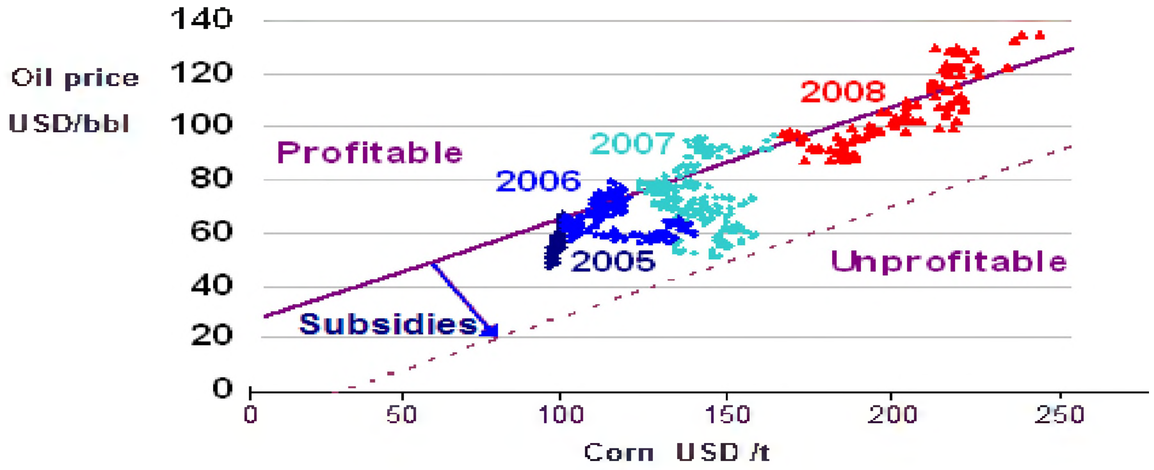
Figure 3. Global ethanol production trends in the major producing countries and regions



Source: IEA data

In the European Union, the situation is very challenging, although there is a 5.75% ***target blending level*** by 2010 in place, profitability is a real issue for many producers. In January 2008 the European Commission put forward a proposed directive, recommending the more ambitious goal of a 10% biofuels ***mandate*** to be reached by 2020, as part of an overall 20% share of renewables in the EU's energy mix. However, this has not yet been adopted by the European Parliament and several EU countries have expressed doubts that they will be able to meet even the 5.75% target by 2010. Also, a current theme in the debate is to set environmental criteria (e.g. life-cycle energy efficiency, CO_2 emissions, crop source) that would limit certain kinds of biofuels - both for production and imports. Recent proposals along these lines could conceivably exclude biofuels based on corn, rapeseed and palm oil, which would mean a very substantial reduction in current production. On the other hand, it would serve to give a boost to 2nd-generation fuels, which will potentially avoid many of these problems.

Figure 4. Corn ethanol profitability depends largely on feedstock costs, competing oil prices and government subsidies

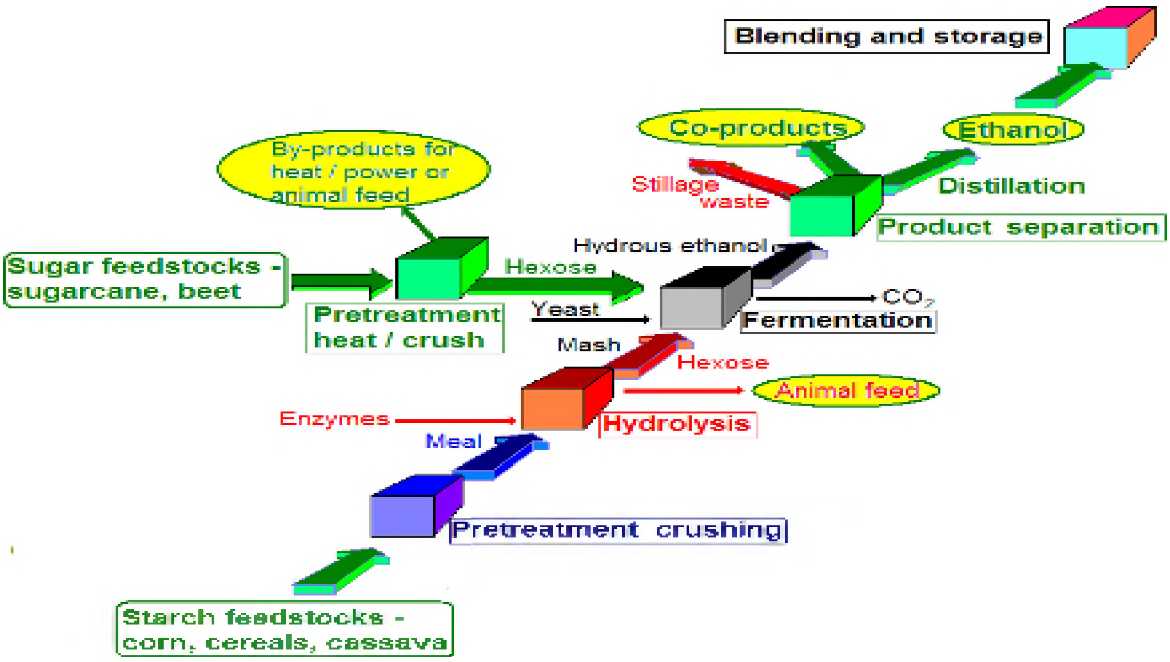


Source: IEA, 2008b

Latest developments for 1st-generation ethanol technologies

The traditional biological conversion routes for bioethanol production are well established (Fig. 5). The main raw materials needing to be extracted are sucrose or starch. For sucrose from sugarcane or sugar beet crops, the juices are first mechanically pressed from the cooked biomass followed by fractionation. The sucrose is metabolised by yeast cells fermenting the hexoses and the ethanol is then recovered by distillation. Starch crops must first be hydrolysed into glucose before the yeast cells can convert the carbohydrates into ethanol. Pre-treatment consists of milling the grains of corn, wheat or barley followed by liquefaction and fractionation. Acidic or enzymatic hydrolysis then occurs prior to fermentation of the resulting hexoses. Although highly efficient, the starch grain-based route consumes more energy (and thus potentially emits more CO_2 into the atmosphere depending on the energy sources used), than the sucrose-based route. From the fermentation process onwards, both routes are almost identical. Overall using either sugar or starch is a mature technology to which few significant improvements have been made in recent years.

Figure 5. Conversion routes for sugar or starch feedstocks to ethanol and co-products

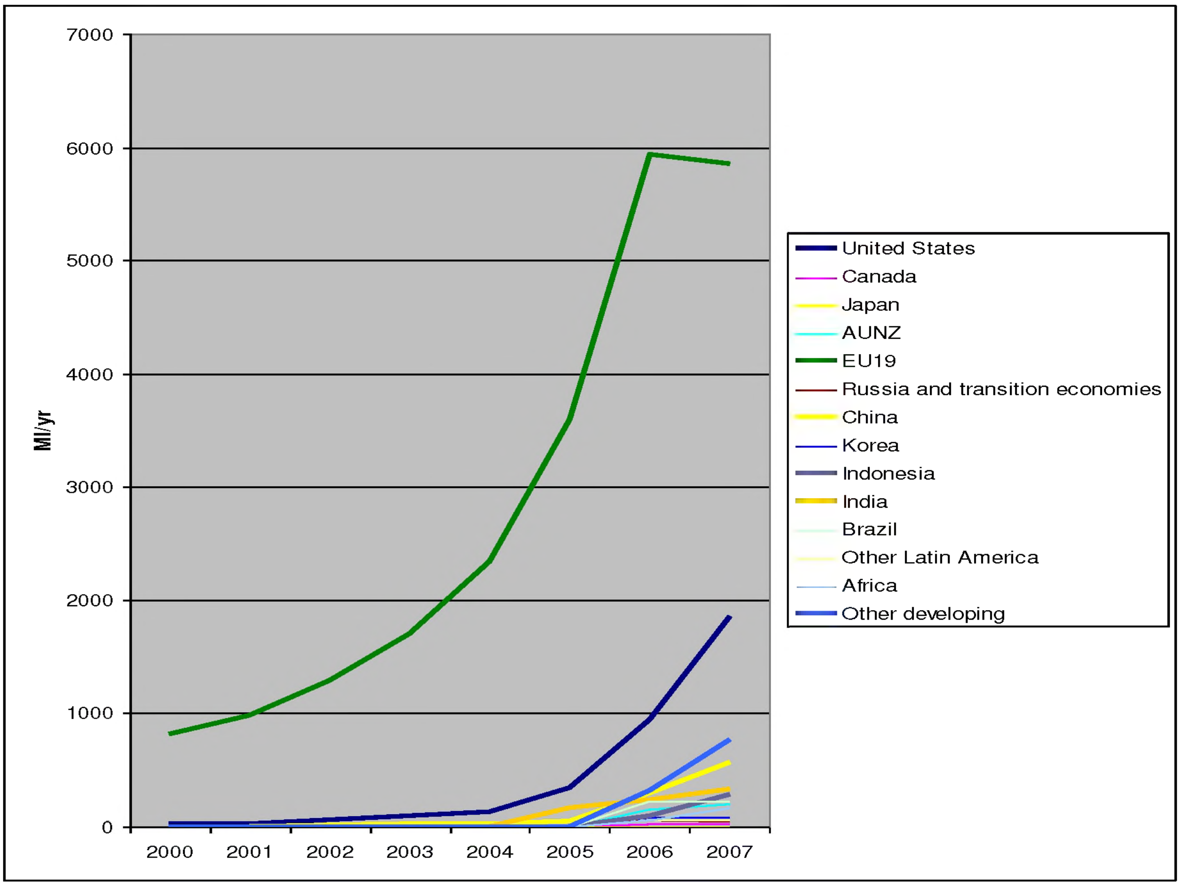


However, the development of these routes continues with step by step improvments and from time to time new technology solutions could still emerge. Generally, the RD&D focuses on the optimisation of energy integration and finding value-added solutions for co-products deemed as "wastes" in existing production facilities. For example combustion of process residues followed by the capture of some of the heat for on-site use and possibly power generation is one traditional solution, but this is often carried out inefficiently with disposal of the waste biomass the main objective. Following privatisation of the power sector in many countries, the ability to export excess power to the grid has resulted in incentives for on-site construction of more efficient CHP systems that generate around 10 times the electricity needed on site. In future designs of large-scale bioethanol production plants the waste ligno-cellulosic raw materials arising from the processing of sugar cane, corn, small cereal grains etc could possibly be better utilised on-site as feedstock to produce additional ethanol (see Part B).

2.3 Biodiesel

The production of biodiesel from converting raw vegetable oils and fats to esters is relatively simple at either small or large scales and is well understood. Production has continued to increase in several countries and world regions (Fig. 5). Many new process facilities were opened during 2006/2007 including in Belgium, Czech Republic, France, Netherlands, Germany, Italy, Poland, Portugal, Spain, Sweden, South Africa and the UK. Plans for new biodiesel plants and/or increased palm oil and Jatropha plantations were announced for Bulgaria, India, Malaysia, Singapore, and the Philippines as well as Brazil based on algae feedstock (see Part C). However in Germany, the world's leading biodiesel producer, a change in government policy to phase out excise tax exemptions for biodiesel due to the total cost has resulted in several plants closing and EU production declining (Fig. 6).

Figure 6. Global biodiesel production trends in the major producing countries and regions



Source: IEA data

The potential for biodiesel is more limited than for ethanol. Production increased by a factor of 10 from 2000 to 2007 to reach around 8.6 Mtoe or 0.2% of total diesel fuel demand. In Europe where

70% of road transport fuel is diesel, 5.8 bn l of biodiesel (2% of total diesel fuel demand) was produced in 2007, mainly from oilseed rape and imported palm oil. In the US where only 20% of transport fuel is diesel, only 1.8 bn l was produced, mainly from soybean. Brazil has a programme for expanding the soybean production area although recent statements have stated soybean production should not be expanded for biodiesel use. Palm oil is grown mainly in Malaysia and Indonesia but other developing countries are following suit. Around 85-90% of palm oil production is used for food preparation and competition has resulted in comparatively high, but fluctuating commodity costs. Around 80% of the total cost for palm oil biodiesel is for the oil feedstock. Used cooking oils and meat processing by-products (tallow) are comparatively cheap feedstocks but are in relatively limited supply.

Using biodiesel from rapeseed oil or palm oil to replace mineral diesel can result in significant GHG reductions (Fig. 2), though as described above, this neglects the potential GHG increases associated with indirect land-use change. Other local air-polluting emissions from diesel are also usually reduced (such as PM_{10} particulates that can adversely affect human respiration), though in OECD countries with strong emissions control regulations, these impacts are likely to be small. In the developing world the impacts may be much larger. Overall the impacts of biodiesel emissions are less than from diesel, but remain far from ideal with the possibility of higher NOx and some carcinogens.

Currently, most biodiesel fuels can only compete without subsidies when crude oil prices are high and vegetable oil commodity prices are low. Indeed, increases in the price of vegetable oils (91% between 2004 and 2007) have seriously undermined biodiesel profitability. In the EU biodiesel production from rapeseed in 2007 was estimated to cost more than 3 times as much to produce as conventional diesel (OECD, 2008). Since there is limited opportunity to further reduce costs, subsidies, tax exemptions, etc. are therefore imperative at this stage, although a progressive phasing out could be envisaged in the future. In Germany, excise tax exemptions, until recently, have driven the demand and in the US, a federal subsidy of USD 0.26 /l plus state incentives exist.

Developments in 1st-generation biodiesel technologies

Concerns at deforestation have also resulted from the various initiatives to produce more vegetable oil feedstocks for biodiesel in several countries, particularly palm oil in Indonesia and Malaysia and soybean in Brazil. Consequently there has been considerable interest in other oil-bearing crops that can grow on marginal or semi-arid lands. *Jatropha* is one example, but, like most crops, without adequate water and nutrient replenishment, it cannot produce high oil yields over the longer term. Nevertheless, investments in several large plantations have been made.

The basic inter-esterification process for biodiesel manufacture at normal pressure and ambient temperature (Fig. 7) can easily be reproduced although the quality of the resulting fuel can vary and international standards are now in place to ensure stringent fuel specifications are met. One key element of market penetration in Europe was the development of the biodiesel standard, EN 14214, as a basis for quality assurance. This led to biodiesel becoming accepted as a reliable fuel by the diesel engine and fuel injection equipment manufacturing industries.

During the process of converting a vegetable oil or animal fat into biodiesel many unwanted reactions and chemical substances can develop and contaminate the fuel. Quality assurance of the product is therefore imperative, just as it is for diesel and other petroleum fuels where universally accepted standards have long been in place. The difference with biodiesel is that it can be manufactured and sold by numerous small producers so that maintaining quality by frequent testing of batches is difficult to achieve. Variable characteristics of a typical fatty acid methyl ester fuel can include the heat value (energy content per litre), viscosity and lubricity properties, as well as contamination by free fatty acids, solid particles, mono- and di-glycerides, catalyst salts, glycerine, methanol[4], water, etc. (Fig. 8).

The modern, diesel engine is expected to provide high performance and be highly fuel efficient with a fuel system manufactured to very fine tolerances. It is designed to produce very low emission levels of particulate matter (PM), hydrocarbons (HC) and NOx (nitrous oxides) as

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[4] Methanol could be replaced by ethanol or butanol where these are readily available and a cheaper option.

demanded by health supporting legislation. The fuel used must therefore be of the highest quality, regardless of whether it is of fossil or biological origin. To achieve this, the biodiesel fuel standard EN 14214 involves 30 different criteria and limits. However to be effective, stringent penalties are needed for biodiesel manufacturers who do not meet the standard.

Figure 7. Inter-esterification of triglycerides (oils and fats) to esters.

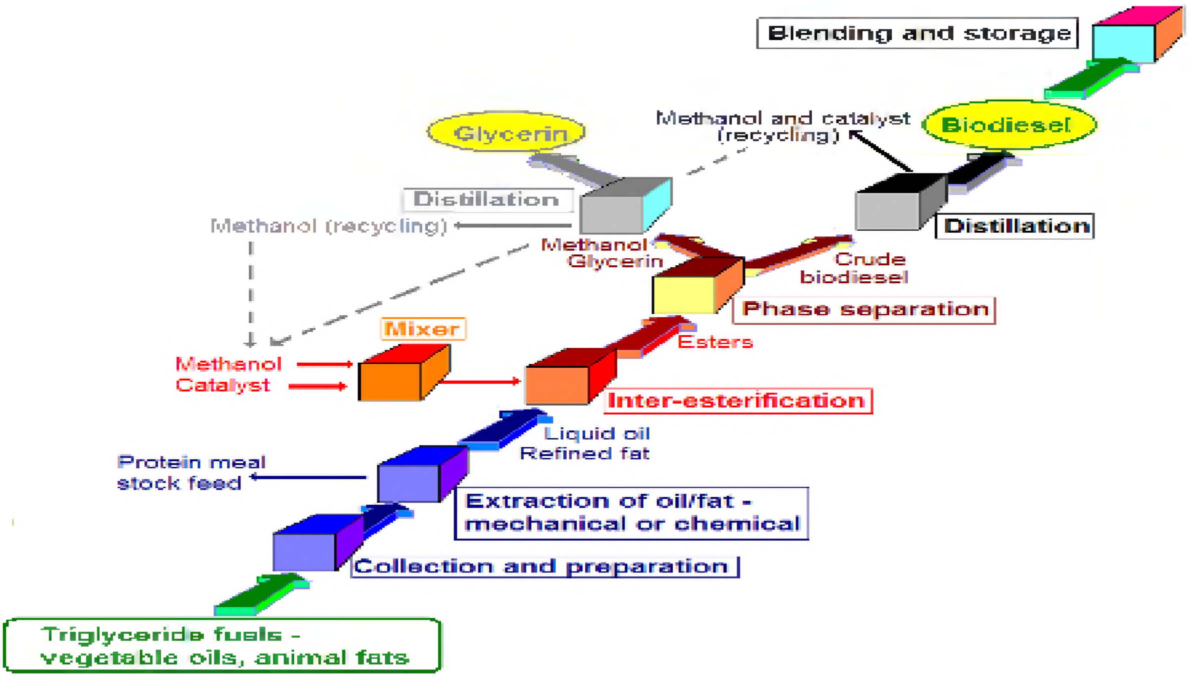
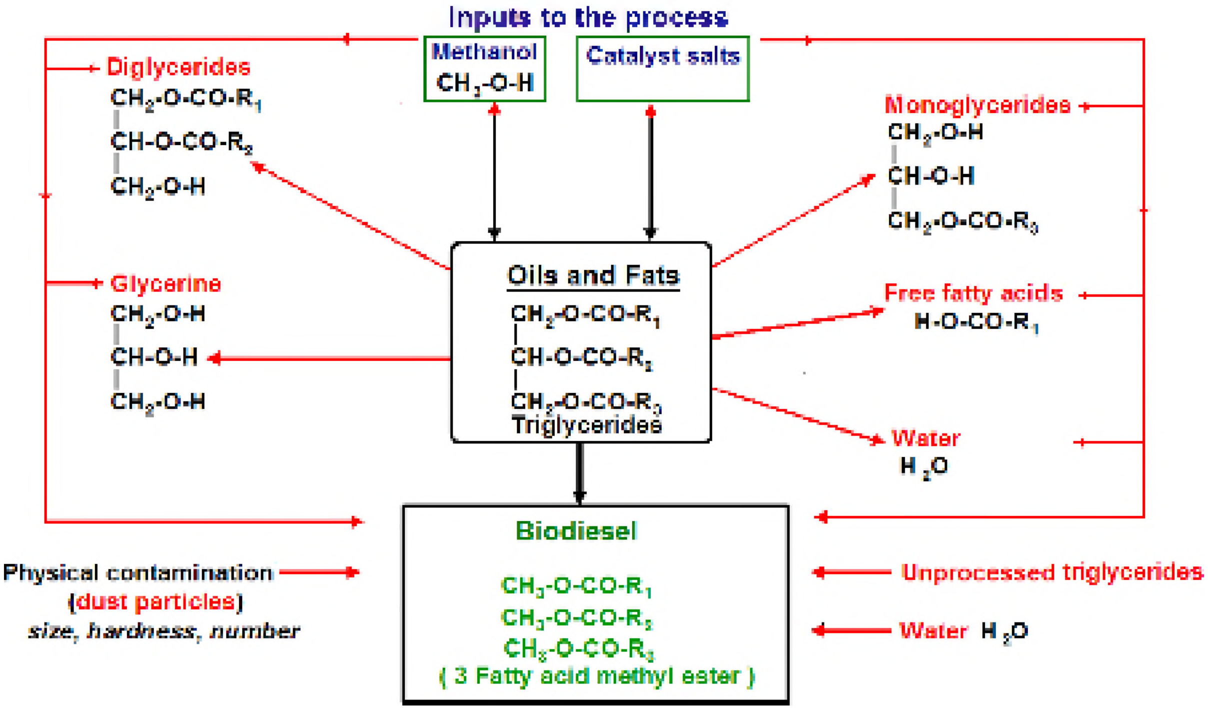


Figure 8. The inter-esterification of trigyceride oils and fats can lead to various contaminating chemicals being deposited in the biodiesel fuel during the process.



Source: Körbitz, 2007

The emergence of a number of improved processes in order to reduce the production costs is on-going. However such modified technologies often have weaknesses in terms of reaching the desired quality and high yield levels -the aim being to convert above 99% of all available triglycerides and free fatty acids in a raw oil feedstock into fatty acid methyl esters. A number of factors relating to the process technology have an influence on profitability. Yield of biodiesel as a factor of process efficiency is second in importance only to market price. A 10% drop in yield can result in a 25% drop in profitability (Körbitz, 2007). Feedstock costs are the next most important factor with a 10% increase resulting in a 20% loss of profitability. Therefore selecting a multi-feedstock biodiesel production technology that is both highly efficient and flexible will enable the producer to choose, store and process a variety of different oils and fats and to be able to purchase feedstocks from the cheapest source.

A number of suppliers exist that offer proven process technologies. The proceedings of a 2007 workshop targeted at investors in the biodiesel industry, supported by the International Energy Agency, Bioenergy Agreement, Task 39 and based on the comprehensive study "*Biodiesel Production: Technologies and European Providers*" (Bacovsky *et al*, 2007) describes the various process technologies in detail. It is available free of charge from the Austrian Biofuels Institute (www.biodiesel.at). Details of these technologies will therefore not be repeated here. However, as a summary, the development of a long-term, national biodiesel industry can be fulfilled by a few key criteria (Körbitz, 2007).

1. High quality biodiesel should be produced according to well defined standard specifications.
2. Suitable, reliable and low cost feedstock supplies, possibly from a variety of food as well as non-food oilseed plants and other sources, need to be assured with contracts in place for the long term.
3. The site selected for a biodiesel production plant should have low logistical supply costs and strong synergistic factors such as good road access for delivery of feedstock and export of product, or possibly be close to a port.
4. A highly efficient and flexible biodiesel production process technology should be selected.
5. Profitable markets with secured take-off conditions need to be identified.
6. A wealth of information on biodiesel technologies and markets is readily available so should be utilised.
7. A supportive national legal framework should be established to secure long term production and industrial profitability.

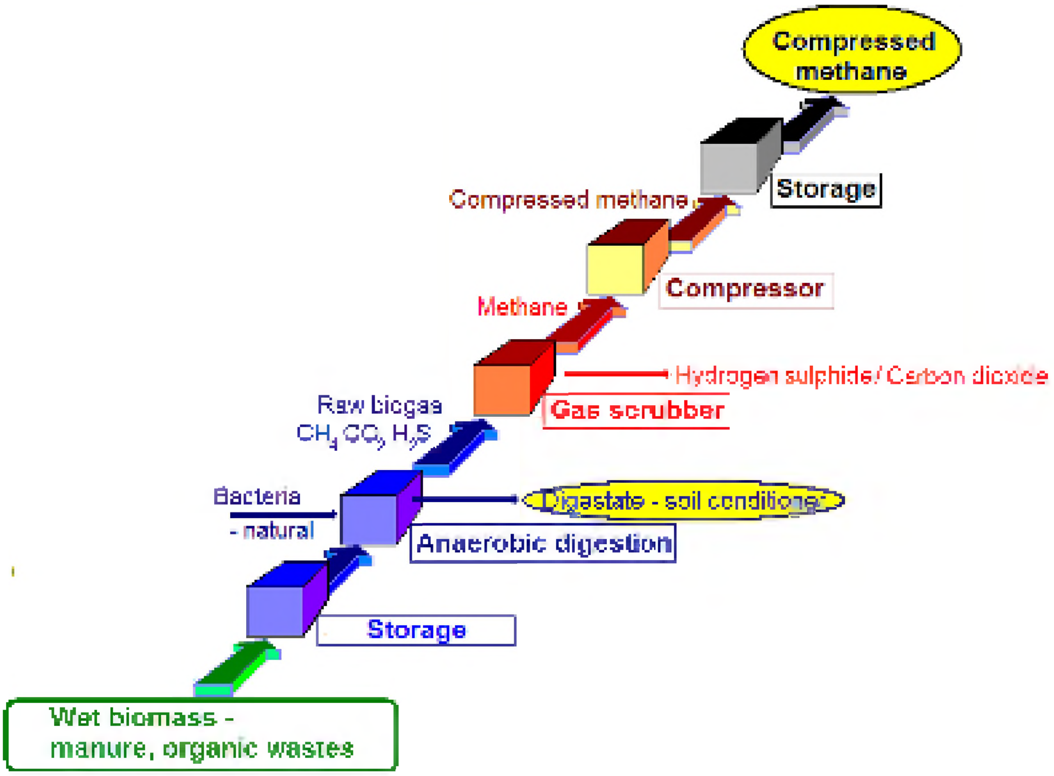
Investing into a biodiesel production plant and running such an industry according to these criteria should lead to a long term, profitable enterprise with a secured competitive position.

2.4 Biogas

Anaerobic digestion of wet organic wastes such as animal manure, sewage effluent or food crop processing wastes to produce biogas (mainly CH_4 + CO_2) is a mature technology (Fig. 9) at both the small domestic scale, as in India and China, or at the larger community scale, as in Denmark and Germany. Increased interest has developed in Europe where green crops are being purpose-grown as additional feedstock. The efficiency of converting biogas or landfill gas to electricity using gas-engine driven generating sets is around 20% whereas if the biogas was used directly to supply heat, as in a community district-heating scheme, it would be nearer to 60%. Nevertheless, most biogas is used for power generation, usually sold to the grid as encouraged by generous feed-in tariffs, although several on-site CHP plants also exist. Landfill gas CHP and power generation projects are also encouraged by government support schemes.

Little of the 230 PJ/yr of biogas produced in EU countries is used as a vehicle fuel. Additional clean-up costs are required to remove both hydrogen sulphide to avoid engine corrosion and CO_2 that would otherwise take up limited on-board storage space. (Gas scrubbing would also be needed before injecting into the natural gas grid but not before direct combustion on-site). Gas clean-up costs are in the region of USD 5 - 15 /GJ depending on the size of plant (Tilche & Galatoa, 2007) although new clean-up technologies under development include water scrubber absorption, pressure swing adsorption, membrane separation, or chemical adsorption. Compression is also needed resulting in a lower overall efficiency, but there is still often limited vehicle range due to the added weight and volume of the storage tanks on-board. Therefore it is projected that only small contributions to transport fuels are likely to be made from biogas in the near future and no further analysis has been undertaken here.

Figure 9. Anaerobic digestion process to produce biogas from biomass feedstocks



2.5 Barriers to growth of 1st-generation

There are a number of concerns about the potential drawbacks of 1st-generation biofuels although many of these issues are not new and have been extensively discussed and examined. Concerns about the recent rapid growth in oil and food prices, security of future energy supplies particularly oil for transport, and the need for climate change mitigation have brought renewed focus on the costs and benefits of biofuels. The high expectations that arose from earlier publicity are now starting to diminish, at least for some biofuels, as the practical realities become better understood. The media, and consequently the layman, are usually unable to discern between one biofuel and another. As a result, growing public and political concerns on the use of all biofuels in general relate to:

- food security and contribution to food shortages and higher food prices;
- the true production and societal costs excluding subsidies;
- limited returns on sometimes risky investments;
- reduced share prices of listed companies on the stock market;
- modest GHG reduction benefits at times for high cost /t CO_2 equivalent avoided;
- impact of biofuels-related land use change on deforestation and habitat loss;
- other potential resource and environmental impacts including competition for water supplies where not properly managed and fertiliser run-off; and
- the challenges of producing and certifying sustainable biomass.

The cost and sustainability of 1st-generation biofuels has increasingly been criticised (Doornbosch and Steenblik, 2007; Fargione *et al* 2008; Searchinger *et al* 2008). Within a period of just a few months in 2007 biofuels, which had previously been considered a key option to address oil supply scarcity and climate change, were considered as poor solutions to these goals. Since that time, the debate surrounding biofuels has intensified and their economic and environmental credentials have been examined in great detail. A number of processes to examine biofuels and their role in meeting energy security and climate goals have been initiated, taking into account the possibility that they will affect markets other than energy.

To obtain a more balanced view between “good” and “bad” biofuels and their impacts, and to clearly identify the opportunities for developing countries to produce their own transport fuels (with potential for export), the Rockefeller Foundation supported the formation of a “Sustainable Biofuels Consensus” document in March 2008 that has since been widely reported[5]. As a result of an intensive discussion between contributors (who were selected for their wide-ranging expertise on biofuels trade, policy, land use, finance, law, economics, sustainable development and conversion technologies), it became clear that some 1st-generation biofuels have significant potential for greater global deployment since their benefits clearly outweigh their disbenefits. However other biofuels can result in net negative impacts and therefore require more careful consideration by policy makers and investors.

Defining and developing clear criteria for the sustainable production of biomass, and eventually developing a certification process for producers, is a goal sought by a wide range of governments and organisations (IEA, 2007). Initiatives such as the Global Bioenergy Partnership (www.globalbioenergy.org), the Roundtable on Sustainable Biofuels (http://cgse.epfl.ch) and the German *International Sustainability and Carbon Certification* Project (www.iscc-project.org) are already making progress in this area, though the work is far from finished. In the mean time, many governments continue to mandate increasing biofuels production regardless of source although there are signs this is changing. For example the US Energy Independence and Security Act (December 2007) requires the production of 136 billion litres (bn l) of “renewable fuels” by 2022 (over 5 times the current ethanol production level in the US). The policy includes a limit of 1st-generation biofuels of less than 57 bn l, around 40% of the total. It also has minimum GHG saving thresholds for the differenet categories of fuels, (the lowest being 20% less than gasoline/diesel), and a requirement that all fuels be sourced from biomass harvested from land that was cleared or cultivated prior to the enactment of the Act. The EU is aiming to source 10% of total energy in transport fuels from renewable sources by 2020 and, according to the draft Renewable Energy Directive, biofuels must comply with sustainability criteria in order to count towards the target and qualify for supportr schemes of Member States.

For any product entering the market and experiencing rapid growth, periods of market instability often result from imbalances in demand and supply. For biofuels, securing reliable feedstock supplies without compromising food security has become a concern in many countries, as has bringing new production capacity on stream fast enough to meet the increasing demand. Planning procedures have at times curtailed the rate of deployment (IEA, 2007).

Demand growth is largely affected by policy decisions which often tend to be short term. This leads to fluctuations in supply which can mean that while some new plants are being constructed, others are closing down and plans for new developments are put on hold (Annex 1). Growing concerns over the sustainable production of biomass and the food-versus-fuel debate have certainly resulted in investment uncertainty in the EU (along with the somewhat bizarre double subsidy opportunity from “splash and dash” for B99 imports from the US). Elsewhere the drivers for energy security and sustainable development opportunities appear to be over-riding such issues, although a number of other barriers remain for increased deployment of 1st-generation biofuels.

Production costs

Without government subsidies, few 1st-generation biofuel plants would continue to operate, even at the recent high oil (petroleum) prices, other than sugarcane ethanol in Brazil and producers with niche feedstocks - used cooking oil, tallow etc. The recent rises in commodity prices for corn, palm oil, wheat etc. have made some biofuel production less profitable even with increased oil prices, corn ethanol being an example (Fig. 4). In fact a natural economic feedback is probably occurring in places like the US whereby as oil prices rise, demand for biofuels rises, driving up feedstock demand and price and thus increasing biofuels prices, until they reach a point of parity with oil taking into account any subsidies. The tendency in the US for the ethanol price to stay close to the subsidised point of zero profit suggests such a dynamic. However, feedstock commodity price

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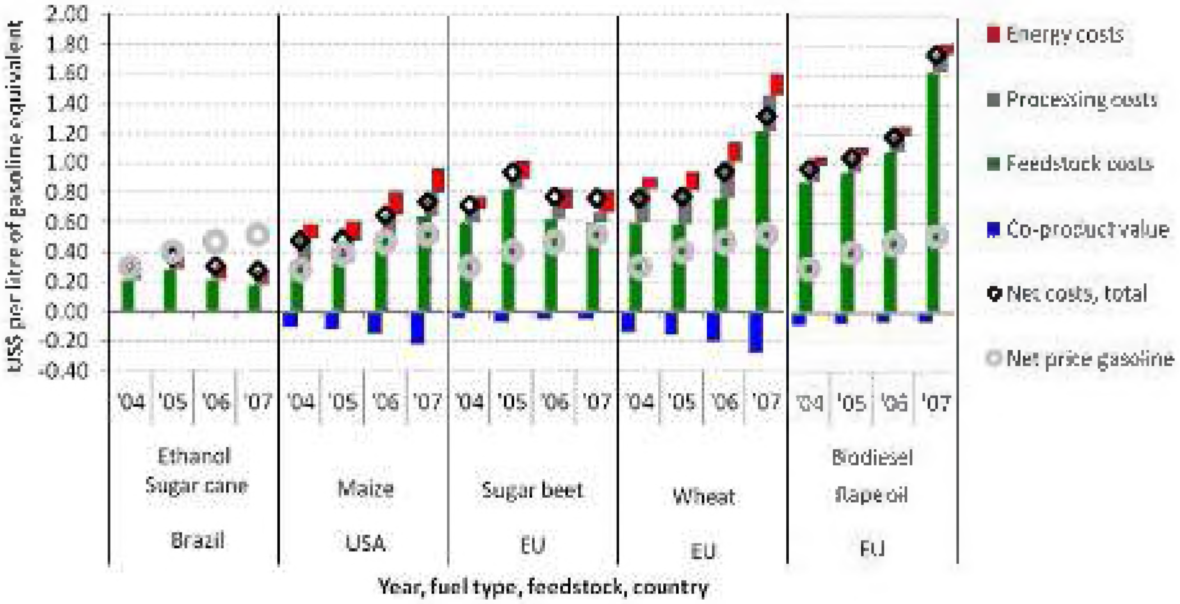
[5] Two of many web sites where the reference can be sourced are
www.globalbioenergy.org/1624.html and
http://www.renewableenergyworld.com/assets/documents/2008/FINAL%20SBC_April_16_2008.pdf

increases are also partly related to many other factors, including the increasing demand for food commodities especially milk and meat products, declines in crop yields and reserves as a result of recent droughts and storms, higher energy prices, possibly speculative trading, export restrictions in some countries and the deprecatiation of the US dollar.

Feedstock costs as well as energy costs are key factors, and both have contributed to higher biofuel production costs in recent years (Fig. 10). The exception is Brazilian sugarcane ethanol, which is very competitive at current fuel prices. One difference between Brazilian ethanol and ethanol produced in the US or EU is that Brazil apparently has been able to expand feedstock production in line with the growth in demand (for both ethanol and sugar), helping to prevent price escalations. Ethanol growth rates in Brazil have been slower than in the US in the past few years, which may also have helped avoid "overheating" the market.

Figure 10. Production costs of 1st -generation biofuels 2004-2007.



Source: Data from Aglink-Cosimo database, LMC International, IEA and other sources. The co-product value of exported electricity generated from bagasse in some plants in Brazil is not shown.

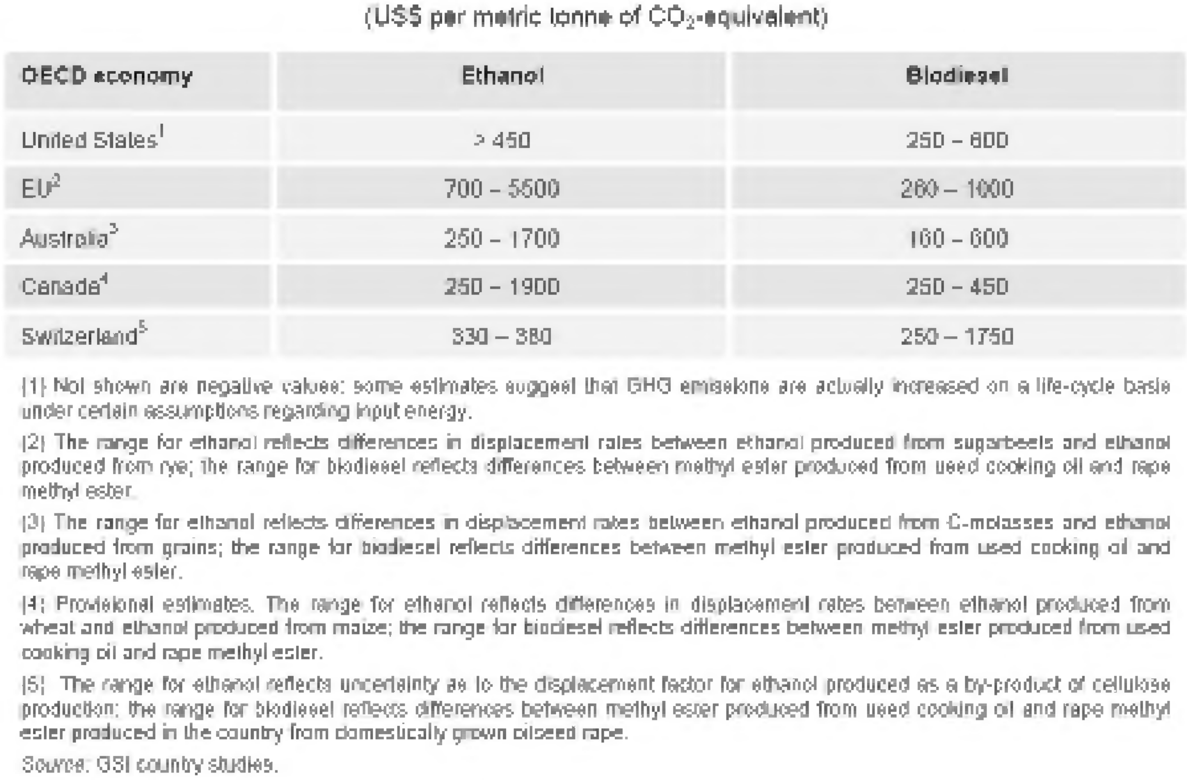
It is recognised that 1st-generation biofuels other than sugarcane ethanol are often an expensive way to meet environmental goals in particular, but also to provide greater energy security (Table 2). This is likely to remain the case in the future, considering that, although there are likely to be incremental improvements in technology, there are unlikely to be any breakthroughs. In addition feedstock costs account for 55-70% of total production costs and these are unlikely to fall sufficiently to make 1st -generation biofuels more competitive.

Competition with food and fibre products

It is clear that the development of some bioenergy options, particularly food-based biofuels, has had an impact on food supplies. Concerns have grown that higher food prices will have devastating effects on the developing world, where disposable incomes are lower. Increased biofuels production has received much of the blame, and although largely unjust, could impact on future expansion rates. The "Mexican tortilla crisis" saw prices rise to USD 1.81/kg from only USD 0.63/kg the previous summer. A shortage of Mexican maize had resulted in increased imports from the US. Here the "yellow" maize used for livestock feed is in high demand for ethanol production and has undoubtedly resulted in price rises. However for tortilla production "white" maize grown for human consumption is normally used, the price of which had not risen nearly as quickly for a variety of reasons (Körbitz, 2007).

Prices of grains, fats and oils have risen dramatically in nominal terms in recent years (Fig. 11). From January 2005 until February 2008 rice increased by 62%, maize 131%, and wheat 177%. The price of fats and oils began to rise somewhat later around mid-2006. Higher food prices, although benefiting some developing countries who are net food exporters, risk eliminating much of the progress in poverty reduction that has occurred in recent years with corresponding increases in malnutrition and potentially famine.

Table 2. Estimated costs of CO_2 reduction based on current biofuels support schemes



(US$ per metric tonne of CO_2-equivalent)

OECD economy	Ethanol	Biodiesel
United States[1]	> 450	250 – 600
EU[2]	700 – 5500	260 – 1000
Australia[3]	250 – 1700	160 – 600
Canada[4]	250 – 1900	250 – 450
Switzerland[5]	330 – 380	250 – 1750

(1) Not shown are negative values: some estimates suggest that GHG emissions are actually increased on a life-cycle basis under certain assumptions regarding input energy.

(2) The range for ethanol reflects differences in displacement rates between ethanol produced from sugarbeets and ethanol produced from rye; the range for biodiesel reflects differences between methyl ester produced from used cooking oil and rape methyl ester.

(3) The range for ethanol reflects differences in displacement rates between ethanol produced from C-molasses and ethanol produced from grains; the range for biodiesel reflects differences between methyl ester produced from used cooking oil and rape methyl ester.

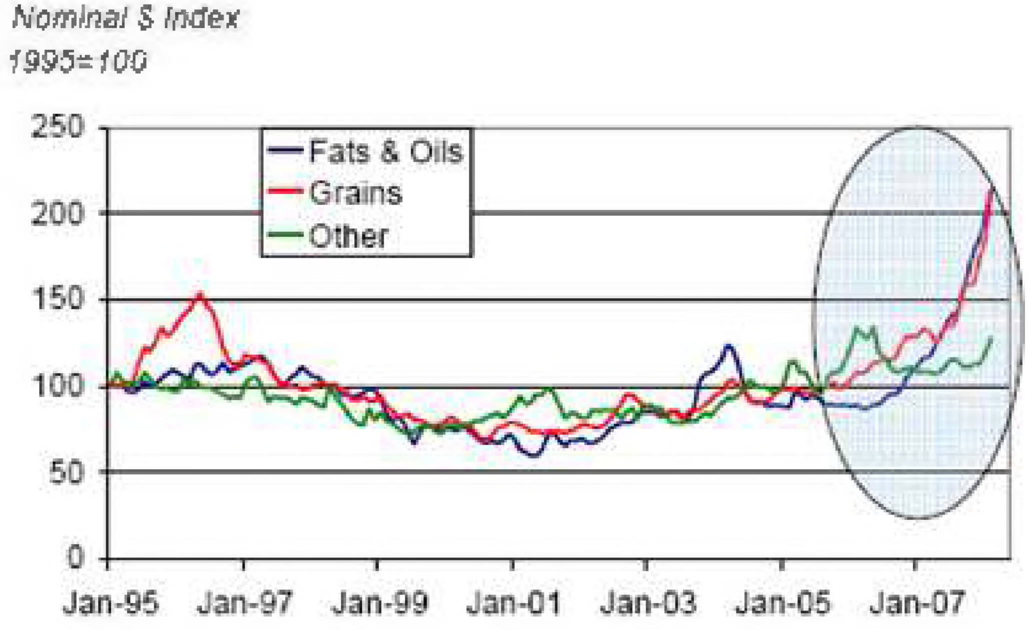
(4) Provisional estimates. The range for ethanol reflects differences in displacement rates between ethanol produced from wheat and ethanol produced from maize; the range for biodiesel reflects differences between methyl ester produced from used cooking oil and rape methyl ester.

