Production of Liquid Biofuels

INSIGHTS FOR POLICY MAKERS

Liquid biofuels are made from biomass and have qualities that are similar to gasoline, diesel or other petroleum derived fuels. The two dominant liquid biofuels are bioethanol and biodiesel (i.e. 80% and 20% of the market, respectively), that together meet about 3% of the global transport fuel demand and are produced using 2-3% of the global arable land. Bioethanol can be produced from sugarcane, corn, sugar beets, wheat, potatoes, sorghum and cassava. In 2011, the largest producers of bioethanol were the United States (63%) using corn, Brazil (24%) using sugarcane, and China. Biodiesel is made from vegetable oils, derived from soybeans, rapeseed, palm seeds, sunflowers, jatropha as well as from animal fat or waste oils. The largest producers of biodiesel in 2011 were the European Union (43%), the United States (15%), Brazil and Argentina (each around 13%).

The advantage of biofuels is that they can substantially reduce greenhouse gas emissions in the transport sector (up to 70%-90% compared to gasoline) with only modest changes to vehicle technology and existing fuel distribution infrastructure. The disadvantage is that, apart from sugarcane ethanol, large-scale production of liquid biofuels based on today’s technology and feedstock would compete with food production for arable land and water, with limited expansion potential in certain cases. Also of concern would be the conservation of biodiversity and the risk of important land-use changes. The use of shared international standards is crucial to ensure that liquid biofuels are produced in a sustainable manner, minimising these possible negative environmental and social impacts due to land-use change and competition for food.

In several countries, research is currently working on the development of advanced biofuels (i.e. second and third generation biofuels), which are produced from non-food, cellulosic biomass such as woody and straw residues from agriculture and forestry, fast-rotation plants, non-food crops (possibly grown on marginal, non-arable land), organic fraction of urban waste and algae-based feedstock. These kinds of feedstock require advanced, capital-intensive processing to produce biofuels, but they promise to be more sustainable, offering higher emissions reduction and less sensitivity to fluctuations of feedstock cost. While the production cost of advanced biofuels is still high, improvements in process efficiency and cost reductions are expected from many ongoing demonstration projects in many countries, with small plants in operation and large plants under construction or planned.

Biofuels have been produced since the 1970s, but the market has expanded in the last ten years with a six-fold increase in production. This growth has been driven by mandates and tax incentives for blending biofuels with fossil fuels for energy security and emissions mitigation reasons. In general, today’s biofuels are not yet economically competitive with fossil fuels, with the sole exception of sugarcane ethanol which enjoys an untaxed retail price as low as US$ 0.6-0.65 per litre of gasoline equivalent (lge). In terms of market potential, the International Energy Agency (IEA) projects that sugarcane ethanol and advanced biofuels could provide up to 9.3% of total transportation fuels by 2030 and up to 27% by 2050. However, this would require at least a three- to fivefold increase in land use for biofuels production and significant yield improvements in developing countries.

The future of biofuels hinges on a number of factors. The economic viability will mostly depend on the price of biomass and oil-based fuels. A large-scale production of biofuels would increase feedstock demand and prices requiring a global market, a similar situation as for oil today. However, technical advances in the production of advanced biofuels from cellulosic feedstock could make available a broader range of non-food biomass such as agriculture and forestry waste, which could ease feedstock supply and prices, and address certain sustainability issues. Policy measures should be very selective in promoting only those biofuel technologies that substantially reduce emissions, avoid adverse land and water uses, and have positive social impacts.

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Production of Liquid Biofuels

HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS –** Biofuels are liquid and gaseous fuels produced from biomass. They can complement and/or replace fossil fuels, and reduce carbon emissions in the transport sector, with only modest changes to vehicle technology and existing fuel distribution infrastructure. This brief deals with the two major liquid biofuels: bioethanol and biodiesel. Biogas is dealt with in ETSAP P11. Liquid biofuels are usually referred to as conventional and advanced biofuels**. Conventional biofuels** are currently produced in many countries and are based on well-known processes and feedstock, e.g. bioethanol from sucrose and starchy biomass fermentation and biodiesel from esterification of vegetable oils. Global production of these conventional biofuels has been growing fast over the past years, reaching the level of 105 billion litres in 2010 (i.e. about 3% of transport fuel demand) and using 2-3% of the arable land. Apart from sugarcane ethanol, conventional biofuels will hardly be sustainable in the future as a large-scale production would subtract feedstock and land from food production and forestry. In addition, they are rather expensive and offer limited reduction of greenhouse gas (GHG) emissions compared to fossil fuels. **Advanced biofuels** promise to be more sustainable, with higher emissions reduction. They are based on biomass resources and land not used for other primary needs such as food production and farming. Feedstock includes ligno-cellulosic residues from agriculture and forestry, fast-rotation non-food crops (possibly grown on marginal, non-arable land), organic fraction of urban waste and microalgae. The conversion of these resources into biofuels requires processes that are under demonstration or development, with small plants in operation and large plants under construction or planned all over the world.

■ **PERFORMANCE AND COSTS –** Energy input, GHG emissions and costs of biofuel production are very sensitive to feedstock, process, co-products and local conditions. The use of international standards is therefore crucial to assess biofuel benefits and costs. Among conventional biofuels, sugarcane ethanol is the most viable option: under favourable conditions, the lifecycle reduction of GHG emissions can reach the level of 70-90% compared to gasoline; even more than 100% if co-products are accounted for. Its untaxed retail price can be as low as $0.6-0.65 per litre of gasoline equivalent (lge), depending on the feedstock price (i.e. 60% of the total cost). All other conventional biofuels are less attractive. Advanced biofuels are rather costly at present ($1.0-1.2 /lge), with about 50% of the cost due to the investment, but they promise GHG reductions comparable to sugarcane ethanol and declining costs over time. The investment cost of a production plant for advanced biofuels with a capacity of 50-150 Ml/yr is estimated to range between $125 million and $250 million. In general, both conventional and advanced biofuels are not yet economically competitive with fossil fuels, with the sole exception of sugarcane ethanol also depending on sugar and oil prices. They are expected to become competitive for oil prices above $130/bbl and/or high carbon prices. Recent analyses suggest that technology improvements would enable ligno-cellulosic biofuels to compete at oil prices of $60-70/bbl (IPCC SRREN).