(5) The range for ethanol reflects uncertainty as to the displacement factor for ethanol produced as a by-product of cellulose production; the range for biodiesel reflects differences between methyl ester produced from used cooking oil and rape methyl ester produced in the country from domestically grown oilseed rape.

Source: GSI country studies.

Source: Steenblink, 2007

Figure 11. Nominal prices for cereals and fats and oils.



Source: Development Prospects Group, World Bank

A number of contributing factors are at play in higher food prices, including low levels of global grain stocks, rising energy costs, rising agricultural production costs, the declining dollar, increased biofuels demand and recent policies by exporting countries to limit their own food price inflation. To these issues can be added droughts in Australia in 2006 and 2007 and poor crops in Europe in 2007, which added to the grain and oilseed price increases, while China has contributed to rapidly increasing import demand for oilseeds to feed its growing livestock and poultry industry.

Given the growth in the use of corn, wheat and oilseeds for biofuels production, many commentators have been attributing much of the growth in food prices to biofuels, however, there is as yet no agreement on how much of the increase in food prices can be attributed to biofuels and estimates can differ widely depending on what time periods are considered, which prices are used (export, import, wholesale, retail) and the different food products covered. For instance, the Council of Economic Advisors suggested that retail food prices had increased by just 3% in a year as a result of biofuels, but this was based only on consideration of the direct and indirect impacts on maize prices. In contrast, the World Bank estimated that as much as three-quarters of food price increases were attributable to biofuels, but this assumed all feedstock cost increases not attributable to increased energy costs were due to biofuels (Mitchell, 2008).

Other crops

Coconut oil (*Cocos nucifera* in African countries, *Acrocomia totai* in Paraguay) could become a source of biodiesel feedstock. Indeed in the 1980s buses were running on raw coconut oil in the Philippines - but with many technical problems. Esters produced from such oil exhibit smooth combustion and high oxidation stability because of the high level of saturation, but the biodiesel has slightly lower energy content per litre than standard food oils. For many fuel specification properties, coconut esters are similar to tallow esters produced from animal fat, which is being used as a biodiesel feedstock where inedible tallow igrades are (www.dft.gov.uk/rfa/db/documentsE4tech_Scenarios_report/pdf available. Other potential crops for biodiesel include jojoba (possibly in arid or semi-arid land), cardamom and peanut which can be grown as a winter rotation crop.

Competition for land and water

On-going deforestation is a continuing cause for concern in many countries. t is possible that continued development of 1st-generation biofuels might lead to net deforestation as more land is changed from permanent forest cover to agriculture. Although it is difficult to determine to what extent this practice is happening, or might occur in the future, significant concerns have been raised, particularly with the growth in palm oil plantations in SE Asia. Biofuels are only part of the problem as much of the cleared land is used for food and fibre crops. However, it is clear that biofuels policies will need to be closely inter-woven with stronger policies to avoid deforestation if net GHG reductions, including from land use change, are to occur from their use. Based on current practices, such biofuels would not be accepted as sustainably produced which would limit the market for them. There is the further risk that expansion of 1st-generation biofuels derived from starch or sugar crops might lead to accelerated net deforestation as more land is converted to agriculture.

In addition the increased use of scarce fresh water for irrigating energy crops is under question. Increasing the irrigated area of food crop production will result in increased yields but competition for the water often exists with other users. Use for energy cropping may be unacceptable. However land treatment of dilute effluent from food processing, treated sewage etc. by irrigating energy crops rather than food crops could be perceived as an acceptable solution.

Multi-feedstock flexibility

From the commercial point of view, technologies and plant designs which are able to process a number of different feedstocks in a flexible way are preferable. Many single food crops used for biofuels are seasonal so to operate a plant all-year-round in order to reduce overheads is offset by high storage costs. A multi-feedstock plant could take the advantage of buying the cheapest feedstocks on the market at a specific point of time throughout the year, including biomass imports. However such plants are more difficult to design at the front-end and also more costly to operate. For processing plants designed for producing both 1st- and 2nd-generation biofuels, one advantage is that many ligno-cellulosic feedstocks makes them easier to store (cereal straw for example requires no drying or chilling) and hence they can be made available all-year round (forest residues for example).

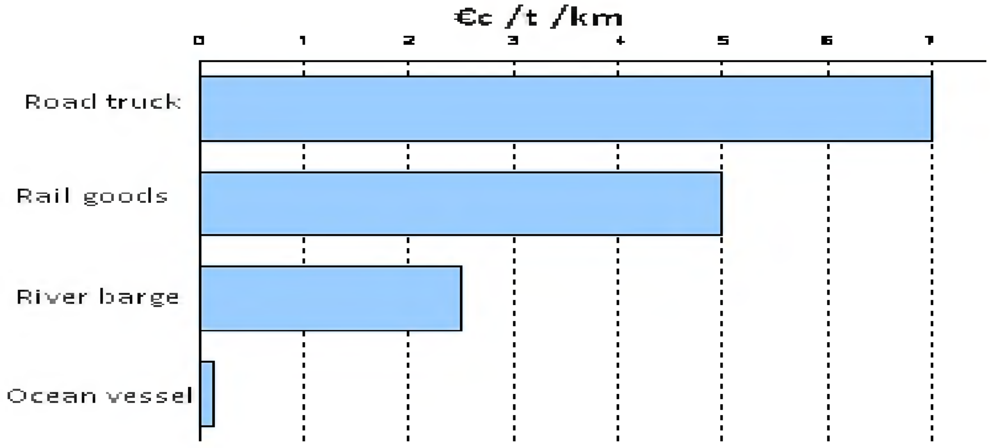
The growing of willow or poplar plantations on agricultural land has begun to a limited degree in Sweden and the US as a result of increased demand to supply biomass feedstocks for heat and power generation. This afforestation from converting previously agricultural land into plantations has taken land out of food production (though usually marginal land is used for growing such low value, energy crops). This practice could increase globally, especially if demand for ligno-cellulosic crops increases in the future.

Second-generation biofuels offer the prospect, with feedstocks produced on idle or marginal lands, to avoid the need to bring significant amounts of new land into agricultural production. The other key factor relating to the complex issue of future land use projections for competing food, fibre or energy crops, is whether the rate of increasing average yields per hectare can be continued. For example the average yield of wheat grown in OECD countries has increased over three times since the 1960s due to new varieties, better farm management practices, improved agri-chemical and fertiliser inputs, reduced storage losses, more efficient mechanisation etc. If moves towards higher-yielding, sustainable production of food and fibre crops can continue worldwide, less land would be needed to meet the demand for food and fibre and energy crops could be grown on the surplus land where sufficient water is available.

Site selection

The logistics and transport costs of delivering feedstock to a 1st-generation biofuel processing facility, then distributing the biofuel to the customers, possibly as a blend with petroleum products, is a key factor for profitability. Several commodities also used for biofuel production are traded worldwide in very large volumes at low price levels. Their transport by water has a clear cost advantage (Fig. 12) and so sites selected for 1st -generation process plants on waterways and harbours would have clear benefits. Where this is not practical, more costly road transport may be a barrier to development. This is also the case for many 2nd-generation feedstocks.

Figure 12. Cost of biomass feedstock transport by mode



© Austrian Biofuels Institute

Source: Vienna University of Economics, Institute for Transport and Logistics

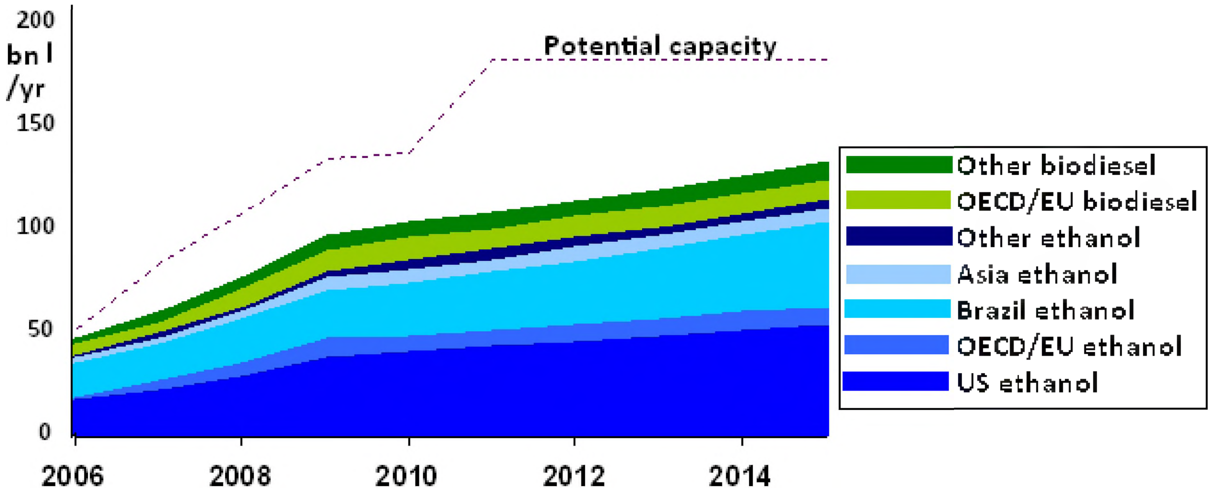
2.6 Future projections for 1st-generation

The share of biofuels in total transport fuels over the next few decades is difficult to predict, though the impacts of current policies that mandate their use can be quantified. The challenge is that biofuel targets or mandates could be expensive or difficult to meet in the short- to medium-term, thus calling into question their viability.

Aside from the EU and US goals, for biodiesel, ambitious expansion plans have been reported in Southeast Asia (Malaysia, Indonesia, Singapore, China), North and South America (Brazil, Argentina, US,) and Southeast Europe (Romania, Serbia). For example by 2010 Malaysia hopes to capture 10 % of the global biodiesel market and China intends to reach a 10 % domestic market share by 2010. Indonesia is expanding its oil palm plantation from 3 Mha in 2003 to nearly 7 Mha by 2008, although only 10-15% of this oil is currently used for biofuel. International concerns at deforestation and ensuring that any biodiesel traded is produced from sustainable feedstocks may curtail this expansion.

IEA recently produced mid-term biofuels projections in its Medium Term Oil Markets Report (July 2008). For ethanol, projections in the medium term are for a slower but steady growth in production out to 2015 based on detailed analysis of markets and policies, and a review of individual processing plants in operation, under construction and planned (Fig. 13), particularly in Brazil and US (IEA, 2008a). A similar rate of growth is predicted for biodiesel. In 2006 and 2007 biofuels represented around 30% of incremental non-OPEC supply growth and this could rise to 50% by 2013. In other words, outside of increases in OPEC production, biofuels was one of the most important sources of increased transport fuel world-wide over the past 2 years.

Figure 13. Biofuel production in the medium term by region and potential global processing plant capacity



Source: IEA 2008b

Looking out to 2030, several scenarios suggest a slow but steady increase in the share of biofuels resulting in up to 10% of total global transport fuel by then (IEA, 2006; IPCC, 2007). Smaller shares are projected for 1st-generation due to land and water constraints and the potential constraint of future certification requirements to ensure the biomass feedstock is produced sustainably. An exception is ethanol from sugarcane in Brazil (and potentially other developing countries), which is expected to increase steadily regardless of 2nd-generation or certification developments. Therefore achieving this level is usually considered dependent upon the successful development of competitive 2nd-generation biofuels within a decade or so from now.

Interestingly, the work conducted by the consulting company E4tech for the UK's Renewable Fuel Agency "Gallagher Review" (www.dft.gov.uk/rfa/db/documentsE4tech_Scenarios_report/pdf) showed that the proposed global targets for biofuels add up to around 10% of total projected transport fuel demand in 2020. Whether these targets are eventually met will determine if the scenarios mentioned above were too low at the upper bound of 10% by 2030.

PART B) Second Generation Biofuels

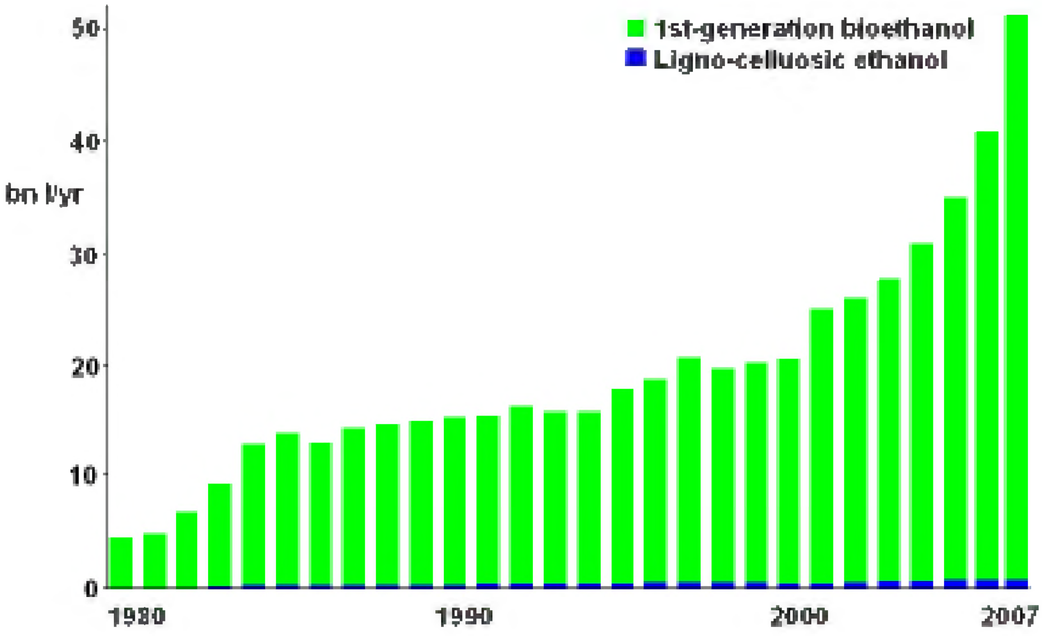
3 Overview – Feedstocks and Supply Chain

Projections for 2nd-generation fuels to become commercial are wide ranging but often considered unlikely to occur before 2015 (IEA, 2008a). The basic conversion technologies are not new and their commercial development has been a long time coming - successful development is not yet guaranteed. Considerable investment in pilot and demonstration plants has been made worldwide but how and when commercial scale-up can be realised is the key question. This will be assessed in the following Part B of this report.

Second generation biofuels are expected to be superior to many of the 1st- generation in terms of the concerns discussed in Part A, namely energy balances, greenhouse gas emission reductions, land use requirements, and competition for land, food, fibre and water. However they do not produce co-products such as animal feeds which should also be considered in a comparison (Renewable Fuels Agency, 2008).The main reason why they have not yet been taken up commercially, despite their potential advantages over 1st-generation biofuels, is that the necessary conversion technologies (from feedstock to finished fuel) are not technically proven at a commercial scale and their costs of production are estimated to be significantly higher than for many 1st-generation biofuels at the moment. Further research is required on land use requirements, effects of co-products, water use and energy for processing as outlined below.

These 2nd-generation biofuels have remained around 0.1% of total ethanol biofuel production (Fig.14)[6]. There is still much work to be done in terms of improving 2nd-generation biofuel technology pathways, to reduce costs and to improve performance and reliability of the conversion process. Significant RD&D challenges remain before wide-scale deployment is possible, but there are now several pilot-scale plants in operation with a few larger demonstration plants planned or under development. This section of the report outlines the technology pathways and current state of development of 2nd-generation biofuels, RD&D needs and potential barriers, as well as discussing the pilot and demonstration programmes.

Figure 14. World ethanol production from 1st generation and ligno-cellulose



Source: Mabee and Saddler, 2007

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[6] Care is needed when interpreting national statistics since industrial ethanol production is often grouped with biofuel ethanol.

Second-generation biofuels can be broadly grouped into those produced either biochemically or thermo-chemically, either route using non-food crops, especially from ligno-cellulosic feedstocks sourced from crop, forest or wood process residues, or purpose-grown perennial grasses or trees. Such crops are likely to be more productive than most crops used for 1st-generation in terms of the energy content of biofuel produced annually per hectare (GJ/ha/yr). In addition certain feedstocks crops, including Jatropha grown for oil, could possibly be grown on marginal land, though the yields per hectare are likely to be low. The challenge lies in converting the cellulose, hemicellulose and lignin polymers into ethanol, synthetic diesel or other liquid fuels including for aviation and marine purposes.

In general, 2nd-generation biofuels face a number of significant barriers before they can realise their potential to reduce GHG emissions from the transport sector. These include the following.

- *High costs of production* are a fundamental barrier to deployment. A global system that incentivised the reduction of GHG by placing a value on carbon emissions (such as a carbon tax) would help put 2nd generation biofuels on a more level-playing field with fossil fuels, but would probably not be enough in itself to lead to commercialisation. Reductions in the costs of biomass feedstocks, transport logistics and conversion processes will be required to overcome this barrier.
- *Logistics and supply chain challenges* in order to cost effectively deliver feedstock to the gate of a large plant need to be overcome. Current harvesting, storage, and transport systems are inadequate for processing and distributing biomass at the scale needed to support significant production of large volumes. The lack of experience in operating large-scale plants demanding large volumes of biomass creates the problem of requiring expensive infrastructure expansions where current handling and storage facilities are inadequate. Once the demand for the biomass feedstock has been established, the infrastructure will grow, but in the meantime, this chicken-egg problem will be a constraint. Producing and delivering biomass feedstocks in large volumes will require significant investments throughout the supply chain—from feedstock production and transport through conversion processing and product delivery. It should be noted however that there is much to learn from the sugarcane industry where some mills receive 300,000 t or more of biomass per season delivered by specialist trucks or even mini-rail systems.
- *Industry and consumer acceptance of biofuel quality,* from a business perspective, needs biofuels to perform as well, or better than, similar fossil-energy-based products in order to facilitate their rapid uptake. Industry partners and consumers must believe in the quality, value, and safety of biomass derived products. So international fuel specification standards developed for 1st-generation biofuels need to be extended to include 2nd-generation products.
- *Perceived risky investments* can be significant financial barriers to commercial deployment of emerging technologies. There is a role for governments to help under-write the risk to some extent in order to demonstrate that 2nd-generation technology functions successfully at a commercial scale. A clear and stable long-term policy framework is then needed to ensure that industry and financiers can invest with confidence.
- *Agricultural/forestry sector changes* needed to supply biomass feedstocks from residues and crops implies a significant shift in the current business models as well as in international trade of feedstocks and biofuels. This implies major change in both policy and business practices that will take time to achieve.
- *Misunderstanding of environmental/energy tradeoffs* is occurring because the adoption and development of 2nd-generation biofuels is still at an early stage. There is an urgent need for a systematic evaluation of the impacts of expanded 1st-and 2nd-generation production on the environment, from local, national and international perspectives including GHG mitigation and food supply. Some work is being done in this area, but to date a comprehensive integrated analysis is lacking. There is a risk that without it, poor policy decisions could result in negative unexpected consequences for GHG emissions, the environment, biodiversity, land ownership, and producer and consumer welfare. Optimal approaches and locations for 2nd-generation facilities should be identified that maximize GHG reductions while minimizing cost and impacts on the environment and other agricultural markets (especially in terms of food crops). Understanding land use change issues is as important for 2nd generation technologies as it is for 1st generation.

A detailed description of the other barriers to 2nd -generation biofuels and their potential environmental benefits and trade-offs is beyond the scope of this report. The rest of Part B discusses ligno-cellulosic feedstocks, supply logistics, technology pathways for the biochemical and thermo-chemical routes, and pilot and demonstration plants in operation or planned.

3.1 Feedstocks

To be acceptable, biofuel feedstocks must be sustainably produced in terms of agricultural practices, forest management, protection of biodiverse ecosystems, responsible and efficient use of water, and free of exploitation of landowners. For 2nd-generation they do not compete with food and fibre. Many developing countries could theoretically benefit from strategic partnerships with public and private sector organizations from both industrial countries and the more advanced developing countries such as Brazil, which have knowledge and experience in the production, distribution and consumption of biofuels. However care should be taken to ensure that biofuels should benefit the national economy of a developing country and also support the poorest people mainly in the rural areas. Many of these are small subsistence farmers and landless rural labourers entirely dependent on agriculture and forestry for their livelihoods. The advent of large companies seeking government support to buy up cropping land cheaply in order to produce biofuels for exporting to developed countries (with possible negative impacts on food supplies, rural communities and the environment) is a serious risk.

Ligno-cellulosic feedstocks

Biomass is the most important renewable energy source today. In 2005, total combustible renewables and waste consumption was estimated at 1 149 Mtoe, with around 94% of this being solid biomass or "ligno-cellulose" (IEA, 2008a). Ligno-cellulosic biomass (Box 1) is an abundant and renewable feedstock,with an estimated annual worldwide production of 10-50 billion dry tonnes (Galbe & Zacchi, 2002) though only a small portion of this could be utilised in practice. This includes cereal straw, wheat chaff, rice husks, corn cobs, corn stover, sugarcane bagasse, nut shells, forest harvest residues, wood process residues. The technical potential from available annual supplies has been estimated in energy terms at over 100 EJ per year[7], with costs in the range of USD 2-3/GJ annual (IEA Bioenergy, 2007).

Box 1. Composition of ligno-cellulose

Ligno-cellulose is the botanical term used for biomass from woody or fibrous plant materials, being a combination of lignin, cellulose and hemicellulose polymers interlinked in a heterogeneous matrix. The relative importance of each of the polymers can vary significantly with the feedstock type. The combined mass of cellulose and hemicellulose in the plant material varies with species but is typically 50 - 75% of the total dry mass with the remainder consisting of lignin. Cellulose is a straight chain polymer consisting of units of glucose (a 6 carbon (C6) sugar) less one molecule of water connected via specific linkages so that each link has a formula $C_6H_{10}O_5$. Hemicellulose is a heterogeneous material which in agricultural and woody substrates is primarily a polymer of predominantly xylose and arabinose (both pentoses, being C5 sugars), combined with three different hexoses (C6). Lignin is composed of a number of phenolic compounds that may act as an inhibitor to the hydrolysis or fermentation of sugars so its presence creates challenges for bioconversion processes (Robinson *et al.* 2002).

In the biochemical conversion process that relates to the concept of bio-refineries, lignin represents a potential valuable source of chemical feedstock. In ethanol plants it may be combusted to provide process heat and power. In the thermo-chemical route, all polymers, including lignin, are converted to synthesis gas.

One reason that enzymatic hydrolysis of ligno-cellulosic feedstocks has proven to be a challenge to date is due to the strength of the specific ß1_4 glycosidic bonds between the monomer sugar units.

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[7] Assuming 20 GJ/ dry t of biomass, this equates to around 5 bn t/yr. Current world primary energy demand is around 485 EJ/yr.

This makes cellulose difficult to break down into its constituent sugars. Unfortunately, there are only a relatively small number of natural bacteria systems which can affect this break down. They include the bacteria present in the stomach lining of ruminants (responsible for enteric-methane production and hence a contributor to GHG emissions) and certain fungi. These bacteria contain enzymes which hydrolyse the cellulose. In contrast, hemicellulose is a polymer that is easily hydrolysed by weak acids, bases and a wide variety of enzymes. Lignin, which encrusts the plant cells, cementing them together and strengthening the entire plant, is only degradable by a few organisms. Perennial grasses such as switchgrass contain relatively low levels of lignin, whilst woody biomass contains high levels. This variation affects what are the desirable properties of feedstocks and how potentially difficult (expensive) it is to convert the raw feedstock into fermentable sugars. The processing of ligno-cellulosic materials is therefore much more complex and expensive than for 1st-generation sugar and starch-based biofuel industries.

Thermochemical conversion, through pyrolysis/gasification and Fischer-Tropsch synthesis to produce distillate fuels, does not depend on bacterial or enzymatic processes and hence the cellulosic nature of feedstocks is less of a concern. However feedstock quality (consistency, purity, water content) is more important for thermochemical pathways.

Agricultural feedstocks

Agricultural feedstocks and residues, particularly bagasse, are likely to offer some of the lowest cost ligno-cellulosic feedstocks available in significant quantities (ORNL, 2007). Bagasse (and wood process residues) are concentrated at the processing plants whereas other sources such as cereal straw need to be collected from the field as a separate and more costly operation. Integrated production of several harvested products is possible with some crops. Whole crop harvesting of oilseed rape for example could provide oil for cooking, high-protein meal for pig and poultry feed, and straw for 2nd-generation biofuel production.

The range of variation in ligno-cellulosic constituents between various agricultural residues being considered for bio-chemical (enzymatic hydrolysis) ethanol production is relatively low. For instance, cereal straws from both Europe and North America are characterized by cellulose between 35-40% of total oven dry weight, hemicellulose between 26-27%, and lignin between 15-20% (Misra, 1993). The balance of the mass is made up of non-organic ash and silica which for straw can vary between 10-20% (higher in rice straw than cereal straw) and 2-5% for wood. Even within a single cereal species, some chemical variation occurs within the specified ranges due to both environmental and genetic factors.

Moisture content of the delivered feedstock is particularly important for thermo-chemical processes. For both biochemical and thermo-chemical systems it can impact on the delivered cost of energy to the processing plants. Cereal straw residues typically contain about 10-20% moisture content when freshly harvested, maize stover 20-30%, bagasse and rice straw 40-50%, and woody biomass over 50%. Some biomass materials tend to be hygroscopic so that dry straw when harvested and baled, for example, may become higher in moisture over time depending on atmospheric humidity. Forest residues will initially become drier after harvest but then stabilise before varying with atmospheric humidity. This has important impacts on transportation considerations, as high moisture content feedstocks will have higher delivered costs per unit of energy since the delivery truck would be weight-limited. Very low moisture content feedstocks could also have high delivery costs per unit of energy as the truck would then be volume-limited (see below).

Significant research is underway to look at a number of perennial species of vegetative grasses. Switchgrass is one such species. Recent research in the US suggests average yields of 60 GJ/ha (net) could be achieved in some regions (Schemer *et al.*, 2008). Estimations are that average yields could reach nearly 37 dry t/ha in 2050, without the need for genetically modified crops (Table 3), being around two and a half times today's average yield (NRDC, 2004).

Forest feedstocks

The forest industry has recently expressed strong interest in becoming providers of biomass for bioenergy (for heat and power generation) and biofuel production using both softwood and hardwood residues from the existing wood processing plants. This could assist the industry overcome a decline in recent decades, with long-term losses in the real value of pulp and paper products impacting on all sub-sectors. Residues from the wood processing industry can provide low-cost feedstocks already collected on site. Bark, off-cuts, sawdust, shavings etc., are particularly attractive for thermo-chemcial processing due to their low moisture content (<20%) and uniform properties. As a result however, the majority are already used for bio-materials (chip boards; garden mulch etc.) though some remain available for other uses. Black liquor, a by-product of kraft pulp mills (consisting of lignin in a slurry form), has significant potential to increase the efficiency of the fuel using gasification technologies to produce synthesis gas feedstock for biofuel production.

Table 3. Current yields of Switchgrass, projected annual incremental increases, and subsequent yields for several regions in the US.

Region	**2004 average yields (dry t/ha/yr)**	**Annual gains anticipated from conventional breeding/selection (dry t/ha)**	**Projected future yields (dry t/ha/yr)**	
			2025	**2050**
North east	11.9	0.18	15.7	20.2
Appalachia	14.3	0.71	29.3	47.2
Corn belt	14.7	0.44	23.9	34.9
Lake states	11.8	0.18	15.5	19.9
South east	13.5	0.67	27.6	44.4
Southern plains	10.5	0.53	21.6	34.8
Northern plains	8.5	0.13	11.2	14.4

Source NRDC, 2004

Another potential secondary source of biomass is from urban wood residues, (such as demolition timbers, pallets, containers, packaging etc.). However, this maybe less suitable as a feedstock for biofuels given its potential variability and could be better suited for direct combustion for heat.

For the enzymatic hydrolysis of wood residues, the species variation in basic chemistry is even more significant than in agricultural residues, particularly when comparing softwood and hardwood species. Softwood includes species of pine, spruce, hemlock and fir that have a cellulose content around 40% of total dry weight which is slightly higher in hardwoods up to 42%. Hemicellulose ranges between 18-28% for softwoods, and 24-33% for hardwoods, whereas lignin ranges between 27-34% for softwoods, and 23-30% for hardwoods. The differences between the characteristics of wood, straw and vegetative grasses can create particular challenges for bioconversion in multi-feedstock plants.

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 (Sjöström 1993). This lignin chemistry 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.

New biomass feedstocks

Growing new energy crops, particularly perennial grasses (e.g. *Miscanthus,* switchgrass, prairie grass) and short-rotation forest species (e.g. *Eucalyptus,* poplars, *Robinia*), are being considered specifically for the purposes of accumulating biomass (Annex 2). These crops can be high yielding when grown under good conditions and harvested over long seasons to provide a steady supply stream at the processing plant, thus avoiding costly storage of large biomass volumes for several months between harvests.

Genetically modified crops

Crops conventionally used for enzymatic hydrolysis biofuel production are being bred to provide higher yields of sugar or starch rather than for quality of taste in order to obtain higher biofuel yields per tonne and per hectare. Much progress can still be achieved from traditional plant breeding techniques that is not controversial. Instant ethanol-yield assessment is now possible, based on samples of grain taken from trucks delivering to a processing plant. This can be used for calculating payments to the growers. The results can also be used by breeders and growers to tailor hybrid selection and crop management to give the highest ethanol yields possible. Similarly oilseed rape grown specifically for biodiesel is being bred with higher concentrations of certain fatty acids (eg linoleic acid or euricic acid) to give desirable properties such as enhanced lubricity. Conventional breeding and selection techniques still have much to offer new energy crops, but genetic modification (GM) may overtake these practices.

GM could be a useful tool in developing fast-growing energy crops to gain higher yields from lower inputs. It could result in reduced demands for insecticides, lower fertiliser inputs, less need for water, (either from reducing the costs of irrigation or to enable commercial production to take place on marginal or semi-arid lands). GHG emission reductions (as indicated in Fig. 2) are also claimed from the manufacture of fewer agri-chemicals and fertilisers, as well as from the greater uptake of conservation tillage since fewer weeds need to be controlled, thereby maintianing or increasing the soil organic matter and hence carbon content.

Whether public acceptance for GM energy crops will be gained is uncertain in some regions. It could be more accepted than for food crops, although similar environmental issues and unwanted gene transfer concerns will still result. Currently, over 100 Mha of crops from GM sources are claimed to be grown worldwide in 22 countries (mainly North and South America). Apparently the 1.4 billion ha that has been planted over the last 10 years has been without any major issues arising to date (www.isaaa.org/resources). Alfalfa (lucerne) was the first perennial crop to be approved for its herbicide tolerance. It is therefore conceiveable that vegetative grasses could also be successfully genetically modified to give them properties suitable for biofuel conversion. To date, however, relatively little breeding research, either conventional or GM, has been undertaken on non-food energy crops.

The growing interest and investments in GM crop-based biofuels relate to crop biotechnology that can offer significant advantages for increasing the efficiency of biofuel production per hectare. The claim is that biotechnology and other improvements will enable industrialised countries to continue to produce surplus supplies of food, feed and fibre and coincidentally achieve ambitious goals for biofuels in the near-term (www.isaaa.org/resources). In developing countries, investments in crops for biofuel production should not compete with food crops but should complement the programmes in place for food, feed and fibre security.

Jatropha

Many non-food oilseed species are potentially available for cropping including the physic nut (*Jatropha curcas*). This produces a suitable oil for conversion to biodiesel and is looking promising as a crop for planting in semi-arid climatic zones with marginal soils. Investment interest is high (see for example D1 Oils, UK - www.d1plc.com) but to optimise production of the crop will need more time for further breeding and yield improvements together with harvesting and handling techniques. At present high yields are only achieved on good soils with relatively high inputs. The promise for commercial production on marginal land is yet to be fulfilled.

In China the National Development and Reform Commission has approved the construction of three biodiesel plants using *Jatropha* oil feedstock. The plants, with a total capacity of some 170,000 t/yr, will be divided between the country's three main state oil companies: Sinopec will invest in a 50,000 t/yr plant in Guizhou; PetroChina (part of the China National Petroleum Corp, CNPC) will establish a 60,000 t/yr plant in south-west Sichuan; and the China National Offshore Oil Corporation (CNOOC), will build a 60,000 t/yr plant on Hainan Island. Construction and successful operation at near-full capacity should help China achieve the production of 2 Mt/yr of biodiesel by 2020 without endangering food supplies. However, pricing is still a major issue to be resolved, with around

100,000 tonnes of existing facilities, mainly using waste cooking oil feedstocks, uneconomic at current retail price levels when competing with subsidised oil products.

3.2 Biomass feedstock R&D

Reducing the costs of biomass feedstocks from dedicated sources is important in reducing risk and encouraging investment, as well as lowering the costs of the resulting biofuels.This will require improvements in feedstock production and logistics. RD&D goals for biofuel feedstocks should focus on the following.

- Feedstocks of sufficent quality and physical properties need to be developed in conjunction with progress in both biochemical and thermo-chemical conversion technologies that will allow optimum production of biofuels in a systems approach. Genomic and agronomic strategies are needed to maximise the biomass yield and to improve the quality of feedstocks.
- Field trials will be necessary to evaluate and demonstrate these new feedstocks, and be conducted on a regional basis because of the variations in growing conditions and also because of their suitability to different feedstocks.
- The genetic modification of ligno-cellulosic feedstocks is an important research topic. If feedstocks can be modified to make their pre-treatment or conversion easier or less costly, then important reductions in the production costs of 2nd-generation biofuels could be achieved.
- Biotechnology developments need to focus on improving process efficiency to gain higher biofuel yields and improve the growth and conversion characteristics of the feedstock. The design and manipulation of plant cell wall composition and structure could be a useful route to maximise the yield of biofuels.
- Definition and development of sustainable biomass feedstocks is required, along with validation tools to assess the environmental impacts of different feedstocks in various locations under a range of conditions.
- Feedstock homogeniety characteristics need to be easily assessed and understood to ensure optimisation of processing into biofuels and a fair method of payment for the grower.

3.3 Biomass supply logistics

Biomass residues that are removed from the growing area at harvest and accumulate at the processing plants (for example bagasse, rice husks, sawdust and bark from pulp logs) can have a disposal cost. They are therefore considered to be free-on-site or even have a negative value if the disposal costs are avoided by their utilisation. Other biomass residues need collection from the forest or field after harvest of the main product which can be a costly activity.

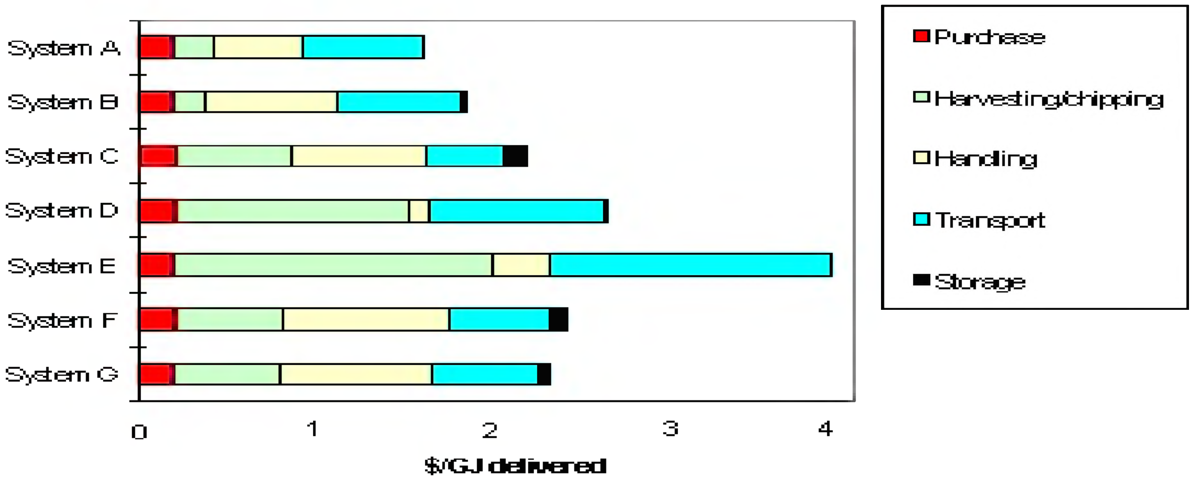
The fibrous nature of ligno-cellulosic biomass and its low energy density (particularly with a high moisture content) make it difficult and costly to collect, store, handle and transport. The present systems available are largely derived from agricultural and forestry systems, are costly, and would be inefficient for handling the large quantities of biomass feedstock needed for large-scale 2nd - generation biofuels production.

Although crop and forest residues can be collected, stored and delivered at relatively low cost under some circumstances, dedicated energy crop feedstocks are likely to be significantly more costly to grow, harvest and deliver. Important reductions in the delivered costs of these feedstocks need to be achieved to help lower the cost of biofuels production.

Some pre-processed biomass material is already travelling long distances to markets such as wood pellets from Canada shipped to Scandinavia for use in district heating plants or palm oil from Malaysia arriving in Sweden and the Netherlands for biodiesel feedstock. However the logistics of transporting, handling and storing the often bulky and variable raw biomass material for delivery to the bioenergy processing plant gate is a key part of the supply chain that is often overlooked in the early stages of planning (IEA, 2007).

If not collected at the time of harvest using integrated systems then residues, often widely distributed, will need to be brought to a central location. The method will vary with the type of residue, terrain, available machinery type, location, soil access etc. and the relative cost of collection will be considerable. Careful development and selection of a system from those 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 (Fig. 15). In this example, over a transport distance of 80km, the total delivered cost at less than $2/GJ for system A (based on transport to a centralised chipper with no intermediate storage), are around half the delivered cost of system E (based on a mobile, in-forest chipper/forwarder system). Full details of the systems are presented elsewhere (IEA, 2007).

Figure 15. Delivered costs of forest arising can vary with the choice of system.



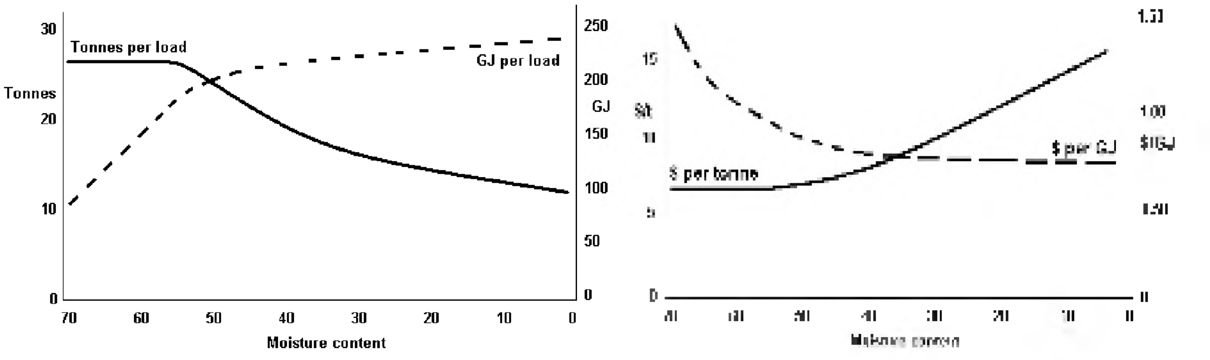
Source: IEA, 2007.

Most forms of biomass and bioenergy carriers tend to have a relatively low energy density per unit of volume (e.g. GJ/m^3) or mass (e.g. MJ/kg) compared with fossil fuels with the same energy equivalent. For example ethanol has an energy content of ~22 MJ/l whereas gasoline is ~34 MJ/l; air dried woody biomass is around 12-15 GJ/t and sub-bituminous coal around 20-25 GJ/t (low heat values). This usually makes handling, storage and transportation more costly per unit of energy carried.

The variable moisture content of biomass adds a further complexity. Take for example a truck load of wood chips produced from the branches and tops of a freshly harvested plantation forest. At the time of harvest, trees contain at least 50% water by weight so if the pile in the truck weighs 26 tonnes, 13 t is the “dry matter” of the biomass and 13 t is the water in the biomass. On combustion the load would have an available energy content of around 195 GJ. If the truck is now loaded with the same volume, but with the biomass only chipped after the branches have been left in the forest for a few weeks to naturally air dry down to say 20% moisture content (mc), then the load would now weigh 16.3 t of which the dry matter remains at 13 t but the moisture present in the biomass now only weighs 3.3 t. The energy content of the load will now be higher at around 280 GJ but it is also lighter to transport. Being drier, the biomass will also burn more efficiently. If the truck had a 26 t maximum payload capacity, then the original load size would be limited by the weight of the wet, freshly harvested chips and not by the volume of the load. If the load of dry wood chips carried could have been increased in volume so as to meet the maximum payload (assuming the truck design allowed for a bigger size load, perhaps by adding higher extension sides), then the load would now contain 21.8 t dry biomass and 5.2 t moisture, thus giving an overall energy content of 370 GJ. Hence the transport cost /GJ of available energy would be a lot less as the truck is operating at full load capacity and less water is being transported (Fig.16).

Some forest and crop residues may not be cost competitive because the biomass resource is dispersed over large areas leading to high collection and transport costs. Where road transport cannot be avoided, due to the low energy density of many solid and liquid forms of biomass, impacts from numerous vehicle movements are inevitable (Table 4).

Figure 16. Delivered biomass energy costs (USD/GJ) depend on optimising the moisture content.



(a) (b)

Note: *Based on a maximum 26 tonne payload truck over a cartage distance of 35 km and a charge of USD 0.42/t/km.*

Table 4. 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 hr	40-60	3 - 5 / yr	1 - 3% within 1 km radius
Demonstration	40000-500 000 l/yr 3000 hr	100-1200	10 - 140 / yr	5 - 10% within 2 km radius
Pre-commercial	1-4 Ml/yr 4000 hr	2000-10 000	25 - 100 / month	1 - 3% within 10km radius
Commercial	25-50 Ml/yr 5000 hr	60,000-120,000	10 - 20 / day	5 - 10% within 20 km radius
Large commercial	150-250 Ml/yr 7000 hr	350,000-600,000	100 - 200 / day and night	1-2% within 100km radius

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

The forest and sugar industries have largely overcome the large-scale transport problems of bulky feedstocks after many years of experience. Sugarcane processing plants for example typically handle around 300,000 t of sugarcane billets during the 6- to 7-month harvesting season and as a result need an efficient transport system. Some sugar mills have built a network of narrow gauge railway tracks to connect the growing areas directly with the mill.

The collection and transport of biomass can result in increased use of vehicles, higher local air emissions from their exhausts, and greater wear and tear on the road infrastructure. Who should pay for the extra costs is difficult to determine. Where the roads are maintained by higher charges placed on local ratepayers, most of whom receive little benefit from the passing of heavy trucks through their district, the problem can be hard to resolve.

Improving the collection and storage

The logistics of supplying a bioenergy plant with sufficient volumes of biomass from a number of sources at suitable quality specifications and possibly all year round, are complex. Storage of solid biomass is usually outdoors and possibly on concrete pads if located close to the conversion plant. Forestry and agricultural residues can also be stored in the forest on landings or on the farm until needed. Then they can be collected and delivered directly to the conversion plant on demand. At times this requires considerable logistics to ensure only a few days of supply are available on-site, where storage can be costly, but that the risk of non-supply at any time is low.

Losses of dry matter, and hence of energy content, commonly occur during the harvest, transport and storage process. This can either be from physical losses of the biomass material in the field during the harvest operation, spilling off a truck, or by the reduction of dry matter of the biomass material which occurs naturally during storage over time as a result of respiration processes and product deterioration.

Storage of biomass is often unavoidable due to its seasonal production versus the commercial objective of reducing overheads by producing biofuels all-year-round. To provide a constant and regular supply of fuel for the plant requires either storage or multi-feedstocks to be used, both of which add costs to the system. Since biomass tends to have relatively low energy density (whether as a solid, liquid or gas), and is organic, then the storage of large volumes can be costly, especially when covered. For dry material such as straw the risk of fire when stored in large piles is high. Green materials such as bagasse or wood chips are also risky being prone to spontaneous combustion when stored in piles due to bacterial action causing heat build-up. Regular stirring of the piles to dissipate the heat is the usual solution. Innovative supply chain processes for delivering forest arisings to bioenergy plants have been developed to overcome many of the logistical problems identified (see one example in Fig. 17).

Figure 17. Compacted bales of forest residues produced for easy transport by road or rail.

(Source: John Deere Company; www.timberjack.com)

Supply chain logistics R&D

A range of research activities are required to find solutions to reduce the delivered ligno-cellulosic biomass costs and improve system efficiency, including the following.

1. Dedicated biomass harvesting systems need to be developed for the new crops under evaluation.
2. Biomass storage systems need to be improved to ensure homogeniety of feedstocks before and after transportation to the processing facility.
3. Pre-processing systems need to be developed that minimise the weight and space required for a given energy content to reduce transportation costs. Crude oil became a transportable commodity over time. Similarly the biomass feedstock also needs to be processed locally to increase its energy density before transporting it long distances to a central bio-refinery. Pyrolysis to produce liquid “bio-oil” is one such option under evaluation as is torrefaction (www.thermalnet.co.uk).
4. New packaging and handling systems need to be developed with lower capital, energy and operating costs than the current pellet and briquette systems for straw, wood chips, sawdust etc.
5. Overall integration and improved infrastructure and handling systems need to be developed in order to ensure the timely delivery and storage of large-quantities of feedstock to 2nd-generation processing facilities, while maintaining product quality as much as possible and avoiding losses from spoilage and waste.

4 Conversion Processes

At present ethanol from ligno-cellulosic feedstocks remains at the late RD&D stage with pilot plants supplying less than 0.1% of world ethanol production (Fig. 13). Several new demonstration plants are under construction but full commercial scale plants are yet to be built, although the beginning of serious commercial investment was evident during 2007. In the US funding of USD 385 M has been 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 has been provided for demonstration bio-refinery plants to produce a range of products and a further USD 375 M granted to three specialist 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.

The private sector, including several biotechnology companies such as Novozymes, is also investing heavily including in major RD&D programmes. Other financiers and venture capitalists have also invested in the construction of several 2nd-generation pilot and demonstration plants around the world. Several oil companies have also invested in research including:

- Chevron - USD 40M 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); and
- ConocoPhillips – USD 22.5M over 8 years to Iowa State University.

Several technological conversion routes exist for producing 2nd-generation liquid or gaseous biofuels from solid biomass (Table 5). However, none have yet reached the fully commercial stage, hence no clear technology leader or pathway has emerged. The bio-refinery concept, usually based on either thermo- or bio-chemical routes, is where biofuels are produced from single or multi-feedstocks along with one or more co-products, as well as possibly heat and power produced for use on site and/or for export. The concept of producing small quantities of high value products (e.g. chemicals) and larger quantities of low value products (e.g. biofuels) theoretically maximises returns from the biomass feedstock by improving economic performance in the same way that oil refineries do for crude oil today.

Table 5. Classification of 2nd-generation* biofuels

Biofuel group	**Specific biofuel**	**Biomass feedstock**	**Production process**
Bioethanol	Cellulosic ethanol	Ligno-cellulosic materials.	**Advanced enzymatic hydrolysis and fermentation
Synthetic biofuels	Biomass-to-liquids (BTL) Fischer-Tropsch diesel (FT) Synthetic diesel Biomethanol Heavier alcohols (butanol and mixed) Dimethyl ether (DME) P-series* (ethanol + MTHF etc)	Ligno-cellulosic materials.	***Gasification and synthesis
Biodiesel (hybrid of 1st and 2nd)	NExBTL H-Bio Green pyrolysis diesel* Algal oil*	Vegetable oils and animal fats. Ligno-cellulosic materials. Algae	Hydrogenation (refining) ***Pyrolysis Cultivation
Methane	Bio synthetic natural gas* (SNG)	Ligno-cellulosic materials.	***Gasification and synthesis
Bio hydrogen	Hydrogen	Ligno-cellulosic materials.	***Gasification and synthesis or **biological processes.

*Some fuels listed can be classified as “advanced” biofuels - see Part C).

***Bio-chemical route*: After comminution of the biomass feedstock and pre-treatment, ethanol can be produced by the hydrolysis of ligno-cellulosic raw materials, the fermentation of the extracted sugars followed by distillation and formulation to give the final fuel product. Fermentation of glucose sugars is mature commercial technology, but the hydrolysis of agricultural residues and woody biomass and the fermentation of pentose sugars still need further development.

****Thermo-chemical route*: - indirect liquefaction methods requires the biomass to be first pyrolysed to bio-oil, or gasified and the product gas cleaned and processed to form synthesis gas (mainly CO and H_2).This gaseous mixture can then be used in a commercial chemical process to synthesise a range of liquid biofuels including methanol, Fischer-Tropsch diesel, DME (dimethyl ether) or as gaseous methane or hydrogen fuels.

On-going research at all levels (laboratory, pilot plant and demonstration plant) is needed to perfect processes and technologies, with tailoring of the processes to different feedstocks. It is thus not clear at this stage, which feedstocks, processes and pathways might yield the least-cost biofuels, or have the greatest potential for cost reductions over time. There is no obvious technological solution and RD&D to enable comparisons of a range of options will be needed.

4.1 *Bio-chemical route*

Interest in ethanol from ligno-cellulosic feedstocks is not new, and there has been considerable research into the development of bio-chemical pathways over the last two to three decades. In Norway, a large wood processing company, Borregaard (www.borregaard.com) has been operating a spruce log bio-refinery for many years with ethanol as one product. Since the company aims for the high values products, from 1 t of dry woody biomass, only 50kg of ethanol is produced. The 400kg of cellulose co-product is sold for speciality purposes but in theory could also be used to produce more ethanol if the small world market for speciality cellulose became less competitive. In Sweden, as well as a 55 Ml/yr cereal ethanol plant already operating, a dilute acid hydrolysis pilot plant in Örnsköldsvik has produced 18 Ml/yr of ethanol since 2004 from various forest material feedstocks supplied from a nearby pulp mill. So the technical feasibility of producing ethanol from ligno-cellulosic feedstocks has long been proven, but large volume, commercial-scale production has not been feasible due to the relatively high costs. However, with continued improvements to conversion technologies, the focus on the future pricing of carbon emissions, and high energy prices, commercial-scale production has become more viable. The present main challenges remain the technical hurdles to low cost production.

In principle, the key steps involved are similar to those for current ethanol production that converts grain starch to ethanol. However, each step presents a significant technical challenge when ligno-cellulosic feedstocks are used, because:

1. the strong bonds in ligno-cellulosic feedstock require pre-treatment so that the polysaccharides can be accessed for conversion;
2. cellulose, unlike starch, is not hydrolysed by conventional enzymes and requires the application of sophisticated (hitherto expensive) cellulase enzymes;and
3. novel micro-organisms are required to ferment the xylose sugars extracted from the hemicelluloses since common yeasts will not work

It is only with recent advancements in biotechnology that improved micro-organisms and enzymes have been designed with sufficient activity for commercial cellulose hydrolysis to be considered credible.

Process overview and potential ethanol yields

Bio-chemical conversion uses biological agents, specifically enzymes or micro-organisms, to carry out a structured deconstruction of the ligno-cellulose into its base polymers and to further break down cellulose and hemicellulose into monomeric sugars including glucose and xylose (Fig. 18). These sugars can then be fermented into ethanol. Feedstocks are based upon agricultural and forest biomass (either residues or dedicated crops) but could also include the potential recovery of biomass from urban municipal solid waste (MSW) streams.

The bio-chemical platform consists of three main process elements - pretreatment, enzymatic hydrolysis, and fermentation. Process steps also include feedstock harvesting, handling, recovery and transport; comminution of the biomass to give small and homogeneous particles; fractionation of the polymers; separation of the solid lignin component; and end product recovery. The cellulose undergoes enzymatic hydrolysis to produce hexoses such as glucose. Pentoses, mainly xylose, are produced from the hemicellulose, thereby fully utilizing the feedstock. This theoretical configuration identifies a number of potential products but it may be that different industries will select different products and markets as a focus, in which case actual bio-refineries would likely produce a more limited selection of outputs (see Part B).

It is estimated that ethanol yields from the bio-conversion of ligno-cellulosic feedstocks range between 110 and 300 l/t dry matter (Table 6) (Mabee *et al.*, 2006; ORNL, 2006). Typical small cereal straw collectable yields of 3-5 dry t/ha and for maize (corn) stover, 4-6 dry t/ha, would result in ethanol yields per hectare varying widely between 350 to 1600 l/yr. Since most crop residues only have low economic value (when used for animal feed, bedding, composting or heating) and also often produce a problem of disposal with associated costs, cereal crops have been bred and managed historically to reduce the straw and stover yields. Once there is a value for ligno-cellulosic feedstocks however, these yields per hectare could be easily increased. Collectable forest residue yields vary widely with tree species, age at harvest, growing conditions etc. but when calculated on a dry t/ha per year basis, would be in a similar range to crop residues.

Figure 18. Ethanol production from ligno-cellulose via the bio-chemical route

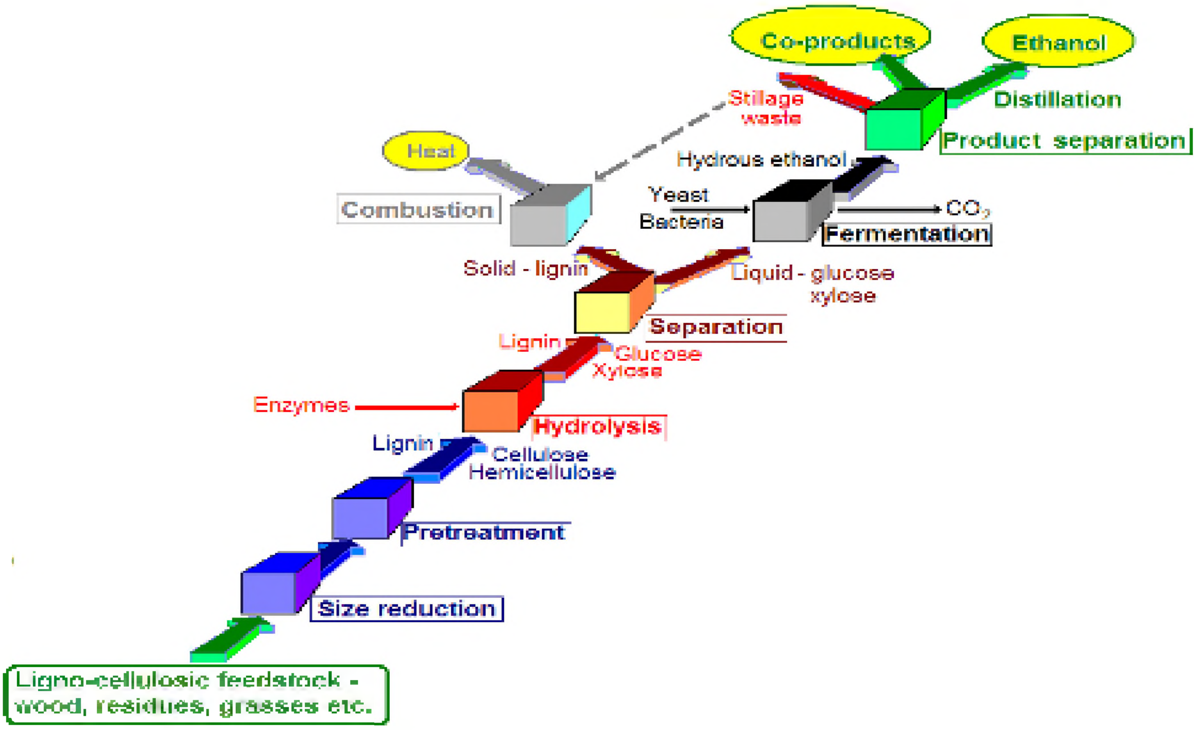


Table 6. Typical ethanol and energy yields recoverable from agricultural (straw, stover) or forest (wood) residues.

	Ethanol yield (litres / dry t)		Energy yields* (GJ ethanol /dry t)	
Feedstock	**Low**	**High**	**Low**	**High**
Agricultural residues	110	270	2.3	5.7
Forest residues	125	300	2.6	6.3

* *Based on 21.1 MJ/l ethanol lower heating value (23.6 MJ/l higher heating value).*

Given the energy content of ligno-cellulose is around 20GJ /dry t, the process conversion efficiency of 1 tonne of feedstock to give an energy yield of 2.3-2.6 GJ of liquid biofuels at the low end of the range is only around 12-15%. At the high end of the range, 5.7 -6.3 GJ of biofuels is obtained, being closer to 35% efficiency. This reflects the theoretical maximum conversion efficiency possible based on a ligno-cellulosic material containing 70% carbohydrates and obtaining virtually complete conversion of carbohydrate-to-ethanol (with a 51% efficiency). High efficiency conversion has been successfully achieved under laboratory conditions, but whether possible under industrial conditions is uncertain. The overall energy efficiency of the conversion process could be improved by combusting the lignin to provide process heat, or possibly by using some of the carbohydrate component for purposes other than for ethanol production.

Substantial amounts of CO_2, waste water effluent and solid residue consisting of lignin, leftover carbohydrates, proteins and cells are also formed in the process. About one third of the initial raw feedstock material by weight ends up in this residue. It has a relatively high energy content and is combusted, can produce considerable amounts of heat and electricity. However, since the optimal utilisation of the major co-products is essential for the economy of the process, upgrading the solid residue to produce high value bio-chemicals or bio-materials should also be evaluated.

An overview of the technology status of each of the sub-processes is given in Table 7.

Table 7. Status of each sub-process involved in bio-chemically converting ligno-cellulose to ethanol.

Sub-process	Objectives	State of development
Pretreatment	Properly size the material. Produce ideal bulk density. Remove dirt and ash. Rapid depressurisation to explode fibre. Open the fibre structure.	Demonstration/commercial - but needs optimisation for different feedstocks and downstream processing.
Fractionation	Cyclone to separate solids from vapours.	R&D.
Enzyme production	Cost and processing rate are key factors.	Commercial -but needs further cost reductions to reach USD 0.02-0.03 /litre of ethanol.
Enzymatic hydrolysis	Produce C6 and C5 sugars. Reduce viscosity.	Early demonstration.
Hexose fermentation	Standard yeast	Commercial.
Pentose fermentation	Standard yeast is not suitable. New micro-organisms dictate yield and rate. This affects feedstock demand / unit of product and capital expenditure on plant.	Research/pilot plant moving towards commercialisation.
Ethanol recovery	Distillation to obtain 99.5% ethanol.	Commercial.
Lignin recovery and applications	Separate lignin and other solids. Combust for heat and power or to produce biomaterial co-products.	Research/pilot plant -co-products to improve economic performance.
Waste treatment		Research/commercial

Pretreatment methods and developments

Designed to optimise the biomass feedstock for further processing, the aim of a pretreatment process is to expose cellulose and hemicellulose for subsequent enzymatic hydrolysis, and is one of the most critical process steps. The key performance goals for pretreatment technologies and processes (Tamutech, 2007) are to:

- maximise the yields of both hexose and pentose sugars in downstream processing;
- facilitate the recovery of lignin for later combustion;
- minimise the production of chemicals that inhibit downstream enzymatic processing such as furfural and hydroxymethyl furfurals;
- be flexible enough to cope with varying ligno-cellulosic feedstocks;
- avoid expensive biomass comminution (size reduction by grinding, milling, pulverising etc.);
- utilise low cost chemicals and minimise waste streams; and
- have low energy requirements and low capital costs.

Due to the strong bonds of the ligno-cellulose structure, pretreatment processes are generally severe and represent a significant cost element of the whole pathway. So optimisation of this process is important. The aim is to open up the cellular structure of the plant material so that the cellulose is exposed to the enzymes that can then start hydrolysing the polysaccharide polymers into sugars. Many technologies have been studied, but none seem to be ideal and some researchers are therefore revisiting older (non-enzymatic) methods, such as hydrolysis with strong acids. Steam explosion under mildly acidic conditions is currently the state-of-the-art pretreatment technology.

In sugar- and starch-based processes, pretreatment can be as simple as pressing sugarcane or sugar beet to extract sucrose, or shucking corn cobs in order to separate the starch-rich kernels for further processing. When dealing with ligno-cellulosic feedstocks however the pretreatment step uses techniques analogous to traditional mechanical pulp processing where the lignin is either softened to release individual cellulosic fibres and/or removed to create a low-lignin pulp. Traditional mechanical pulping isolates fibres through a physical refining process which leaves much of the intact lignin present in the resulting pulp.

A number of different pretreatment methods to improve separation and subsequent hydrolysis as well as co-product generation[8] include:

- water-based treatments (e.g. flow through, partial flow through, steam-explosion);
- acidic treatments (e.g. dilute or concentrated acid including H_2SO_4, controlled pH);
- alkaline treatments (e.g. ammonia freeze explosion (AFEX) and ammonia recycle percolation (ARP); and
- organic pulping treatments (e.g. organosolv using acetic acid or ethanol).

The pretreatments can be classified as biological, physical, chemical or a combination.

- *Biological* pretreatment typically utilise wood-degrading fungi to modify the chemical composition of the feedstock. In essence, soft and brown rot fungi primarily degrade the hemicellulose while white-rot fungi more actively attack the lignin. A major disadvantage of biological/fungal treatments is the typical residence time of 10-14 days, which reduces the commercial potential of these approaches. For these reasons, biological pretreatments are considered to be less attractive commercially.
- *Physical* pretreatment involves mechanical breakdown of the biomass feedstock by hammer- or ball-milling into smaller particles to increase the rate of subsequent enzymatic hydrolysis. Physical treatments improve hydrolysis yields by disrupting cellulose crystallinity and increasing the specific surface area of the feedstock rendering it more accessible to attack by cellulases (Mais *et al.* 2002). Physical pretreatment is relatively insensitive to the differing physical and chemical characteristics of the biomass but the processes do not result in lignin removal. Hence the ability of cellulases to access the cellulose that remains is limited and inhibited (Berlin *et al.,* 2006). Furthermore, the high energy inputs required mean that physical pretreatment has yet to be proven economically viable at the commercial scale.
- *Chemical* pretreatment pulping processes in commercial use today involve the removal of lignin to produce pulp for various paper products. Although these processes could be considered as potential pretreatment methods they are optimised to maintain the fibre/strength integrity of the pulp, rather than to increase accessibility to the cellulose. The relatively high value of pulp can justify the high capital and operating costs of chemical pulping, whereas lower-value biofuels must seek cheaper pretreatment options. Acid and alkali elements as used in pretreatment that have been assessed to date have had the primary goal of enhancing enzyme accessibility to the cellulose by solubilising the hemicellulose and lignin, and to a lesser degree decreasing the degree of polymerisation and crystallinity of the cellulosic component. Pretreatments that reduce cellulose crystallinity include mild swelling agents such as NaOH, hydrazine and anhydrous ammonia, and extreme swelling agents such as sulphuric or hydrochloric acid (Wood & Saddler, 1988).
- *Combination pretreatment* using 'physio-chemical' processes have received considerable attention in recent years. AFEX, organosolv pulping and steam pretreatments are attractive because of their ability to generate readily hydrolysable substrates from the ligno-cellulosic biomass. Treatments that reduce the lignin content of the substrate include organosolv pulping, where the pulping liquor used could be one of a range of organic solvents including ethanol, glycerol, or ethylene glycol.

Several aspects that affect the viability of the overall process include the handling and preparation of the feedstock prior to the pretreatment step, the need to minimise processing costs, and the need to maximise the value of co-products derived from the hemicellulose and lignin streams. For example, if a process has a requirement for very fine, uniform feedstock with a maximum particle size of less than 10 mm, this will have a significant impact on the overall economic viability of the

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[8] Currently being assessed through the USDOE funded Biomass Refining programme, *Consortium for Applied Fundamentals and Innovation* (CAFI), linking researchers from universities in the United States and Canada, www1.eere.energy.gov/biomass/technology_evaluation

overall process because of the energy requirements to produce this fine material (Wooley *et al.* 1999).

Various pretreatments have been shown to be better suited for specific feedstocks. For example, alkaline-based pretreatment methods such as lime, AFEX, and ARP processes can effectively reduce the lignin content of agricultural residues but are less satisfactory for processing recalcitrant substrates such as softwoods (Chandra *et al.*, 2007). Acid-based pretreatment processes have been shown to be effective on a range of ligno-cellulosic substrates, but are relatively expensive and not suitable for all feedstocks (Mosier *et al.*, 2005).

A summary of the conditions and chemicals used in different pretreatment methods is given in Table 8 (Wyman *et al.*, 2007). It is unlikely that one pretreatment process will become standard as each method has its inherent advantages/disadvantages, particularly as related to specific feedstocks (Table 9).

Table 8. Summary of pretreatment systems for ligno-cellulosic feedstocks.

Pretreatment system	Temperature (°C)	Reaction time (minutes)	Chemical agent	Chemical load (%)
Dilute acid	160	20	H_2SO_4	0.49%
Flow through	200	24	--	
Partial flow	200	24	--	
Controlled pH	190	15	--	
Steam-explosion	190	5	SO_2	3%
AFEX	90	5	Anhydrous ammonia	100%
Organosolv	200		Ethanol	50%
ARP	170	10	Ammonia	15%
Lime	55	4 weeks	Lime	0.08 g CaO / g biomass

The wide range of of biomass pretreatment technologies are at varying stages of development. Given their pre-commercial stage, selecting the best option is difficult. There is potential for improvement given that current processes do not meet cost and performance goals. The main problem is that they require significant capital investment and have quite high operating costs. They are thus a major cost component of the bioethanol production process. The capital cost of a dilute acid pretreatment process for a 200 Ml bioethanol plant is in the order of USD 25 million with dilute acid more costly and lime even more so (Wyman et al., 2007; Eggeman & Elander, 2005).

Pretreatment technologies may emerge which are suitable for specific feedstocks and situations as individual pretreatment technologies have different characteristics with varying strengths and weaknesses. The dilute acid, concentrated acid and steam explosion processes, are closest to commercialisation with steam explosion considered as the state-of-the-art.

Feedstock characteristics in relation to pretreatment.

Since different feedstocks respond in varying ways to different pretreatments the optimal approach differs. For example, laboratory testing has shown that the recovery of glucose, hemicellulose sugars and lignin from softwood after steam-explosion pretreatment can be significantly lower than for agricultural residues or hardwoods such as poplar. The lower lignin recovery may serve as further evidence of the difficulty that softwood poses including the tendency found in the steam-explosion pretreatment process for lignin redeposition and condensation on the surface of fibres. This problem is one of the primary drivers for assessing alternative pretreatment methods for softwoods. Complicating this is that some softwoods, such as Norway spruce (*Picea abies*), may respond to steam-explosion in a manner closer to agricultural residues, consequently reducing the need for a costly delignification stage (Boussaid *et al.* 1999).

Sugar recovery.
The low glucose and hemicellulose sugar concentrations found with some pretreatments is a problem because a significant amount of the sugars that could be utilized in ethanol production, as well as in other products, can be lost. This may in part have to do with the physical architecture of the pretreatment process and the fact that soluble hemicelluloses are sometimes destroyed or escape in solution in the wash from this system. A goal of the pretreatment should be to introduce the least amount of process complexity in order to add minimal cost.

Table 9. Advantages and disadvantages of optional pretreatment systems

Pretreatment system	**Advantages**	Disadvatages
Dilute acid	The hemicellulose fraction is hydrolysed into pentose sugars and the downstream hydrolysis of the cellulose is improved	Requires expensive reactor components and downstream acid neuatralisation which increase capital costs. High temperatures can degrade sugars, resulting in lower yields and elements toxic to fermentation organisms. Can be addressed with two temperature process, or use counter-current reactor.
Concentrated acid	Allows lower temperature. Reactions that reduce degradation of sugars are reduced.	Expensive. Requires acid to be recovered and re-used to become more competitve.
Steam-explosion	Well known route (for fibreboard), Works well for hardwoods. Hemicellulose partialy hydrolysed. Adding dilute acid can raise pentose sugar yields.	Requires after-wash to remove degraded components, leading to loss of solulibised sugars. Some inhibitory by-products possible.
Flow/Partial flow through	May require little feedstock reduction. Dissolves hemicellulose and makes celluose fraction receptive to hydolysis.	As with steam explosion, some degraded products formed that are toxic to fermentation organisms. Still at development stage.
AFEX	Similar to steam explosion, except using ammonia, but hemicellulose fraction is not significantly solubilised to sugars. Lignin- hemicellulose bonds are ruptured and some hydrolysis of the hemicellulose. Greatly reduced production of degraded products that are toxic to downstream fermentation microorganisms. Ultimate sugar yields could be high.	Significant capital costs due to need to capture and recycle the ammonia.

Chemical usage.
Pretreatment costs may be reduced by lowering chemical inputs. Ethanol organosolv has potential for this because there is the possibility of recycling the pulping liquor in a manner similar to that carried out in the commercial Kraft pulping process. Liquor recovery may be combined with product recovery, thereby reducing process costs and lowering chemical usage. However, the presence of ethanol in the hydrolyzate may also act as an inhibitor in the hydrolysis and fermentation processes. By comparison, acid or alkali digestion of portions of the ligno-cellulose matrix result in a high or low-pH pulp, which must be washed before further processing, thereby increasing water use and increasing costs. When pretreatments and feedstocks are matched for

optimal pulp qualities, it has been shown that optimisation of pretreatments can reduce lignin condensation, chemical usage and cost for delignification, and partially reduce lignin inhibition (Tu *et al.*, 2006). Post-treatments may also be a way to reduce chemical consumption. For example, between 35.5% and 43.2% of lignin may be removed from steam-exploded Douglas-fir through the application of only 1% NaOH (w/w) at room temperature (Pan *et al.*, 2006). This post-treatment was effective in enhancing enzymatic hydrolysis yield from 50 to 85%.

Fractionation.
One characteristic of effective pretreatment is the separation of the base components of cellulose, hemicellulose and lignin to facilitate industrial processing of these components and to reduce inhibitors. Successful separation facilitates the generation of heat and power from using the lignin fraction, allowing cellulose and hemicellulose to be converted to ethanol or other co-products. The most effective fractionation will likely be carried out by combining optimised pretreatments with enzymatic hydrolysis and fermentation (Mabee *et al.* 2006).

Enzymatic hydrolysis.
The majority of the proposed commercial-scale biomass-to-ethanol processes announced to date plan to use enzymes rather than acids), in order to facilitate the fast, efficient, and economic bioconversion of cellulose to glucose. Acid hydrolysis is considered to be the more expensive option. Enzymatic hydrolysis is also attractive because, in theory, it produces better yields than acid-catalyzed hydrolysis and it requires less chemical input, which should improve overall economic performance. Enzymatic hydrolysis of starch, as used in 1^{st}-generation ethanol production (Fig. 5), requires a single family of amylases. By comparison, the challenge is much more significant for ligno-cellulose since the effective hydrolysis of the interconnected matrix of cellulose, hemicellulose and lignin requires a number of cellulases, those most commonly used being produced by wood-rot fungi such as *Trichoderma*, *Penicillum*, and *Aspergillus* (Galbe & Zacchi, 2002). In addition, these cellulases must overcome a number of challenging barriers, including:

- unreactive crystalline cellulose,
- presence of lignin blocking reactive sites,
- low substrate surface area,
- low hydrolysis rates,
- substrate inhibition, and
- product inhibition.

Cellulose is intrinsically resistant to enzyme attack in nature and is further protected in ligno-cellulosic biomass by the lignin and hemicellulose. The most promising strategy to facilitate enzymatic hydrolysis of cellulose is therefore to integrate ethanol production into a bio-refinery scheme in which the lignin, hemicellulose and extractive components of the ligno-cellulosic biomass are removed prior to the hydrolysis stage, and converted into valuable co-products to offset the costs of pretreatment and enzymes (see Part C). The identification of pretreatment processes that fit this paradigm remains a major focus of current R&D efforts as optimising the pretreatment techniques can aid in addressing the first three bullet points above (Galbe *et al.*, 2005; Eggeman & Elander, 2005).

Bacteria can also produce enzymes suitable for cellulose hydrolysis. Research is focussed on the ability of Asian longhorned beetles (www.RenewableEnergyWorld.com, 10 September, 2008) and termites to digest cellulose and identifying the cellulase genes present in their hind gut for potential commercialisation. Other anaerobic bacterial systems such as *Clostridium*, offer the potential of both cellulose hydrolysis and glucose fermentation in one step and genetically engineered bacteria that can function at higher fermentation temperatures are also being developed at Dartmouth College, US (Zabarenko, 2008).

Efficient hydrolysis of cellulose requires the synergistic activities of three groups of enzymes.

- *Endo-β-1,4-glucanases* are enzymes that hydrolyze accessible regions on cellulose chains and cleave the chains to provide new sites for other enzymes to interact.
- *Cellobiohydrolases* act on these sites and begin to remove successive cellobiose units (i.e. two joined glucose units).
- *β-glucosidase* is a specialized enzyme that hydrolyzes cellobiose to glucose.

The activity of hemicellulase and other 'accessory' enzymes that act to liberate the carbohydrate components of hemicellulose, which includes both pentose and hexose sugars, are still being explored (Berlin *et al.* 2006).

The US company Codexis specialises in adapting enzymes to create "super enzymes" capable of outperforming naturally occurring varieties in pharmaceutical applications and has recently partnered with Royal Dutch Shell Oil company to expand its work on enzymes for biofuels (www.codexis.com/wt/). The Canadian enzyme producing company, Iogen, has developed a process using a proprietary cellulase system based upon a genetically modified *Trichoderma* to produce straw based bioethanol.

Other challenges involved in enzymatic hydrolysis include:

- minimising the impact of inhibitors that reduce the effectiveness of enzyme activity;
- reducing the cost of enzymes, including by their recycling; and
- identifying whether separate or simultaneous saccharification and fermentation processes represent the least cost route.

Each of these issues is briefly discussed below.

Product inhibition.
One of the primary research goals is to optimise pretreatment in order to maximise yields of cellulose and hemicellulose while reducing the formation of inhibitors to the hydrolysis process that slow down the specific activity of an enzyme. For example Pan *et al.* (2006) showed that removal of between 35.5% and 43.2% of lignin from a steam-pretreated substrate was effective in enhancing the enzymatic hydrolysis yield from 50 to 85%. Inhibition of hydrolysis might be significantly reduced by selective removal or modification of the 'active' fraction of lignin. Berlin *et al.* (2006), showed that lignin interferes with enzymatic hydrolysis by binding to the enzyme, thus forming a triple complex of enzyme-substrate-inhibitor.

In addition, 'end-product inhibition' occurs where the products of hydrolysis (i.e. glucose) actually slow down the activity of the enzymes as they build up. In lignin-free feedstocks, end-product inhibition by glucose is the major factor restricting hydrolysis. End-product inhibition is a particular problem when feedstocks of high consistency are used to produce more concentrated glucose syrup for fermentation. End-product inhibition can be alleviated in a commercial bio-conversion process by using saccharification and fermentation simultaneously.

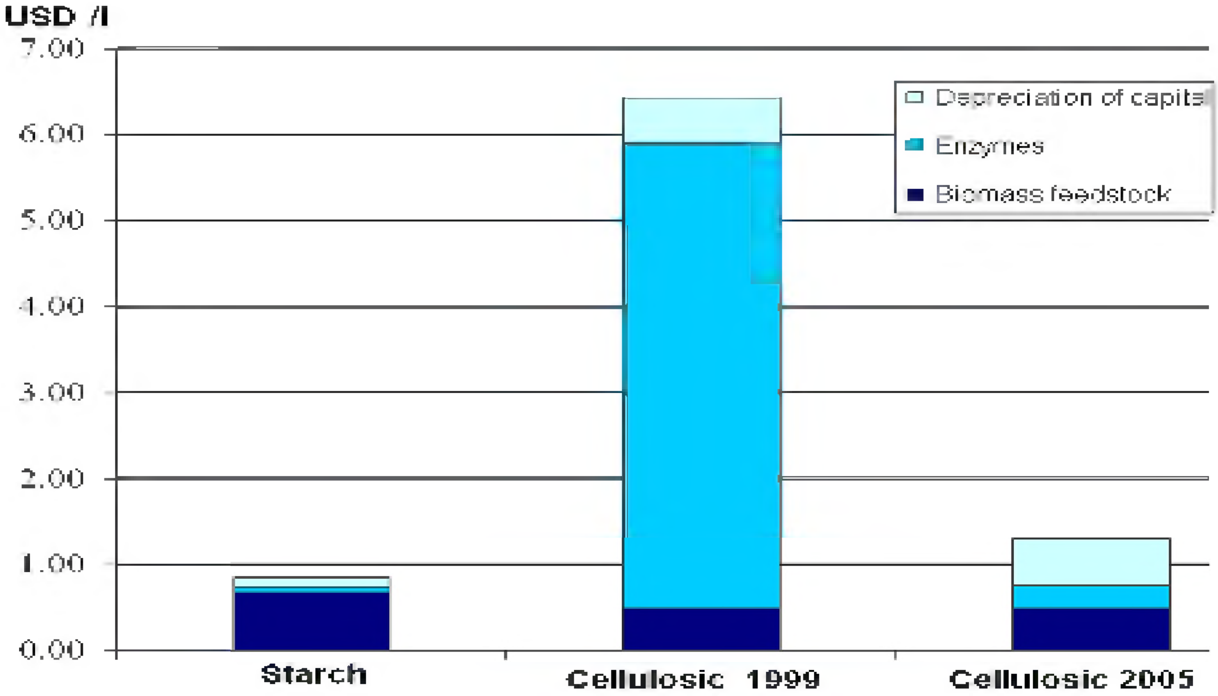
Enzyme costs.
Commercial cellulase preparations are typically deficient in *β-glucosidase* so require supplementing in order to relieve product inhibition caused by accumulation of cellobiose and other soluble sugars (Tengborg *et al.* 2001). This adds to the already substantial cost for enzymes. Although the cost of commercial cellulase preparations has been reduced by up to 20-fold in recent years, enzyme costs are still an obstacle to full-scale process commercialization.

In 1999, the USDOE-funded National Renewable Energy Laboratory developed a research programme to reduce the cost of enzymatic hydrolysis in association with Genencor and Novozymes. In early 2003, Genencor reported a 12-fold enzyme cost reduction of which around a 2.4 fold reduction of enzyme weight per litre of ethanol came from improving enzyme performance. Even higher cost reductions were achieved by streamlining the production process, switching to lower-cost inputs, and making savings on energy consumption. By early 2005, Novozymes reported a 20-fold enzyme cost reduction with a similar breakdown of improved enzyme performance and production cost savings.

An improvement in cost due to the pretreatment used was observed when the original substrate provided to the companies (known as 'old' pretreated corn stover (PCS)) was replaced with a 'new' dilute acid-PCS. Using the 'old' PCS, the enzyme cost was reduced from USD 1.42 to 0.12 /litre of ethanol, while with the 'new', the cost dropped from USD 1.00 to $0.07 /l (Novozymes, 2005; Fig. 19). However, further cellulose cost reductions will still be needed if ligno-cellulosic ethanol is to be competitive with gasoline, even if a carbon price is imposed and oil costs remain high. Another consideration is that this optimisation was targeted specifically at corn stover substrate, so further work is still required to adapt the findings for use on other forms of ligno-cellulosic. New enzyme packages will be needed for different biomass feedstocks and pretreatments. Researchers at VTT in Finland and Lund University in Sweden have looked at the design of thermophillic cellulase enzymes capable of operating at higher temperatures than conventional cellulases. These enzymes offer process benefits if they can achieve faster reaction rates and higher yields.

Enzyme recycling.
Enzymes can be utilised at lower costs if they are 'recycled' by treating multiple batches of feedstock using the same batch of enzymes. This can be achieved by the immobilisation of enzymes on an inert carrier. Normally, enzymes will bind to various components of ligno-cellulose during hydrolysis. Once attached, the enzyme is difficult to recover and typically is carried through the rest of the bio-conversion process. If the enzymes can be attached to a non-reactive substance prior to hydrolysis, they can then be recovered and recycled. Enzyme immobilisation also can result in improved thermo-stability so that the enzymes remain effective for a longer period. For example, the use of an epoxy-activated immobilisation support, *Eupergit C*, has been shown to immobilise a commercial *B-glucosidase* preparation, Novozyme 188 (Tu *et al*. 2006).

Figure 19. Production costs for starch and cellulosic ethanol in 1999 compared with the cost after enzyme and technology improvements by 2005.



Source: Novozymes, 2005
Note: Biomass feedstock costs were based on average costs in 2005 and adjusted according to the expected yields associated with each process. The average corn price was about USD 80/t in 2005/06 but has fluctuated widely since. Rising costs for corn would increase the "starch ethanol" column. The cost of ligno-cellulosic corn stover in 2005 was taken to be between $25-35/t delivered but this estimate may be low.

Eupergit C has been identified as one of the most useful carriers for covalent immobilisation of industrial enzymes because of its ability to stabilise protein conformation by multi-point attachment (Katchalske-Katzir & Kraemer, 2000). Conversion rates (sugar recovery as a percentage of theoretical maximum) remained steady at about 75% for the entire experiment when immobilised enzyme was utilized. This compared with enzymes applied without immobilisation when conversion rates dropped dramatically after the first hydrolysis to below 30% for the remainder of the experiment.

Simultaneous saccharification and fermentation.
Separate hydrolysis and fermentation (SHF) occurs when the enzymatic hydrolysis step is completely separated from the other stages of the process. In contrast, simultaneous saccharification and fermentation (SSF) is when hydrolysis is combined with the fermentation of the carbohydrate intermediates. By combining the hydrolysis and glucose fermentation units, not only

would the number of reaction vessels be reduced, but it would reduce the potential problem of inhibitors reducing the effectiveness of the hydrolysis reaction since any glucose sugars would be removed by the fermenting microbes. The challenge here is that this would necessitate micro-organisms that are effective in similar conditions, which is not the case for current *Saccharomyces* yeasts (which operate optimally at 37°C) and cellulases (which operate optimally at 55°C). There is therefore considerable interest in developing thermophillic enzymes that will ferment glucose and pentose sugars at temperatures required for hydrolysis conditions.

SHF offers more flexibility and makes it easier in theory to alter the process for different end products. However the two separate processes require additional engineering and cost more to build and operate. SSF has been found to be highly effective in the production of specific end products (Gregg *et al.,* 1998). Commercial scale ligno-cellulose saccharification can also involve continuous removal of soluble sugar products by ultra-filtration (Duff & Murray, 1996), thereby reducing end-product inhibition and improving performance.

Fermentation

A key goal for the commercialisation of ligno-cellulosic ethanol is that all sugars released during the pre-treatment and hydrolysis steps are fermented into ethanol. Once hydrolysed, hexoses can be fermented to ethanol using yeasts and bacteria such as *Zymomonas mobilis.* 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 (Weil *et al.*, 2002). For more than 20 years, research activities have been directed towards the development of improved micro-organisms for the fermentation of the pentose sugars. For cost effective processing, such organisms must be able to co-ferment both glucose and xylose streams together. Although C5 pentoses are generally more difficult to ferment, new yeast strains are being developed that can effectively use these sugars. Currently, there are no known natural organisms that have the ability to convert both these C6 and C5 sugars at high yields (Ragauskas *et al.* 2006) although there have been some claims towards this goal using GM micro-organisms. Significant progress has been made in engineering micro-organisms for the co-fermentation of glucose and pentose sugars, but their sensitivity to inhibitors and the production of unwanted by-products remain serious problems yet to be overcome if these systems are to become commercially viable.

One promising GM strategy has been to take ethanologen, a natural hexose, and add the pathways needed to convert other sugars. This has been achieved by adding pentose conversion to *Saccharomyces cerevisiae*, *Zymomonas mobilis*, *Klebsiella* and *E.coli* strains (Helle *et al.* 2004). The need to understand and manipulate ethanol and sugar tolerance and resistance to potential inhibitors generated in pre-saccharification treatments remains a scientific goal. Solutions to these issues will also need to accommodate the variability in biomass resources (Ragauskas *et al.* 2006). While pentose fermentation has been achieved on ideal substrates, (i.e. laboratory preparations of sugars designed to imitate a perfectly-pretreated feedstock), significant work remains to apply this to actual ligno-cellulosic feedstocks.

Lignin recovery.

For softwood, biomass lignin separation and utilisation is a critical issue in addition to the enzymatic hydrolysis step. For example, with steam pretreatment of softwoods a delignification stage is sometimes required in order to prevent lignin from acting as an inhibitor to enzymatic hydrolysis downstream in the process. Recent results indicate that other pretreatments, such as the organosolv pretreatment, may entirely avoid this stage (Pan *et al.* 2006). This “fractionating pretreatment” process has gained new relevance for biomass pretreatment because the economic necessity for multiple co-products has become increasingly evident. It produces a particularly high-quality lignin fraction with potential for several industrial applications and hence has the potential to reduce the overall process cost. By comparison, other pretreatments such as steam-explosion technology may have lower potential for lignin recovery, but have lower operational costs.

Process Integration

Due to the large number of individual processes in the overall conversion of ligno-cellulosic biomass into bioethanol, there remains considerable potential for process integration. This could have benefits in terms of lower capital and operating costs, as well as ensuring the optimum production of valuable co-products. Given that development is still at the pre-commercial stage, it may take some time to arrive at the most efficient process pathways and systems. Although improved process integration and simplification should result in reduced costs, this may not necessarily be the least cost route for ethanol production, since the production of valuable co-products might, under some circumstances, warrant a larger number of linked, but separate, processes.

A two-stage fermentation process, where pentose and glucose are fermented separately, maybe required to achieve the most effective fermentation of both sugars. Although, this maybe a drawback, it can have advantage as the separate processing of the sugars enables fine-tuning of the process to maximise yields and provides the opportunity to produce valuable co-products. For example some of the C5 sugars could be processed into xylitol or levulinic acid.

A potential area of process integration is if the pentose fermentation unit could be configured downstream of the glucose fermentation unit, provided that the presence of pentose sugars does not inhibit glucose fermentation and there was intermediate removal of the bioethanol product prior to the pentose sugar fermentation unit. Another option for process consolidation could be achieved by using thermophillic bacteria that can ferment both glucose and pentose sugars, known as simultaneous saccharification and co-fermentation (SSFC).