■ **POTENTIAL AND BARRIERS –** The scenarios of the International Energy Agency (IEA) suggest that sugarcane ethanol and advanced biofuels could provide up to 9.3% of transportation fuels by 2030 and up to 27% by 2050. These estimates are mostly based on available agriculture/forest residues and non-food energy crops, 10% of which (i.e. 7.5 Gt/yr by 2030) could provide 120-150 billion lge of liquid biofuels (i.e. almost 50% of the 2030 biofuels demand). However, estimates for global biomass potential vary considerably. Recent analyses suggest a potential production of 85 EJ (including biofuels and bioenergy) from agricultural and forestry residues by 2050, 60 EJ from surplus forest growth and 120 EJ from surplus arable land used for dedicated energy crops. While the surplus arable land is uncertain, this potential exceeds the 2050 IEA-projected bioenergy demand (i.e. 65 EJ biofuels and 80 EJ heat and power). Depending on residue availability and food production, the land used for energy crops could grow from today’s 30 Mha to 100-160 Mha by 2050, with significant yield improvement in developing countries. At present, potential areas have been identified in a few countries and their use is still controversial due to water availability. In the future, the competitiveness of advanced biofuels will depend on prices of feedstock and fossil fuels. Access to ligno-cellulosic feedstock could reduce biofuel prices, while larger production could increase feedstock demand and prices. Policy measures (e.g. mandates and incentives) for blending biofuels with fossil fuels are now in place in many countries and foster market growth. However, policies should only promote biofuels with best performance in terms of GHG reduction and land-use. Environmental impacts, such as those caused in some countries by the extensive production of biodiesel from palm oil are to be avoided. The United States has set specific targets for advanced biofuels (i.e. 60 billion litres by 2022) but requires a reduction of 50-60% of GHG emissions on a lifecycle basis. In the European Union, biofuels have to provide at least a 35% GHG reduction compared to fossil fuels. Potential for biofuel production has been identified in developing and emerging countries (e.g. Brazil), but measures are needed to ensure sustainability and avoid land-use changes.

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PROCESS AND STATUS

Biofuels are liquid and gaseous fuels that are produced from biomass feedstock. They can complement and replace fossil fuels and reduce carbon emissions in the transport sector with only modest changes to vehicle technology (i.e. engines) and to existing infrastructure for fuel distribution. Depending on the feedstock type, maturity and sustainability of the production process, biofuels are referred to as *conventional* (1st generation) and *advanced* (2nd and 3rd generation) biofuels. Conventional biofuels are based on commercial feedstock and processes currently in use in many countries. They include liquid fuels, such as bioethanol[1] from sugar- and starchy crops, biodiesel[2] from oil crops and waste oil, and biogas for anaerobic digestion and other processes. This brief deals with liquid biofuels, primarily bioethanol and biodiesel, while biogas and related applications are dealt with in ETSAP P11, E05 and T03. Apart from sugarcane ethanol, most of today's liquid biofuels scarcely appear to be sustainable in the future because large-scale production would compete with food production in terms of feedstock, arable land and water use. In addition, they are rather expensive and offer only a limited reduction of greenhouse gas (GHG) emissions compared to fossil fuels, with high emissions abatement costs. Major drawbacks also include risks for biodiversity and deforestation (land-use change). Advanced biofuels promise to be much more sustainable as they are based on biomass resources and land not used for other primary needs (e.g. food production, farming), such as ligno-cellulosic residues from agriculture and forestry, fast rotation plants, non-food crops (possibly grown on marginal or non-arable land), organic fraction of urban waste and algae-based feedstock. However, the conversion of this feedstock into biofuels requires advanced processes that are still under commercial demonstration (e.g. production of cellulosic ethanol, biomass-to-liquid diesel) or under development (e.g. algae-based biofuels). Large-scale production of biofuels would also involve a logistic infrastructure to collect a large amount of feedstock.

Commercial production of liquid biofuels (bioethanol) started in the 1970s in Brazil and the United States based on sugarcane and corn feedstock, respectively. Over the last ten years, liquid biofuel production has been growing fast in many countries, boosted by mandates and tax incentives for blending biofuels with fossil fuels for road transport. This is part of the policy for energy security and mitigation of GHG emissions. The global production (mostly based on conventional biofuels) has grown from 16 billion liters in 2000 to about 105 billion liters in 2010 (82% bioethanol and 18% biodiesel), accounting for about 3% of today's transport fuel on an energy basis [1] and using almost 3% of global arable land. Leading bioethanol producers in 2010 were the US (i.e. 58% of the global production, mostly from corn) and Brazil (i.e. 31%, mostly from sugarcane) while 58% of world biodiesel is produced in the EU (mostly in Germany, from rapeseed oil), also with important production in Thailand and Malaysia (palm oil biodiesel). Brazil and the US are also major consumers of bioethanol (i.e. 21%[3] and 4% of the domestic road transport fuel, respectively) while Europe is the largest consumer of biodiesel (i.e. about 2% of the transport diesel fuel). Commercial production of 1st generation biofuels in emerging and developing countries (e.g. Argentina, Brazil, China, Thailand, Malaysia) is an income opportunity for rural communities, but the compliance with sustainability criteria and standards is often questionable. For example, in some countries the extensive cultivation and trading of palm oil for biodiesel production has resulted in land-use change and deforestation. In 2011, the biofuel trading from Brazil, Latin America and South East Asia to the EU, Japan and the US has reached the level of 0.8 billion litres of bioethanol and 2.8 bln litres of biodiesel (mainly Argentina and Indonesia exporting to the EU) [2].