Taking integration to its logical conclusion would result in a system where all the enzymes required are produced by a single microbial community in a single reactor operating under the same conditions. This could potentially have considerable cost advantages but represents a significant research challenge. Although such technology is far from being commercially proven or available, the potential cost reductions would be significant. Current estimates are that, if successfully developed, an integrated bioprocessing system could potentially produce bioethanol for USD 0.15 /l assuming a feedstock cost of USD 40 /tonne.

As mentioned, there is potentially a trade-off between increased process integration to maximise ethanol yield at low cost and those that reduce the potential of generating value from a multi-product, biorefinery approach. Which process pathway and level of integration that minimises overall ethanol production costs, taking into account the value of any co-products, is not currently clear. In any event, it is likely that this will vary depending on the feedstock and location, which could affect the value of co-products.

Bio-chemical route R&D

Fundamental research into the dynamics of bioconversion has focused on the cost of enzymatic hydrolysis, which must be tailored to the complexity of the ligno-cellulosic matrix. The most fundamental research issues for the bioconversion platform include:

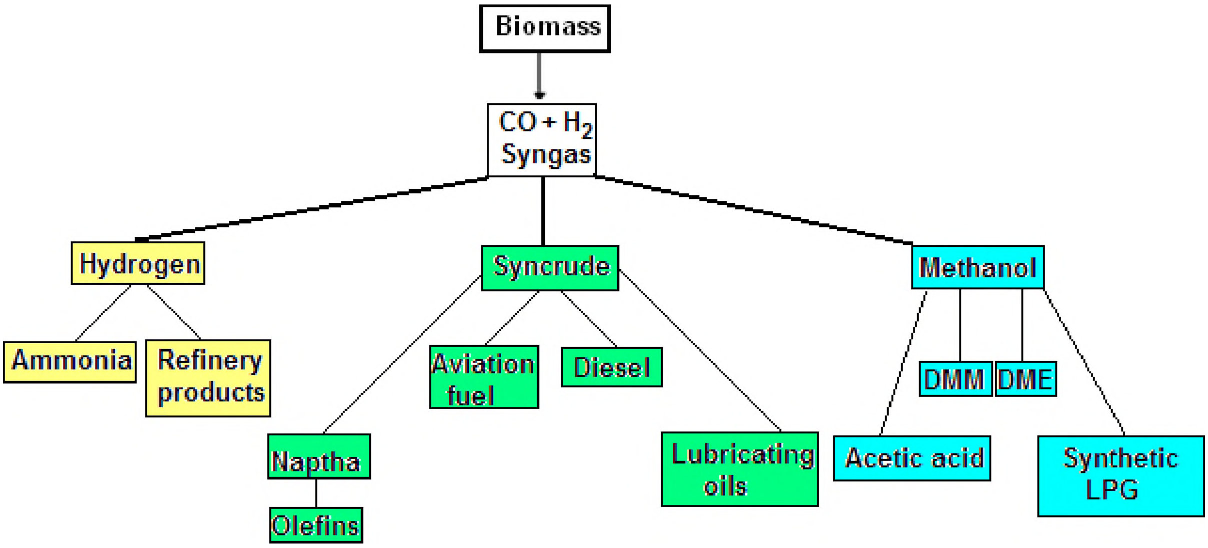
- producing low-cost homogeneous feedstocks, (with local pyrolysis of bulky biomass material into a concentrated liquid, then transporting it to the processing plant could be one solution);
- improving the effectiveness of the pretreatment stage to optimise biomass for enzymatic hydrolysis and a number of non-traditional pulping techniques are being examined;
- decreasing the cost of the enzymatic hydrolysis stage by studying the dynamics of bioconversion which must be tailored to the complexity of the ligno-cellulosic matrix, as well as improving their efficiency;
- decreasing the costs by recycling of enzymes;
- improving overall process efficiencies by capitalizing on synergies between various process stages;
- fermentation of pentose sugars in order to obtain maximum biofuel production;
- improving the process economics by creating useful co-products that can add revenue; and
- developing methods for handling, treating, using or disposing of the residues from the process.

4.2 Thermo-chemical route

In contrast to the bio-chemical approach, the thermo-chemical route for biofuel production is largely based on existing technologies that have been in operation for a number of decades. Historically the approach has focused on the conversion of coal-to-liquid fuels and chemicals, but the most recent activities have been in using stranded natural gas resources. This section covers biomass-to-liquids (BTL).

Basically the thermo-chemical route involves the production of a synthesis gas (syngas), which is cleaned, before usually being passed through the Fischer-Tropsch (FT) process to create a range of liquid fuels suitable for aviation and marine applications as well as chemicals, but primarily synthetic diesel. The advantage of this approach is that the FT process is an off-the-shelf technology that is available commercially today as used in the SASOL coal-to-liquid processes in South Africa for example. The key challenges remaining relate to the gasification of the biomass, producing a clean gas of an acceptable quality and the high intrinsic cost of the process. A range of potential fuels can be derived from syngas depending on the processes used (Fig. 20). There are also other less common thermo-chemical routes as discussed in Part C). For example the German company Lurgi has developed a different approach in producing methanol from syngas then converting it to long chain hydrocarbons.

Figure 20. Fuel and chemical processing options from synthesis gas feedstock.



DMM = dimethoxy methane; DME = dimethyl ether

Synthetic and FT diesel from BTL

In the thermo-chemical route, dry ligno-cellulosic biomass feedstocks from agriculture, forests or municipal solid waste are initially subjected to a severe heat treatment in the presence of a controlled amount of air (or oxygen) so that gasification takes place to produce syngas. This "synthesis gas" consists of a mix of mainly CO and H_2 with some CO_2, methane and higher carbon compounds. The gases generated are cleaned by removing the tars, then filtered and the clean gas collected ready for use (Fig. 21). It can be used as a chemical building block when the component gases are ultimately reassembled into a range of fuels or industrial chemicals including long-carbon chain synthetic diesel and aviation fuels. This BTL process combines elements of pyrolysis, gasification, and catalytic conversion. Pyrolysis (heating in the absence of oxygen to produce mainly bio-oil) and gasification can produce energy carriers for the generation of electricity and heat independently of catalysis. The potential product range can be increased when the entire platform is implemented in a bio-refinery (Part C).

Fischer-Tropsch synthesis produces a wide range of hydrocarbon products, as well as releasing a large amount of heat from the highly exothermic synthesis reactions. Reactor design imporovements and process advances have focussed on heat removal and temperature control. Development of the catalysts used in the FT process has focused on improved lifetime, activity, and selectivity. Single-pass FT synthesis always produces a wide range of olefins, paraffins, and oxygenated products such as alcohols, aldehydes, acids and ketones with water as a by-product. The proportions of these products can be varied by adjusting temperature, pressure, feed gas composition (ratio of H_2/CO), catalyst type and catalyst composition. In addition, product upgrading is possible after their production to maximise the value and revenue.

As a generality:

- high-temperature FT synthesis leads to the production of synthetic gasoline and chemicals;
- low-temperature FT synthesis leads to the production of waxy products that can be cracked to produce synthetic naphtha, kerosene or diesel fuel.

The diesel produced from FT synthesis is a high-quality product with an energy density similar to conventional petroleum diesel, a high cetane number and low sulphur content (Table 10). The possibility of producing naptha and other middle distillates is also very attractive. Given the likely increasing trend towards heavier crude oils in the global production mix of crudes, such lighter products offer attractive properties.

***Figure 21.** Thermo-chemical conversion process to produce synthesis gas from ligno-cellulosic feedstocks*

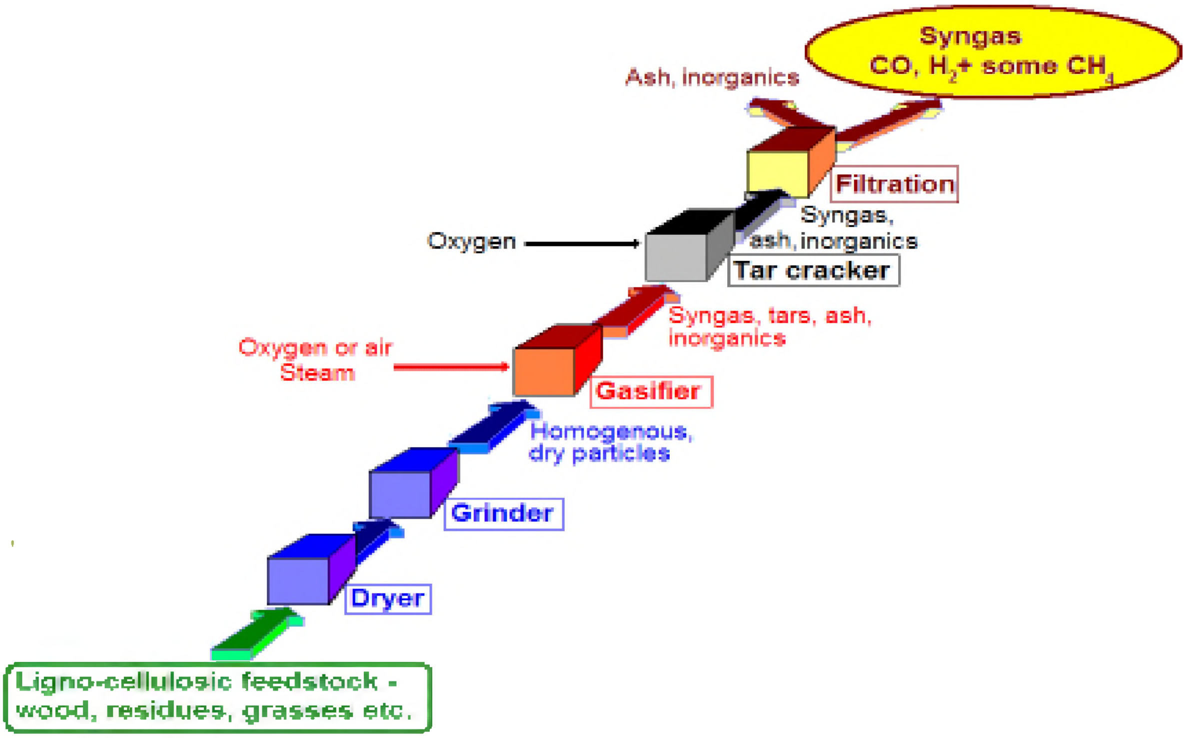


***Table 10.** Comparisons of properties of mineral oil and BTL-derived fuel products*

Fuel	**Chemical forumlae**	**Energy content (MJ/l)**	**Density (kg/l)**	**Octane number**	**Cetane number**	**Suitability as chemical feedstock**
Gasoline	C_4 - C_{12}	31.2-32.2	0.72-0.77	90-95	-	No
Methanol	CH_3OH	15.4-15.6	0.79	110-112	-	Yes
Mineral diesel	C_{15}-C_{20}	35.3-36.0	0.82-0.84	-	45-53	No
BTL diesel	C_{12}-C_{20}	33.1-34.3	0.77-0.78	.-	70-80	No
Naptha	C_5-C_9	31.5	0.72	50	-	Yes
BTL Naptha	C_5-C_9	31.5	0.72	40	-	Yes
Dimethyl ether	CH_3OCH_3	18.2-19.3	0.66-0.67	-	55-60	Yes
Hydrogen	H_2	8.9	0.074	106	-	Yes

Source: Kavalov, 2005

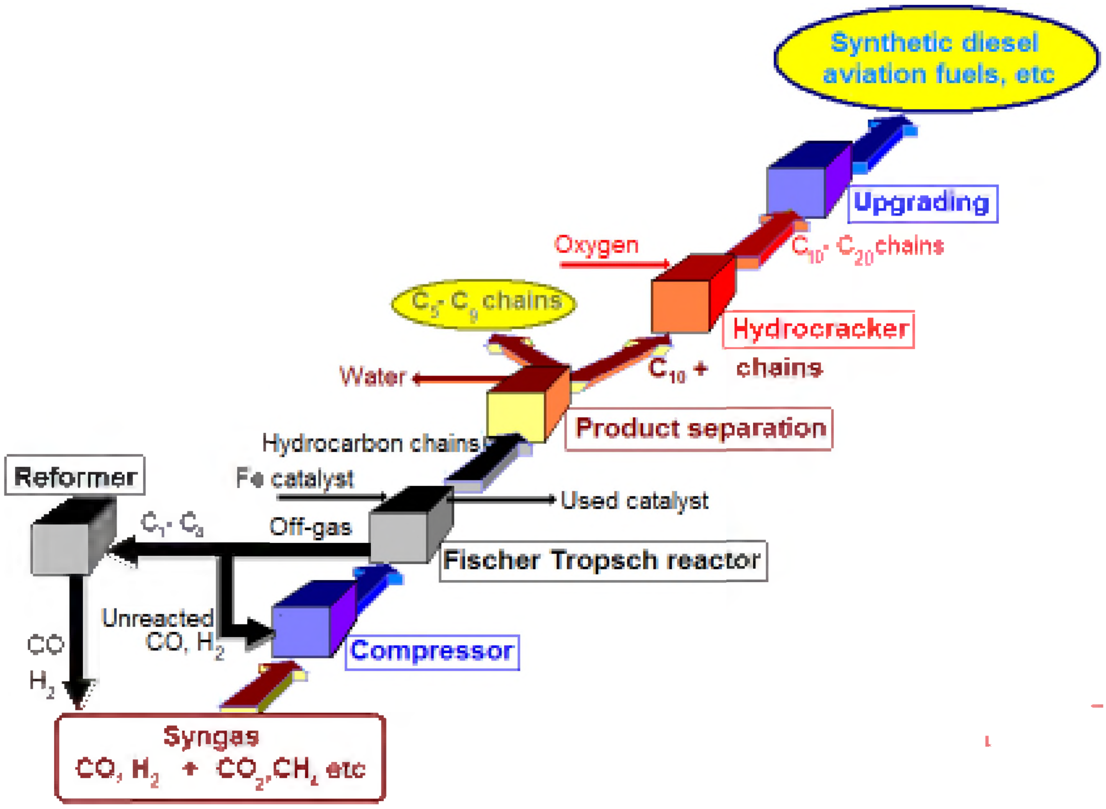
Stages in the thermo-chemical route

The stages during the syngas production process (Fig. 21) are first described, followed by those during the conversion of syngas to synthetic biofuels (Fig. 22). The thermo-chemical platform provides the opportunity for a number of additional co-products to biofuels. Each syngas component (CO, CO_2, CH_4, H_2 etc.) could be recovered, separated, and utilised. The volatile tar component, which can act as a technical barrier to large-scale production, has been exploited as a feedstock for value-added chemicals by companies such as Choren, Ensyn and Enerkem (Branca & Di Blasi, 2006) (see below).

Biomass fuel conditioning

For efficient gasification, the biomass fuel needs to be below 20% moisture content with an even particle size. The feedstock may need drying if it is above 15-20% moisture content wet basis as is usually the case for ligno-cellulosic resources (except perhaps for cereal straw). Drying is a mature technology and several commercial dryers are available. The compact solutions usually employ flue gases at relatively high temperatures. Recent focus however has been placed on relatively low drying temperatures combined with the utilisation of secondary (waste) heat from the process. The design challenges revolve around the extensive utilisation of secondary heat combined with a large plant capacity requiring large feedstock volumes.

Figure 22. Process for the conversion of syngas into synthetic biofuels



The grinding stage is a comminution process that prepares the biomass for further processing.

Gasification process

Gasification of the comminuted feedstock is achieved by partial combustion in the reactor at 700°-1500°C (typically around 850°C) in limited oxygen conditions. This generates the synthesis gas which can be used for industrial processes, for biofuels production, or for further combustion in gas-engines or gas-turbines to provide heat and electrical power. Significant technical hurdles remain to be overcome, particularly regarding biomass-derived syngas clean-up requirements and associated char build-up problems. This is critically important because impurities in the syngas can poison the catalysts of the FT process and could therefore render the process uneconomic.

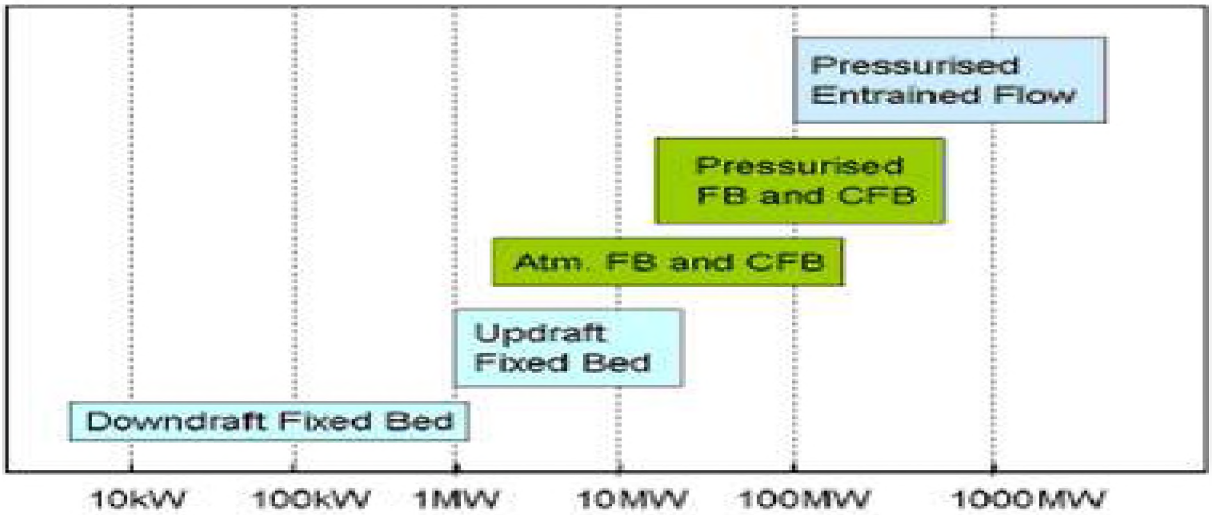
Alternatively, the process could be stopped at the pyrolysis stage (heating to 450-600°C in the absence of oxygen) to create mainly liquid bio-oil but also gaseous and solid products. The bio-oil has physical properties similar to crude oil, so can be relatively easily transported. It might also be used as feedstock for value-added chemicals, or, after refining, to produce biofuels (Part C).

The thermo-chemical route is inherently expensive given the feedstock and capital costs required. In addition to this barrier, which is present for coal or gas feedstocks, BTL faces a novel challenge, which is the gasification of biomass at commercial-scale to the exacting standards required for FT synthesis. IEA Bioenergy Task 33, Thermal Gasification, is in the process of analysing the characteristics of syngas production from the perspective of the quality needed for biofuel processing by the FT process (www.ieabioenergy.com/Task.aspx?id=33). In spite of many years of research and commercial endeavours, cost effective and reliable methods of gasification at the commercial scale remain elusive. Various gasification technologies have been developed and commercialised, but have been focused on gasification for power generation, where high calorific value gas is the target and impurities less of an issue than for FT synthesis.

Gasification technologies need to meet a number of criteria for BTL production, including the ratio of CO to H_2, ability to scale up to large commerical plant sizes (above 100 MW), and clean gas produced without impurities that might inhibit the catalysts and that would be expensive to clean up.

There are three main types of gasifiers - fixed bed, fluidised bed and entrained flow. Fixed bed updraft or downdraft designs, and fluidised bed bubbling (FB) or circulating (CFB) designs are direct air-blown gasifiers operated at atmospheric pressure, used in power generation but are unsuitable for BTL production. In addition, fixed bed downdraft gasifiers face severe constraints in scaling above 1MW and are fuel inflexible, being able to utilise only fuels with well-defined properties. Fixed bed updraft gasifiers have fewer restrictions in scaling, but are still not large enough for commercial BTL applications (Fig. 23). In addition, the syngas produced contains a lot of tars and methane. Given the constraints on scalability and the level of impurities in the desired syngas, pressurised oxygen-blown direct entrained flow gasifiers would appear to be the most suitable concept for BTL.

Figure 23. Gasification technology scale versus market requirement.



Source: Rensfelt, 2005

An entrained flow gasifier does not encounter large size restrictions and its capacity can easily reach several hundreds of MW. If the particle size is reduced to less than 1mm particles, tar-free syngas can be obtained with a relatively high CO and H_2 content compared with other designs of gasifiers (Table 11). However an energy cost is then involved with the fuel preparation and pulverising some forms of ligno-cellulosic feedstock is very difficultin practice. If feedstocks can be successively comminuted into small particles, entrained flow gasifiers are able to successfully convert a wide range due to the extreme process conditions involved. This allows significant flexibility in feedstock composition, so use of multi-feedstocks to meet all-year-round demand is possible. However, only relatively pure feedstocks can be used if the gasifier does not have the facility for slag removal, as molten slag will be formed from the ash at the high temperatures involved.

Another potential option is the preliminary gasification of biomass in, preferably, a pressurised circulating fluidised bed reactor. The gas formed is then fed to the second gasification stage in an entrained flow gasifier. The advantage of this approach is similar to pyrolysis, in that relatively little comminution is required of the biomass and a wide range of feedstocks can be processed. A potential drawback though is maintaining a stable feed flow due to variability in the output of the circulating fluidised bed processes being common.

A number of commercial gasification processes are under evaluation, all of which could have a commercially available FT plant added downstream if the syngas is of sufficient quality. Also technology for the final upgrading of FT liquids is commercially available from suppliers of oil-refinery processes.

Table 11. Components (% dry volume) and properties of syngas produced from woody biomass feedstock by various gasification technologies

	CO	*H_2*	*CO_2*	*CH_4*	*N_2 / Ar*	*C_2*	*Net heat value (MJ/m^3)*	*H_2/CO ratio*
Atmospheric, air-blown, direct CFB	*19.3*	*15.6*	*15.0*	*4.2*	*44.5*	*1.4*	*5.76*	*0.81*
Atmospheric, O_2-blown, direct CFB	*26.9*	*33.1*	*29.9*	*7.0*	*0.7*	*2.4*	*8.85*	*1.23*
Pressurised nitrogen, O_2-blown, direct CFB	*16.1*	*18.3*	*35.4*	*13.5*	*12.3*	*4.4*	*8.44*	*1.14*
Pressurised CO_2, O_2-blown, direct CFB	*16.1*	*18.3*	*46.9*	*13.5*	*0.8*	*4.4*	*8.05*	*1.14*
Atmospheric, steam blown, indirect	*42.5*	*23.1*	*12.3*	*16.6*	*0*	*5.5*	*13.64*	*0.54*
Pressurised, O_2-blown, direct entrained	*46.1*	*26.6*	*26.9*	*0*	*0.4*	*0*	*7.43*	*0.58*

Technically the most advanced biomass gasification/FT process for biofuel production is probably that of Choren that has a 45 MW_{feed} demonstration plant reaching the commissioning stage in Freiburg, Germany. A number of other gasification options are being developed by research institutes. VTT in Finland is developing fluidised bed biomass gasifier technology using a 500kW demonstration plant. At the CUTEC-Institute in Germany, the EU is helping fund the development of a 400kW circulating fluidized bed reactor demonstration plant in addition to a 2 litre Fischer-Tropsch pilot plant. The EU has also funded the 5 year project “Chrisgas” which began in 2004 with the aim to develop a commercial biomass gasification solution for synthesis gas production. The goal of the project is to convert the existing air-blown 18MW gasifier at Varnamo, Sweden to an oxygen/steam blown system to produce pure synthesis gas aimed at biofuel applications.

Gas clean-up

This has long been a challenge for biomass gasification which produces tars as part of the process. These need to be cracked so they do not inhibit the process and so that their energy content can be captured. Several types of clean-up technologies have been tested and evaluated for both large- and small-scale gasifiers but the problem remains a major design constraint of many demonstration biomass gasifier systems. Solids in the form of ash and inorganics also need to be extracted from the gas by cyclone or filtration techniques.

FT conversion

The gaseous products from pyrolysis or gasification can be synthesised by passing over specific catalysts, to create a variety of chemical products. In the FT process for example (Box 2), the syngas will normally be used for the production of synthetic diesel and gasoline but it could also be used for the synthesis of methanol, ethanol and other higher alcohols. These in turn can be used as transport fuels or as chemical building blocks.

The earliest catalysts used for FT synthesis were iron (Fe) and cobalt (Co). These catalysts degrade when exposed to toxic impurities in the syngas that reduce their effectiveness which has implications for the gasification process. Today the catalysts come from Group VIII transition metal oxides. For large-scale commercial FT synthesis reactors, heat removal and temperature control are the most important design features in order to optimise product selection and maximise catalyst lifetimes.

There are four basic FT reactor designs in use commercially:
- fixed-bed tubular;
- high-temperature circulating fluidized-bed;
- fixed fluidized bed SASOL advanced Synthol;
- low-temperature slurry reactor.

The fixed fluidized bed SASOL reactor has replaced the circulating fluidized bed reactor design because it costs half as much for the same capacity and also has lower operating costs. In addition, it also has better thermal efficiency with a less severe temperature gradient and a lower pressure drop across the reactor, while allowing greater process flexibility (in terms of product distribution) and the possibility for scale-up to 20,000 barrels of fuel per day.

Box 2. Fischer-Tropsch process.

This is a catalysed chemical reaction in which carbon monoxide and hydrogen are produced from the gasification of a solid feedstock such as coal or woody biomass into a range of liquid hydrocarbons. Typical transition metal catalysts are based on iron and cobalt.

$$(2n+1)\ H_2 + n\ CO \rightarrow CnH\ (2n+2) + nH_2O$$

The process was developed in 1923 by Prof Franz Fischer and Dr Hans Tropsch at the German Kaiser-Wilhelm Institute of Coal Research. A patent application was lodged in 1925 and commercial uptake was based on syngas made from coal. In the 1940s, 600,000 t/yr of liquid fuels were produced from coal in Germany from coal. After World War II competition from cheaper oil made coal-to-liquids uneconomic. However due to UN trade sanctions and with no available source of petroleum for fuel production, South Africa built three coal-to-liquid SASOL plants in the 1980s using the FT process to convert coal to gasoline and diesel. They are still operating.

Natural gas can also be converted, as in the Mobil gas-to-gasoline process used in New Zealand after the 1970s oil shocks to produce synthetic gasoline in the 1980s for local use and export. However the plant was closed down after the oil price dropped and the gas supply became constrained. The natural gas was first converted into methanol before that gas was then converted to gasoline using the breakthrough zeolite catalyst ZSM-5.

Shell Oil has operated a commercial FT-diesel plant in Bintulu, Malaysia since 1993. Known as the Shell middle distillate synthesis (SMDS) plant, it uses natural gas as a feedstock to produce primarily low-sulphur diesel fuels and food-grade wax.

Similar conversion technologies can be applied to biomass-derived syngas. However before catalysis the raw syngas must be cleaned in order to remove inhibitory substances that would inactivate the catalyst. Volatile tars as well as sulphur, nitrogen, and chlorine compounds should be removed. The ratio of hydrogen to carbon monoxide in the syngas may need to be adjusted and the CO_2 by-product may need to be removed.

Other options for the use of syngas

Methanol

Syngas can also be used to produce methanol, another potential biofuel that can be generated through catalysis but would then compete with the majority of methanol cheaply derived from natural gas. It has a high octane number but relatively low energy value per unit volume compared to gasoline (Table 10). It is mostly used to produce MTBE (methyl tertiary butyl ether) which is used as an octane booster (although in the USA and elsewhere this has now been banned as a fuel additive due to its carcinogenic properties). Methanol can also be used as a stand alone fuel, in blends with gasoline, or as a potential hydrogen source, because it has a favourable 4:1 hydrogen:carbon (H:C) ratio. For methanol synthesis however the biomass-based syngas tends to be hydrogen-poor compared to natural gas-derived syngas. Methanol synthesis requires a ratio of 2:1 hydrogen:carbon monoxide (H:CO) to be cost-effective but research is ongoing to allow lower H:CO ratio syngas to be used. Concerns at greater environmental impacts and health risks compared with ethanol exist.

The German company Lurgi has developed an alternative route with its new MtSynfuels process. Methanol synthesis from syngas (MegaMethanol® technology) is used for olefin production (MTP® process) and oligomerization (MtSynfuels process). Using this technology, Lurgi can produce synthetic transport fuels which meet the relevant specifications.

Higher alcohols

Another potential catalytic conversion of biomass-based syngas is to higher alcohols. Ethanol and other higher alcohols form as by-products of both FT and methanol synthesis, and modified catalysts have been shown to provide better yields (Putsche, 1999).

Summary

This section has outlined some of the more promising gasification technologies being developed that could be matched with a BTL process. Gasification and the syngas reforming phase still require development to give reliability though a number of fairly mature technologies are already available.
There are three basic approaches for this phase:

- fluidised-bed gasification and catalytic reforming;
- fluidised-bed gasification and solvent-based tar removal; and
- entrained-flow gasification at a minimum temperature of 1,000°C.

The third option based on an oxygen-based pressurised gasification process is likely to be the preferred route for BTL. A summary of the potential liquid biofuel production yields from thermo-chemical platforms is provided in Table 12.

Table 12. Biofuel yield ranges per dry tonne of feedstock from thermo-chemical processes based on synthesis gas production.

	Biofuel yield (litres/t)		Energy content (MJ/l)	Energy yields (GJ/t)	
Process	**Low**	**High**	**Low heat value**	**Low**	**High**
Syngas-to- FT diesel	75	200	34.36	2.57	6.87
Syngas-to- ethanol	120	160	21.10	2.54	3.38

Source: Mabee et al. 2006, ORNL, 2006, Putsche, 1999

Thermo-chemical route R&D

Gasification elements of the thermo-chemical platform for the production of biofuels are close to commercial viability today using various technologies and at a range of scales, although reliability of the process is still an issue for some designs. However, assembling the complete technological platform, including development of robust catalysts for biofuel production and modeling of capital and production costs, will require more RD&D investment. It is also recognised that major technical and economic challenges still need to be resolved.

A technical challenge to the production of biofuels and chemicals is the nature of most biomass-based syngases which are considerably more heterogeneous than natural gas-based syngas leading to resulting variations in quality. Well documented technical approaches can produce hydrogen, methanol and FT liquids from syngas, but the input gases must be relatively clean in order for these processes to function in a commercially viable way. The number of inhibitory substances in the syngas, as well as the overall composition of the gas mix, vary with biomass feedstocks and gasifier design and thus it is more problematic to process. Investment in RD&D to obtain long-term reliability of the process is essential if widespread deployment is to occur.

Problems associated particularly with the FT synthesis reflect the syngas composition. These include low product selectivity (the unavoidable production of unwanted co-products, including olefins, paraffins, and oxygenated products) and the sensitivity of the catalyst to contaminants in the syngas that inhibit the catalytic reaction. Research to improve the ability of catalysts to resist inhibitors is required to lower the cost of production so that the synthetic diesel can become cost competitive with petroleum products.

The cost of the syngas production can be more than 50% of the total process cost (Spath & Dayton, 2003). Most economic studies have indicated that deployment of large scale commercial plants is required to gain the necessary cost reductions from both economies of scale and learning experience for these processes.

5 Commercial Investments in 2nd-Generation Plants

The emergence of the first commercial bioethanol production plants utilising ligno-cellulosic raw materials is just beginning. Industrial pioneers include Royal Nedalco (the Netherlands), logen (Canada), Diversa/Celunol (USA), Abengoa (Spain) and the Broin & DuPont consortium (USA). The investment costs of a new 2nd-generation biofuel plant, at least in the early stage of development for a medium scale plant producing around 50 - 150 Ml/yr, will be in the range of USD 125 - 250 M.

5.1 Biofuel process cost assumptions

The future projected costs of ligno-cellulosic biofuel are wide-ranging, partly depending on the feedstock costs chosen for the assessment. The estimated production costs of 2nd-generation bioethanol in the literature currently range from USD 0.60 - 1.30 /l. The potential for cost reductions is estimated to drive production costs down, possibly to as low as USD 0.25 and 0.35 /l (Riese, 2007). Other predictions on which US targets are based converge by 2020 at around USD 0.30 - 0.40 /l (IEA, 2005; Perlack *et al*, 2005).

Investment costs

Estimates of capital cost investments for ligno-cellulosic ethanol plants using a variety of pretreatment technologies, no pretreatment, and an "ideal" pretreatment as discussed above, based on US conditions were provided from a modelling exercise by Wyman *et al.* (2007). Capital investment for each of the different pretreatment configurations (Table 13) appears relatively high being well above the USD 0.66/litre cost for the "ideal" system. The value of pretreatment in reducing fixed capital costs per litre of capacity is apparent, but there was no significant difference in capital cost between systems. Primary drivers in choosing a pretreatment technology will therefore be the feedstock characteristics, the operating costs, and the necessary expertise available.

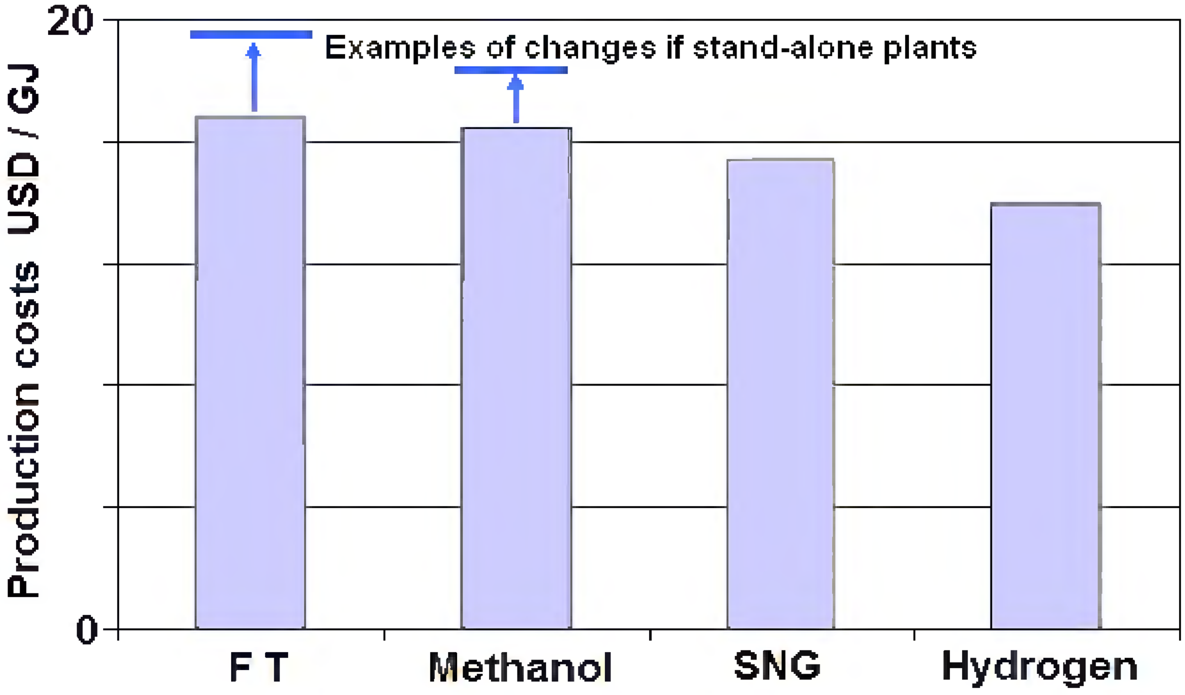
Data for thermo-chemical technology options is not readily available. VTT, the Finnish research organisation, has estimated investment requirements for plants of capacity in the range of EUR 220 - 250 M (approximately USD 300-400 M). The estimated production costs for alternative syngas utilisation options to produce methanol, synthetic natural gas (SNG) or hydrogen (Fig. 24) were based on a 260 MW_{feed} plant assuming interest on capital at 10%, a 20 year life, and feedstock delivered for EUR 36 /GJ. It was assumed that drying of the biomass feedstock from 50% moisture content wet basis (mcwb) at harvest to 30% mcwb was achieved using secondary heat and then further down to the 15-20 % mcwb suitable for use in the gasification process by using heat from by-product steam. The costs increase slightly where biofuels are produced in a stand-alone plant rather than in a plant integrated with an existing one but still appear to be optimistic compared with other assessments.

Table 13. Capital investment costs for various pretreatments calculated from a number of bio-chemical ethanol plants in US.

Pretreatment system	Total fixed capital (USD M)	Annual plant capacity (Ml /yr)	Fixed capital cost /litre of capacity (USD /l)
No pretreatment	200.3	34	5.88
Dilute acid	208.6	212	0.98
Hot water	200.9	166	1.21
Steam-explosion	190.4	200	0.95
AFEX	211.5	215	0.98
ARP	210.9	175	1.20
Lime	163.6	185	0.88
"Ideal" pretreatment	162.5	245	0.66

Source: Wyman et al. 2007

Figure 24. Estimated production costs for thermo-chemical FT liquid biofuel production options, methanol, synthetic natural gas (SNG) and hydrogen production plants.



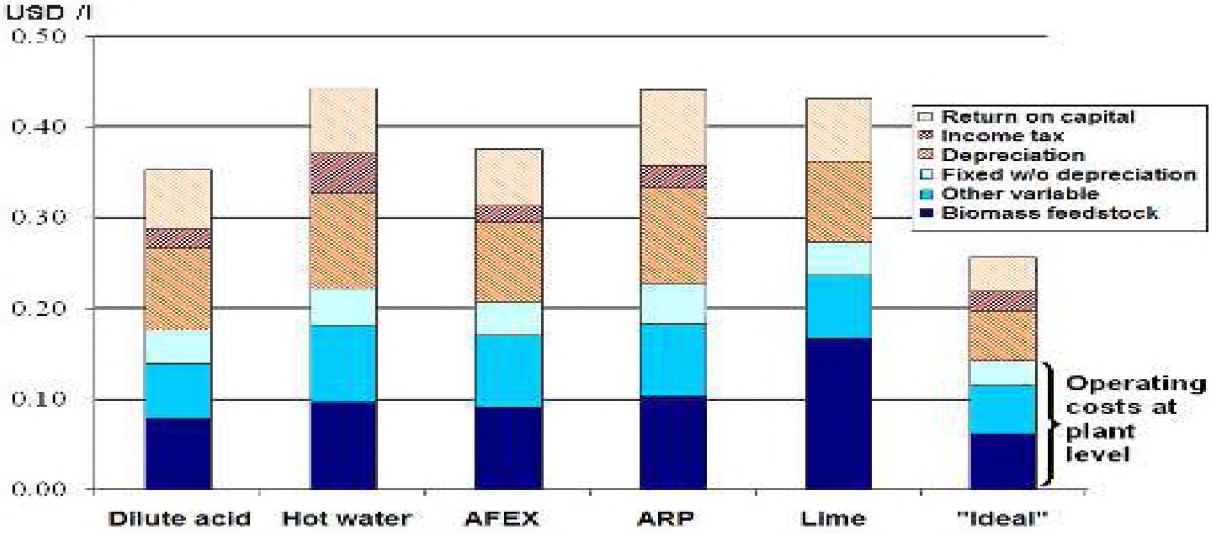
Source: McKeough & Kurkela, *2007*

Operating costs

The estimated operating costs for bio-chemical ethanol production with different pretreatment technologies have been modeled using US data and apply most directly to that country (Fig. 25). There was relatively little difference between costs, the hot water, ammonia recycle percolation (ARP) and lime pretreatments being slightly more expensive than those of dilute acid and ammonia freeze explosion (AFEX).

The biomass cost was based on varying yields using different pretreatments. Corn stover as the base case feedstock was estimated to cost approximately USD 25-35 /t delivered to the plant (around USD 2-3 /GJ). Higher costs for the ligno-cellulosic feedstock would increase the total cost of production. Other variable costs include energy, chemicals and enzyme inputs. Fixed costs without depreciation include labour, maintenance and insurance. The plant was depreciated over a 20 year period.

Figure 25. Operating costs for ligno-cellulosic ethanol plants using corn stover feedstock and various pretreatment systems



Source: Wyman *et al.*, 2007

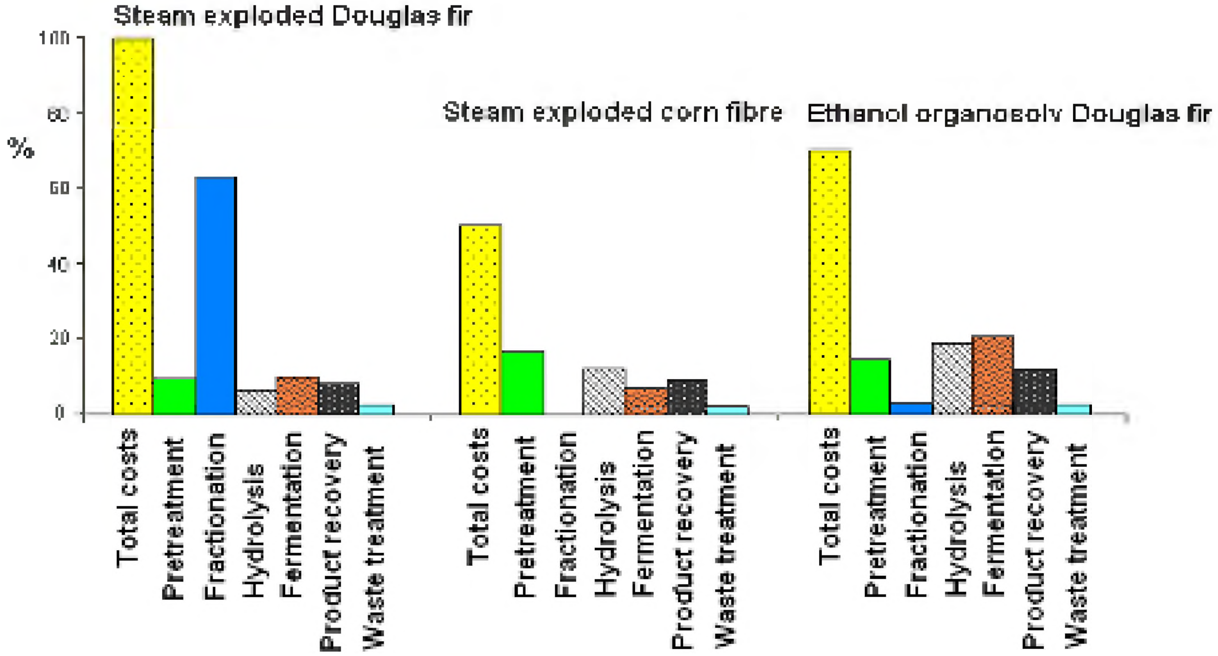
Process costs for steam-pretreated Douglas-fir, steam-pretreated corn fibre, and ethanol organosolv-treated Douglas-fir were compared by Mabee *et al.* 2006 (Fig. 26). Cost comparisons were provided on a relative basis to the normalized current best laboratory results for the SO_2 steam-explosion of Douglas-fir. No additional co-product values, including that for lignin, were included in the analysis.

Aden *et al.* (2001) identified the cost of enzymes as a critical issue, but since then lower enzyme costs have changed this barrier. More recent analysis indicates that the overall cost of delignification associated with pretreatment remains a larger cost hurdle to overcome for softwood ligno-cellulosic substrates (Mabee *et al.* 2006). Alternative pretreatment technologies, such as organosolv, may prove to be a more beneficial method for handling softwood substrates.

The value of lignin co-products has been shown to be a crucial factor in making the softwood-to-ethanol process economically viable (Aden *et al.*, 2002; Boussaid *et al.*, 2000). This is because ethanol production costs decrease significantly when the lignin co-product value rises (Mabee *et al.*, 2006). Sufficiently high lignin values of about 1.5 times the normalized ethanol production cost could render the process cost neutral, as the co-product value is able to cover the costs of ethanol production. However, increased costs of delivered biomass feedstock could easily double the cost of the process given current market conditions. Since high-value lignin co-products can economically justify ethanol production, further research should focus on developing these products.

The value of lignin as a fuel substitute for heat and power generation on-site can be significant with gas and electricity prices having doubled in the past 10 years. One tonne of softwood lignin embodies around 22.2 GJ/t of energy (lower heating value). This is worth approximately USD 240 in energy value to a mill in the US that currently utilises natural gas for heat supply. Elsewhere, at current energy prices, on-site generation of heat and power for in-mill use may be economic, particularly where government support exists. For example, the Canadian Renewable Energy Deployment Initiative (REDI) managed by Natural Resources Canada, can be used to offset 25% of purchase and installation costs of biomass energy systems, up to a total of CAN 80,000 per installation.

Figure 26. Operating costs for unit operations of ligno-cellulosic ethanol plants for varying feedstocks and pretreatments.

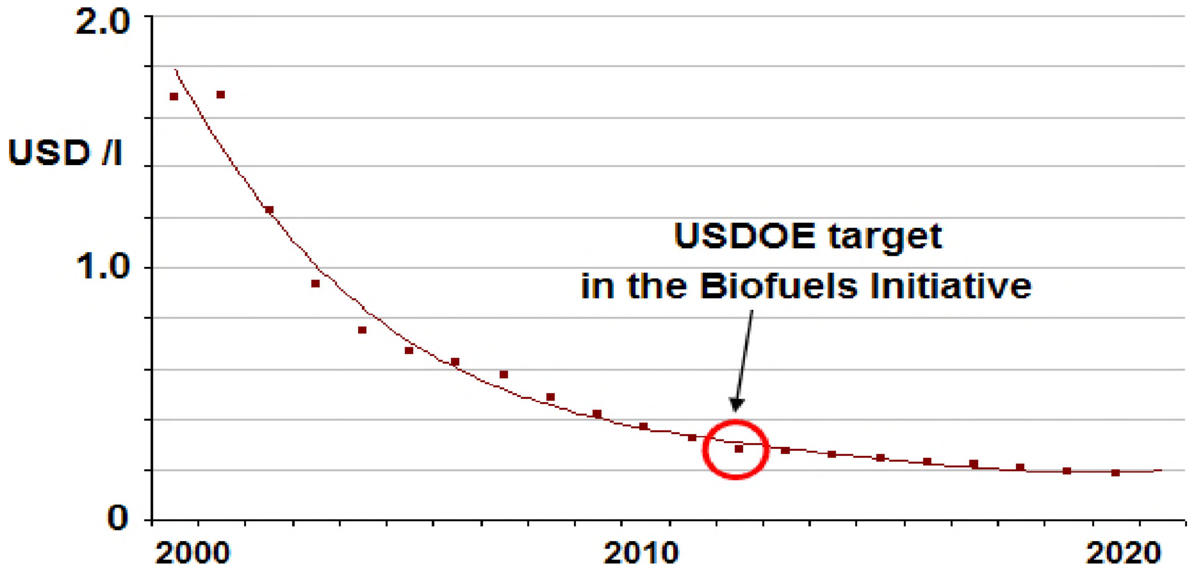


Source: Mabee *et al.*, 2006

Total cost assessments and targets

The most recent targets for ethanol cost reductions are included in the US Biofuels Initiative (BFI), which is a component of the Advanced Energy Intiative announced by President Bush in his 2006 State of the Union Address (USDOE, 2008). Under the BFI, the target is to achieve cost reductions that make ligno-cellulosic ethanol competitive with corn ethanol by 2012. Essentially, this translates into an ambitious target of approximately USD 0.28 /l (USD 0.42 /lge). Based on estimates of current costs of production, this cost reduction would represent a major improvement (Fig. 27). The targets are not technology specific nor based on detailed cost analyses of biomass supply chain and process plant operations. Whether they can be reached or not remains to be seen.

Figure 27. Extrapolation between recent cost estimates for 2nd-generation ethanol production in the US (2002 to 2006) and the USDOE target in 2012, with a forecast to 2020.



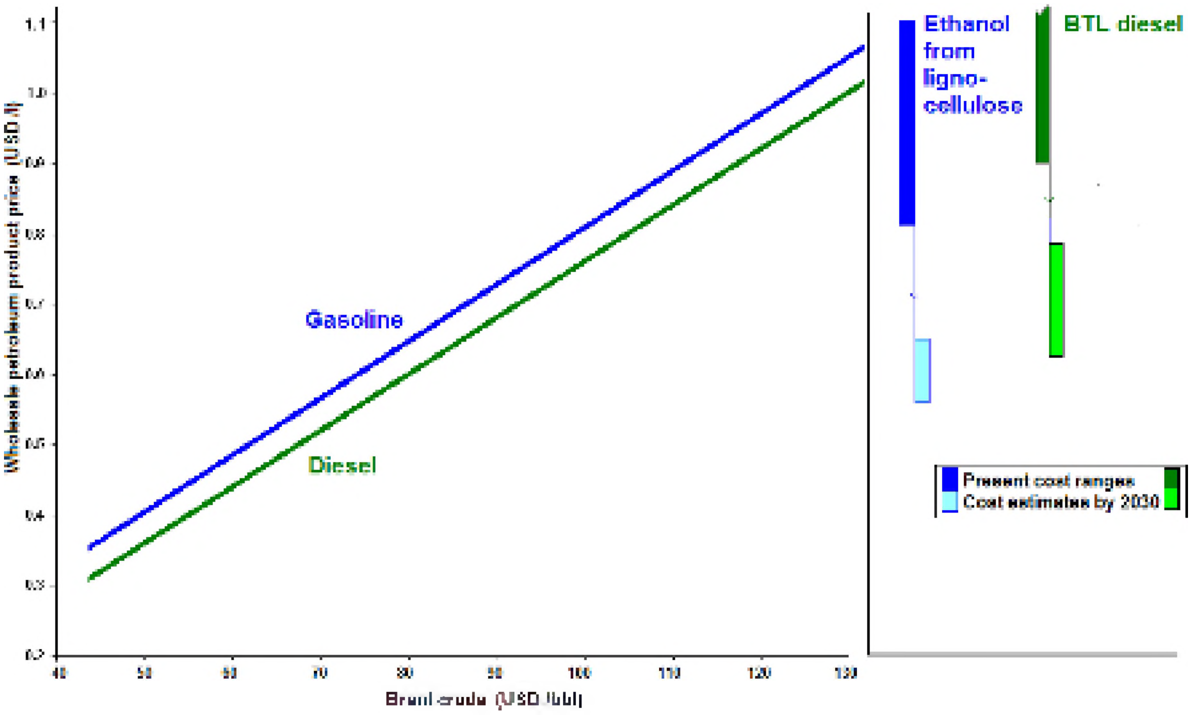
More conservatively by comparison, the IEA has developed a set of cost projections based on the potential market penetration of 2nd-generation biofuels out to 2050 (IEA, 2008a). The rate of cost reduction (Table 14) will depend on feedstock prices, economies of scale from large plants, integration of new technologies and benefits of experience and learning. Extrapolation gives 2nd-generation ethanol costs on a litre per gasoline equivalent (lge) basis of around USD 0.65 - 0.75 /lge in 2020, being higher than the USDOE target. It is important to note that the results in Table 14 are for the very ambitious scenario, where global annual CO_2 emissions are reduced 50% by 2050. The assumptions underlying the results are therefore based on 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.

Table 14. IEA 2nd-generation biofuel cost assumptions for 2010, 2030 and 2050

Lignocellulosic conversion technology	Assumptions	Production cost- 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

Another way of looking at the potential costs, was presented in the IEA analysis in the *World Energy Outlook 2006*. This compared production costs for a range of biofuels (free of subsidies) with competing daily free-on-board wholesale gasoline and diesel prices correlated with the crude oil price over a 16 month period. Since then the cost of production of some 1st-generation biofuels has 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 risen. A simplified version of the analysis (Fig. 28), using the 2nd-generation biofuel cost ranges as extracted from the literature at the time, indicated that, excluding any subsidies, biofuel production costs would need to be at around USD 0.80 /lge to be competitive with wholesale gasoline and diesel prices with oil at USD 100 /bbl.

Figure 28. 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 RDD&D.



Source: Based on IEA World Energy Outlook, 2006, section on biofuels.

The EU industry-led RENEW project (*renewable fuels for advanced powertrains* www.renew-fuel.com) suggested a BTL plant based in Poland and using the Choren process could produce liquid biofuels from straw and forest residues for around €0.85 / lge dropping by 10% in 2020 due to more intensive short rotation feedstock production.

The main reasons for the major discrepancies between the various published cost predictions relate to varying assumptions for feedstock cost and the future timing for the commercial availibilty of both the feedstock supply chain and conversion technologies. Comparisons between the bio-conversion and thermo-chemical routes have proven to be very contentious within the industry, with the lack of any real cost data being a major issue. The following sections describe various pilot and demonstration projects for both biochemical and thermo-chemical routes. A better understanding of the costs should result but much of the analysis is commercially sensitive and not in the public domain.

5.2 Selected 2nd-generation demonstration plants (case studies)

Integration of various process steps and increasing overall process efficiency is being improved by integrated research programmes which combine process development units with pilot or demonstration-scale facilities around the world. Process development units are operating at the University of British Columbia, at Lund University in Sweden, at RISO/DTU in Denmark, and at the US National Renewable Energy Lab (NREL). Other pilot facilities include Etek Etanolteknik in Sweden, the Abengoa demonstration plants in Spain and the USA, and the Iogen demonstration plant in Canada. There are also several networks of researchers that work at different process scales who have combined their efforts to address the key issues. It should be noted that most of these facilities have been designed to produce bioethanol as their primary product, but can be configured to examine a variety of co-products.

A wide range of technologies are under development to produce ethanol from ligno-cellulosic biomass but none have proven to be commercially viable. As part of the US "Advanced Energy Initiative" with a goal to produce 147 bnl of ethanol by 2017, the USDOE has introduced a full programme of support for demonstration plants and associated research programmes (Section 9.1.2). The government will become a partner with up to 40% share of the total costs. These investments, spread over 4 or 5 years, included:

- USD 385 M for 6 near commercial-scale demonstration plants planned to be built by various companies but not proceeding without government support due to the current high commercial risk of the technology.The successful applicants out of the 24 proposals include one thermo-chemical, one hybrid thermo-chemical/fermentation, one acid hydrolysis, one hybrid enzyme hydrolysis/thermo-chemical and two enzyme hydrolysis plants.
- USD 230+ M for 7 (+ 2) pilot-scale (10% of full scale) biorefineries.

A summary of US companies with capacity in bio-conversion of ligno-cellulosics to biofuels, including those recipients of the USDOE grants, is given in Table 15. There is however some uncertainty about some of the projects proceeding and whether any resulting surplus funding will be reallocated if they do not. In any new industry such as 2nd-generation biofuels, the commercial and financial investment risks are high. Several companies have recently announced project withdrawals or changes to their original plans, and these are outlined below (although recent global concerns relating to investment security may have increased the perceived risks resulting in further changes). Further details of other selected plants in both Europe and the US are also described below with yet others listed briefly in Annex 2.

Bio-chemical ethanol and bio-refinery demonstration projects

Abengoa Bioenergy

Abengoa Bioenergy is the owner of five 1st-generation ethanol processing plants in US and six in Europe. It acquired the Brazilian ethanol producer Dedini Agro for USD 300 M. In association with Diadic International it has invested in four 2nd-generation pilot plants co-located with its starch/cellulose plants, three in US.

Table 15. USDOE funding support for commercial 2nd-generation plant capacity, planned or under-construction.

Demonstration plants	Total investment/ USDOE investment (USD M)	Annual production capacity (Ml /yr)	Project location	Feedstock	Date funded
Bio-chemical					
Abengoa Bioenergy LLC	190 / 76	43	Colwich, Kansas	Corn cobs, corn stover, switchgrass	28 February 07
Bluefire Ethanol	100 / 40	65	Corona, California	Municipal solid waste	28 February 07
Iogen Biorefinery Partners LLC	200 / 76	70	Shelley, Idaho	Wheat straw	28 February 07
Poet	200 / 80	120	Emmetsburg, Indiana	Corn stover	28 February 07
Thermo-chemical					
ALICO	83 / 36		LaBelle, Florida	Citrus wastes	28 February 07
Range Fuels	225 / 76		Soperton, Georgia	Wood chips, wood waste	28 February 07
Total investment / USDOE	**998 / 385**				
Biochemical bio-refineries					
Ecofin, LLC	77 / 30	4.9	Washington County, Kentucky	Corn cobs	29 January 08
ICM	86 / 30	5.7	St. Joseph, MO	Switchgrass, forage sorghum, corn stover	18 April 08
Lignol Innovations	88 / 30	9.5	Commerce City, Colorado	Woody biomass, agricultural residues	18 April 08
Mascoma	136 / 25	7.6	Monroe, TN	Switchgrass and hardwoods	29 January 08
Pacific Ethanol	73 / 24	10.2	Boardman, Oregon	Wheat straw, stover, poplar residuals	18 April 08
RSE Pulp	90 / 30	8.3	Old Town, ME	Woodchips (mixed hardwood)	29 January 08
Verenium	92 / TBD	5.3	Jennings, Louisana	Bagasse, energy crops, agricultural residues, wood residues	14 July 08
Thermo-chemical biorefineries					
Flambeau LLC	84 / 30	22.7	Park Falls, Wisconsin	Forest harvest residues	14 July 08
New Page	84 / 30	20.8	Wisconsin Rapids, Wisconsin	Wood process residues	18 April 08
Total investment / USDOE	**810 / 230+**				

- A 200 Ml/yr plant in Spain currently produces 2.5% of its product from wheat straw. Distillers dried grains (DDG) from the wheat grain feedstock and food grade CO_2 are co-products.
- In York, Nebraska, with a USD 36.1M grant from USDOE, a 1t/day pilot plant is using corn stover (residues after harvesting the grain). The cellulosic component of the facility opened in October 2007. This facility is being used as a R&D test bed for new equipment and catalysts to break down organic compounds and is providing valuable data for other Abengoa projects.
- The planned commercial plant in Colwich, Kansas with up to $76M funding available from USDOE, is a 43 Ml/yr integrated bio-refinery plant using 700 t/day of corn stover, wheat straw and switchgrass to produce ethanol, synthesis gas and heat. Both bio-chemical and thermo-chemical pathways will be employed in this facility. The feedstock will be processed into 400 t/day of ethanol via bio-chemical routes; 300 t/day of syngas by thermo-chemical routes with the long term strategy to convert this gas to ethanol and biochemicals. The organic food company SunOpta Bioprocess Group is also a partner with a particular interest in the steam explosion pre-treatment including a continuous reactor that pretreats the biomass at the temperatures and pressures required for subsequent enzymatic hydrolysis to produce fermentable sugars.
- While the Colwich facility is under construction, Abengoa has recently released plans to spend $300 M to build a 700 t/day biomass cellulosic ethanol production plant in Hugoton, Kansas, which will produce 200 Ml /yr of cellulosic ethanol.
- Abengoa began construction of one of the first 2nd-generation commercial scale biomass-to-ethanol facilities in August, 2005. This facility is co-located with the new cereal ethanol plant in Babilafuente (Salamanca), Spain and commissioning is underway. The plant will process 70 tonnes of agricultural residues, such as wheat straw, each day and produce over 5 Ml /yr of fuel grade cellulosic ethanol (giving 19 Ml/yr in total) as well as co-products including distillers dried grains (DDG) from the wheat grain feedstock and food grade CO_2. Abengoa Bioenergy New Technologies (ABNT) is providing its proprietary process technology and the process engineering design for this facility. The goals for the biomass plant are to commercially demonstrate the biomass to ethanol process, optimise plant operations, and establish a baseline for the future expansion of the ethanol industry.
- ABNT is also taking part in a number of other projects. These include the RENEW Project, funded by the 6th Framework Programme of the European Commission, to develop, compare, (partially) demonstrate and train personnel on a range of fuel production chains for motor vehicles. This project is coordinated by Volkswagen AG (Germany). ABNT's contribution to the project is to optimise the bioethanol production, in part by comparing bio-chemical and thermo-chemical routes
- ABNT is investigating the production of energy crops through the Agrobihol project, funded by the Spanish Ministry of Education and Science. This project will assess the viability of producing bioethanol from sweet sorghum and Jerusalem artichoke crops.
- The Abengoa company is also investigating the production of “E-diesel”, obtained by adding bioethanol to conventional diesel in a blend varying between 5 and 15%. This mixture, combined with an additive for fuel stability, can be used in conventional diesel engines with little or no modifications. E-diesel has been tested in the US and Brazil, where no significant operational or material problems have been reported. By blending diesel with 8% ethanol and less than 1% of an adequate additive, significant performance improvements may be achieved compared with neat diesel. These include reductions in visible smoke, particulate matter, carbon monoxide, and nitrogen oxides as well as CO_2.
- Ethanol has been established as a hydrogen source, representing a bridge for the transition towards a hydrogen-based economy. ABNT is exploring the production of hydrogen from ethanol that can be achieved through a catalytic reaction. Hydrogen generation from bioethanol has advantages of the broad scale at which this technology can be applied, while generation costs are lower compared with other renewable sources.

BlueFire Ethanol

This company is currently using concentrated acid hydrolysis in a 300 l/day ethanol pilot plant in Japan based on demolition wood feedstock. It is planning a 72 Ml/yr biorefinery project in Mecca, Southern California using 700 t/day of sorted green waste, wood waste from landfills, and other cellulosic urban wastes. Recently, BlueFire announced that it has received the first installment of up to USD 40 M funding available from USDOE to expand the technology to full commercial scale.

Upon completion, the California plant will produce approximately 65 Ml/yr of cellulosic ethanol per year.

Iogen Biorefinery Partners

Iogen is an industrial enzyme manufacturer in Ottawa. Diversification into using enzymes for ethanol production led to construction of a 40 t/day pilot plant operating on wheat straw and corn stover. Shell invested USD 29 M in the project in 2003 with the institutional investor, Goldman Sachs, investing another USD 30M more recently. In July 2008, Shell increased its ownership of Iogen from 26.3% to 50%. The partnership was planning to expand into Idaho by building a USD 200 M, 70 Ml/yr plant due for completion in 2009 and aiming to digest and hydrolyse 700 t/day of wheat, barley and rice straw, corn stover and switchgrass, with up to USD 76M available from USDOE in support.

However, an Iogen spokesperson has been quoted saying that the company has “suspended” its plans to build the plant in Idaho in order to focus on Canadian endeavours. The Idaho plant could be built in the future, but the company has suspended focusing on that location and at this time is not actively pursuing the allocated USDOE funding.

In March 2008, the Canadian government announced that Iogen’s application for funding from Sustainable Development Technology Canada (SDTC) had proceeded to the due diligence phase. SDTC administers the CAN 500 M NextGen Biofuels Fund, designed to support up to 40% of eligible project costs for the establishment of first-of-kind large demonstration-scale facilities for the production of next-generation renewable fuels. This contribution is repayable based on free cash flow over a period of 10 years after project completion. If successful, Iogen’s application will support a large biorefinery in the province of Saskatchewan.

Scale up of future plants to produce 1 bnl /yr each is being considered. Iogen and Shell also signed a letter of intent with the Volkswagen Group in early 2006 to study the feasibility for developing an ethanol plant in Germany.

Poet

Poet, formerly Broin, is the largest dry mill starch-to-ethanol producer in the US and has the objective to add ligno-clluose ethanol capability to all 22 of its plants. It is partnered by Novozymes to provide the commercial enzymes and E.L.du Pont de Nemours to provide the fermentation technology. A 200 Ml /yr 1st-generation corn-based ethanol plant in Emmetsburg, Iowa is planned to be converted to an integrated corn-to-ethanol and cellulose-to-ethanol biorefinery. It will demonstrate production of 470 Ml/yr of ethanol with 75% to be produced from corn feedstock and 25% from 840 t/day of residual corn fibre, stover and cobs. The ligno-cellulosic feedstock cost will be USD 30-60 /t after fractionation of the harvested whole-crop on site into corn grains, cobs, and corn fibre which will be added to the stover. Up to USD 80M is available from USDOE towards a total cost of USD 200 M to build the additional facility on to the existing corn-based dry mill plant. The expansion is at the design stage with construction due to start in 2010 aiming for start-up in 2011.

Recently Poet announced that construction of a USD 4 M pilot-scale cellulosic ethanol production facility will be completed in late 2008. This is the next step in the company’s aim towards full commercialisation of cellulosic ethanol following recent expanded research investment at the laboratory scale. The plant will allow the company to build upon recent technology advances before starting construction on its commercial cellulosic production facility in 2009 and be operational in late 2011. The pilot plant will be adjacent to Poet's corn ethanol pilot facility and a 30 Ml /yr ethanol production facility in Scotland, South Dakota.

Ecofin, LLC

Ecofin, LLC is an affiliate of Alltech Inc. whose mission is to improve animal health and performance by adding nutritional value to animal feed and, through this, enhance the performance of the animal to increase production. The proposed bio-refinery plant will be located in Washington County, Kentucky. It will use novel, solid-state enzymatic complexes to convert a potentially wide range of ligno-cellulosic feedstocks, including corncobs, to ethanol and other nutritious feed sources, hence minimizing waste. A grant of up to USD 30M from the USDOE is to be used towards the establishment of the bio-refinery in the rural community of Springfield. It is estimated it will employ 93 people when operating at full capacity. The project has also received a USD 8 M incentive from the Kentucky Economic Development Finance Authority (KEDFA).

The facility will also have the capability to produce algae, a plant that needs little besides sunlight and carbon dioxide (section 8). Algae can theoretically produce 45,000 litres of biofuel /ha/yr, whereas corn can produce 4,500 l/ha/yr. Additionally, algae can absorb up to 1100 t CO_2 /ha when grown commercially. As part of the project's research component, Ecofin will coordinate R&D activities with the University of Kentucky and the University of Cincinnati.

ICM Incorporated

More than 750 employees work to engineer, build, and support the global biofuels industry's most efficient ethanol plants. ICM is the industry's leading technology provider; their patented process technology being behind more than 15 bn l of North America's annual ethanol production.

The proposed plant will be located in St. Joseph, Missouri, and will utilise diverse and relevant feedstocks including agricultural residues, such as corn fibre, corn stover, switchgrass and sorghum. The plant will integrate bio-chemical and thermo-chemical processing and demonstrate energy recycling within the same facility. The proposed location will site a pilot-scale bio-refinery adjacent to an existing 200 Ml/yr 1st-generation ethanol facility. Much of the necessary infrastructure (road, rail, water, electrical, utility, and wastewater treatment) already exists, eliminating significant capital expenditure in the new project. The USDOE will provide up to US$ 30 M to this project.

ICM, Inc. has several collaborators including Ceres, Inc.; Edenspace; South Dakota State University; AGCO Corporation.; USDOE's National Renewable Energy Laboratory (NREL); National Center for Agricultural Utilization Research (NCAUR); Novozymes, VeraSun Energy Corporation; and SunEthanol, Inc.

Lignol Innovations Inc.

Lignol Innovations is a US-based company with a publicly traded Canadian parent in Vancouver, British Columbia. Lignol has acquired and since modified a solvent-based pre-treatment technology, "organosolv" that was originally developed by a subsidiary of General Electric. This technology was operated at the demonstration scale in the 1980s for the pulp and paper industry, but at the time was deemed economically unviable. Lignol has now built a 1 t/day pilot plant in Vancouver to evaluate hardwood and softwood residue feedstocks in the co-production of ethanol, lignin and furfural so that commercial investment risks might be minimised. The pilot plant is being expanded to allow scale-up and further testing of the organosolv process.

In addition a proposed bio-refinery, will be co-located with a petroleum refinery in Commerce City, Colorado, and, using the biochem-organisolv process, will convert hard and soft wood residues into ethanol and commercial products. Other participants and investors include Suncor Energy and Parker Messana & Associates. The USDOE will provide up to US$30 M to the Colorado project.

Nedalco

In Europe, the Dutch company, Nedalco, is planning to build a USD 200 M plant that would produce 200 Ml/yr of ethanol by late 2008 (Flach, 2006). It is first awaiting the establishment of favourable Dutch policy on ethanol. The feedstock will mostly be molasses and by-products from the nearby wet milling, wheat starch plant of Cerestar. Nedalco is planning to supply 25% of the new capacity with cellulosic ethanol giving it the capability to use a wide variety of feedstock imports such as palm kernel meal.

An anonymous competitor of Nedalco is reportedly planning to build a 1st-generation plant with a capacity of about 120 Ml/yr near Amsterdam. Feedstock of this plant will probably be wheat. The profitability of domestic ethanol production depends significantly on the policy for ethanol imports, and in particular the policy toward ethanol imported from Brazil. In 2005, it was reported that the Rotterdam port imported 650,000 Mt of ethanol (most for non-fuel purposes). The major part of these imports was destined for the Swedish and UK markets, but ethanol imports are seen as a potential threat for domestic ethanol production.

Mascoma and DuPont-Danisco

Mascoma's single-step cellulose-to-ethanol method termed "consolidated bioprocessing" (CBP), uses advanced technologies to make ethanol from non-food based renewable sources such as wood chips and other biomass. At the same time, Mascoma is collaborating with research partners globally to identify and patent additional biomass-to-ethanol technologies including for pretreatment, enzymatic hydrolysis, and fermentation technologies.

Mascoma has embarked upon a pilot project in Rome, New York, which is now under construction and is expected to be completed by the end of 2008. Three rounds of fundraising since 2006 have raised approximately USD 95 M, with investors including General Motors, Khosla Ventures, Flagship Ventures, General Catalyst Partners, Kleiner Perkins Caufield & Byers, Vantage Point Venture Partners, Atlas Venture and Pinnacle Ventures.

In January 2008, the USDOE announced that Mascoma Corporation, with the University of Tennessee, was among the recipients of a $26 M grant for the development of biomass conversion technology to be located in Tennessee. However, by summer 2008 the company indicated that it would be reducing its role in this project to that of a technology provider. Du Pont has now taken the lead role in developing this project. It is assumed that the DOE funding granted to this project will continue to flow to the Tennessee site.

Mascoma is now focusing its efforts to build its first commercial-scale cellulosic ethanol plant on Michigan's Upper Peninsula. In the spring of 2008, the company entered into agreements with the Michigan Economic Development Corporation, Michigan State University (MSU) and Michigan Technological University (MTU). These alliances are designed to help bring this facility to a location south of Sault Ste. Marie. Mascoma is also partnering with JM Longyear, a natural resource company with significant project development experience. Mascoma chose Michigan in part for the access to sustainable forest biomass and agricultural residues, readily available in the state. The collaboration with MSU and MTU will develop scientific processes that utilise Michigan feedstocks for cellulosic ethanol production.

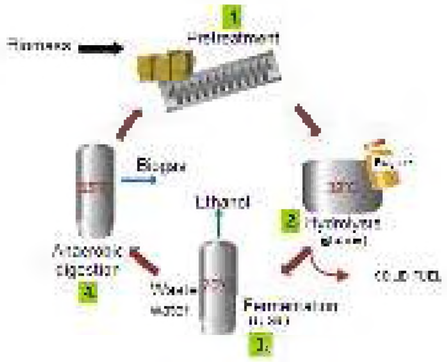
DuPont-Danisco is a USD 140 M, three-year commitment joint venture begun in May 2008 linking E.I. DuPont with Genencor, a division of Denmark-based Danisco AS. Their aim is "to develop and commercialise the leading low-cost technology solution for the next generation of biofuel produced from non-food sources". DuPont specialises in pretreating the biomass material to break it down, Danisco-Genencor has the enzyme science to transform the cellulose into sugar and DuPont knows how to convert the sugar into ethanol through fermentation. DuPont-Danisco is embarking on a project with the University of Tennessee, taking on the role originally occupied by Mascoma Corporation. This project will initially target corn stover and sugarcane bagasse as feedstocks to produce ethanol fuel, but may expand to include switchgrass grown on local farms. The pilot refinery has been scaled back from original plans and will produce just under 1Ml/yr, instead of the 19 Ml/yr capacity initially envisioned.

The two parent companies have partnered on the key technologies involved in a DuPont-Tate & Lyle plant that opened in nearby Loudon, Tennessee in 2007. That plant makes Bio-PDO (propanediol), a corn-based polymer that can replace petroleum products in fabrics, face creams, carpets and a variety of other products.

Pacific Ethanol

Pacific Ethanol Inc., of Sacramento, California is a leading producer of low-carbon biofuels in the Western US. It is planning to add cellulosic conversion capability to its corn-based ethanol facility in Oregon. The proposed plant will be in Boardman, and will convert agricultural and forest product residues to ethanol using BioGasol's proprietary conversion process. The USDOE will provide up to USD 24.3 M to the project. The BioGasol Concept (Fig. 29) follows a fairly typical bioconversion process of pretreatment, hydrolysis, fermentation, but then adds an anaerobic digestion stage to treat the process wastewater. Approximately 15% of the input feedstock is separated out as a solid, which can be used for combustion to drive the process. The remainder of the feedstock, including nearly all carbohydrates, is converted into fuels, including bioethanol (the main product) and hydrogen. Anaerobic digestion is used to convert any remaining biomass in the process water into methane. The BioGasol Concept is currently being demonstrated in Denmark.

Figure 29. The BioGasol process concept of wastewater treatment by anaerobic digestion



RSE Pulp & Chemical

RSE Pulp & Chemical is part of the RSE renewable energy and technology-based business consortium that consists of 22 companies in the US and Canada. The proposed bio-refinery facility will be installed in an existing pulp mill in Old Town, Maine, and will produce cellulosic ethanol from ligno-cellulosic (wood) extract. The project uses a proprietary process for pre-extracting hemicelluloses during the pulping process. This process has been proven on a laboratory and pilot scale, and RSE now aim to prove the viability of the process at the demonstration plant level. RSE Pulp & Chemical participants and investors include University of Maine Orono, Maine and American Process Inc., Atlanta, Georgia. The USDOE will provide up to USD 30 M in support for the project.

Verenium

Verenium Corporation, the product of a merger between Diversa and Celunol, is a pioneer in the development of next-generation cellulosic ethanol and high-performance specialty enzymes. The USDOE is providing funding to Verenium, among other enzyme companies, for the development of improved enzyme systems to be used in converting biomass into cellulosic ethanol. The total grant to four companies is US $33 M which will be appropriated over a four-year period beginning 2007. Verenium plans to use the funds to support ongoing activities at its 5.3 Ml/yr demonstration-scale facility in Jennings, Louisiana, which uses bagasse and other cellulosic feedstocks to produce ethanol. The plant was opened in late May 2008 and has almost completed commissioning of producing ethanol and validating performance and cost assumptions and is close to commercial start-up.

Japanese companies Bio Ethanol Japan Kansai in January 2007 used Verenium's technology to build a demonstration project that can produce 1.4 Ml/yr in Osaka, Japan, with plans to scale it up to 4 Ml/yr in 2008. Verenium was also awarded a USDOE grant for the construction of a small-scale bio-refinery, announced on July 14, 2008. Actual funding levels had not been released at the time of writing but probably will be used to expand the Jennings facility.

Genera Energy

Genera Energy is a limited liability company formed by the University of Tennessee Research Foundation for the purpose of managing the RD&D operations of the cellulosic ethanol bio-refinery in Vonore, Tennessee. This facility is expected to become active in 2010. Genera Energy will help transform the technological developments made by researchers into products for the marketplace. Earlier this year the university announced a farmer incentive programme for production of switchgrass as a feedstock for the bio-refinery, contracting with 16 farmers within 80 kilometres radius of the site to produce 300 hectares of switchgrass this year. The number of participants is expected to increase to accommodate the growing needs of the bio-refinery, and approximately 2,500 hectares should be in production by 2010.

EthosGen

EthosGen is a US company with a long-term interest in ethanol production from ligno-cellulose. It differs from others by aiming to grow the C4 grass hybrid feedstock under a controlled environment greenhouse adjacent to the processing plant, thereby eliminating transport costs. The company has been investigating developing a plant in Sweden. The claim is that it would provide a 73% cost reduction compared to corn-based ethanol due to a patented enzymatic reaction that is specific to the proprietary genetically engineered grass strain. All demands for heat and power can be generated on site. The pilot plant is designed to have a 5000 m^2 greenhouse for USD 1.2 M investment, producing a claimed but highly ambitious, 500 t/yr of biomass (www.dtnag.com/dtnag/common). This, it is claimed, would produce around 270,000 l/yr of ethanol equating to around 540 l ethanol / wet tonne biomass or over 500,000 l/ha/yr! This exemplifies how many claims relating to biofuel production made in the media or on the internet need careful scrutiny.

Thermo-chemical BTL demonstration projects

Ambitious future energy scenarios, such as the IEA *Energy Technology Perspectives* 'BLUE' scenario that analysed the technologies needed to achieve 50% reduction in CO_2 emissions by 2050, (IEA, 2008a), anticipate that BTL processes could produce more biofuels than 1st-generation ethanol and biodiesel plus 2nd-generation ethanol combined (Fig. 30). In this scenario it is projected that biofuels would meet around a 25% share of total transport fuels, but mainly for aviation, marine and heavy road transport with light duty vehicles electric-powered or plug-in hybrids. This scenario assumed there will be increasing incentives for governments to reduce dependence on imported oil, reduce GHG emissions, and support rural regions and sustainable deployment by producing the fuels locally.

BTL-based biofuels can be fed into the existing infrastructure; can have a high energy density of around 40 MJ /l so are suitable for long distance transport vehicles including aircraft; can be used in existing and advanced compression ignition engines; and can be stored. They are clean burning with very little sulphur or aromatic compounds, create few exhaust gas emissions, and can be produced from a wide range of feedstocks (Bienert, 2007a).

In several demonstration applications, further cost reductions are anticipated through economics of scale in larger commercial plants when the economics of gas conditioning, synthesis and final upgrading should improve significantly. The front end would need to become suitable for multi-feedstocks however at increased cost, and the delivered feedstock costs would increase due to a greater collection and transport radius.

While BTL technologies are not yet commercially proven, several pulp and paper concerns have begun installing gasification technologies which might be able to take advantage of future developments. For example, the company Intrinergy has announced the installation of a biomass gasifier at Coastal Paper in Wiggins, Massachusetts, while Tolko has partnered with Nexterra to create a syngas development programme in Kamloops, British Columbia, Canada.

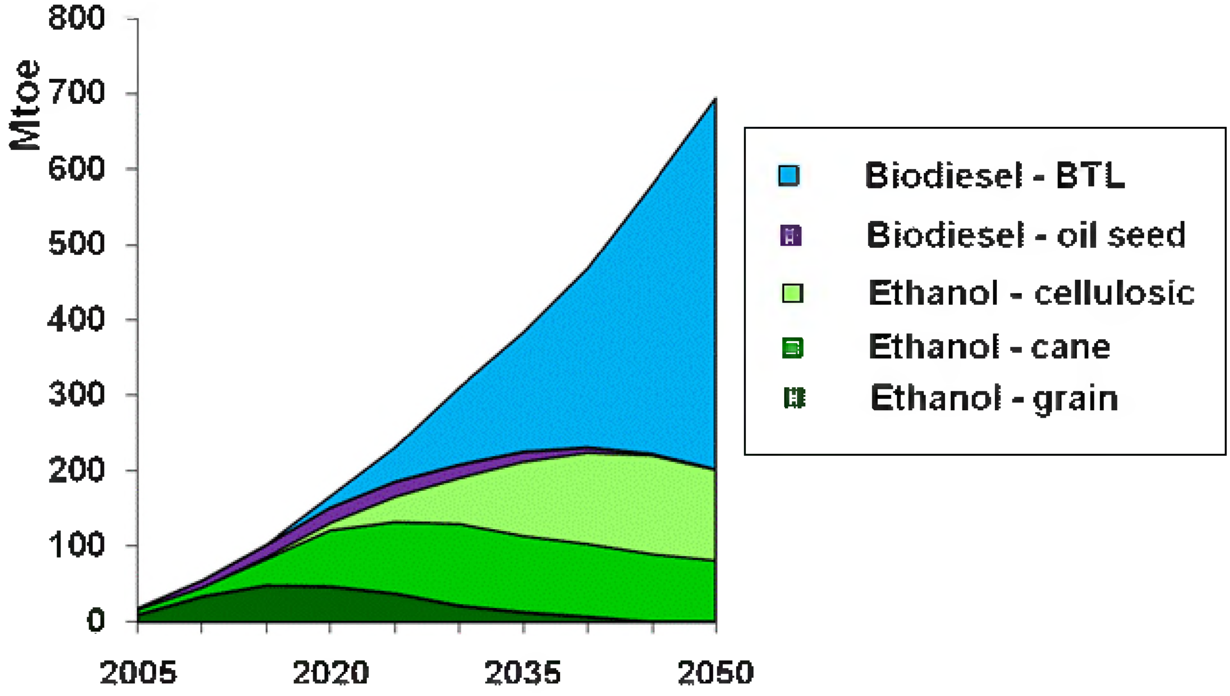
Typical commercial BTL plant capacities could vary from 200 -300 MW_{feed} using an integrated approach of biofuel production with existing industrial complexes, or even be considerably larger.

Where a biofuel process is integrated in a pulp and paper mill or municipal combined heat and power (CHP) plant, the main considerations would be the logistics of delivering the biomass supply and efficient integration with the existing production process. This concept of a bio-refinery is seen as a means of reducing the total additional capital cost per unit of biofuel capacity and hence decreasing the overall costs of the end products. A consortium comprising Neste Oil and Stora-Enso, is aiming to construct its first large plant of around 200 MW_{feed} at a pulp mill by the end of 2013.

ALICO

Alico Inc., a US land management company (http://alicoinc.com), was planning to use a two-stage gasification/biocatalytic process technology developed and patented by Bioenergy Resources Inc., Arkansas. The hot gases would be scrubbed, cooled and filtered before entering a bioreactor where fermentation occurs. The 52.6 Ml/yr ethanol plant was to be built in Florida and would require 770 t/day of demolition wood and vegetable waste feedstocks (including citrus peel) and possibly bagasse from local sugarcane production at a later stage. Over 6 MW of power was to be generated as well as other co-products including 50 t/day of ammonia for fertiliser manufacture and 8.8 t/day of hydrogen. Up to USD 33M support was made available from USDOE. Florida State also provided grant funding. However, in early June 2008 ALICO announced that it would no longer explore the construction of a production facility in Florida. In light of this move, New Planet Energy LLC, assumed full ownership of the project and is acquiring a suitable site. At the time of writing, it is unknown what changes will be made to the existing project.

Figure 30. Projected transition between 1st- and 2nd-generation biofuels over time.



Source: IEA, 2008a

Choren

This German company patented their novel BTL concept in 1994 and initially produced methanol from woody biomass in 2003 at the laboratory scale, and later FT liquids from wood. The aim was to enable biomass to be processed on a decentralised basis. The company has now developed a "Carbo-V" 3-stage gasification process based on gasification and low temperature carbonisation followed by the reduction of carbon dioxide and water over red hot char. The necessary process heat is produced by means of partial biomass combustion.

The stages of the process are carried out separately as follows:

- shredding then drying of the biomass to around 15-20% moisture content wet basis;
- low temperature (550°C) and pressure (1-5 bar) pyrolysis/carbonisation with the temperature controlled by feeding in controlled amounts of oxygen to produce low temperature, tar-rich volatiles and solid char;
- higher temperature gasification, around 1400 - 1500°C, in the combustion chamber (above the melting point of the biomass fuel's ash), where oxygen is present to convert the volatiles to tar-free gas;
- char from the low temperature gasifier is ground into pulverized solid fuel and blown into the hot gases beneath the combustion chamber where it reacts with the gasification medium endothermically in the entrained-flow gasification reactor to produce a raw synthesis gas;
- gas is cooled by the waste heat exchanger to produce steam then conditioned and cleaned via a gas shift reactor to the scrubber where contaminants such as chlorides and sulphides are removed by liquid sprayed into the gas stream;
- hydro-cracking of the long chain molecules to produce the liquid "Sundiesel" fuel;

- ash particles and char that have not been entirely converted are separated from the raw gas in the de-duster and recycled back to the combustion chamber;
- molten ash flows down the inside wall of the combustion chamber into a water bath below the gasifier where vitrified solid ash is formed.

Entrained flow gasifiers can typically only produce a low hydrocarbon gas, tend to have low efficiency and cannot be easily fed with solid biomass particles. The Choren process was therefore designed to increase the process efficiency. After low temperature gasification, the pyrolysis gas and char enter the high temperature, oxygen-blown gasifier from which the raw, tar-free gas is cooled in a heat exchanger to produce steam, and the syngas is then de-dusted and scrubbed. Chemical quenching is used to recover the high temperature heat by blowing char particles into the hot gas after it leaves the combustion chamber. The carbon in the char, which also contains all the ash, is not completely converted. The residual char is then fed back into the combustion chamber where it is fully exploited as the ash is melted and then vitrified into slag granules that could possibly be used as a construction material. Decreasing losses in the combustion chamber by direct cooling adds to the gasifier efficiency which is claimed to be around 80%. An advantage is that absolute combustion of the tar-free gases can occur without needing catalytic gas cleaning. The gas mix has a low methane content even when produced at pressures below 30 bar. However at the present stage of development, the mixture is also too low in hydrogen content for the gas balance needed, so hydrogen produced during the refining of fossil fuels is added at high energy cost.

After gasification and gas treatment, the syngas is converted via the Shell middle distillates synthesis (SMDS) FT process (Box 2) and upgraded. Choren has negotiated access to SMDS for BTL applications. Physical and cold flow properties of the FT liquid from the SMDS showed a lower density, lower sulphur content, slightly lower pour point, very high cetane number of 83, very low polycyclic aromatised hydrocarbons (PAH), slightly lower lubricity, and lower viscosity at the standard 40°C compared with diesel standard DIN EN 590 (Bienert, 2007b).

Following the successful results from the 1 MW_{th} low temperature gasifier pilot plant in Freiberg, a 15 MW_{th} demonstration gasifier was built for incorporation into the 45 MW_{th} plant currently nearing commissioning. This plant design aims to produce 16.5 Ml /yr of "SunDiesel" linked with a power plant. The USD 140 M investment will require around 75,000 t /yr of biomass feedstock of which half will be from crop residues and half from wood chips. Gas clean up still remains a problem to be solved and the efficiency of biomass feedstock to liquids is around 45%. Commercial production is planned for late 2008 with the BTL fuel to be initially blended with diesel.

The current research aim of Choren is to improve and optimise the whole BTL system and the properties of the automotive fuels by investigating different catalysts and plant operating parameters including temperature, H_2/CO ratio and syngas input. Greater feedstock flexibility was sought for the project by introducing autothermal pyrolysis at the first stage. To achieve this, the biomass needs to be below 35% moisture content (wet basis) initially, have < 5% impurities, be smaller than 120x50x30 mm particle size, and be delivered to the plant at relatively low costs.