The International Energy Agency (IEA) estimates that the use of liquid biofuels could grow fast in the coming years, reaching a level of 9% (11.7 EJ) of the total transport fuel (126 EJ) by 2030 [4] and about 27% by 2050 [5]. This could avoid the emission of around two billion tonnes (Gt) of CO_2 per year and contribute significantly to halving GHG emissions by 2050, compared with the current level. Some 90% of this contribution would come from advanced biofuel technologies that are not yet commercially available. Several pilot and demonstration plants producing advanced biofuels are already in operation or have been announced for the next years in both OECD and

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[1] Bioethanol is a high-octane fuel used to replace and complement gasoline in spark-ignition engines and to reduce the CO_2 emissions. Oxygen in its molecular form enables a relatively low-temperature combustion, which also reduces the emissions of CO, NOx and volatile organic compounds (VOC). If a large amount of fertilizers is used to grow the feedstock, bioethanol could lead to increased N_2O emissions on a lifecycle basis. Other drawbacks include miscibility with water, aldehyde emissions, compatibility issues with some plastics and metals and high latent vaporisation heat (i.e. cold start issues). Benefits from ethanol combustion (e.g. high compression ratio) compensate for the low energy content compared to gasoline. Conventional spark-ignition engines can run with 5-10% (E5, E10) ethanol-gasoline blends with almost no technical changes. *Flex-fuel vehicles* (several million in use in Brazil, the United States and Sweden) can run on up to 85% ethanol blend (E-85) with modest technical changes (ETSAP T06). Ethanol can also be used in compression ignition (diesel) engines if additives are used to compensate for its low cetane number.

[2] Biodiesel is a high-cetane fuel, which can be fully blended with fossil diesel to run compression ignition engines. It offers low emissions of GHG, sulphur compounds and particulate matter compared with fossil diesel. In current practice, a 5-20% (B5, to B20) 1st generation biodiesel (fatty acid methyl ester, FAME) is blended with fossil diesel. A full blending (up to B100) is possible for advanced biodiesel.

[3] 12.2% hydrous, and 8.4% anhydrous

non-OECD countries. Soon the production capacity for advanced liquid biofuels is forecast to reach the level of about 175 million litres of gasoline equivalent (lge) per year [1], with an additional capacity of 1.9 billion lge/yr under construction or planned and further 6 billion lge/yr potentially available in a few years. To put these figures into context, the advanced biofuel penetration envisaged by the IEA in its mitigation scenarios is 250 billion lge/yr by 2030.

***Conventional Biofuel Technologies* -** The production of 1st generation biofuels is based on well-known technologies that are still evolving to improve energy efficiency and reduce GHG emissions and costs.

■ **Bioethanol –** Commercial bioethanol can be produced from many types of feedstock, including sugarcane, sugar beets, corn (maize), wheat, potatoes, sorghum and cassava. Production from sugar crops (i.e. sugarcane, sugar beet, sorghum) is based on the fermentation of sucrose followed by distillation to fuel-grade ethanol. Production from sugarcane is particularly easy and efficient because a considerable amount of sucrose is readily available, and crushed stalk (bagasse) can be used to provide heat and power to the process, as well as to other energy uses. If starchy crops (e.g. corn) are used as the feedstock, an additional step (hydrolysis) is needed to convert starch into sugar, followed by fermentation and distillation. The low efficiency of the starch conversion can be improved (and costs lowered) using enzymatic hydrolysis and valorising co-products (e.g. animal feed). Apart from sugarcane ethanol, bioethanol production is a rather energy-intensive process whose economic and environmental benefits are sensitive to the technology process, feedstock and co-product prices.

■ **Biodiesel –** Commercial production of biodiesel is based on trans-esterification of vegetable oils (chemically or mechanically extracted from rapeseed, palm seeds, sunflowers, etc.), animal fats and waste oil through the addition of methanol (also biomethanol or other alcohols) and catalysts, with glycerine as a by-product. Biodiesel production from animal fats and waste oils is cheaper and more efficient, but the basic feedstock is limited. In principle, some vegetable oils could be used directly as a fuel, but this would involve risks for the vehicle engine.

***Advanced Biofuel Technologies* –** To address the sustainability issues of conventional biofuels, advanced biofuel technologies focus on non-food feedstock, including agriculture and forest residues, organic and woody fraction of urban waste, short-rotation forestry (e.g. eucalyptus, poplar, robinia, willow), genetically modified crops and perennial grasses (e.g. miscanthus, switch grass, jatropha) grown on marginal, non-arable land, though with moderate yields. Most of this feedstock is ligno-cellulosic biomass consisting of 50-75% (dry mass) cellulose and hemicellulose, and 50-25% lignin, a phenolic compound. The lignin content is usually high in woody biomass and lower in agriculture waste and perennial grasses. The conversion of ligno-cellulosic feedstock into liquid biofuels is based on two main processes, i.e. biochemical and thermochemical conversion [6], whose commercial feasibility is currently under demonstration in a number of plants all over the world. These processes exploit not only the sugar, starchy and oil components of the feedstock but all the available ligno-cellulosic materials, thus considerably enlarging the available biomass resource.

■ **Biochemical Process -** The biochemical process is based on enzymatic or acidic hydrolysis to convert cellulose and hemicellulose into sugars, followed by fermentation and distillation to ethanol, the same as the conventional process. Converting cellulose into sugar is more challenging than converting starchy biomass for 1st generation biofuels as lignin tends to inhibit hydrolysis and must be removed. To facilitate the process, a pre-treatment (biological, physical or chemical) is needed to comminute the feedstock. The need for pre-treatment and enzymes for hydrolysis makes the overall process rather costly though enzymatic hydrolysis is cheaper than acidic hydrolysis. Research efforts aim to reduce enzyme costs, recycle enzymes, increase the efficiency of pre-treatment (e.g. steam explosion technique), improve lignin separation and obtain simultaneously saccarification and fermentation. Lignin can be used as a source of chemicals or as fuel for heat and power generation.