The Choren consortium has a longer-term vision for a fully commercial plant to be built by 2011-2012, assuming the demonstration plant proves successful in 2008-2009. This standard 600-700 MW_{th} plant would produce around 250 Ml/yr of liquid fuel from 1 Mt oven dry biomass (assuming around 50% overall conversion efficiency). An investment cost of at least USD 600M for the plant would be required along with up to 20 ha of land including for biomass storage and biofuel storage tanks. It would employ 150 staff plus an additional 700 to provide the biomass supply. By 2020 the vision is for this plant to be replicated by more than 45 plants throughout Europe requiring biomass feedstock from 6 Mha in order to produce around 600 PJ/yr of liquid fuels and to meet around 7% of total diesel transport demand (Bienert, 2007b).

A basic life cycle analysis of the "Sundiesel" biofuel produced, comparing it with conventional diesel, was undertaken on behalf of Volkswagen and DaimlerChrysler (Baitz *et al.*, 2004). Using feedstocks from "waste wood" and "standing timber" and transport distances of 50km and 200km, three process scenarios were evaluated for their impacts on global warming, summer smog, eutrophication and acidification.

1. *Self sufficiency* is the current process where the gases, oxygen and nitrogen, are produced via air separation. Electricity and hydrogen (needed for the process and produced by the homogeneous water gas reaction), are all produced on site so no external sources of energy or materials are needed.
2. *Partial self sufficiency* is technically equivalent to self sufficiency but the oxygen and nitrogen are purchased externally and brought into the plant, and the power is purchased from the grid.
3. *Future* is where the electricity, hydrogen and oxygen are all supplied externally but from renewable energy sources. The yield of liquid fuel therefore increases as a result. This scenario demonstrates the greatest potential for reducing the environmental impacts assessed compared with diesel but in all cases GHG emissions and summer smog potential were reduced.

Development work on gasification and reforming is also under evaluation by VTT Finland, the Värnamo consortium in Sweden, the University of Vienna in Austria, as well as in numerous small studies (Annex 2).

Range Fuels

Range Fuels Inc. uses a thermo-chemical process to turn biomass into synthetic gas and then biofuel. It has been testing its technology in pilot-scale units for the past seven years The company is planning a demonstration plant in Georgia using a novel gasification process. In November 2007, it began construction of its first 80 Ml /yr phase of a commercial ethanol plant in Soperton, with plans for completion in 2009. The plant is designed to be able to be scaled up to 400 Ml /yr. The syngas produced will be cleaned then compressed to around 10 MPa and converted in a catalytic synthesis step at 350°C. Eventually 150 Ml/yr of ethanol and 34 Ml/yr of methanol will be produced from 1200 t/day of wood residues and woody biomass energy crops. Up to USD 76M is available for support for this project from USDOE.

The start-up phase has raised over USD 130 M from Passport Capital, Blue Mountain, Khosla Ventures, Leaf Clean Energy Company and Pacific Capital Group (with participation by the California Public Employee Retirement System).

Flambeau River Biofuels LLC

Flambeau River plans to construct a demonstration biomass-to-liquids (BTL) biorefinery in Park Falls, Wisconsin. This plant will be co-located with a papermill, and will use wood residues to produce about 22 Ml/yr of FT diesel fuels and waxes. The plant will also recover at least 1 PJ of renewable process heat per year under contract to Flambeau River Papers, which will help make FRP become one of the first integrated pulp and paper mills in North America to be fossil fuel free. Among the partners are Auburn, Brigham Young, Michigan Tech, NC State, and the University of Wisconsin, as well as the USDA Forest Products Laboratory and Oak Ridge National Laboratory. The plant is scheduled to be in operation in 2010 and the US DOE will provide up to US$ 30 M to the project.

Flambeau River has also signed a memorandum of understanding with American Process in Atlanta to build a forest pulp mill bio-refinery at its Park Falls, Wisconsin mill that is expected to produce 75 Ml /yr of cellulosic ethanol from black liquor gasification.

NewPage Corporation

The company is planning a new plant, to be located in Wisconsin Rapids, Wisconsin, to take wood wastes and convert them to FT diesel fuel. NewPage Corporation of Miamisburg, Ohio, recently acquired Stora Enso North America, the original applicant for this funding opportunity. It is the largest printing paper manufacturer in North America. The US DOE will provide up to US$ 30 M for the project.

Partners include TRI; Syntroleum; USDOE's Oak Ridge National Laboratory; and the Alabama Center for Paper and Bioresource Engineering at Auburn University.

NewPage has also signed an agreement with Chemrec to evaluate the feasibility of building a black liquor gasification plant at its mill in Escanaba, Michigan. Preliminary indications are that converting pulp process waste into syngas and then into liquid biofuel could provide as much as 50 Ml /yr.

Summary

There are a number of pilot-scale and demonstration plants either operating, under development or planned with fully commercial developments not expected until the next decade or two (GBEP, 2007). The rate of development will depend on the timing and success, or otherwise, of the demonstration projects, continued RD&D investment by public and private sectors, and other government support to encourage risk-averse investors to build full scale plants. Higher capital investment is required than for 1st-generation plants. Therefore 2nd-generation biofuels are likely to remain more costly to produce than some 1st-generation types but could possibly be cheaper than oil products in the future (in terms of $/l gasoline equivalent) assuming that the crude oil price remains high.

6 Sustainable production of biofuels

Increasing concerns have been expressed recently regarding the sustainable production and use of biofuels. These relate to both environmental issues (such as water depletion, water pollution, air pollution, biodiversity loss, soil and forest carbon stock decrease) and social issues (such as land occupation, exploitation, health, social conflict derived from food / energy resource competition). A particular concern relates to the complexities of land use and land use change inter-linked with climate change impacts. The methodology of life cycle analysis to determine the benefits and disbenefits from using biofuels or petroleum fuels continues to be developed but care is needed when interpreting results. For example some analyses allocate inputs and outputs to all the co-products whereas others only consider the biofuel outputs and all environmental and social costs are placed on these. This debate has been reviewed and thoroughly addressed by the IEA in a contribution published in the OECD (2008) report *Economic Assessment of Biofuel Support Policies.* Therefore sustainability issues including GHG and energy balances will only be considered here in relation to 2nd-generation biofuels.

Another thorough assessment of biofuels, their sustainable production and opportunities for trade, especially for developing countries, can be found in the *Sustainable Biofuels Consensus*, painstakingly compiled by a team of wide ranging experts and supported by the Rockefeller Foundation (Sims, 2008). The 8 page document aims for a balanced debate to assist policymakers, developers and financiers understand the key issues. It states:

When produced responsibly, increased global biofuels trade, transport use and production can be cost-effective, equitable and sustainable. Many nations have the ability to produce their own biofuels derived both from agricultural and forest biomass and from urban wastes, subject to adequate capacity building, technology transfer and access to finance.

Trade in biofuels surplus to local requirements can thus open up new markets and stimulate the investment needed to promote the full potential of many impoverished countries.

This vision also responds to the growing threat of passing a tipping point in climate system dynamics. The urgency and the scale of the problem are such that the capital investment requirements are massive, and more typical of the energy sector than the land use sectors. The time line for action is decades, not centuries, to partially shift from fossil carbon to sustainable live biomass.

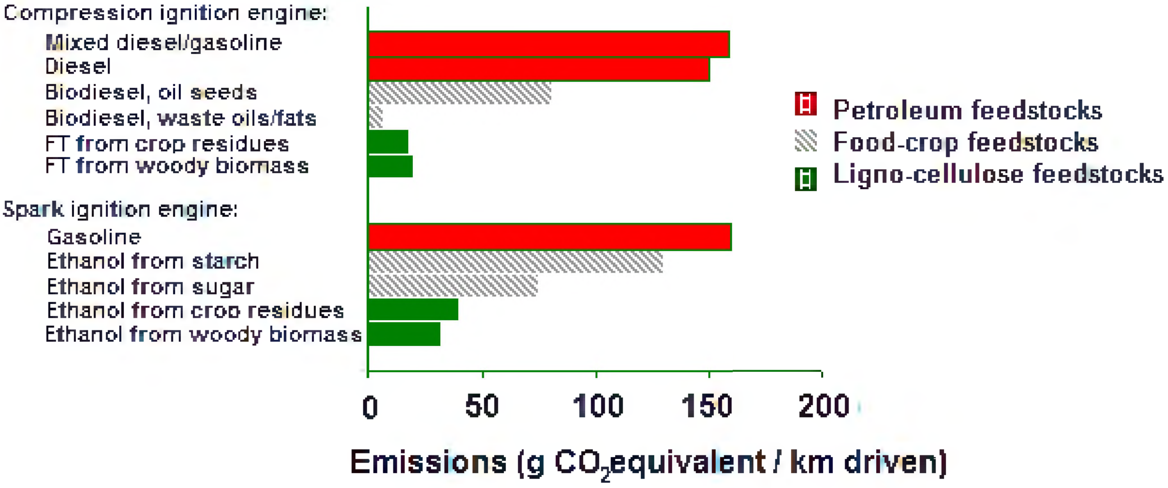
The Sustainable Biofuels Consensus calls upon governments, the private sector, and other relevant stakeholders to take concerted, collaborative and coordinated action to ensure sustainable trade, use and production of biofuels, so that biofuels may play their key role in the transformation of the energy sector, climate stabilisation and resulting worldwide renaissance of rural areas, all of which are urgently needed.

6.1 Environmental impacts

The IEA analysed 60 life-cycle analysis (LCA) studies of biofuels (OECD, 2008). Only 18 included non-GHG environmental impacts and less than a third included 2nd-generation biofuels. All of those that did however showed a net improvement of GHG emissions of around 60-120% compared with petroleum fuels. Land use GHG emissions were not included but co-products were. Hence the ability to achieve >100% reductions when co-products are also able to substitute for fossil fuels to generate heat and power for example. Both the ethanol and synthetic diesel routes from ligno-cellulose produced GHG emission reduction ranges similar to displacing gasoline with sugarcane ethanol (Fig. 2).

Some studies compared cellulosic liquid biofuel production with both 1st-generation food-crop based liquid biofuel production and conventional petroleum use (Fig. 31). A significant reduction in GHG emissions resulted. Two other integrative reports have brought together major LCAs that had been conducted in North America with a number from countries in Europe. The VIEWLS (2005) project corroborated data released in an earlier report by the Institute for Energy and Environmental Research in Heidelberg, (although that study provided some additional LCA reviews) (Quirin *et al.*, 2004). Both the earlier and follow-up reports showed that biofuels made from both crop and forest ligno-cellulosic materials are characterised by reduced CO_2 emissions compared with similar petroleum-based liquid fuel products. Within the bounds of analytical accuracy, GHG emissions reductions from using ethanol were similar whether it was produced from ligno-cellulose or sugar feedstocks.

Figure 31. Comparison of GHG emissions from biofuels and conventional fuels for transport



Sources: Spitzer & Jungmeier, 2006; VIEWLS, 2005.

The few LCA studies that have considered non-GHG environmental impacts of 2nd -generation biofuels showed for both bio- and thermo-chemical routes, reduced acidification, lower summer smog levels and less eco-toxicity compared with petroleum fuel use. However, due to their agricultural origins and fertiliser use during feedstock production from energy crops, eutrophication increased.

A common concern relates to the removal of too many agricultural or forest residues from the soil whcih might increase soil erosion or reduce the soil nutrient status over time. The appropriate amount that can be removed varies with soil type and site conditions as is prescribed by IEA Bioenergy Task 31 that has studied this issue (www.ieabioenergy.com). Returning the ash to the land after some processes where it is produced (e.g. gasification) is an option being already practiced by some biomass combustion plant operators.

The amount of water and processing chemicals used for 2nd-generation biofuel production can also be an issue needing consideration. In addition the treatment of the stillage resulting from distillation can involve additional costs to minimise the environmental impacts.

6.2 Energy balance

Energy output/input ratios for producing liquid transport fuels do not provide a complete comparison but, along with net energy yields per hectare, can be a useful indicator. For example, a review of energy balance studies carried out by the US National Resources Defence Council (NRDC, 2006) indicated that, under current production methods, corn (starch-based) bioethanol gave only a slight improvement in energy efficiency over petroleum fuels, while cellulosic ethanol can improve this by up to four times. In five of six studies analysed (Fig. 32), corn ethanol provided an energy return (MJ out in 1 litre of biofuel / MJ of energy in) of between 1.3 and 1.65. The single dissenting study that gave a negative energy balance (Pimentel & Patzek, 2005), used significantly higher energy inputs than are usually considered standard, thus generating far lower energy returns than were obtained by the majority of researchers in this field. Accounting for co-products was not included.

For ligno-cellulosic ethanol, three out of four studies indicated energy returns ranging from 4.4 to 6.6 energy units out for every energy unit in. These results are consistent with the potential for the cellulose-to-ethanol process to be independent of significant fossil-based energy inputs where the co-products are used for heat and power generation. Again, the dissenting Pimentel & Patzek (2005) study used higher energy input figures than the standards used by most researchers. Overall, the results indicate that development of 2nd-generation biofuels utilising forest residues has the potential to improve energy efficiency and the overall energy balance in the biochemical route. In the thermo-chemical route, the lignin is converted to syngas so is not available to provide process heat. However the process demands fewer energy inputs than biochemical ethanol, so importing energy is not too critical to overall costs.

These studies are examples of numerous other studies that have shown similar results. However few assess the share of renewable energy used in the energy inputs which can affect how the results are interpreted.

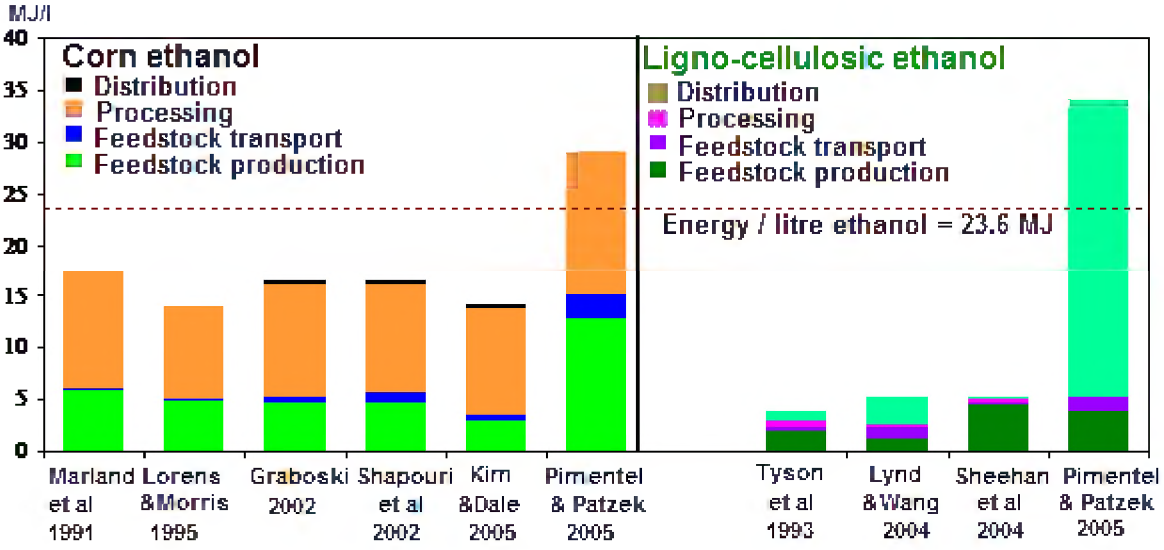
6.3 Transition from 1st- to 2nd-generation

Where 1st-generation biofuels have been most successfully deployed to date as in Brazil, US, Germany, China, the infrastructure and markets have become well established. This includes storage, blending, distribution and transport of the wholesale biofuels as well as vehicle engine testing, acceptance of standards by engine and fuel system manufacturers, establishing suitable dispensing nozzles and pumps at service stations, and modifying storage tanks where necessary.

Initially 2nd-generation fuels will remain more expensive per litre and require significant capital investment in conversion plants until their production costs are reduced from learning experience. However feedstock costs and availability for 1st-generation will determine the rate of growth of the 2nd generation industry. If 1st-generation growth continues to be supported by policies of some governments, then a delay in bringing 2nd-generation on stream could result, especially if government funding goes towards supporting 1st-generation by means of subsidies and grants rather than looking forward to the longer term. More risky long term investments in advanced biofuels RD&D may be a less popular policy as perceived by the public. In addition there is a view that encouraging a large market for 1st -generation biofuels will provide confidence and experience in the supply chain for 2nd-generation to evolve quicker. There is also the potential for 2nd-generation biofuels to begin production added on to 1st-generation processing facilities (as Abengoa are planning in their US plants). Exactly how well different 1st-generation biofuels could become a bridge for 2nd-generation varies with the situation and requires further evaluation.

In order for 2nd-generation biofuels to become competitive, incentives must be geared to the type of biofuel under consideration. This could be based on energy balances, life cycle assessment of greenhouse gas emissions, or sustainable production of the biomass. Therefore care is needed during policy development since there have been widely differing assessments undertaken (OECD, 2008; Young, 2007).

Figure 32. Comparison of net energy investment (input/output) of bioethanol production from various studies



Source: NRDC, 2006.

6.4 Recommendations relating to environmental and social policies[9]

- Agree on internationally compatible fuel quality technical standards whilst recognising that several countries are already engaged in efforts to harmonise these standards.
- Adopt local, bilateral, regional and/or other frameworks for biofuels trade agreements with the objective of collaborating with existing frameworks to achieve convergence towards a comprehensive international land use improvement agreement.
- Harmonise life-cycle-analysis methodologies for biofuels, including GHG life-cycle accounting methodologies, recognising that efforts both at the international and national levels, are already under way and involve continued mapping of degraded and marginal lands and continued mapping of carbon stocks, areas rich in biodiversity, and other high conservation value areas.
- Address positive and negative indirect effects of biofuels trade, use and production. In an ideal world, sustainability criteria would be applied to all food, fodder, fibre and energy production and thus put biofuels on a level playing field with fossil fuels. Until such a system exists, there will be an excess of indirect positive and negative impacts on conservation areas, GHG balances, and food security from land use change, as well as price variations specifically associated with biofuels.
- Continue global research to identify and quantify links between biofuels and land use change; provide mechanisms to promote biofuels that do not have negative land use change impacts; develop mechanisms that mitigate the negative impacts but do not unduly increase transaction costs for producers; and install social safeguards at the national level that ensure vulnerable people are not further disadvantaged through food and energy price increases and other potential negative economic side effects.
- Reward positive impacts and investments, including through carbon management and soil carbon uptake, including by the production and addition of bio-char as a co-product of biofuel production.
- Enhance market opportunities and open up capital investement flows in order to follow the most profitable business models. Under-funded benefits fall into the categories of rural and social development; ecosystem services, including biological carbon fixation and water resource management; as well as better land management practices that might reduce crop yields but restore ecosystem health, such as conservation agriculture.
- Reward better practice which will require using existing and innovative tools to ensure that markets reward environmental and social performance, including carbon sequestration and biological carbon fixation.

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[9] The Sustainable Biofuels Consensus (Sims, 2008) was used as a basis for this section.

- Ensure that biofuels development is accomplished by shared benefits, rights and rules of law and to recognise that biofuel projects create significant rural and social development benefits. These will however possibly be under-invested in due to difficulties in integrating many smallholders into markets, tendencies to concentrate buying power within supply chains, and a lack of financial markets for small producers.
- Business models exist that equitably share benefits throughout the supply chain, especially at the farmer level. National policies, bilateral agreements, foreign assistance, and international financial institutions should give preferential treatment to these types of production systems to the extent feasible and to projects that encourage development of small scale production and regional biofuels markets.
- Use informed dialogues to build consensus for new projects and promote an informed and continuous dialogue engaging all relevant stakeholders. This is key to ensuring equitable distribution of benefits of biofuel projects, and to addressing other elements of sustainability. It is particularly important to encourage biomass producers, both farmers and foresters, into the dialogue. To be effective, these dialogues must be translated into the allocation of public and private budgets to meet the consensus achieved on priorities for specific projects and RD&D portfolios.
- Build capacity to enable producers to manage carbon and water. Capacity building programmes are needed for farmers, foresters and small and medium-sized enterprises active in bioenergy and biosphere carbon management systems, such as bio-char soil improvement techniques and water management technologies. Capacity building is also needed for the development of effective technology innovation systems involving research and education, extension, industrial capacity to participate in joint ventures with supportive government agencies and an engaged civil society.
- Make sure that trade policies and climate change policies work together. This will include Official Development Assistance (ODA), national subsidies and payments. There is a need for a clear commitment for national climate change policies, including those that promote biofuels, to be additional to ODA. This is best achieved by climate change policies that drive direct foreign investment by energy sector players, in harmony with trade policies and sustainability requirements. Guided by national stakeholders' consensus of the recipient countries, ODA should focus on helping to initiate and develop the institutions needed for sustainable rural development and respective business models, and support countries in defining and meeting sustainability requirements. In connection with biofuels development, ODA should also partner with development and UN agencies such as UNFAO, UNCTAD, UNDP, UNEP and UNIDO and the private sector to help in reducing transaction costs of sustainable development schemes.

PART C) Future Biofuels and Policies

7 New Feedstocks and Advanced Conversion Technologies

Several other liquid fuels, sourced from biomass feedstocks and suitable for use in transport applications are under evaluation. This section briefly describes the potential for algal feedstock and several of the advanced conversion technologies. Some are already reasonably close to market (such as hydrogenated biodiesel). Those still at the R&D phase are commonly termed "3rd-generation biofuels". However there is no accepted definition for this group, so here they are addressed more generally as "advanced bioofuels".

Task 41 "Bioenergy Systems Analysis" of the IEA Bioenergy Implementing Agreement, recently completed an overview of RD&D requirements for biofuels. The work has been used widely in this section, but more detailed assessments of several of these new technologies can be found in their report (IEA Bioenergy, 2008).

7.1 Algal feedstocks

Algae are the fastest-growers of the plant kingdom. When photosynthesising, certain species can produce and store inside the cell, large amounts of carbohydrates and up to 50% by weight of oil as triglycerides (www.oilgae.com). The conversion of algae oil into biodiesel is a similar process as for vegetable oils based on interesterification of the triglycerides after extraction, but the cost of producing algae oil is relatively high at present. The potential for algae has been understood for many years and research was widely undertaken in the 1970s, for example by the US DOE, before abandoning it in the mid-1990s. More recently, worldwide interest has been renewed.

Algae can be produced continuously in closed photo-bioreactors but oil concentration is relatively low and capital costs are high. To collect the biodiesel feedstock more cheaply would need high volumes of algae to be cultivated in large facilities at low cost, hence the interest in growing the algae in open ponds, including sewage ponds where nutrients are in abundance and the sewage is partly treated as a result. In practice a problem is contamination of the desired culture by other organisms that limit algal growth. A combination of closed and open systems is an option (Huntley & Redalje, 2007). The microbes are initially grown in closed reactors under controlled conditions that favour continuous cell division and prevent contamination. A portion of the culture is transferred daily to an open pond where it is subjected to stress and nutrient deprivation. This stimulates cell concentration and oil production within a short residence time before contamination can occur. Oil production costs of around USD 84 / bbl were claimed with cost reductions thought possible due to improved technology and experience.

The micro-algae oil yield per hectare is claimed to be 16 times higher than palm oil and up to 100 times higher than for traditional vegetable oil crops grown in soil. Algae also consume 99% less water. But to produce large oil volumes, large surface areas of ponds are involved requiring high capital investment. In addition, since algae absorb CO_2 emissions, they are also being studied to clean flue gas from coal-fired power plants. The injection of CO_2 collected from fossil-fuelled thermal power plants could be used to enhance growth.

Currently researchers at University of Minnesota and elsewhere are evaluating the optimum strains of algae and determining how to extract the oil most efficiently. Increased funding has been received from governments, oil companies, utilities and venture capital firms over the past two years. However although no valuable arable land is needed, the cost of production and processing is thought to be around a relatively high USD 5 /l. In New Zealand, where a Range Rover was powered by an algae biodiesel blend in 2006, researchers say uncertainty remains about when algal biofuels will become commercially viable[10].

The US Defence Advanced Research Projects Agency, is funding research into producing jet fuel from plants, including algae. Honeywell, General Electric Inc. and the University of North Dakota are involved.

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[10] http://www.eeca.govt.nz/search/?q=algae

AlgoDyne Ethanol Energy Corp. has conducted a series of biofuels initiatives in Brazil including planned bio-kerosene projects with airlines and the development of a pilot plant for ethanol production from algae. In September 2006, the Brazilian biofuel company Tecbio announced that it was working with NASA and Boeing to develop a bio-kerosene aviation fuel. A flight test was carried out in 1984 with 100% bio-kerosene in a twin-prop Bandeirante aircraft manufactured by Brazilian company Embraer that also developed a small ethanol-powered plane. A new version of the fuel claimed to overcome several technical hurdles is to be patented in 2008. If algae could provide 80,000 l/ha/yr as some claim, some 320 bn l/yr of "bio-jet" fuel could be produced on a landmass equivalent to the size of the US state of Maryland and be sufficient to supply the present world's aircraft fleet with 100 percent of its fuel needs.

In Hawaii, Royal Dutch Shell has established a company, Cellana, to work with the small local company HR Biopetroleum and build a demonstration plant on the island of Kona to commercially harvest algae and demonstrate that it can be technically viable to convert it into biodiesel. A 2.5 ha site has been built close to seawater ponds where the algae has been growing for 2 years. The construction of a separate 1 000 ha site is also planned to evaluate whether algae can become economic when scaled up to a commercial level. If the results are encouraging, the next step would be to build a 20 000 ha site. Since seawater and coastal land can be used for production, there will be no competition for agricultural land and water resources. Other companies with an interest in algae for biofuel production include www.solixbiofuels.com and www.greenfuelonline.com

A recent overview of algae potential for transport fuels conducted for the IEA Advanced Motor Fuels Implementing Agreement (McGill, 2008), concluded that even if the technical barriers can be overcome, the practical barriers such as location, land use etc. will take many years to be removed and that commercialisation will be evolutionary, not revolutionary.

Hydrogenated biodiesel

Catalytic hydrogenation and cracking of oils and fats is not strictly a new process and is already entering the market. So in this sense, especially where edible oils and fats are used, it could be classified as a "1st-generation" biofuel with similar issues of sustainability of feedstocks. It converts triglycerides into high-quality synthetic biodiesel. Since the process involves the application of hydrogen, it is well suited to be integrated into an oil refinery in which hydrogen is generated as a part of the process. There are several examples of this approach including the H-Bio process of Petrobras, the Canadian Super-Cetane process, and the commercial NExBTL process of the Finnish company Neste Oil. In addition two 800 kt plants are envisaged in Rotterdam and Singapore.

In the NexBTL process the oils are hydrogenated by a direct process in dedicated plants whereas ConocoPhillips and others are employing an indirect process where the oils are added downstream in the oil refinery. Since the process is refinery-based, it benefits from the existing infrastructure including energy supply, blending facilities, transport logistics and laboratories. The resulting fuel can be mixed with mineral oil diesel at any blend without any problems as they have similar properties but is has a superior quality that helps lower exhaust emissions. It is also more stable than biodiesel during longer-term storage. The first commercial-scale plant was commissioned in summer 2007 and the second plant is under construction at Neste Oil's oil refinery in Porvoo, in Finland.

The Brazilian oil company, Petrobras, has developed the H-Bio biodiesel process which hydrogenates mixtures of vegetable oil and petroleum. It announced the start of production in December 2006.The output is a mixture of diesel and hydrogenated vegetable oil rather than a separate biodiesel component as in the case for the NExBTL process.

Dimethyl ether (DME)

DME (CH_3OCH_3) is produced from coal or natural gas commercially but could also come from biomass feedstocks. It is gaseous at ambient conditions, but liquefies at moderate pressures (5-8 bar). Hence it could be mixed with LPG (liquid petroleum gas consisting of mainly butane and propane) or be a useful substitute for it. As well as a vehicle fuel in converted spark ignition engines, it is used widely for heating and cooking, and hence could be an option in developing countries to replace the very inefficient use of dung and fuelwood at the domestic and village scale. Unlike methanol, DME is non-toxic. It can be used in gas turbines or fuel cells for power generation, and as a good quality vehicle fuel in compression ignition engines. It emits lower NO_x and SO_x emissions than diesel, has zero particulates, and has lower life cycle GHG emissions than most other biofuels. Existing LPG storage and distribution facilities can be utilised for DME but where these are not available, costly infrastructure is required since it is gaseous under normal temperature and pressure.

It has usually been produced by converting syngas (mainly CO + H_2) into methanol which is then distilled and catalytically dehydrated using ZSM-5, a zeolite catalyst. A simplified process has been applied using new bi-functional catalysts to produce DME directly from the syngas in a single step (IEA Bioenergy, 2008). Various process designs have been proposed for the co-production of methanol and DME, and for the cogeneration of DME and electricity. Production costs remain a constraint for dedicated biomass DME plants. Investment costs for a conventional DME production process amount to USD 11/GJ to USD 20/GJ per year (Sakhalin Energy, 2004). The capital investment costs for bio-DME production are estimated to be between USD 450 and 1050 per tonne of biomass input capacity, with conversion efficiencies between 45 and 65% (Londo, *et al.*, 2008). Production costs could be in the order of USD 11.6 to 14.5/GJ in Sweden, but lower than this in developing countries (Atrax Energy, 2002 and IEA analysis). The Volkswagen / SYNCOM led industry analysis in the EU funded RENEW project (www.renew-fuel.com), showed DME could be produced from low cost Swedish forest residues for around €14 / GJ.

DME has a higher cetane number than oil-based diesel which makes it more suitable for application in compression ignition engines. DME has the advantage of burning cleaner than oil-derived diesel. Potential drawbacks are that it contains only around half the energy of oil-based diesel which increases fuel consumption and requires larger fuel storage tank volumes compared with a similar on-board tank of diesel. Due to its low viscosity and lubricity properties, it can also cause reliability and leakage problems with pumps and injectors. A mandatory maximum filling level of 80-85% of capacity, as a safety margin in case of high ambient temperatures, is required (as for LPG). Some engine modifications would be required, notably a more sophisticated injection system. In particular, the dedicated injection system appears to be a key technical challenge for the automotive use of DME. These technological drawbacks, combined with the high production costs, mean that DME is probably a long-term alternative to fossil fuel derived diesel.

In Sweden, Chemrec and Volvo are evaluating commercial production via black liquor gasification (IEA, 2008a). The University of Southern California's Loker Hydrocarbon Research Institute has developed fundamental chemistry to transform CO_2 to DME or methanol and together with UOP LLC, a Honeywell company, they are jointly developing new technology to transform carbon dioxide into cleaner-burning alternative fuels (www.greencarcongress.com/dme/index). Further work is needed on the development of a commercially viable process.

Bio-synthetic natural gas (SNG)

Bio-SNG (as opposed to coal-to-SNG) can be produced either from wet biomass streams through anaerobic digestion or supercritical water gasification or from relatively dry biomass through gasification then requiring a methanation process to form SNG from the CO and H_2. Different components can be converted into methane by changing the catalyst of the process. The process is strongly exothermic and therefore part of the energy of the gaseous components is lost in the form of heat which has to be removed from the reactor and the SNG cooled before storage. Efficient recovery of the reaction heat, which amounts to about 20% of the heating value of the synthesis gas, is essential for any industrial methanation technology. Bio-SNG has similar qualities to natural gas, so a benefit is the possibility to distribute it via natural gas pipeline grids.

As a vehicle fuel, SNG is similar to compressed natural gas (CNG) or liquefied natural gas (LNG). Hence it must be compressed or liquefied to reduce its volume for on-board storage, which both have an energy and cost penalty. It is a clean burning fuel with relatively low CO, NO_x and particulate emissions.

Conversion routes include stand-alone SNG, SNG co-produced with FT synthetic diesel, and biomass gasification in super-critical water (though due to the syngas composition, this is more suited to hydrogen production than SNG). In the combined route with FT diesel production, the off-gas from the FT reactor is taken to a methanation reactor and, using a Ni-based catalyst, converted to SNG.

The catalysts are sensitive to impurities, so a gas clean-up process is required, though this remains technologically challenging. In Austria however, Gussing town already has a biomass gasification CHP plant integrated with a SNG plant that has been working successfully for several years.

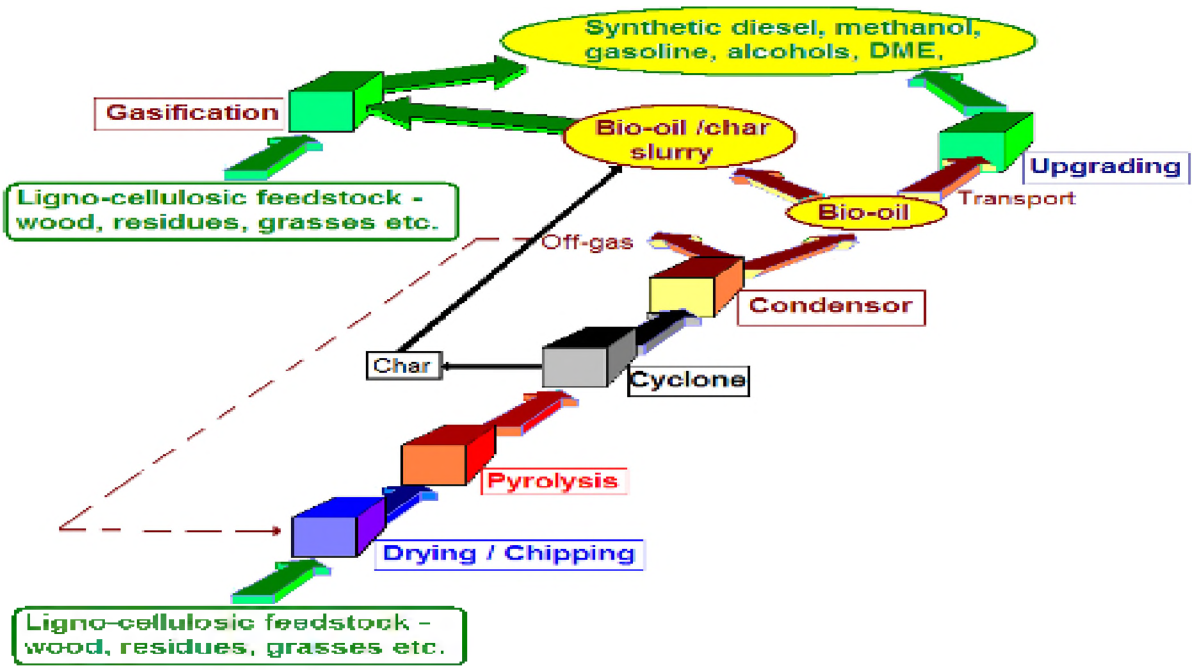
In Switzerland, district heating using the woody biomass available has proved largely uneconomic so an alternative option is being evaluated. "Gazobols" is the Swiss "gas from wood" project based on gasification followed by a novel methanation conversion process with a claimed 72-80% efficiency based on a demonstration plant (www.e4tech.com). A commercial scale 30 MW_{sng} plant is planned to be built in Vaud to produce around 750 TJ /yr of SNG, requiring around 130 000 t/yr of woody biomass. However a feasibility study showed that the plant could not currently compete with methane produced as biogas from animal wastes and sewage due to the high feedstock cost of around USD 9 /GJ due to the labour intensive forest industry. Biogas is currently purchased by the gas industry for USD 17.50 with the intention to blend 10% into natural gas sold as transport fuel. However the requirement to "scrub" the biogas prior to injection into the network can be costly so producers are considering power generation instead when a guaranteed 20 year feed-in tariff begins in September 2008. Therefore a niche market for the Gazobols methane could result, albeit at a higher price.

A demonstration plant is planned in Sweden by Goeteburg Energi AB that intends to convert forest residues to SNG and use the heat for district heating.

Pyrolysis diesel

The fast pyrolysis of solid biomass feedstock into a bio-oil allows larger particle sizes (up to 5mm) to be used than for some other gasification technologies, thereby reducing the biomass comminution costs and energy inputs. Bio-oil, containing a wide range of chemicals, can be produced by thermal decomposition of biomass in the near absence of oxygen (Fig. 33). The twin-screw pyrolysis reactor for example, is a mature technology. It is similar to entrained flow gasification, but the temperature is lower (~500°C) and it operates at atmospheric pressure. The chopped biomass is not heated directly, but with a hot sand medium (similar to fluidised bed gasification). The pyrolysis gases are cooled down as quickly as possible (in a few seconds) to temperatures below 100°C and a liquid condensate (pyrolysis oil) is obtained. The char from the pyrolysis process is separated from the sand in a cyclone, then milled and the char powder mixed with the pyrolysis oil, forms a bio-oil / char slurry, thereby increasing the overall carbon conversion efficiency. This mix could then be fed into a direct entrained flow gasifier without too many concerns. However, the drawback of the technology is that pyrolysis oil is a strong acid and thereby necessitates expensive storage and handling equipment constructed of corrosive resistant materials. In addition its low flashpoint raises safety issues.

Figure 33. Pyrolysis of biomass linked with gasification to produce syngas.



Fast pyrolysis under controlled process conditions can result in a greater proportion of liquid products and the residual solid char can be used to provide heat for the process and for drying the biomass. The bio-oil can be refined into an acceptable diesel fuel substitute by:

- hydro-deoxgenation (using high pressure hydrogen);
- using a zeolite catalyst which is cheaper but produces lower yields;
- steam reforming into syngas which can be converted into a range of liquid fuels; or
- blending with diesel using surfactants to reduce the high viscosity characteristics.

Several pyrolysis pilot plants have been constructed in Germany (Henrich, 2007), US, Australia and Brazil but scaling up for commercial liquid transport fuel production is expensive.

Producing pyrolytic bio-oil is a means of separating the biomass production site from the processing site since it has similar physical properties to crude oil and a higher energy density than the original biomass, it is a relatively cheap energy carrier that enables easy transport of the stored, high density energy prior to its application. Bio-oil can be burned for direct heat production in a combustion process; used as feedstock in a biorefinery for extraction of chemicals; or gasified to syngas. Selecting the technology with the most promising environmental and economic attributes from the optional routes available for the thermo-chemical conversion of biomass, continues to be under review.

Hydrogen

This energy carrier is considered by some to be the fuel of the future for both stationary and vehicle applications. However it is not analysed in detail in this study but merely briefly presented for completeness. The benefits of hydrogen include a very high energy content per unit weight (about 120 MJ/kg compared with biofuels at 25 - 35 MJ/kg), flexibility of use, and storability. However hydrogen is relatively expensive to produce, doesn't occur naturally, requires expensive dedicated infrastructure and has a low energy density per unit of volume.

Currently about 95% of the world's hydrogen production is based on natural gas but it can be produced in many ways from many primary energy sources. It can be converted into a wide range of useful energy services by means of several different technologies including mobility using converted internal combustion engines or fuel cells installed in vehicles.

Hydrogen could make a CO_2-free energy system feasible if it was to be produced using either nuclear power, renewable energy or biomass, or if any CO_2 produced from fossil fuels during its production was successfully captured and stored. Possible development of the hydrogen economy will take time as significant investments in infrastructure will be needed.

Several production routes from biomass exist. For example, steam reforming of methane or ethanol is a catalytic process in which the light hydrocarbons react with steam to produce a mixture of hydrogen and carbon dioxide.

$$CH_4 + 2\,H_2O \rightarrow 4\,H_2 + CO_2 \qquad \Delta H = 164 \text{ kJ/mol}$$

$$CH_3CH_2OH + 3\,H_2O \rightarrow 6\,H_2 + 2\,CO_2 \qquad \Delta H = 174 \text{ kJ/mol}$$

The carbon dioxide is removed from the mixture to produce high-purity hydrogen. This method is the most energy-efficient commercialised technology currently available, and is most cost-effective when applied to demand for large volumes requiring continual supply. The potential problem is that contaminants remain that would potentially poison a fuel cell system.

Another method of thermal hydrogen production is partial oxidation of solid biomass in large gasifiers to form synthesis gas. The method can also be applied to a wide range of hydrocarbon feedstocks including natural gas, heavy oils, and coal. Commercially available processes to separate the hydrogen from the other gases include pressure swing absorption (PSA), cryogenics, or low temperature membrane systems. Its primary side-product is carbon dioxide. This approach allows more recalcitrant feedstocks, such as ligno-cellulosics, to be used as feedstock. Researchers have shown that steam-pretreated corn stover may be fermented using microbes found in wastewater treatment plants, producing biogas containing equal amounts of carbon dioxide and hydrogen (Datar ***et al.***, 2007). Experimental yields approached 90% of theoretical carbon, indicating that the majority of carbohydrate and some lignin within the feedstock had been converted.

Hydrogen can also be produced from water using electricity in electrolysers. This method is more costly then using fossil fuels in steam methane reforming or partial oxidation, but would allow more distributed hydrogen generation and open possibilities for using electricity generated from renewable and nuclear sources. The primary by-products are oxygen from the electrolyser and carbon dioxide from electricity generation. Conversion efficiencies of these technologies are in the range of 60 – 85%. A better approach might be to use micro-organisms to liberate hydrogen from water by catalysing the photolysis process. Researchers at Penn State have announced the development of a catalyst system that could achieve theoretical efficiencies an order of magnitude greater than natural photosynthesis which only achieves 1-3% of the theoretical maximum (Hoertz & Mallouk, 2005) with the research continuing.

Other methods that could produce hydrogen without CO_2 emissions are still in the early development phases. They include thermo-chemical water-splitting using nuclear and solar heat, photolytic (solar) processes using solid state techniques (photo-electrochemical electrolysis) and fossil fuel hydrogen production with carbon sequestration. Genomics may also be applied to hydrogen production. For example, bacteria such as *E. coli* can be genetically modified to increase the expression of hydrogen (Maeda ***et al.***, 2008), increasing the potential yield of hydrogen from a substrate such as glucose by as much as 50%. The IEA (2005) publication "***Prospects for Hydrogen and Fuel Cells***" provides a detailed assessment of the potential pathways for producing hydrogen, the state of development of fuel cells, and likely future technology developments and challenges.

Bio n-butanol

Butanol (C_3H_7OH) can be produced from biomass fermentation and also used to substitute for ethanol as a biofuel (or as a co-solvent for ethanol/methanol gasoline blends). It can be produced from conventional or ligno-cellulosic feedstocks and can be blended safely at relatively high levels with both gasoline and diesel. Unlike ethanol it can be transported in oil pipelines and has better fuel quality characteristics. The SunOpta BioProcess Group constructed the first modern cellulosic alcohol plant in France 20 years ago, complete with on-site enzyme production. Following biomass preparation, the raw materials are subjected to auto-hydrolysis pretreatment. The resultant hemicellulose and cellulose are subjected to enzymatic hydrolysis to produce fermentable sugars. Butanol is produced by fermentation and concentrated by distillation for use as a transport fuel.