■ **Thermo-chemical Process** - The thermo-chemical process (i.e. biomass-to-liquid, BTL) is similar to the process to produce liquid fuels from coal (see ETSAP P05). It includes biomass pre-treatment, gasification at around 850°C in controlled air/O_2 atmosphere to produce syngas[4], clean-up of syngas and the well-known catalytic Fischer-Tropsch (FT) conversion to produce a variety of fuels – basically diesel and jet fuel from low-temperature FT, and gasoline and chemicals from high-temperature FT. The process offers a number of variants and products: the syngas can also be used to produce hydrogen (shift reaction), methanol, ethanol and DME. In principle, the gasification could be stopped at the pyrolysis stage (450-600°C) to produce bio-oil (syncrude) to be refined. Various options exist regarding the key components of the process, such as the gasifier (fixed bed, fluidised bed and large-scale entrained-flow gasifier), the FT reactors and the catalysts. The process does not produce lignin as all

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[4] A mix of CO and H_2, plus CO_2, CH_4 and impurities

the ligno-cellulosic matter is gasified. Biomass gasification is an energy- and capital-intensive process. Research efforts aim to improve its performance and reliability, impurity separation and FT conversion and to reduce costs.

■ **Hydrogenation of Vegetable Oils -** The catalytic hydrogenation of vegetable oils (HVO) and animal fats, followed by cracking [6], is an alternative process to produce high-quality biodiesel. This process requires a considerable amount of hydrogen, but it is well-known and close to market uptake, with several demonstration plants in operation.

■ **Algae-based Biofuels –** Algae have recently gained attention as a potential feedstock for biofuels. In principle, they offer high yield (several times the yield of palm feedstock, [6]) and large CO_2 absorption by photo-synthesis, with up to 90% lower water needs than terrestrial crops, possible use of saline or waste water and no need for arable land. Algae contain approximately 33-50% lipids and triglycerides for biodiesel production, the rest being sugar and proteins for bioethanol production. They are considered primarily for biodiesel and jet fuel production since fewer alternatives exist to replace these fuels. However, algae cultivation in open ponds requires regions and sites with the appropriate climate, sunshine and water nutrients, whereas alternative cultivations in closed photo-bioreactors are very expensive. In addition, cultivations are vulnerable to contamination, and an efficient technology is needed for oil extraction. A number of pilot and demonstration projects exist all over the world, but there is consensus that commercial production of algae biofuels, also referred to as 3rd generation biofuels, will take at least ten years to materialise.

Other Processes and Fuels - Many other processes can provide biofuels. **Fast pyrolysis** (i.e. low-temperature 400-600°C gasification in the absence of O_2, followed by quick cooling at 100°C to obtain a condensed oil) can convert biomass into bio-oil to be refined into diesel [6]. Pyrolysis enables the use of larger size (5mm) biomass particles, thus saving pre-treatment costs in comparison with other processes. It is rather energy-intensive, with products depending to a certain extent on how fast heating and cooling occur. Pyrolysis oil can be rather acidic and corrosive, thus requiring more expensive storage and handling. A by-product is bio-char, which can be used as solid fuel or as a fertilizer. The **hydrothermal process** consists of a biomass treatment with pressurized water at temperatures of 300-400°C, which can produce bio-oil with a lower water and oxygen content than fast-pyrolysis oil. The **biological and chemical conversions of sugar into alkanes** are alternative processes for producing sugar-based ethanol and buthanol from ligno-cellulosic feedstock. Buthanol has a higher energy density (29.2 MJ/l) than ethanol and is more similar to gasoline. Another option is the production of **dimethylether (DME)** from biogas via conversion into methanol, followed by distillation and dehydration using zeolite catalysts. DME is a high cetane fuel which can be used in diesel engines or to replace propane in liquefied petroleum gas (LPG). Unlike methanol, DME is not toxic, emits less NOx and SOx than fossil diesel and no PM, but its energy content is 50% lower than that of fossil diesel [6]. It can also be used for cooking and heating. **Biomass-based hydrogen** can be obtained by steam reforming of bioethanol and methanol or even from biomass gasification, followed by syngas water shift reaction and separation (i.e. pressure swing absorption, cryogenic or membrane separation), with CO_2 as a by-product. Biological production of hydrogen is also under investigation. In comparison with other fuels, hydrogen offers a high energy density (120MJ/kg) per unit of mass but a very low energy density in volume. Its use as a practical, commercial fuel requires further R&D and time (ETSAP P11). Processes for biofuel production that require medium- to high-temperature heat can find important efficiency and economic synergies with concentrating solar power (ETSAP TB E10).

Biorefineries – The same as oil refineries, biorefineries consist of a cluster of facilities to convert diverse biomass into a variety of biofuels and by-products that would enable a more efficient use of basic resources and investment in comparison with the current biofuel production. Pulp and paper production plants that also produce electricity from black-liquor residues can be regarded as an early example of biorefinery.

A graphic overview of feedstock, processes and output for advanced biofuels is given in Figure 1. The IEA [1] provides a qualitative evaluation of the level of maturity of biofuel technologies (Figure 2). Advanced biofuels that are close to commercialisation (cellulosic ethanol, BTL/FT diesel and HVO) are expected to demonstrate reliable operation within five years and achieve commercial-scale production in 10 years, with at least a 50% lifecycle reduction of GHG emissions compared to conventional fuels. More time is needed for algae-based biofuels and biorefinery process integration. R&D efforts are in place in many countries with an increasing global spending (i.e. US$ 800 million in 2009 [7]). Global standards may help improve quality and sustainability of biofuel production.

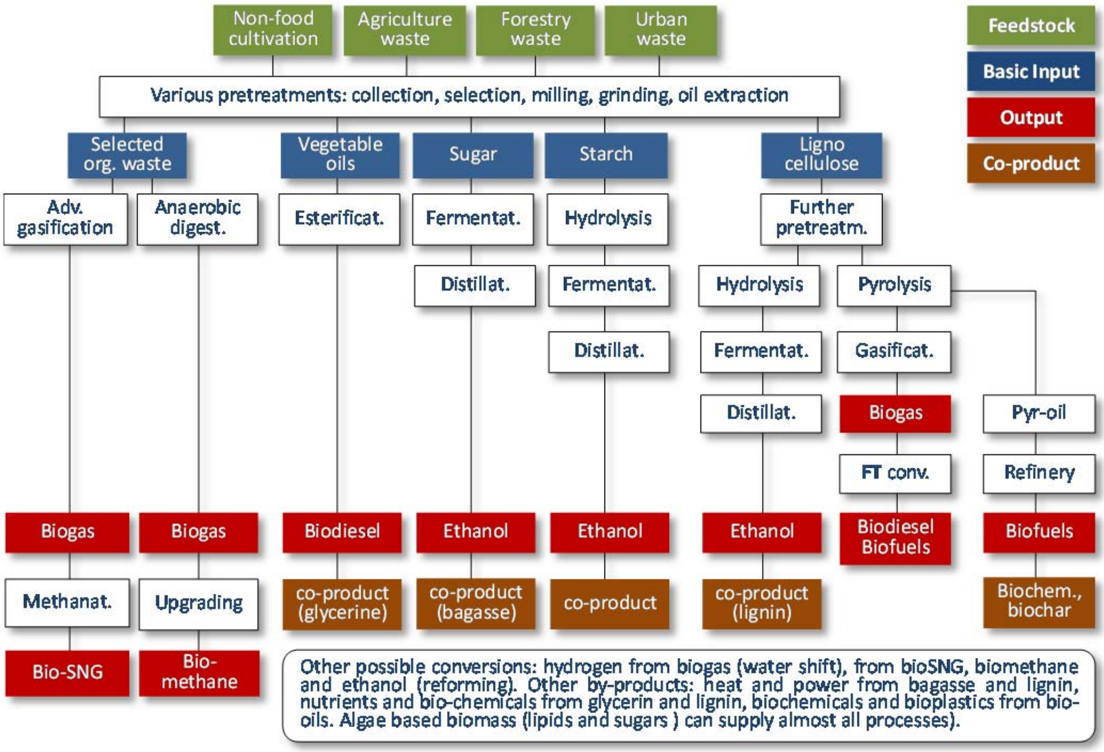

Figure 1 Feedstock, processes and output for sustainable biofuel production

PERFORMANCE AND SUSTAINABILITY

Energy and fossil fuel input, as well as GHG emissions involved in biofuel production, are very sensitive to the feedstock (i.e. type, yield, fertilizers used for cultivation), conversion process, co-products and local conditions. All these elements are sources of significant uncertainties in estimating biofuel performance in terms of energy efficiency and GHG emissions. In many processes, technology variants or bad management may lead to a significant increase in emissions, thus eliminating most of the benefits. In contrast, benefits can increase considerably if the energy input is provided by the feedstock itself and by-products are accounted for. It is also clear that feedstock cultivation should avoid land-use changes of arable and forestry areas and maximise as much as possible the exploitation of waste and residues and the use of non-arable lands or degraded soils for growing non-food energy crops. International initiatives (e.g. Global Bioenergy Partnership) offer recommendations and criteria to assess the sustainability of biofuel production, and some countries have already set standards. In the EU Renewable Energy Directive, biofuels must provide at least a 35% GHG emissions saving compared to fossil fuels to be eligible for the EU emissions reduction targets; for new plants, this threshold will increase up to 50% by 2017. In the United States, advanced biofuels must demonstrate a minimum GHG reduction of between 50% and 60% on a lifecycle basis, including land-use change. Estimates of biofuel emissions reduction usually refer to lifecycle emissions avoided with respect to fossil fuels for a certain feedstock and production process and account for fossil energy input (i.e. fuel, electricity with the relevant energy mix, heat) and fertilizers used to grow feedstock. Estimates usually do not account for possible emissions associated with land-use changes for feedstock cultivations. The IEA [1] has reviewed a number of analyses [9,10,11].

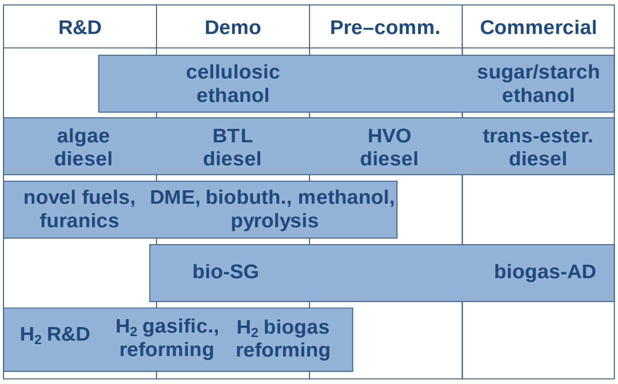

Figure 2 Status of biofuel technologies [1, 7]

Results show that many conventional biofuels offer moderate reductions in GHG emissions compared with equivalent fossil fuels.