P-series fuel

Mixing ethanol with methyltetrahydrofuran (MTHF), butane, pentanes and alkanes is an "alternative fuel" (as defined by USDOE) developed exclusively by Pure Energy Corporation in US. The blend of components can be adjusted to suit market conditions and ambient operating temperatures. The fuel normally contains no more than 40% (by energy content) of petroleum-products and can be up to 100% biomass-based when both the MTHF and ethanol are produced from ligno-celluose feedstocks. Then the fuel has been claimed to reduce GHG emissions by 50% compared with gasoline (IEA Bioenergy, 2008).

The MTHF can be produced by dehydration of pentose and glucose to produce furfural and levulinic acid. If the fuel component production is carried out as separate processes, it would be less thermally and cost efficient than if conducted within a bio-refinery concept. How best to optimise both bio-processing and catalytic conversion technologies within a bio-refinery needs further evaluation as does the potential for thermal depolymerisation.

8 Bio-refineries

The term 'bio-refinery' is widely thought of as the concept of multi-products produced from varying biomass feedstocks. It is analogous to that of a petroleum refinery processing a range of crude oils. IEA Bioenergy, Task 42, "Co-production of Fuels, Chemicals, Fuels and Materials from Biomass" (www.ieabioenergy.com/Task.aspx?id=42) was established in 2007.

Oil refineries have been in existence for over a century. During that time, the process has become increasingly more sophisticated, with the number of products growing from a handful of oils and lubricants to a full suite of over 2,000 materials, chemical products, and fuels. Bio-refineries have been around even longer.

Since the early 1700s a number of chemical forest products, based on extractives, were the basis of a thriving forest industry including pitch (partially dried resins), pine tar (liquefied resins), turpentine (from distilled resins), and rosin (the involatile residues from resin distillation). These products were widely used in wooden shipbuilding and operation. Even in 1995 about 1.2 Mt of rosin worth approximately USD 400 M and around 330,000 t of turpentine worth USD 50 M were produced (Coppen & Hone, 1995). The future development of the modern bio-refinery concept will likely parallel that of the oil refinery with significant changes in the technology and approach expected as experience is gained and knowledge develops. Oil refineries have evolved beyond simple distillation of the feedstock to produce a handful of products up to complex thermal and catalytic cracking and reforming processes. Much of the evolution of this industry has resulted from major societal upheavals such as wars or from major changes in political focus such as the US Clean Air Act. Some of the lessons learned by chemical and process engineers from oil refinery developments could be applied to bio-refineries, so the time required for the industry to develop naturally may be shortened.

Biochemical and thermo-chemical processes for producing biofuels are capable of delivering a number of chemical or material co-products. A bio-refinery can either derive final, marketable products directly or create intermediate products that can be processed into new end-products in facilities elsewhere. Higher value co-products will probably be needed to enhance the overall economics of 2nd-generation biofuel production and the Norwegian Booregarrd "bio-refinery" concept could become a model for this fledgling industry (www.borregaard.com). The plant employs over 900 personnel and has been operating for over 3 decades. Several truck loads of spruce logs are delivered daily for storage on site and waste biomass products provide process heat. Ethanol is only a relatively minor, low value product of the processing activities but this could be modified as markets dictate, and the multi-product concept remain.

The bio-refinery concept in its simplest form provides more complete utilisation of the biomass feedstock. In existing plants for example, this could include combustion of sugarcane bagasse for heat and power generation or the co-production of high protein animal feeds from corn or vegetable oil feedstocks. The concept could be expanded to incorporate more efficient use of chemicals and materials at all stages in the supply chain, including crop production, integrated harvesting, conversion, product separation, waste treatment and disposal, and final distribution of the products.

The bio-refinery model enables the agricultural and forest sectors to diversify their traditional markets and products, to become more energy self sufficient, and to displace fossil fuel-based products with low carbon and renewable alternatives. A ligno-cellulose-based bio-refinery can offer many environmental, economic, and security-related benefits (GBEP, 2007). For example, energy, fuels and chemicals made from sustainably produced biomass are all characterised by reduced CO_2 emissions when compared to petroleum use and can thus play a role in meeting the challenges of climate change (IPCC, 2007). Therefore in principle, bio-refinery products can offset GHG emissions and help fulfil national obligations under the Kyoto Protocol or 'clean air' targets set by domestic policy.

The processing facilities required to convert biomass into value-added products create direct and indirect jobs (more than in an oil refinery of similar output especially when the supply chain is included), provide regional economic development, and can increase resource-dependent incomes in rural areas. Overall the bio-refinery concept offers a new path forward for land-based industries in both developed and developing countries by providing an opportunity to diversify beyond the bounds of traditional food, feed and fibre products.

8.1 Bio-products

A bio-refinery is characterized by its ability to create high value co-products from residual biomass for supplying niche markets while reserving the bulk of the material for low-value commodities. As an example, some corn ethanol production facilities in the US continue to provide starch for a variety of purposes, and can also derive high-value protein for sale to food and animal feed producers. Furthermore, a range of potential bio-products can also result, depending on the relevant technology platform (Table 16).

Bio-products derived from agricultural biomass are currently well developed as there has been significant investment into their development in Europe and the US. Chemical co-products have higher economic potential and hence are currently the subject of increasing interest. They include the general categories of adhesives and resins, platform chemicals, plastics, paints, inks, soaps, coatings, cleaning compounds, lubricants and hydraulic fluids, greases, pesticides, toiletries, fragrances, and cosmetics as well as soil conditioners and fertilisers (PRA & CANUC, 2002; Crawford, 2001).

Table 16. Categories of bio-products produced in bio-refineries and selected pioneer companies involved in their production

Bio-product	Platform		Company examples
Bulk polymers: ▸ polylactide (PLA); 3-hydroxypropionic acid; 1,3-propanediol etc.		▲ Biochemical	NatureWorks, DuPont, Cargill
Nutraceuticals: ▸ xylitol; arabitol etc.			Codexis, Borregaard
Chemical building blocks: ▸ glycerol; furfural; levulinic acid; succinic acid etc.	Thermo-chemical ▼		DuPont
Biofuels: ▸ ethanol; bio-hydrogen etc.			Iogen, Abengoa
Biofuels: ▸ bio-oil; methanol; ethanol; Fischer-Tropsch; BTL etc.			Choren
Bioenergy: ▸ electricity; steam; combined heat & power (cogeneration); district heating; wood pellets etc.			Mature technology - numerous

Some chemical co-products are specific to certain biomass feedstocks. Zein, for instance, a high-value product used in biodegradable plastic films and packaging, can only be extracted from corn gluten meal, which in turn is a co-product of ethanol production. Forest biomass also has unique chemical properties that may be exploited in the development of specific chemical co-products. Currently at the pilot- or demonstration scales, these include lignin-derived composites, furfural, acetic acid, and cell matter (McAloon *et al.*, 2000). Other co-products specific to ligno-cellulosic include levulinic acid used as a building block in the manufacture of industrial products, including the fuel additive MTHF and the herbicide//pesticide, delta-amino levulinic acid. A pilot plant for this process has been constructed in New York State (Crawford, 2001).

In addition to ethanol, a number of basic chemicals required for advanced manufacturing can be generated from biological sources (Spath & Dayton, 2003; Werpy *et al.*, 2004). Most chemical co-products can be created from the most basic chemical building blocks of sugars and alcohols, and therefore are not related to specific biomass feedstocks. Some examples follow.

- Polyols, used in a variety of products, including antifreeze, plastic bottles, brake fluid, synthetic fibres, resins, autobodies, and sweeteners, can be derived from xylose and arabinose.
- Using genetically modified (GM) micro-organisms, glucose can be converted into 3G (1,3-propanediol), which can then be used to manufacture the polymer 3GT in existing facilities. 3GT has unique properties, such as stretch recovery, resiliency, toughness, and easy dye capability.
- To produce ethylene, the largest petroleum-based commodity chemical used as a precursor in a variety of industrial processes, ethanol can be dehydrated. Bio-based ethylene is projected to cost about USD 0.30 /kg, as opposed to USD 0.20 /kg for petroleum-based ethylene, although the recent higher oil price will make it more competitive.
- Using GM bacteria, succinic acid can be produced from sugars. This chemical acts as a precursor in many industrial processes, and can be used in the manufacture of butanediol, tetrahydrofuran, and pyrrolidinones used in the manufacture of plastics, paints, inks, and food and as a possible replacement for the benzene class of commodity petrochemicals (Crawford 2001).
- Paraffinic naptha can be produced through the BTL route which, when cracked, maximises the production of ethylene and propylene which can be processed to make renewable polyethylene and polypropylene (NNFCC, 2007).

- Other interesting possible co-products include lactate acid and ascorbic acid (vitamin C).

With significant development, a variety of niche products can also be created in a bio-refinery. Health-related chemicals, which can include nutraceuticals, essential oils, pharmaceuticals, drugs, and medicines, have a large potential global market. The extraction of chemicals and substances with specific healthcare applications continues to be a growth industry.

As the bio-refinery concept is developed, it can be anticipated that integrated food and industrial processing will begin to occur within the same facility. For instance, the Archer Daniels Midland plant in Decatur, Illinois, was designed for the bio-refining of agricultural crops (Crawford, 2001). It has demonstrated that the price of feedstock, grain in thie example, is of key importance to the profitability of a bio-refinery. As an example, increased prices for US corn in recent years, due in part to increasing competition between food and ethanol production made ethanol producers more reliant on government subsidies. Producing high-value co-products from the corn feedstock would increase the robustness of the ethanol industry and help to protect it against risks associated with fluctuations in grain prices. Moving towards ligno-cellulose biomass will also help remove the industry from the influence of food prices and increase the supply of biomass available for the sector's growth.

Research and development

Priorities for bio-refinery production include the development of genetically enhanced crops, both to increase production and to engineer the biomass feedstock so that it is more easily converted and processed into industrial products. There are benefits to be had from:

- improving fractionation and separation of agricultural and forest wastes;
- improving hydrolysis and fermentation (particularly for ligno-cellulosics);
- identifying new processes for catalysis and biocatalysis; and
- demonstrating technologies through pilot- and demonstration scale facilities (BRDTAC, 2001).

Specialised GM 'biofuel' feedstocks, which include dormant cellulose-degrading enzymes, are a potential goal of genetic research, as identified in the US Department of Energy's *Genomics: Genes to Life* programme. The potential impacts of these feedstocks have not been well explored by scientists and a number of ecological and social questions still need to be addressed before the benefits of GM research can be fully implemented. Until these questions have been answered, it is perhaps better to consider genetic research as a tool for better understanding the growth and development of bioenergy feedstocks, and for providing conventional plant and tree breeding programmes with guidance on future selections. Politically, there needs to be integrated government and industry coordination; market-pull strategies including financial incentives and environmental mandates for bio-products; the development of standards for application to bio-products; education and outreach; and enhancements to the supply of biomass (BRDTAC, 2001).

8.2 Biorefinery designs

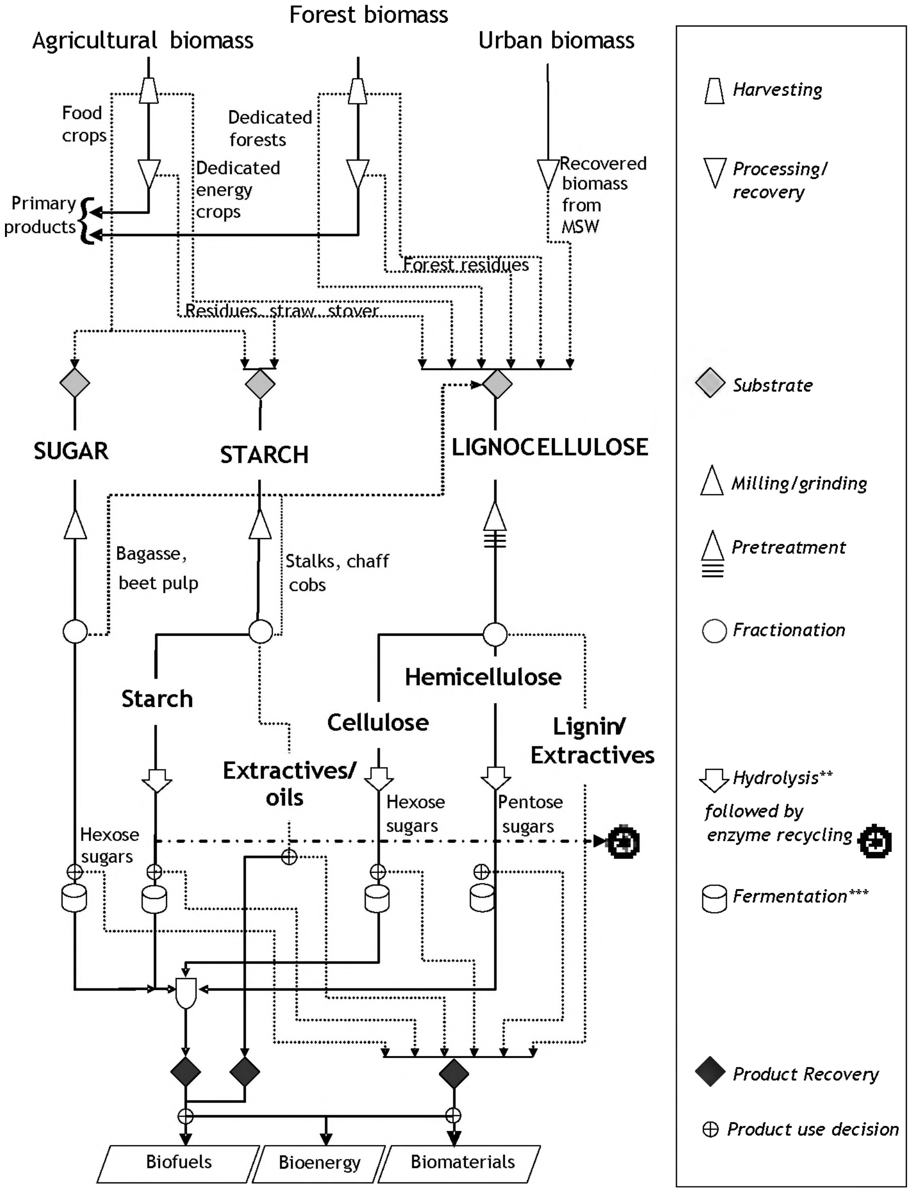
There are many concepts for bio-refineries, each with a different mix of feedstocks and products. This section aims to provide a basic overview of the complex issues involved.

Existing starch-based bio-refineries could be used as a model for those using ligno-cellulosic feedstocks. A report '*Top value added chemicals from biomass*' identified candidate products and specified the necessary technology pathways for each of them which are either under development or commercially available (Werpy *et al.*, 2004). A range of products, including sorbitol, furfural, itaconic acid, glutamic acid, xylitol/arabitol, and glycerol are already produced commercially. A bio-refinery using the bio-chemical conversion platform could provide inexpensive sugars as feedstocks for many of these processes (Fig. 34). Where only ligno-cellulosic feedstocks are available, there are still good opportunities to develop a bio-refinery based solely around thermo-chemical processes with the production of syngas a pivotal component (Fig. 35).

Older pulp and paper mills are examples of the bio-refinery concept at work (albeit relatively inefficient ones), as they were often used to produce chemical co-products and burned waste biomass in a recovery boiler to generate power for internal use. An alternative approach to building new plants could be to retrofit existing pulp mills in order to add new process stages that liberate wood chemicals or to more efficiently generate heat and power (Mabee & Saddler, 2006).

Pulp mills designed around older sulphite pulping technology have good potential to be adapted to produce a variety of chemical co-products, including ethanol, without major changes to the pulping process. However greater efficiency in the pulp and paper industry, and advancement of the Kraft pulping process so that almost all chemicals and waste are fully utilised, have reduced the potential for these mills to be modified as bio-refineries. One option could be for gasification technology to replace the less efficient recovery boiler in order to produce more power from the same amount of biomass and, at high pressures, also provide syngas for the production of high-value co-products.

Figure 34: Biochemical conversion process overview using multi-feedstocks to produce multi-products.



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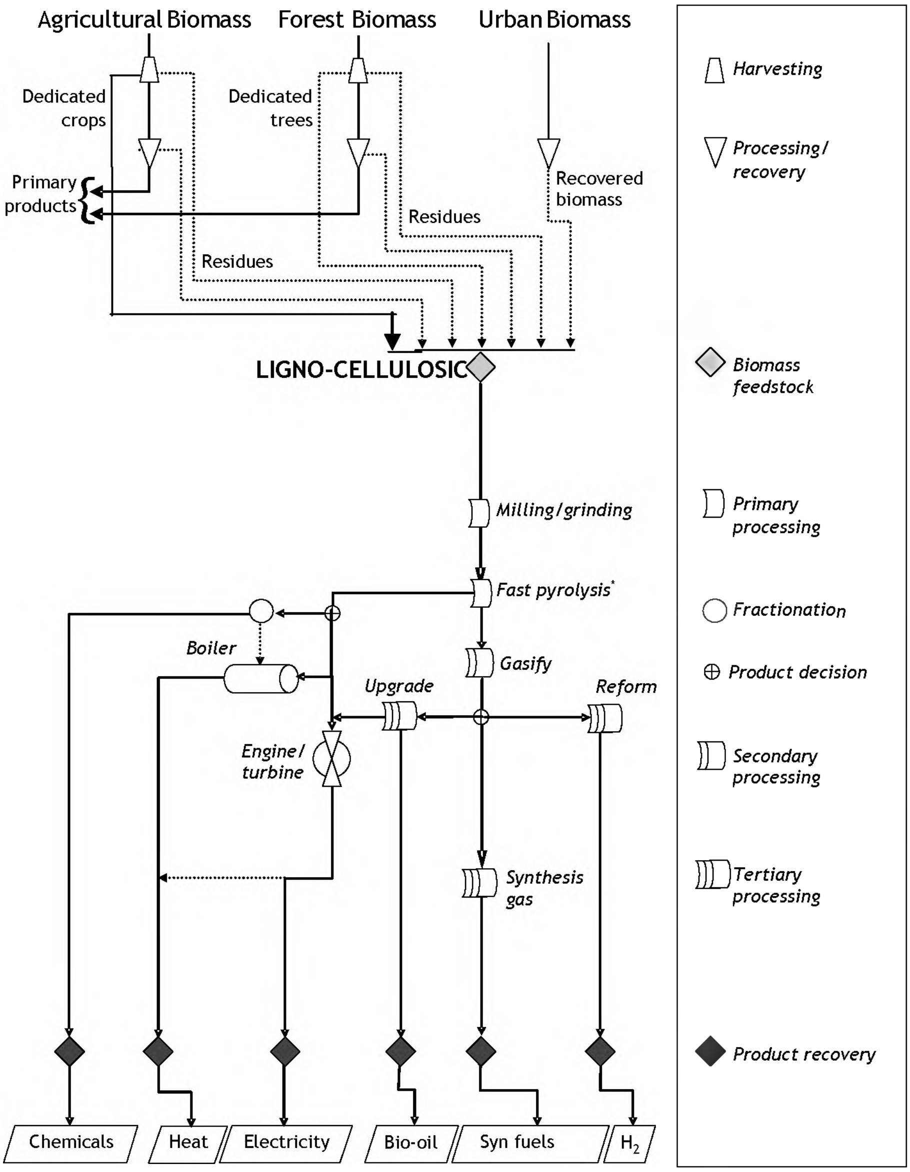
* Pretreatment technologies can include water-based, acid, alkali and organic chemical treatments as well as physical processes.

** Enzymatic hydrolysis includes enzyme production and potential recycling.

***Fermentation stage includes yeast production.

Source: Mabee *et al.*, 2005

Figure 35 Thermo-chemical conversion process overview using multi-feedstocks to produce multi-products.



*Fast pyrolysis produces a number of vapours which can be condensed into value-added products such as bio-oil.

Source: Mabee *et al.*, 2005

For sawmills it may be expedient to expand the existing mill site by adding new processing facilities to allow the better utilisation of mill residues with minimum transport costs. In some cases however, the costs involved and economies of scale may dictate the creation of new large-scale ‘green field’ facilities, purpose-built for either thermo-chemical or biochemical processing. In general terms, biochemical conversion systems can be cost-effective at relatively small scales, while thermo-chemical conversion require larger facilities.

8.3 Pilot and demonstration bio-refinery plants

Several pre-commercial projects are underway to produce bulk bio-polymers for use in textile and packaging applications. In the US, Natureworks LLC, a joint venture of Cargill and Teijin, produces from corn (*Zea mays*) the polymer product, polylactide (PLA) used for bulk packaging in the food and beverage sector (www.natureworksllc.com). At a wet milling facility, starch is separated from the other components of the corn kernel and converted into dextrose. This is fermented in a process similar to making yoghurt to create lactic acid from which the chemical lactide can be created. Water is removed and crystallisation then creates the high-performance PLA polymer. This can also be used to make Ingeo™ fibre, a textile product that can be used in clothing and other applications (USDOE 2006a). The company is also working with Genencor International and Iogen with the aim to expand their feedstock to ligno-cellulosics.

The multi-national chemical and health care company E.I. DuPont de Nemours & Co., in partnership with the Diversa Corporation, is developing processes to transform ligno-cellulosic materials into 3-hydroxy-propionic acid (3-HPA), which can be reduced to 1,3-propanediol. This chemical is processed into a polymer fibre marketed as Sorona Fibre. 3-HPA can also be dehydrated to produce a variety of acrylic products including acrylic acid and acrylamide, which can then be used in products such as baby nappies.

ABNT (www.abengoabioenergy.com) is pursuing the development and implementation of an integrated biorefinery based on a gasification system with the syngas used initially for steam generation. The steam will provide the heat requirements for the entire plant, including enzymatic hydrolysis to ethanol, and also for the heat for an adjacent 1st-generation starch-to-ethanol plant. The longer term goal is to use the syngas for the catalytic synthesis of ethanol after the necessary technology has been developed. Laboratory research is being applied to develop and improve the catalysts for ethanol synthesis. In a joint project, a demonstration plant will be erected to study the syngas cleaning and conditioning and its use for alcohol synthesis.

8.4 Horizontal and vertical bio-refining

'Horizontal' bio-refining is a single facility that is capable of generating a selection of fuels, heat and power, chemicals, and material products from a single feedstock. Bio-refining as a 'vertical' concept, enforces recycling into every stage of the biomass production and processing system.

Ligno-cellulosics are fundamentally a recyclable material. Pulp fibres, for example, are recycled and reused several times in paper sheets, and timber can be salvaged and reused in the hands of a skilled craftsman or a do-it-yourself builder. For forest products, an integrated strategy that creates a recycling standard throughout the value chain would encourage fibres to be moved from timber products, to panel and beam products, to bio-materials, to cardboard and paper applications, and finally to chemical, fuel and energy recovery.

A vertical bio-refinery makes it possible to extend the utility of a single tree over several hundred years and would greatly enhance the ability of the world's forest resource to meet multiple demands for materials, chemicals, fuel and energy. It would build on the forest industry's reputation as an environmental steward and would create new product opportunities across the entire spectrum of traditional and non-traditional uses. Combining vertical and horizontal bio-refinery strategies could provide a future bio-refining industry with a roadmap for a responsible future.

8.5 Social benefits

It is difficult to make accurate assumptions about the role that bio-refineries could play in terms of employment, health, sustainable development, cohesion of rural communities etc. However, most commentators believe that the development of a bioenergy industry in a region will provide jobs, and that bioenergy and biofuels enterprises can become important opportunies for improving rural economies in both developed and developing countries. IEA Bioenergy Task 29, "Socio-Economic Drivers in Implementing Bioenergy Projects (www.ieabioenergy.com/Task.aspx?id=29) specialises in this area. Some specific examples of employment estimates include the following.

- The US Department of Agriculture predicted that 4,500 jobs will be created per every million litres of ethanol produced, thus reflecting direct employment within the mill, increased employment on the farms, and the creation of secondary jobs to provide equipment and services for these operations (www.eere.energy.gov/biomass).
- The US DOE predicts that advanced technologies currently under development will help the biomass power industry install over 13,000 MWe by the year 2010, with over 40% of the fuel

supplied from nearly 2 Mha of energy crops and the remainder from biomass residues. This would create an additional 100,000 jobs and significantly help rural economies (www.greenjobs.com).

- In Europe, predictions estimate that the increase in energy provided from biofuel production could result in the creation of over 515,000 new jobs by 2020 taking into account the direct, indirect and subsidy effects on employment, and the jobs displaced in conventional energy technologies as they decline (www.greenjobs.com).
- In Brazil, over 700,000 rural jobs have been created in the sugar-alcohol industry since its inception, at a rate of approximately 30,000 jobs per Ml of ethanol production (AFTA, 2000).

8.6 Environmental benefits

Bio-refineries have the potential to provide significant environmental benefits that can be measured as net greenhouse gas (GHG) emission reductions through a life cycle assessment approach. A key issue under consideration is how best to allocate emission reductions to a biofuel when a range of co-products are involved. Bio-refinery products usually have significantly lower GHG emissions when substituted for equivalent petroleum-based products. For instance, the combined benefits of combining bioenergy heat and power and biofuel production from ligno-cellulosic corn stover are estimated to reduce GHG emissions by 113%, when compared to the production and use of gasoline (Sheehan *et al.*, 2004). The net energy balance in terms of (energy in/energy out) may also be measured using a life cycle approach. In most studies, biofuel products from a biorefinery are characterised by a positive energy balance (NRDC, 2006).

Development of bio-refineries to produce biofuels and co-products usually requires a supportive government policy framework, as well as research and development support in order to overcome the existing technological barriers. Several developed countries and large multi-national corporations are seeking to develop a range of substitutes for petrochemicals. Energy security, dwindling oil and gas supplies and mitigation of climate change all provide strong long-term drivers for the development of a comprehensive bio-refinery industry that includes biofuel production.

Biorefineries can also provide the benefit of encouraging carbon sequestration. Demand for biomass provides an impetus to increase carbon stocks in agricultural soils and forests, both of which play an important role in the global carbon cycle. The stocks of these carbon reservoirs may be significantly increased by human activity, and in many cases the Kyoto Protocol permits the inclusion of these increases in the national carbon accounts. For example, between 2008 and 2012 the use of low tillage agriculture and other practices in Canada are expected to create an increased agricultural soil carbon stock of 10 Mt (Environment Canada, 2002). Over the same period, it is anticipated that forest carbon stocks that may be accounted for within the Kyoto Protocol rules, will increase by 20 Mt, although this prediction was made prior to the ongoing outbreak of Mountain pine beetle which is decimating forests in Western Canada. An effective bio-refinery industry would give a strong incentive to further increase the carbon stocks of agricultural soils and forests.

In a future carbon-constrained global economy, the use of fossil fuels will be restricted and there will be increased demand for renewable products arising from biomass resources. Consequently, bio-refineries and bio-products will play an increasingly important economic role.

9 Supporting Policies

This section briefly reviews policies relating to seeking the greater deployment of biofuels. More up to date details can possibly be found at REN21 (2007) and IEA policy web sites[11]. In addition the Global Bioenergy Partnership has recently reviewed the state of bioenergy development (GBEP, 2007). Mandates for blending biofuels into gasoline or diesel have been enacted in at least 36 states and provinces and 17 countries, including 9 developing countries (REN21, 2007). These are mainly for 1st-generation biofuels and in most cases excise tax exemptions and /or state and federal government support subsidies are offered to consumers and producers. It should be noted however that due to concerns about the sustainable production of 1st-generation biofuels, some governments are reviewing their current policies and target dates.

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[11] http://renewables.iea.org

Most current policies have been instigated to support 1st-generation biofuels. Where 2nd-generation biofuels are specifically encouraged, this is highlighted in the text below.The effectiveness of biofuel policies in several countries is discussed in the IEA publication *Deploying renewables - principles for effective policies* (IEA, 2008c). In addition the Global Bioenergy Partnership has provided details of policies relevant to bioenergy and biofuels for G8 + 5 countries in a recent report (GBEP, 2007). However few government policies specifically relate to 2nd-generation biofuels, one exception being direct support grants for reducing the cost of enzyme production in US

Policies specifically addressing 2nd-generation biofuels (other than for RD&D support) include the US Energy Independence and Security Act, 2007 and, to a lesser degree, the EU draft Directive proposal of January 2008 where it was assumed they will provide a substantial share of total biofuels by 2020, and in order to help acieve this, the contribution made by biofuels from wastes, residues, non-food cellulosic material and ligno-cellulosic materials towards meeting national obligations is to be twice that of other biofuels.

Together, the US and EU policies could result in a 5-15% increase in global 2nd-generation biofuel uptake by 2020 (OECD, 2008). However, if rapid commercialisation occurs, this could radically affect commodity markets and land use as a consequence. If much of the required feedstock can be produced on marginal land currently not in food production, then this impact would be lower.

9.1 Support policies for commercialisation

Biofuels have the potential to meet three broad policy goals: improved energy security, reduced GHG emissions and support for agriculture / forestry and rural communities. Biofuels have been advocated strongly in the past decade as a potential substitute for petroleum-derived gasoline or diesel fuels (see for example MacLean *et al.*, 2000; McMillan, 1997) and to reduce dependence upon foreign oil (Wyman, 1994). Their use is generally associated with lower GHG emissions and improved energy balance compared to petroleum-based fuels (VIEWLS, 2005). However more recent debate concerning the land use change resulting from increased biofuel production raises some doubt as to their overall GHG mitigation potential. Policies should only support biofuels that significantly reduce GHG emissions per kilometre travelled compared with using fossil fuels

As the biofuels industry is based on agricultural (and potentially forest) biomass, development of the industry will lead to a diversified rural economy and increased employment, which can support domestic development goals (Evans, 1997; Hillring, 2002; Mabee *et al.*, 2005). The industry has long been promoted as a means to substitute renewable, sustainable biomass for fossil reserves of oil, which may in turn increase the security of energy supplies.

The ability of biofuels to meet these disparate policy goals make biofuels an attractive option to policymakers, offering solutions to a number of domestic challenges. However, the reason they have not developed extensively to date is due to their high-costs. Policy support for basic RD&D, and deployment is therefore needed in order to increase the competitiveness of biofuels (Jolly & Woods, 2004) as well as to discriminate between good and bad biofuels.

Policy options to support biofuel production can be 'top-down' since they are enacted on a national or regional basis and impact on all producers and consumers. An example is having a national target whereby policymakers publically declare the intention to meet a certain level of demand (often expressed as a percentage of overall demand) in the domestic transportation fuel supply by a certain date. Top-down policies place the emphasis upon governments, which are then responsible for creating a supportive environment towards industrial expansion.

A national target should not be confused with a renewable fuels standard (or obligation). A target sets legal standards for the minimum levels at which biofuels must be blended into transportation fuels but a standard also includes the fuel characteristics being appropriate. A renewable fuel standard places the emphasis upon industry, which, in order to sell the biofuel, must first meet the standard for their products in order to be eligible for sale. In order to ensure credibility of the targets, non-compliance by the industry is generally penalised in some monetary way.

Another approach is the application of a reduced rate, or even exemption, of biofuels from national fuel excise taxation schemes. This has the effect of reducing biofuel production retail costs and thus increasing potential sales and profits. This type of incentive can be considered as a subsidy to industry, although depending on the competitiveness of the market, lower prices may be passed on to consumers.

Policy options acting in a 'bottom-up' fashion impact only on particular industrial or consumer participants in the biofuels marketplace, for example, direct government funding of capital for private projects that increase biofuel processing capacity or upgrade fuel distribution networks. Normally, these types of policies are enacted in a competitive fashion, whereby various industrial producers can compete for funding for their specific projects which are then carried out in conjunction with government. Another bottom-up type of policy would be increasing biofuel use in government for corporate vehicle fleets.

In some countries, multiple policies covering these options have been enacted to support biofuel development (see for example Gulbrand, 2006; Jensen, 2006; BRDTAC, 2002). Multiple policies mean that determining the effectiveness of an individual policy is often difficult. See Annex 3 for a discussion of country level biofuels support policies.

Generally speaking, national targets or renewable fuel standards provide certainty about the quantity of biofuels used, but not about the cost of meeting the target. Targets have to be ambitious, but achievable, otherwise very expensive options are required to meet the target and potentially sub-optimal investments and choices will be made. In contrast, excise duty exemptions or producer credits mean that the cost per litre of fuel is certain, but the level of consumption is uncertain as are the overall costs which depend on the market uptake of this policy. Given the importance of feedstocks in overall biofuels costs and the volatile nature of most 1st-generation feedstocks, this can also lead to boom and bust cycles in the industry.

The current trend is more towards targets and renewable fuel standards, but this is not without dangers. Meeting these targets requires that the targets are achievable and that complementary policies are in pace to support R&DD and early deployment of innovative technologies. Otherwise, the risk is that the cost of meeting the target means that it could be watered down or abandoned under pressure from consumers and/or industry, leading to missing broader environmental targets or placing additional pressure on other sectors to deliver more. Integrated policy pacakages not only minimise risk and costs in the longer run, but also ensure that policies remain credible.

9.2 Recommendations for future policy support packages

The key to future deployment of 2nd-generation biofuels rests with governments in taking an integrated approach. Biofuels policy must target three key areas: ongoing R&D, demonstration projects and deployment policies.

Policies specifically designed to support 2nd-generation biofuels should be part of a comprehensive strategy for bioenergy development, and be included in an overall framework to address climate change in order to ensure that bioenergy feedstocks go to their highest value use. Where feasible, funding for 2nd-generation biofuels and/or bio-refinery development should be harmonised with national and regional renewable energy programmes which incorporate biomass production and utilisation. Links with other synergistic policies should also be made where feasible in order to maximise support for infrastructure development. These could include linking policies relating to energy security, rural employment, agricultural assistance, transport, health, and support for new industries. Such an integrated policy approach could be crucial in helping determine, for specific applications, the optimum technological platform (for example, between ligno-cellulosic ethanol produced biochemcially versus biomass-to-liquid thermo-chemical routes).

In the specific case where there is an emphasis put on development of the rural economy through manufacturing alternative value-added commodity products, the bio-conversion platform could provide the best immediate opportunities by way of appropriate bio-refining activities. In the specific case where there is a requirement for biomass to meet bioenergy demands for heat or electricity, the thermo-chemical platform could offer the best immediate opportunities for bio-refining activities.

RD&D investment

Continue strong support for R&D investment around 2^{nd}-generation biofuels, should have particular emphasis on developing links between industry, academia, and government. Support for 2nd-generation biofuels however should not be committed at the expense of programmes designed to support 1st-generation development. Rather, the type of feedstock and biofuel should be considered in a complementary but distinct fashion with regard to policies due to the difference in stage of development.

- 1^{st} generation biofuels are based on well understood feedstocks and mature conversion technologies, although, with some exceptions, these tend not to be cost-competitive. The process can be further improved with resulting cost reductions of the biofuels produced. Emphasis is needed on sustainable production and co-product developments. In a market which benefits from government measures such as biofuel quotas and reduced excise taxes, it is questionable whether further public RD&D support should be provided for these mature technologies or whether the industry should now make the RD&D investments.
- 2^{nd}-generation technologies are being demonstrated with some becoming close to full commercialisation. However, they remain unproven and not cost-competitive. The feedstock supply chain to supply large volumes of feedstock all year round is often not well understood. Significant additional research needs to be funded in order to improve processes and feedstocks, and reduce costs.
- Advanced biofuels need further additional generic research undertaken to ensure they are satisfactory and affordable.

Demonstration policy

In order to accelerate the commercialisation of 2^{nd}-generation biofuels and ensure that their costs come down as rapidly as possible, early demonstration of new feedstocks and conversion processes is essential. This will enable experience gained with plant design and operation to inform commercial plant developers and thereby help reduce capital and operating costs.

Given the pre-commercial stage of 2^{nd}-generation biofuels and the uncertainty surrounding which combinations of feedstocks and pathways potentially represent the least cost, a wide range of different feedstock and process configurations ideally needs to be supported at near commercial-scale demonstration plants. Currently, with one or two notable exceptions, support for demonstration projects does not match the aggressive medium-term and long-term goals of many countries. This needs to be urgently rectified, with funds or other support structures provided that reduce private sector risk to a low enough level to ensure demonstration plant are actually built.

Deployment policy

In order to reduce the risk to investors and to create a positive environment for the participation of financial institutions, all levels of government (local, state, national and regional) should consider a six-component approach to support the demonstration and pre-commercial testing of 2nd-generation biofuel technologies.

1. Identify and utilise existing government programmes that can minimise the economic risk to investors associated with establishing 2^{nd}-generation biofuels and/or bio-refinery infrastructure.
2. Introduce feedstock producer incentives for use in the sustainable production of feedstocks used for 2^{nd}-generation biofuels, reflecting the distinct nature of these products compared with those used for 1^{st}-generation biofuels. The costs associated with feedstock production, the supply chain and delivery to the conversion plant should be taken into account. These incentives may be in the form of tax incentives or producer credits, should support the potential for co-products and bio-refining activities, and be complementary to 1).
3. Introduce an economic incentive to encourage consumer utilisation of 2^{nd}-generation biofuels, possibly in the form of excise tax exemptions which translate to lower retail fuel prices at the pump. These incentives should be complementary to those in 1) and 2) above.
4. Introduce incentives at the producer and/or consumer level that identify and target purchase of specific bio-products produced in association with biofuels at a biorefinery. This will encourage the development of infrastructure that can combine 2^{nd}-generation biofuel

production with other value-added products. These incentives should act in a complementary fashion to the programmes and incentives identified in 1) - 3) above.

5. Utilise indicators of environmental performance, including net energy balances and net GHG emissions, as a means of delivering incentives for 2nd-generation biofuel production. This would provide policymakers with a science-based approach to delivering support to 2nd-generation biofuels and bio-refining technologies, without creating a disincentive for continued production of 1st-generation biofuels. Where appropriate, specific policy instruments could encourage development of bio-refinery facilities over biofuel-only production facilities. They could also encourage linkages between bio-refining and traditional bioenergy platforms for cogeneration and wood pellet production. As part of this policy strategy, life cycle assessment tools could be applied to confirm performance in terms of energy balances and net GHG emissions. Any carbon credits earned could be awarded to the producers. 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 the policy with regional and international emission trading schemes, such as those already in place between member states of the EU.
6. Develop a better understanding of the available ligno-cellulosic biomass resources that could be utilised for 2nd-generation biofuel production or biorefinery applications. In some locations there may already be enough agricultural and/or forestry residues to support a biofuel industry in the early stages. However a rapid development of demand for 2nd-generation biofuels could deplete these supplies, thereby encouraging the implementation of energy crop production such as switchgrass, eucalyptus, poplar and willow. Programmes that might support a better biomass resource assessment could include comprehensive national inventories of agricultural and forest activities, better modeling of production and supply chain activities through computer simulation, and increased communications with international monitoring agencies that support the goals of sustainability and ecosystem management.

This approach may not be not easy to implement however and it could be difficult to assess the impact since, as stated above, determining the effectiveness of an individual policy using a multiple policy approach is often difficult. The use of taxation measures according to net GHG reductions could be a simpler approach.

10 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 greenhouse gas (GHG) emissions as a result of detailed life cycle analyses, and related direct and indirect land use change issues, their perceived environmental benefits have more 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, such as vegetable oil-based biodiesel, 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, 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 in RD&D has been made during the past decade following increasing public and private investments. 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 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 biofuel products become competitive with petroleum fuels as well as with 1st-generation biofuels. Emphasis will need to be given to aviation, marine and heavy vehicle applications which will have limited alternatives. After 2020 or thereabouts, 2nd-generation biofuels 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.

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Annex 1. Instability of the biofuel market

A single day of news concerning the biodiesel industry exemplifies the growth but also the instability of the biofuels market as it develops, News on this randomly selected day, as presented in the Kingsman Biodiesel News Summary 2 December 2007 (www.kingsman.com) is summarised below.

- Finnish Neste Oil Corp. is planning to build an 800,000 Mt/yr biodiesel BTL plant in Singapore to be onstream in 2010, for a EUR 550 million (US$810 million) project value. The unit is expected to use palm oil as its main raw material.
- Grain company Zarneni Hrani Bulgaria, owned by Chimimport, is to launch an initial public offering (IPO) of up to 25% of its shares and is expected to put on-stream a 100,000 t/yr biodiesel plant in early 2008. The firm is to invest EUR 50 million ($73.2 million) in another biodiesel plant with the same capacity to be completed in the summer of 2010.
- Despite a wider first-half pre-tax loss on lower turnover, UK's Viridas PLC plans to build a biodiesel plant in Brazil while rationalising its traditional underwear businesses in UK and Germany.
- The US company Great Plains Oil & Exploration expects to finalise by year-end its plan to build an oilseed crushing facility and refinery for biodiesel production in Eastern Montana, based on camelina. This crop is claimed to fit well into rotations, is drought and frost tolerant, requires minimal inputs and does not compete with food uses.
- The Defense Logistics Agency has awarded a $6.95 million contract modification to Southern Counties Oil Co. operating as SC Fuels, Orange, California, for biodiesel fuel. All of San Francisco's municipal car fleet of 1,500 diesel vehicles have been converted to run on B20.
- Kazakhstan will adopt a legal framework in 2008 for the development of the biofuel industry, planning to construct at least two more plants in the next 18 months. The government had completed a feasibility study for a state-run bioethanol and biodiesel plant in northern Kazakhstan to be ready in 18 months from now, and targeting the EU. The country has the potential to produce 300,000 Mt/yr of biodiesel and export half having started to grow rapeseed in its northern provinces. It harvested 20.1 Mt of wheat in 2007 and could produce 1 bn l (0.9 Mt) /yr of bioethanol. Biohim Co. is the only biofuels company. It can produce 57,000 t/yr of bioethanol in its $100 M unit opened in 2006. However it is not currently operating. The manager said that he managed to sell 4,000 t to Vitol this year.
- Chemrez Technologies in the Phillipines has increased the price of coco methyl ester by P4 - 6 /l to reflect the price increase in coconut oil to $1,200 /t which trails the uptrend in palm oil prices. The company's biodiesel plant is currently running at 60% of its 60,000 Mt nameplate capacity. When the B2 mandate begins, production could rise to 80%. The firm also intends to increase capacity to 90,000 Mt.
- The Brazilian city of Araraquara is to host an algae-based biodiesel plant, to be built starting in January 2008 by Biopetro Brasil for $3.44 M. 30 Ml of biodiesel will be produced as of August 2008 reaching 200 Ml in the next three years. Biopetro Brasil is an investment fund formed by a group of U.S entrepreneurs, which could invest as much as $90 M in the next 10 years. The technology is imported from Canada. The algae will be grown in the city's water and sewerage station but the plant will also use sunflower and castor bean oils.
- Australian Biodiesel Group says that with the shutdown of its biodiesel production from November 2007, it expects to sell less than 7 Ml in total for 2007 giving revenue of $10 million, and a net loss of around $17 million.
- Delhi-based Ansal Properties and Infrastructure Ltd has decided to invest in biodiesel. The company has already planted 50,000 saplings of the *Jatropha Cucas* plant and is planning to plant 2,000,000 plants per year for the next 2 years.
- The Economic Community of West African States is financing a biofuels project in Ghana with the aim for 1 M ha to produce 600,000 t in 5 to 10 years, which is around 80% of their diesel imports.