Among conventional biofuels, sugarcane ethanol is the most efficient technology because sugar crops offer high yields, sugar extraction is easy, and bagasse can be used to provide heat and power to the process. With all these conditions in place, the fossil energy input to the process can be very low and bioethanol can offer a 70-90% reduction of the lifecycle CO_2 emissions compared with fossil gasoline (i.e. ~2.8 $kgCO_2/l$), if no land-use change occurs. Even more than a 100% GHG emissions reduction can be achieved if co-products are accounted for. The balance is less favourable for feedstock other than sugarcane. Ethanol from sugar beets, corn, cereal grains and conventional biodiesel require higher energy input and offer lower CO_2 emission reductions. The use of recycled oils and animal fats is also very attractive in terms of CO_2 reductions, but the basic resource is limited. Advanced biofuels (e.g. ligno-cellulosic ethanol, BTL diesel) also offer very high performance (more than 100% emission reduction) although processes are less proven and consolidated. Typical values and ranges for land-use yields, co-products and CO_2 emissions reduction for conventional and advanced biofuels are given in Table 1. For some processes and feedstock, the CO_2 balance can be negative, meaning that the production and use of biofuels generate more emissions than fossil fuels.

Apart from sugarcane ethanol, the energy balance (i.e. energy output-to-input ratio) of conventional biofuels is modest (e.g. 1.3-1.65 for corn ethanol) while advanced biofuels (e.g. ligno-cellulosic ethanol) offer values of 4.4 to 6.6 [12]. The typical energy efficiency (i.e. biofuel-to-feedstock energy content ratio) of ligno-cellulosic biofuels from agriculture and forest residues range from 12-35%, assuming a biomass energy content of 20 GJ/t (dry biomass), a biofuel yield of 110-300 litres of ethanol (22.3 MJ/l) or 75-200 litres of biodiesel (34.4 MJ/l) per tonne of biomass [6,13,14]. To put these figures into context, the maximum theoretical efficiency achievable in converting all ligno-cellulose carbohydrates into ethanol is about 50%. This limit may be exceeded if the energy content of lignin is accounted for. Efficiency translates into land-use, considering that the agriculture yields of cereal straw and corn stover is about 3-5t/ha and 4-6t/ha, respectively (dry biomass).

Typical figures for advanced biofuel production plants (size, capacity factor, logistics, biomass supply area) are given in Table 2. It should be noted that, during the harvesting season, commercial sugarcane ethanol plants can handle some 300,000 t of biomass over 6-7 months and that large 2nd generation plants could handle up to 600,000 t/yr, with more complex logistics.

Table 1 Current and projected biofuel yields and lifecycle CO_2 reduction compared to fossil fuels [1]

Feedstock/ Biofuel	Yield 2010 (2050)	Co-products	CO_2 reduction vs. fossil fuels
	(lde-lge/ha)[5]	(kg/l biofuel)	%
Sugarbeet Ethanol	2800 (3700)	0.25 Beet pulp	25 to 65
Corn (maize) Ethanol	1800 (2400)	0.3 DDGS	-20 to 60
Sugarcane Ethanol	3900 (4800)	2.5 Bagasse	70 to 105
Cellulosic Ethanol /SRC	2200 (3700)	0.4 Lignin	50 to 110
Rapeseed Diesel	1500 (2100)	0.1 Glycerine 0.6 Presscake	15 to 85
Soy seed Diesel	600 (900)	0.1 Glycerine 0.8 Bean meal	na
Palmseed Diesel/FAME	3200 (4800)	0.1 Glycerine, 0.25 Bunches	25 to 80
BTL Diesel/ SRC	3100 (5200)	Low-temp heat, Pure CO_2	55 to 120
HVO Diesel	2000 (3400)	0.1 Glycerine	15 to 84
Algae Diesel	Na	Several	-50 to 65

Notes: Biofuel yields do not account for land-use reduction due to co-products. Emissions from land-use change are not included. Emission savings of more than 100% are due to the use of co-products. One litre of ethanol=0.65 lge. One litre of biodiesel = 0.90 lde. One litre of adv. biodiesel = 1lde. The average yield of woody crops from short rotation coppice (SRC) =15t/ha. IEA analysis based on yields and emissions from sources [5, 21, 26, 27, 28, 29, 30, 31, 32, 33, 34] and [17, 35, 36]

Table 2 Typical figures for advanced biofuel production [5]

Type	Plant capacity	Capacity factor	Biomass oven	Truck traffic	Biomass production area (*)
	l/yr	hr/yr	dry t/yr	-	%
Pilot	15k-25k	2000	40-60	3-5/yr	1-3, 1km
Demo	40k-500k	3000	100-1200	10-140/yr	5-10, 2km
Pre-comm.	1M-4M	4000	2k-10k	25-100/m	1-3, 10km
Comm.	25M-50M	5000	60k-120k	10-20/day	5-10, 20km
Large comm.	150M-250M	7000	350k-600k	200-400/day	1-2, 100 km

(*) % of land within an area of given radius

CURRENT COSTS AND COST PROJECTIONS

Biofuel costs and prices depend on the highly variable prices of feedstock and the capital costs of production plants. Commercial competitiveness of biofuels also depends on the variable prices of conventional fuels (gasoline and diesel). This means that current prices, price projections and economic competitiveness of

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[5] Litres of diesel equivalent (lde), litres of gas equivalent (lge).

biofuels are all highly variable and sensitive to market conditions.

■ **Conventional Biofuels –** In general, biofuels are not yet economically competitive with conventional fuels (i.e. gasoline, diesel), the sole exception being the Brazilian sugarcane ethanol. This means that promotion policies are still needed to aid the market uptake of biofuels and enable the cost reductions associated with large-scale production. The cost of conventional biofuels is very sensitive to the feedstock price, which accounts for 50-60% of the final cost of Brazilian sugarcane and for between 80-90% of the cost of palm biodiesel, corn ethanol and rapeseed diesel (assuming a biomass cost of US$ 2-3/GJ and an energy content of 20 GJ/t). However, actual feedstock prices depend largely on local conditions. For example, reported prices of sugarcane tops/leaves are US$ 3-8/t (fresh matter) in Brazil, US$ 8-15/t in Thailand and US$ 20-30/t in India [16,17,25]. Also uncertain is the cost of dedicated non-food cultivations. Biomass transportation costs also vary considerably from a typical ¢0.1/t-km for ocean shipping to ¢10/t-km for road transport.

The cost of conventional biofuels is unlikely to decrease significantly over time as the cost of conventional feedstock tends to increase in both energy and non-energy markets. As a consequence, the economic competitiveness of conventional biofuels is expected to remain questionable in the absence of a significant increase in the current oil price. The IEA analysis [15] suggests that, with corn prices between US$ 150/t and US$ 250/t (without subsidies), the US corn-based ethanol is profitable for oil prices above US$ 90/bbl and US$ 130/bbl, respectively, while subsidies set much lower profitability thresholds (i.e. above US$ 50/bbl and US$ 90/bbl, respectively). The emissions reduction cost of conventional biofuels is also high (above US$ 200-300/tCO_2).

■ **Advanced Biofuels -** At present, advanced biofuels are significantly more expensive than conventional biofuels, but their cost is expected to become more attractive over time. For all processes, the cost of a commercial-scale production is highly uncertain and sensitive to feedstock prices and local conditions, but technology advances and cost reductions are more likely to occur for the biochemical production of ethanol than for the well-known BTL process. To become economically competitive with sugarcane ethanol and conventional gasoline, the typical price of advanced biofuels (either BTL-diesel or lignocellulosic ethanol) should be as low as US$ 0.6/lge, almost 50% below the current level. It is worth noting that available analyses [18] suggest that in countries such as South Africa, Brazil and Thailand, the production cost of advanced biofuels could be about 33% lower than the international cost. In these estimates, investment costs account for 50%, feedstock for 35%, and O&M and energy for the rest, an important factor being the plant capacity factor. In some countries (e.g. Brazil and South Africa), the use of bagasse (US$ 4-8/t) from sugarcane ethanol production as the basic feedstock for advanced biofuels could be even more attractive due to the high concentration and the lower impact of transportation.

Advanced biofuels are more capital-intensive than conventional biofuels. The investment costs for a commercial-scale plant with a capacity between 50Ml/yr and 150Ml/yr range from US$125 million to US$ 250 million [6] – that is, up to ten times more than a conventional biodiesel plant with the same capacity. Investment costs vary considerably as a function of the biomass pre-treatment and conversion process.

The IEA [1] provides estimates of typical international biofuel retail prices (untaxed), which account for feedstock, conversion process, fuel distribution and value of co-products (Table 3). Because biofuels differ from fossil fuels in terms of energy content (e.g. ethanol energy content by volume is two-thirds that of gasoline), biofuel costs are usually given as US dollars per litre of gasoline or diesel equivalent (lge or lde). For conventional biofuels, the dominant cost element is the feedstock cost (50-90%) while, for advanced biofuels, the investment cost would be more important (40-50%), with feedstock accounting for 35-40%. Co-products (e.g. glycerine, bagasse, lignin, waste, heat and power) can reduce the biofuel cost by up to 15-20%. The IEA also provides scenarios for biofuels prices and competitiveness (Table 3). In the low-cost scenario, sugarcane ethanol remains the cheapest liquid biofuel while the prices of advanced liquid biofuels fall over time, reaching parity with fossil gasoline and diesel by 2030. In the high-cost scenario, because of high feedstock and process costs, advanced biofuels remain more expensive, and only sugarcane ethanol becomes economically attractive (assuming an oil price of US$ 130/bbl). Of course, oil prices above US$ 130/bbl and carbon prices above US$ 50/tCO_2 could significantly improve the competitiveness of biofuels. Recent analyses (IPCC SRREN, [47]) indicate that potential improvements could enable lignocellulosic biofuels to compete at oil prices of US$ 60-70/bbl with no revenue from CO_2 mitigation.

Some important aspects should be taken into account considering the prices given in Table 3. First, actual prices vary significantly, not only with technology and feedstock, but also with the production scale and local conditions. Secondly; price uncertainty increases with the move from conventional to advanced biofuels. Thirdly, the prices of conventional feedstock are more sensitive to variability of agriculture prices. Fourthly, in the future, access to a broader range of non-food and residual feedstock should improve price stability and competitiveness. Finally, on the other hand, a large-scale production of biofuels would certainly increase the feedstock demand, and large production plants would result in long transportation distances and higher logistical costs. The IEA analysis suggests that the current cost of ligno-cellulosic bioethanol (US$ 1.05/lge) and BTL biodiesel (US$ 1.1/lge) would be competitive with fossil fuels at oil prices over US$ 130/bbl. Regarding competitiveness, it should be noted that fuels from unconventional oil, gas-to-liquid and coal-to-liquid processes are competitive at oil prices of around US$ 65/bbl (excluding costs for CO_2 emissions).

As far as algae-based biofuels goes, cultivation and extraction of the raw oil are still expensive processes. The production cost of algae oil (up to 50% of the basic biomass) is also high and uncertain (i.e. from US$ 0.75 to US$5 per litre, excluding conversion to biofuel [19]). The lower and higher bounds refer to the cheapest cultivations in open ponds and the most costly photo-bioreactors. Further research is needed to reduce costs, select optimal algae, reduce risks of contamination and scale up the process.

POTENTIAL AND BARRIERS

Biofuel potential and barriers depend basically on biomass resources and policies to either promote or regulate the sustainable exploitation of bioenergy.