Annex 2. Selected RD&D activities relating to 2nd-generation biofuels not discussed in the main text

a) Other biofuels and related research activities

Country	Plant	Scale	Feedstock	Status	Comments
Netherlands	BioCMN methanol	20kt up to 200kt demo	Glycerine	Pilot plant in Q1 2009	Broad methanol use. Lower CO_2 than methanol from natural gas
France	METEX (METabolic Explorer) biotechnology company producing 1,3-propanediol (PDO)	Laboratory R&D	Glycerine	Pre-industrial	PDO used for manufacturing polymers including polyester textiles, cosmetics, glycol
UK	D1 Oils and BP land use for biodiesel	1 million ha	Jatropha	Expanding plantations in India, Africa and S E Asia	Closing plants for refining 1st generation biodiesel in UK
Brazil / UK	Ineos Enterprises / Viridas biodiesel	500,000 t from 250,000 ha	Jatropha	Land acquisition	Ineos has existing biodiesel facilities in Baleycourt, France
Tanzania / Mozambique / Ethiopia/ UK	Sun Biofuels (SBF) $200,000 processing plant planned.	20,000 t/yr ~ 15,000 ha with 10% planted	Jatropha	Acquired land	Meal toxic so used for briquettes till detoxification becomes viable
Malaysia	GBDI co-venture with Dubai Investment Group (30%)	500,000 t/yr	Jatropha (200,000 ha, 750,000 t/yr plantation planned) and palm oil.	200,000 t/yr biodiesel plant completed at Lahad Datu with phase II expansion planned.	Aim to bring the technology to the Middle East
Netherlands / US	Shell / Virent catalytic "Bioforming" of sugars into hydrocarbon mixtures rather than ethanol.	R & D	Plant sugars from cereals, cane, lignocellulose etc. converted into long chain hydrocarbon molecules	Yields low and costs high at present	Could produce a range of fuels including aviation.
Netherlands	Avantium develops catalytic processes to produce furan-based products for biofuel production with superior properties.	R&D	Furanics produced from sugars and other carbohydrates	Production and engine testing	Co-products of bio-based chemicals
UK	Gasrec, BOC and SITA UK at the Albury landfill site producing liquid biomethane after gas clean-up	5000 t/yr	Landfill gas from municipal solid waste. Claim to recover 85% of the raw gas methane produced.	Operating	Liquefaction technology for landfill gas in agreement with the Linde Group. Fuel to be used by trucks in the waste management and haulage sectors.
US	Novozymes $80+ M plant in Nebraska for enzyme production	Enzymes for cellulosic ethanol	Various	Site acquired for plant construction	Plant designed for expansion for increased

		start-up plants as well as corn ethanol			future demand for cellulosic enzymes
US	Verenium plant in Louisana to conduct combined hexose/pentose fermentations	4000 t/yr	Various under evaluation including bagasse, specially bred energy-cane, wood chips.	Pilot plant upgrades completed in 2006. Optimisation to validate the technology at larger scale in May 2008.	$60 M demonstration plant, aiming for commercial plant by end of 2009.
Belarus / Ireland	Greenfield Project Management ethanol	600,000 t/yr 1st generation plant planned with local company Belgospichepromn	Crops to be grown on radiation contaminated land near Chernobyl.	Feasibility study, feedstock logistics and financing with aim to construct end of 2008	To be based on ethanol facilities operating in Belarus at Mozyr and Bobruisk.
Denmark	Dong Energy / Danisco Genecor	4300 t/yr	Straw - 30,000 t/yr	Planned on site next to the Asnaes 1 GW coal-fired power plant, Kalundborg.	$60M project of which $15m as grants. Other feedstocks to be tested.
US	Sandia Labs / USDOE / Live Fuels to produce a range of advanced biofuels.	Laboratory scale	Algae	Sites located alongside coal-fired power plants to use the CO_2	Land use benefits - claim all US transport fuels could be supplied from 40,000 km^2 (with yields up to 60 t/ha/yr)
US	PetroSun Biofuels, Arizona biodiesel facility	70,000 t/yr after successful pilot plant demonstration in Georgia.	Algae	Construction to start Q3 2008. Company aims to supply 130,000 t/yr of algal oil to Bio-Alternatives biodiesel plant in Louisiana.	Goal to establish 1000 algal ponds in north Mexico to provide 6 Mt/yr of algal oil.
Israel / US	Seambotic / Inventure Chemical using process to produce biodiesel, ethanol and chemicals	"Commercial" scale after a 5 year pilot plant project.	Algae - high yielding oil strains grown in open ponds	Planning stage	CO_2 used to cultivate the algae is recycling rather than sequestration.
Japan	Oenon Holdings, Hokkaido	3000 t/yr	Rice	To operate by April 2009	Half the $40M investment cost to be funded by government.
Mexico	INE (National Ecology Institute)	R&D	*Agave tequilana weber* and *Agave angustifolia Haw.* varieties	Claims of high sugar yields as well as good biomass yields.	Widely grown for tequila and mescal. Low inputs claimed.
US	Parsons and Whittemore vegetable oil esterification-based biodiesel plant co-located with its pulp mill in Claiborne, Alabama			Under construction	Shared utilities by plants to increase thermal efficiencies

b) Lignocellulosic hydrolysis / fermentation to ethanol

Country	**Plant**	**Scale**	**Feedstock**	**Status**	**Comments**
Canada / US	Raven Biofuels / Pure Energy - RVBF.OB using double dilute sulphuric acid pre-treatment to give separate 5 sugar (from hemicellulose) stream to furfural and C6 sugar streams (from cellulose) to ethanol	Pilot plants	Corncobs, sawdust, cereal bran.	4 plants under development.	Lignin used for solid fuel
Austria	Vogelbusch fermentation	R&D improved strain of micro-organism that increases yield of ethanol from hemicellulose	Wood wastes and other wastes containing hemi-cellulose	Patented research	Resolves co-enzyme imbalance when using the yeast *Saccharomyces cerevisiae*
Canada	Lignol Energy	100 t/yr	Range of feedstocks being evaluated	Pilot plant nearing completion - to optimise engineering designs for commercial scale plants.	Aims to evaluate new enzymes and organisms on a range of feedstocks
US	RSE Pulp and Chemical, Maine to pre-extract hemicelluloses during the pulping process	~ 4000 t/yr	Woody biomass products	$30 M USDOE grant awarded for a demonstration plant.	
US	Mascoma / University of Tennessee / Genera Energy	~ 4000 t/yr	Switchgrass	$26 M USDOE grant awarded for a demonstration plant.	Mascoma also built a 1700 t/yr plant in New York to harness ethanol-fermenting organisms and enzymes.
US	Ecofin using solid-state enzymatic complexes in Kentucky plant	~ 3000 t/yr	Wide range including corn cobs	$30M USDOE grant awarded for a demonstration plant.	
US	BlueFire Ethanol building 2 plants and planning 10 plants by 2013 based on sulphuric acid hydrolysis	Two 40,000 t/yr >200,000 t/yr per plant capacity	Various including agricultural residues, wood wastes and switchgrass	Two smaller plants under construction. Others needing finance.	Claim the technology is sound but financing is the challenge. In California
Italy	Mossi & Ghisolf, Piedmont $148 M ethanol plant	250,000 t/yr	Maize (600,000 t/yr) but conversion to cellulosic ethanol in phase II	Under construction. Operating in 2009 with subsequent up-grade to 2nd generation for $177M investment. 20,000 t/yr by 2012 the aim.	R&D to use fibre sorghum or common cane with claimed low fertiliser and irrigation requirements.
Sweden	SEKAB Örnsköldsvik wood pulping plant	14,000 t/yr	Wood chips - fermentation of sulphite pulp liquor	Commercial. Used for E85 blends.	Around 15-20% of total ethanol consumption in Sweden and <1% of total

					EU consumption.
Sweden	Neste Oil testing vehicle emissions from NExBTL fuel use in Stockholm		Mixed oils and fats	Tests till 2010 in 100 vehicles	
Sweden	SEKAB Örnsköldsvik pilot plant operating since 2005.	50 t/yr (1t dry biomass gives 150-200 l/day ethanol)	Cellulose from pine wood chips	$6M government funding for 5000 t/yr demonstration plant.	Aim for commercial scale in 5-8 years.
Denmark / US	Genecor / DuPont company *DuPont Danisco Cellulosic Ethanol*. $140M investment to combine mild alkaline pre-treatment process with enzymatic conversion of cellulose to sugars.		Agricultural residues including corn stover	Pilot plant planned for 2009 with demonstration commercial facility 3 years later.	Sugars converted into high ethanol yields with few by-products using a biocatalyst based on *Zymomonas mobilis*.
Denmark	BioGasol, Lyngby combined ethanol/biogas process: pre-treatment by steam explosion/wet oxidation; hydrolysis, glucose fermentation by yeast; liquid fraction to xylose fermentation using thermophilic anaerobic bacterium; biogas production.	Pilot plant 13 t/yr Demonstration plant 6000 t/yr	Various lignocellulosic sources - first formed into a slurry with the recycled waste process water.	Plant opened 2006 after $3M government investment and demonstration plant under construction	Aim for $0.40 per litre. Novozymes produce enzymes on-site. Xylose fermentation changes hexose and pentose sugars into additional ethanol. Biogas from residual organic matter used on-site or sold.
China / US	Cofco Bio-Energy with auto-hydrolysis and steam explosion unit supplied by SunOpta BioProcess	1.2 t/yr	Corn stover	Operating since 2006	
US	KL Process Design Group, Wyoming using new enzymes	3600 t/yr	Discarded wood, cardboard, paper	Operational	KL claim needs scaling up 15 fold to become viable. Financing a challenge. EU India and Russia licensed
Serbia	Altech biotechnology company, 70% ethanol from corn, 30% cellulose.		Varied	Planning stage with Serbian government supportive and relaxing investment rules for green technologies.	
US	American Energy Enterprises, Brookfield, Connecticut dilute acid hydrolysis ethanol plant to open in November 2009.	100-200 Ml/yr aiming for 400 Ml/yr eventually	Cellulosic -unspecified	Planning	Working with SPEC Engineering and BEI to design and build the plant
Sweden	Etek Etanolteknik AB USD 150 M pilot plant	2 t/day to give 150 000 l/yr ethanol	Forest residues and wood chips	Under construction	Government and industry partners
US	Catalyst Renewables Corporation "Sugar 4" process pathway plant that extracts hemi-cellulose from biomass going to an existing solid fuel boiler for power generation	50 Ml/yr	Woody biomass		New York state USD 10.3 M grant. Gasification has been added to the project

	and steam sold off-site				
US	Colusa Biomass is proposing a plant in California ethanol from rice straw using enzymatic hydrolysis. A "Sugar 2" process pathway	50 Ml/yr			
US	Coskata producing cellulosic ethanol in its laboratories and plans to scale up a pilot project in Madison, Pennsylvania. Proprietary microbes turn the syngas into ethanol	150,000 l/yr		Deliver fuel by early 2009	USD 25 M.Planning a 400 Ml/yr facility by 2011. Raised USD 30 M from Globespan Capital Partners, GM, Khosla Ventures, GreatPoint Ventures and Advanced Technology Ventures
US	Florida Crystals, University of Florida, has USD 20 M state grant to build a cellulosic ethanol plant to be used simultaneously as a commercial facility and a development plant.	4-8 Ml/yr			Florida Crystals harvests 10 Mt of sugarcane annually, refines 4 Mt of sugar and operates a 75 MW renewable power plant at Okeelanta, Florida
US	KL Process Design Group opened wood-fibre cellulosic plant January 2008 near Upton, Wyoming		Ponderosa pine		
US	SunEthanol uses the "Q Microbe" for its "C3 process," which does the ethanol conversion of hydrolysis and fermentation in one step	10 Ml/yr demonstration		Pilot plant under construction to operate in 2009. Demonstration facility under construction	Working with ICM. Investors include VeraSun, Battery Ventures, Camros Capital and LongRiver Ventures. USDOE awarded a $100,000 research grant
US	ZeaChem test facility in Menlo Park, California and pilot plant near Portland, Ohio. Technology converts fermentable sugars into acetate and then gasifies the remaining lignin etc. into hydrogen before mixing the two streams in a hydrogenolysis reaction to produce ethanol.	6 Ml/yr	Poplar trees	Test facility operational. Pilot plant planned	Working with forest manager GreenWood Resources. USD 4 M from Mohr Davidow Ventures. Firelake Capital also an investor
China	CRAC plant at Zhaodond, Hailongjian	Demonstration			
Japan	Bio Ethanol Japan, Kansai	1.4 Ml/yr demonstration	Demolition wood	Operating since January 2007	

c) *Biomass to Liquids (BTL) - thermo-chemical*

Country	Plant	Scale	Feedstock	Status	Comments
US	Syntec - thermo-chemical FT catalyst	R&D	Mixed woody biomass	Pre pilot	Claim 400 l/t biomass with potential for 600 l/t cf corn ethanol at 360 l/t. $0.08 feedstock /l ethanol
Finland Netherlands Singapore	Finnish company Neste Oil's NExBTL process for biodiesel	170,000 t/yr 800,000 t/yr 800,000 t/yr	Various - currently vegetable oils and fats but aiming for non-food sources through the FT route	All three plants under construction. R&D with BTL through FT	Based on an operating 170,000 t/yr plant in Porvoo, Finland.
Canada	Syntec B2A (biomass to alcohol) synthesis gas scrubbed, passed through fixed bed reactor with thermo-chemical catalysts to produce ethanol, methanol, n-butanol, n-propanol.	R&D giving~400 l of alcohols per tonne of biomass.	Various solids including wood, bark, bagasse, stover, straw, MSW	On-going R&D including catalyst evaluation	Process can also produce alcohols from biogas. Claimed 33% conversion efficiency.
US	Coskata, Pennsylvania 3 stage syngas / biofermentation process plant	12 t/yr	Various including wood chips, switchgrass, stover, straw	Construction of demonstration plant	Gasify; clean-up; bio-reactor with micro-organisms to convert CO and H_2 to ethanol; membrane separator. Low water demand.
Argentina / Canada	Dynamotive fast pyrolysis to produce bio-crude	250,000 t/yr feedstock	Dry sawdust, forest residues and MSW biomass	Site negotiations	Bio-crude (bio-oil) can be refined and converted to a range of vehicle fuels and chemicals.
US	ConocoPhillips / Archer Daniels Midland conversion to bio-crude then gasified with steam or oxygen and syngas refined with nanotechnology-based catalyst to produce ethanol. Funded Iowa State University fast pyrolysis project.	Laboratory scale	Various solid biomass	R&D	Collaboration is on transport fuels from biomass
US	Dynamic Fuels (Tyson Foods and Syntroleum joint venture) Geismer, Louisiana, based on front-end FT technology and hydrogenation of the syngas.	250,000 t/yr	Chicken fat and trap grease	Commercial	$135 M investment in old methanol plant
India	Praj Industries. Acid and enzyme hydrolysis with thermal treatment of cellulose to produce a gas processed into liquid fuels.	Large company undertaking R & D including 2nd generation.	Mixed	R&D with a claimed breakthrough	Company with ethanol and biodiesel plant design services. Market interest in Colombia, Ghana and

					Madagascar
US	Cleantech Biofuels, St Louis to build waste to ethanol plant in Golden, Colorado		Solid wastes	Pre-commercial stage	Working with Hazen Research
US	Potlatch Corp developed a comprehensive biorefinery project for its mill in McGhee, Arizona	2000 dry t/day feedstock to give 2300 bbl /day bio-oil. Steam and heat for the lime-kiln also produced	Wood residues		Financial input from Winrock International. Because of integration, thermal efficiency was expected to be as high or higher than others have achieved with larger gas to liquids processes.
US	The global forest products company UPM to become a significant producer of 2nd-generation BTL biofuels. Based on Carbona's gasification technology. USD 6.7 to 13.4 M		Woody biomass	Laboratory testing and modification of the plant started in 2007. Testing expected to be finished by the end of 2008	Co-operating with Andritz and associated company Carbona on the development of gasification and syngas purification technologies
UK	Orchid Environmental Limited, a waste-to-energy company is using Fairport Engineering Group technology to produce biofuel from solid waste and hence reduce landfill volumes.		Municipal solid waste	2 pilot plants planned	Orchid uses proprietary technologies developed by the company to process municipal and commercial waste to produce both a refined biofuel product and various recyclable materials.

Annex 3. Biofuels Support Policies by Country

Brazil

The oldest example of widespread biofuel development is found in Brazil, which produces bioethanol mainly from sugar cane and bagasse residues. Because of Brazil's climate, two seasons of sugarcane growth can be achieved, adding greatly to the potential production of both sugar and bioethanol products. In response to the first oil crisis of the 1970s, Brazil invested heavily in fuel alcohol production primarily as a means of increasing fuel security and saving foreign currency on petroleum purchases. The original policy choice was to create direct funding sources to create biofuel capacity. In 1975, a diversification programme for the sugar industry, called Proálcool, was created. It received large public and private investments supported by the World Bank, allowing expansion of the sugarcane plantation area and construction of alcohol distilleries, either autonomous or attached to existing sugar plants (AFTA, 2000).

A subsequent group of policies introduced in Brazil provided a subsidy for bioethanol use. Two related financing schemes were organized to guarantee fuel sale price; the FUPA programme guaranteed USD 0.12 /l for a blend of 22 % ethanol in gasoline (E22), while the FUP programme provided USD 0.15 l/yr for pure, anhydrous ethanol fuel (E100). Between 1996 and 1997, the total subsidy delivered via these programmes reached about USD 2 bn per annum (AFTA, 2000).

The presence of both a renewable fuel standard and strong subsidies for E100 production, combined with the second oil shock of 1979 resulted in the successful adaptation of engines to E100 fuel use. By 1984, E100 vehicles accounted for 94.4% of domestic automobile manufacturers' production, and in 1988 participation in the E100 programme reached 63% of total vehicle use (Moreira and Goldemberg, 1999). The upward trend ended, however, when high global sugar prices led to a crash in availability of fuel alcohol, resulting in a consumer shift away from E100 vehicles.

From 1989 to 1996, the sugar export market was strong, and thus the cost of sugar to the bioethanol industry increased and fuel bioethanol shortages resulted. In response, the Brazilian government made a failed attempt to restrict sugar exports, and then announced that the fuel market would be deregulated as of 1997. Deregulation began with E100 fuels but subsidies for blended fuels remained in place for two additional years, which had the effect of increasing overall alcohol production at the time. When price controls on E22 were removed in 1999, however, the prices for bioethanol collapsed (AFTA, 2000).

Faced with an excess of bioethanol and collapsed prices at home, major producer groups joined together to form Brasil Alcool SA in March 1999, and made the decision to export excess bioethanol at any price. Later that year, a mechanism to create a monopoly on fuel bioethanol named Bolsa Brasileira de Alcool Ltda was created by the founders of Brasil Alcool. This monopoly drove a dramatic increase in bioethanol export prices for a period after its inception, with prices doubling within a year (Moreira and Goldemberg, 1999). Since 1999, the total production of bioethanol in Brazil has risen, driven by the expansion of export markets for bioethanol, rising world prices for oil, and an increase in domestic oil supply. The Brazilian industry today follows a simple bio-refinery model, where the production of a combination of products, including refined sugar, bioethanol, and heat and power from the combustion of bagasse improves both economic and environmental performances. Brazil controls more than 75% of the world's ethanol export market, with primary exports going to the USA, Europe, Korea, and Japan. Brazil's estimated total annual exports exceed USD 3.1 bn. Several countries that lack significant biomass resources, such as Japan, have made Brazilian bioethanol a part of their renewable fuel strategies.

Brazil's domestic market still utilizes the single largest portion of fuel bioethanol capacity in the country. The presence of a Renewable Fuel Standard means that all Brazilian gasoline has a legal alcohol content requirement ranging between 20% and 25%. Most vehicles are being run on E20 or E22, but sales of flex-fuel vehicles capable of operating on E85 blends are growing. Brazil has developed a unique distribution infrastructure for this fuel, with a network of more than 25,000 gas stations with E20 pumps.

Brazil remains a dominant bioethanol producer and the single largest exporter of this fuel, with shipments expected to hit a record 3 billion litres in the 2006-07 harvest. Rising demand for bioethanol - in part caused by policies in other countries - has created an impetus for new product capacity. Recently, it was reported that UNICA, the sugar industry, plans to open 77 new bioethanol plants by 2013, adding to the existing 248 plants. When complete, this will raise the country's production capacity to about 35.7 bn l/yr.

United States

Development of the bioethanol industry in the United States began in the 1980s. The drivers for the industry were in part the rapid surges in global oil prices experienced in the 1970s and 1980s, which led to rising gasoline and diesel prices. There was also the presence of a strong agricultural lobby which was (and is) interested in creating additional revenue streams for farmers. The US bioethanol industry mainly uses corn, and to a lesser extent wheat, as a feedstock for wet- and dry-milling processes. A number of different policy options have been employed to help build the industry. Both federal and state governments have offered the industry direct funding in the form of public-private partnerships and research funds, as well as tax incentives and state-level renewable fuel mandates, i.e. legislated amounts of renewable fuels contained in fuel sales within the state, defined by blending level or by renewable fuels (DSIRE, 2006; USDOE, 2006a).

Most bioethanol production capacity is concentrated in the Midwest, where corn is found in abundance, and where state and federal government incentives have combined to make an attractive environment for investment in the infrastructure required for bioethanol production. Over half of US production capacity is found in just three states, each of which have supplied significant capital resources to the bioethanol industry.

The total financial commitment that the US has made to biofuels dwarfs the investment of other countries. In 2006, total cumulative funding through national or state programmes applicable to bioethanol exceeded USD 2.5 billion (USDOE 2006b). New programmes, announced since 2007, committed an additional USD 1 bn (Foust, 2008), for the following multi-year initiatives with a wide geographic spread (Fig. A1):

- USD 385 M for six commercial-scale bio-refineries (4 proceeding at the current time);
- USD 240 M+ for 9 pilot-scale (10%) bio-refineries;
- USD 23 M for 5 programmes designed to produce more efficient fermentation microbes;
- USD 34 M for 4 programmes designed to produce more efficient enzymes; and
- USD 405 M to support three new Bioenergy Centers.

Figure A1. Project investments and locations of major biofuel plant USDOE investments in the US.

Other federal funds support a number of incentive programs, including the Alcohol Fuel Credit (a corporate tax credit designated for industry producing bioethanol); deductions for both clean-fuel vehicles and refuelling properties; and the Renewable Energy Systems and Energy Efficiency Improvements Program. The latter programme is designed to aid in the construction of new facilities, and will cover up to 25% of construction costs. Maximum grants for a single project under this programme are USD 500,000, and the fund generally pays out between USD 3-5 M in any given year (DSIRE, 2006; USDOE, 2006a). Significant funding in the US has been directed towards developing cost-effective co-products from the biofuel production process, allowing the creation of 'bio-refineries' with improved economic and environmental performance. Pilot facilities are already operating under some of these funding programmes (USDOE, 2006b).

Recent policy developments stem from the Energy Policy Act of 2005, signed into law by President Bush on August 8, 2005 (US Govt., 2005a). This Act created a nationwide renewable fuels standard (RFS) that will raise the use of bioethanol and biodiesel (and alternative fuels) to 28.4 bn l / yr by 2012, which is effectively 5% of total transport fuel sales. On July 23, 2008, reports in the New York Times stated that Governor Perry of Texas will request that the Environmental Protection Agency temporarily waive regulations requiring the increase of ethanol use, citing concerns over rising food prices. A decision iexpected in the autumn of 2008 (Streitfeld, 2008) was declined with Presidential candidate Mr McCain stating he does not support the current levels of biofuel subsidies.

The '20/20' vision for biofuels (introduced as a Senate Bill July 29, 2005) defined a future biofuel production goal for the US as 75.7 bn l by 2020 (US Govt., 2005b) but the EISA, 2007 has since raised this to 136 bn l by 2022. As the US starch-based bioethanol plant capacity is already quite high, it is unlikely that continued growth could achieve this goal, a fact recognized by USDOE projections (Foust, 2008). Accordingly, in his 2006 State of the Union Address, President Bush outlined the Advanced Energy Initiative, which seeks to reduce US dependence on imported oil by accelerating the development of new, renewable alternatives to gasoline and diesel fuels (USDOE, 2006c). These alternatives include bioethanol and other future biofuels derived from cellulosic biomass.

To determine feedstock availability for cellulosic bioethanol processes, the US Department of Agriculture commissioned a report which explored the technical feasibility of a billion-tonne annual supply. This report found that approximately 1.24 billion dry tonnes of cellulosic biomass could be sustainably produced each year, with about 910 Mt coming from agriculture and an additional 330 Mt from the forest sector (USDA, 2005). Using the efficiency of conversion technologies observed in the literature (Mabee *et al.*, 2005), this would translate to between 110 and 250 bn l/yr compared to current US gasoline use of approximately 500 bn l/yr.

US production of biofuels is significant, but today only comprises about 2.6% of liquid fuel consumption. In order to become a more significant component of the transport fuel sector, biofuel production must grow tremendously, which will require access to cellulosic biomass. The Advanced Energy Initiative includes the Bio-refinery Initiative, which sets a goal of making cellulosic bioethanol cost-competitive by 2012 and which provides significant funding to achieve this goal (USD 91 M in 2006, USD 150 M in 2007) (US Govt., 2006). Bio-refining pilot facilities are already operating with starch-based feedstocks, and these processes have the potential to be applied to cellulose-based biofuel production facilities, which will contribute to the economic viability of these operations. If these measures are successful, cellulosic bioethanol production could easily become the dominant biofuel within the US.

On December 19, 2007, President Bush signed into law the Energy Independence and Security Act (EISA) which comprises 16 titles, each covering a substantive area of energy policy. This latest energy legislation states that biofuel production must increase ninefold by 2022 to meet the renewable fuel standard for gasoline. In addition vehicle fuel economy must improve substantially by 2020 to meet prescribed standards. Otherwise the Act does not implement sweeping changes for renewable and fossil energy, but it does have far-reaching implications in the agribusiness, building design and construction, and appliance manufacturing sectors.

The EISA legislation was designed to reduce US dependence on foreign oil by increasing the supply of alternative fuels sources. It seeks to increase the supply of biofuel by requiring fuel producers to use in the fuel mix a progressively increasing amount of biofuel, culminating in at least 140 bnl of biofuel by 2022. The U.S. Environmental Protection Agency (EPA) is required to revise its regulations to ensure that transportation fuel sold in or imported into the United States contains at least the applicable quantity of biofuels. Although those revisions have not yet been developed, responsible parties under the current EPA regulations relating to biofuels include large refiners, blenders, and importers of gasoline, but exclude small refiners.

EISA differentiates between "conventional biofuel" (corn-based ethanol) and "advanced biofuel." Advanced biofuels are defined as renewable fuels, other than corn-based ethanol, with lifecycle GHG emissions that are at least 50% less than those emissions produced by gasoline or diesel. This should include ligno-cellulosic ethanol assuming this requirement can be met. Beginning in 2016 when conventional annual biofuel volumes are fixed, a progressively increasing portion of renewable fuels must come from advanced biofuels (Fig. A2). Environmental protections have also been included in EISA to prevent the increased use of biofuels from damaging air or water quality.

The EISA will accomplish increased biofuel use by 1.5 M bbl/day of oil equivalent and has caused the Energy Information Administration *Annual Energy Outlook* to substantially review the daily biofuel production shown in its 2007 report to higher levels in the 2008 report (Fig. A3).

Figure A2. US Energy Independence and Security Act targets for conventional and advanced biofuels to 2022.

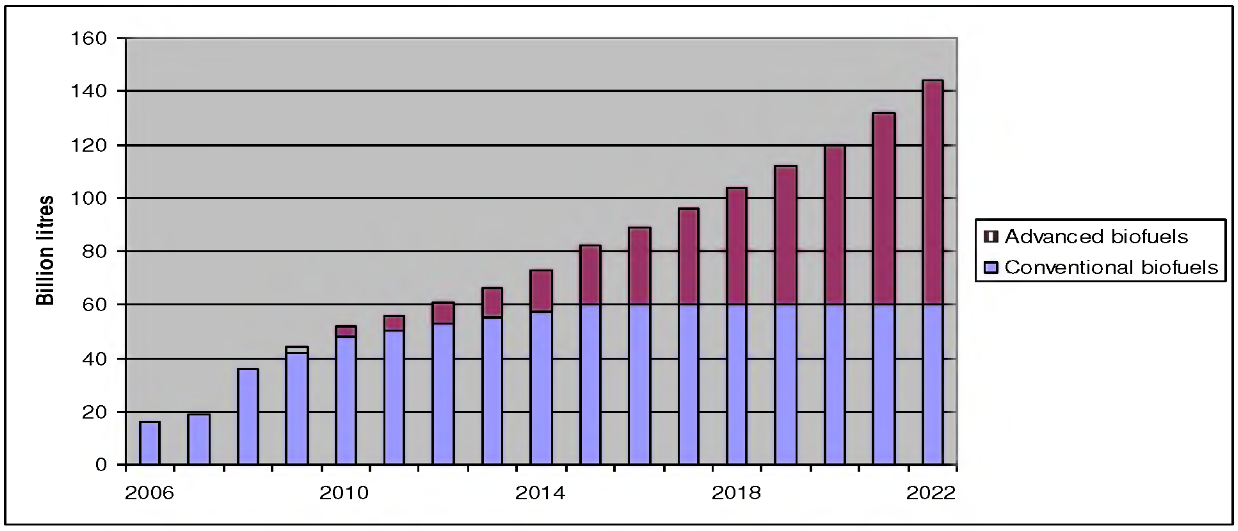
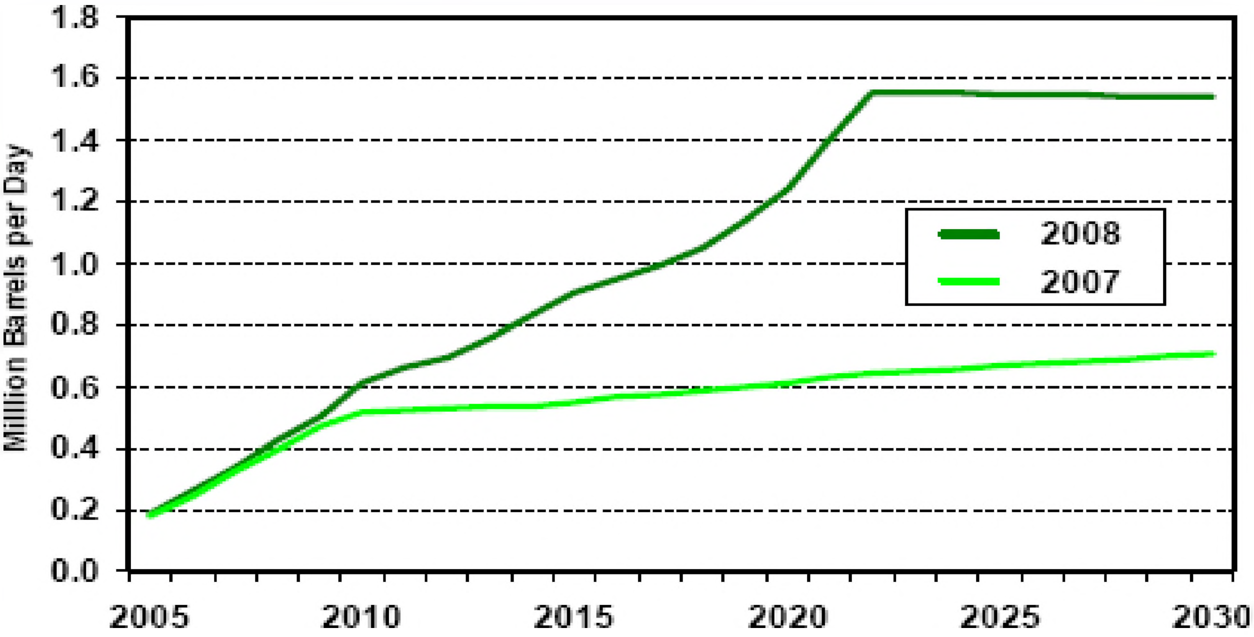


Figure A3. Daily biofuel production/import target levels in the US before and after the Energy Independence and Security Act, 2007 as reported in subsequent EIA Annual Energy Outlooks.



Source: Greene, 2008

European Union

For the member states of the EU, the primary policy tool behind the development of a biofuel industry is the Directive on the promotion of the use of biofuels for transport (Directive 2003/30/EC) (EC, 2003a). The motivations behind this Directive include improving the security of energy supply, and reducing the environmental impact of the transport sector (CEC, 2002). The Directive mandates an increasing share of biofuels from 2% of total fuel supply in 2005 to 5.75% in 2010 (based on energy content) in order to meet these priorities. Due to relatively slow growth in the industry, it is anticipated that renewable fuels will have about 4.8% of the market share by 2010, significantly less than the existing policy target.

The over-riding priorities of the European Commission will impact the behaviour of each member nation in setting national policies relating to biofuels. It can be expected that, while economic factors are not the political priority of the EU, the member nations will have a strong interest in utilising the proposed Directive to meet national goals of employment and economic diversification. From an economic standpoint, it is anticipated that a biofuel contribution of 1% of the total EU fossil fuel consumption would create between 45,000 and 75,000 new jobs (CEC, 2002).

Several member states have passed the biofuels Directive into national law, including Belgium, the Czech Republic, France, Germany, Greece, Latvia, Lithuania, Netherlands and Sweden. Some countries have announced indicative targets that are below that of the Biofuels Directive, including

Malta (target value for 2005 of 0.3%), Hungary (0.4-0.6%), Poland (0.5%), Spain (0.55-0.65%), Italy (1% and 2.5% by 2010) and Cyprus (1%). Each of these countries still plans to achieve national targets of 5.75% by the end of 2010. Slovenia follows a slightly different set of targets, ranging from 1.2% in 2006 to at least 5% in 2010. The UK has established a Renewable Transport Fuel Obligation which places a legal requirement on transport fuel providers to ensure that a specific percentage of their fuel sales is renewable, ranging from 2.5% (by volume) in 2008/09 to 5% in 2010/11 (Mabee, 2007). However obligated fuel suppliers can trade certificates to meet these levels

In implementing the biofuels Directive, some countries have set slightly more aggressive targets, including Austria (revised Fuels Ordinance, 4 Nov. 2004: BGBl. II, No 417/2004). It mandates that all petrol and diesel marketers blend at least 2.5% biofuels on an energy content basis in all fuels sold within the country. Sweden has set their national target of at least 3% biofuels after 2005, and has mandated that renewable fuels be made available at service stations, starting with the largest stations (>3,000 m^3 per annum) in 2006, and progressing to smaller stations (>1,000 m^3 per annum) by 2009. Sweden also has a very aggressive long-term target of 40-50% reduction of fossil fuel use, which should engender significant increases in biofuel use over the next 13 years (Mabee, 2007).

European governments did not utilise excise tax exemptions for biofuels to the same extent as their Canadian and US counterparts. This was because national controls over excise tax rates were complicated by the rules of the European Economic Community (EEC) in a Directive issued on October 16, 1992 which was intended to harmonise the structures of excise duties among all member nations. When France decided to create a support scheme for biofuels that would exempt these fuels from national excise taxes, objections were raised and an appeal to the Commission of the European Communities was made by BP Chemicals Ltd. Ultimately, however, the Commission decided to validate the French decision, allowing an exemption amounting to USD 0.06 /l to be extended through to December 31, 2003 (EC, 2003c). This created the precedent within the EU to allow excise tax exemptions for biofuels, freeing a powerful policy tool for decision-makers within the member nations.

A Directive regarding Tax Relief applying to Biofuels (2003/96/EC) was issued in 2003, permitting all member countries to grant excise tax exemptions as biofuel production becomes more widespread within Europe. It allows exemptions for biofuels produced or blended within European countries (EC, 2003b). This legislation is important due to the high level of excise tax that is currently levied on petroleum fuels in Europe particularly when compared to North America. Within these countries, a reduction of even a few percent can mean significant cost savings. For instance, in Austria, a 10% reduction in excise taxes on biodiesel reduces the retail cost by USD 0.028 /l, being almost equivalent to the federal excise taxes paid for diesel fuel in Canada. A similar percentage reduction in the US federal excise tax for diesel would result in a selling price of USD 0.058 /l and a savings of only USD 0.006 /l (Mabee, 2007).

Today, most EC member states, including Austria, Belgium, Cyprus, Denmark, Estonia, France, Germany, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, Slovakia, Slovenia, Spain, Sweden and the United Kingdom have introduced exemptions at various levels up to 100%, using the precepts laid down in Directive 2003/93/EC. For a complete discussion of these exemptions, see Mabee (2007).

Germany and Italy were careful to include a measure that allowed for adjustments to be made in the case of over-compensation. The German government introduced an Energy Tax Act, which, from 1 August 2006, placed a tax on these fuels. Italy also incorporated measures to adjust in the case of over-compensation and currently provides tax exemptions for an annual quota of 200,000 tonnes of biodiesel during the period 2005-2010, as well as reduced excise duties on bioethanol and related bio-derived additives (Mabee, 2007). Germany is one of few countries with excise tax privileges provided to 2nd-generation Biofuels, under the Biofuels Quota Act, 2006 (GBEP, 2007).

On January 14 2008, the EU Environment Commissioner, Stavros Dimas, announced a rethink of the biofuel programme due to environmental and social concerns. It was felt new guidelines were needed to ensure that EU targets are not damaging, particularly relating to impacts on rising food prices, rainforest destruction, notably from palm oil production, and concern for exploitation by large companies driving poor people off their land to convert it to fuel crops. On January 18 2008 the UK House of Commons Environmental Audit Committee raised similar concerns, and called for a moratorium on biofuel targets, echoing the stance of many non-governmental organisations and environmentalists.

The draft EU proposal released for discussion on 23 January 2008, originally aimed at an obligatory 10% share of energy coming from renewables in the transport sector by 2020. This includes electricity for dedicated electric and plug-in hybrid vehicles but the major portion is likely to be from biofuels. The 35 Mtoe of biofuels needed to meet the 10% target in 2020 would require 20-30 Mha of land. So it is anticipated much of the biofuels would need to be imported. No obvious advantages were evident in the proposal for 2nd-generation biofuels over 1st-generation in terms of overall energy balances or GHG emission reductions. Land would also be required. Responding to the public concerns at the potential environmental and social damage that the 10% target might initiate, in July 2008, the European Parliament's environment committee agreed to cut the renewable sources target to only a 4% share of transport fuels by 2015 when a major review will be undertaken before continuing with the 8-10% target by 2020. European Parliament approval is widely expected for early December 2008.

Funding

Direct funding for research, infrastructure, and development of biofuels is available in a number of EU member states but mainly for 1st-generation technologies. The Federal Public Service of Finance of Belgium for example, called for tenders to market increasing amounts of biofuels, beginning in November 2006 for biodiesel and in October 2007 for bioethanol. Some research funding was also made available. In Cyprus, legislation to comply with the biofuel Directive includes a grant scheme for energy conservation and renewable energy utilization. Under this legislation, four applications for biodiesel plants have been submitted. In the Czech Republic, state aid for biodiesel production has been introduced to a level of about USD 39 M. In Estonia, about USD 5,000 was granted as support to draw up business plans for the production of liquid biofuel production in 2005. Ireland announced a renewable energy grant aid package in 2005 which provides up to USD 86 M annually to a range of projects, including biofuel initiatives. Sweden provided an investment of approximately USD 120 M/yr for energy research which includes transport fuels. The UK created grant programmes to help upgrade infrastructure and to provide direct support for the development of a biofuels industry.

Latvia, Lithuania, and Poland, have provided small levels of support for biofuel development (Mabee, 2007). Other countries have also implemented similar measures to promote biofuels, including resources to support biomass production for non-transport energy purposes (Czech Republic) and to support expanded production of energy crops (Estonia, Slovakia). Fleet biofuel mandates and exemptions are available in Sweden, the UK and Ireland. A previous government in Sweden also released a report entitled '*Making Sweden an oil-free society*', which has among its goals the reduction of petrol and diesel in transport fuels of 40-50% by 2020 (Commission on Oil Independence, 2006).

The European Commission has included 2nd-generation biofuels and improved production methods as a priority area in its VII Framework Programme on Research (GBEP, 2007).

Other biofuel producing nations

Other major biofuel producers include China, which has grown its bioethanol production sector rapidly since 2000 to become the third-largest bioethanol producer after the US. The biofuel industry in China has been subsidised, mostly in terms of funds to construct biofuel plants. Total capacity from four plants in 2005 was about 1.3 bn l, but continuing high prices for oil has led the National Development and Reform Commission to announce that biofuel production will increase dramatically, providing China with the ability to replace about 2 Mt of crude oil by 2010, and 10 Mt by 2020. The Commission also announced that China would begin shifting to non-grain feedstocks, including sweet sorghum, for bioethanol production (NDRC, 2006). Jilin Fuel Alcohol remains the world's largest corn-based bioethanol plant with a current capacity in excess of 350 Ml/yr (Berg, 2004). Some Chinese provinces have announced biofuel mandated targets, although the national government has not yet made any decision about legislating biofuel use (NDRC, 2006).

Canada is poised to become a major biofuel producer already producing about 1 bn l of ethanol annually. Much of the funding being made available to fund R&D in biofuels has depended upon the federal government's environment strategy. This strategy evolved significantly with the ascension of a Conservative minority federal government in 2005 who made a campaign promise to introduce a 5% biofuels mandate. Agreement with provincial governments was reached in May, 2006 and the mandate will take full effect by 2010 (Johnstone, 2006). Recently, the federal government proposed a Clean Air Act, which was tabled on October 19 2006 (Canada Govt., 2006), and which includes legislation to back up this mandate. The merits of including the biofuel initiative within a larger, complex Act was an issue raised in the Canadian election of October 2008, with some parties (notably the Green Party) suggesting that this course could slow uptake of biofuels in the country. As part of their support for biofuels, a USD 0.5 bn fund was created under Sustainable Development Technology Canada (the NextGen Biofuels Fund) to support commercialization of new biofuel technology.

Previous Canadian governments provided substantial support for biofuels, including a cumulative investment of USD 2.34 bn for the implementation of the former Climate Change Plan for Canada, which included incentives for the development and use of environmentally-friendly technologies including bioethanol. The federal Canadian government provided direct funding for the industry through the Ethanol Expansion Program, which in 2004 and 2005 provided a total of USD 102 M in direct funding for 11 projects, 8 of which are currently under development. The federal government provides an excise tax exemption for biofuels, as do the provinces of Manitoba, Ontario, and Alberta (Finance Canada, 2006).

Other nations with biofuel-friendly policies include Australia, where a bioethanol production subsidy is in place that replaces excise tax exemptions at a rate of approximately USD 0.21 /l produced. Capital subsidies have been provided for two bioethanol production plants. In Thailand, excise taxes are waived for bioethanol. In Latin America, production schemes in Peru and Columbia have been linked to urban renewable fuel standards in Columbia. In a move designed to utilise surplus production, the sugar industry in India has successfully lobbied the government for state-level E5 fuel mandates, which were passed in September 2002 and which apply to 9 states and 4 territories. In order to support these mandates, an excise tax exemption was granted and bioethanol prices have been fixed by a Tariff Commission (Pelkmans & Papgeorgiou, 2005). Production from other nations will become more important as capacity comes on-line and the international market for bioethanol continues to develop (Mabee, 2007).

GBEP
Global Bioenergy Partnership

This Report provides a contribution to the Global Bioenergy Partnership (GBEP).
With the support of the Italian Ministry for the Environment Land and Sea.