Biomass Potential – Estimates of the bioenergy technical potential vary considerably, from an optimistic 1,500 EJ/yr by 2050 [20] to more prudent figures of about 500 EJ/yr, up to recent analyses [21,47] that estimate the potential feedstock for biofuels and bioenergy production by 2050 at around 85 EJ from agricultural and forestry residues, plus 60 EJ from surplus forest growth and 120 EJ from surplus arable land for dedicated energy crops, with little or no environmental impact[6]. The total potential exceeds the 2050 IEA-projected potential bioenergy demand (i.e. 145 EJ, including 65 EJ for fuels and 80 EJ for heat and power). A key uncertainty in the available estimates is the surplus agricultural land for energy crop cultivation. The global land use for dedicated non-food, ligno-cellulosic energy crops could grow from today's 30 Mha to around 100-160 Mha by 2050, with a significant yield improvement in developing countries. A potential for energy crops, with low risk for soil and water use and no competition with food production and forestry, exists in regions, such as sub-Saharan Africa and Latin America. However, at present Brazil is the only country claiming to have about 200 Mha of unused pasture for sustainable production of energy crops although this is a matter for debate. In countries such as Cameroon, Tanzania and India, the actual potential seems to be lower than previous expectations, and significant investment would be needed for exploitation, while in countries, such as Thailand and Malaysia, the pressure on cropland is already high. Cultivations of perennial energy crops on degraded, semi-arid soils is also under consideration. This could provide biomass feedstock, reduce the erosion and increase the fertility of such areas, but its economic feasibility has yet to be demonstrated. For comparison, it should be noted that, according to FAO, arable land in 2008 accounted for 1.4 Gha out of the about 4.9 Gha of global rural areas (http://faostat.fao.org). FAO projects a 70% increase in global food demand by 2050 to feed about 9 billion people [22] and suggests that 90% of the additional crop demand could be met by higher yields. The arable land for food production is expected to increase in developing countries and decrease in developed regions. An inventory of rural land resources and potential has been developed by FAO and IIASA [23], but further efforts are needed to collect data at national levels. Water availability is also an important issue.

Table 3 Typical biofuel retail prices (untaxed) and price projections (US$/lge) [1, 5]

	2010	2020		2030		2050	
		Low	High	Low	High	Low	High
Sugarcane Eth.	0.62-0.64[a]	0.6	0.7	0.6	0.7	0.6	0.73
Corn Ethanol	0.71-0.76[b]	0.7	0.8	0.65	0.85	0.65	0.85
Cellul Ethanol	1.0-1.1[c]	0.9	1.05	0.8	0.95	0.75	0.9
Rape Biodiesel	0.98-1.03[d]	0.95	1.1	0.95	1.15	0.95	1.2
BTL Biodiesel	1.0-1.2[c]	0.9	1.05	0.8	1.0	0.75	0.9
Biosynthetic gas	0.90	0.85	0.95	0.75	0.9	0.65	0.8
Fossil Gasoline	0.53-0.54[e]	0.7	0.7	0.8	0.8	0.85	0.85

Cost structure:
a) Feedstock 60%; energy 29%; process 11%; co-product 0%; (lowest reported production cost: $0.3/lge)
b) Feedstock 85%; energy 21%; process 21%; co-product -27%;
c) Feedstock 42%; energy 16%; process 42%; (long term)
d) Feedstock 90%; energy 6%; process 7%; co-product -3%; (highest reported production cost: $1.7/lge)
e) At oil price of US$ 75/bbl

As far as residues are concerned, estimates [24] suggest that around 5 Gt (dry matter) of agricultural residues and 0.5 Gt of forestry residues are currently available for energy production on a global scale (mostly in Asia and America) and that this potential could increase to 6.8 Gt and 0.7 Gt, respectively, by 2030. Using 10% of this biomass for biofuel production would result in 120-150 billion lge of liquid biofuels (or 220 billion lge of biogas) - almost twice the biofuel

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[6] For comparison, the global total primary energy supply in 2008 was about 560 EJ.

demand in 2008 (i.e. 6% of the current total transport fuel demand) and 45-50% of the expected 2030 biofuel demand [25]. The IEA, in its sustainable energy scenarios, projects that biomass could provide about 13.6% of the total primary energy supply (TPES) and 9.3% of total transportation fuel by 2030 [4], and that these figures could increase to 20% and 26%, respectively by 2050 [5].

Policy Aspects – Promotion of biofuels is part of the overall policy to reduce GHG emissions. Mandates and incentives for blending biofuels with fossil fuels are in place in many countries and contribute significantly to the ongoing growth in biofuel use. However, policy measures should only promote advanced technologies with best performance in terms of land use, GHG reductions and socio-economic impact. Particular support should be granted to biofuel production from residues and to ligno-cellulosic crops grown on non-arable land. As access to water is a growing concern in many countries, priority should be given to energy crops that require little or no irrigation. Water use during the biofuel production process (e.g. 4-8 litres of water per litre of cellulosic ethanol) also needs to be carefully considered. At present, the European Union, the United States and other countries provide financial support for advanced biofuels through grants, loan guarantees and feed-in tariff mechanisms. The US has a specific target for cellulosic biofuels (i.e. 60 billion litres by 2022) while the EU supports ligno-cellulosic fuels, waste- and algae-based biofuels by counting twice the contribution to the 2020 renewable energy and GHG emissions targets. Blending targets or tax credits are also in place in Brazil, China, India, South Africa and Thailand, among others. International quality and sustainability certifications are needed for biofuel and feedstock trading, in particular for developing countries. In the EU, market penetration of biodiesel has been significantly boosted by the establishment of quality standards while sustainability certifications would help regulate the production in developing countries. High costs, poor infrastructure, lack of know-how and inadequate labor skills remain major barriers to biofuel production in developing countries. Methodologies to assess the emissions reductions from biofuels need to be consolidated and shared at the international level, and more reliable data on direct/indirect biofuel-induced land-use change (LUC/ILUC) are needed.

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(This brief is based primarily on references 1, 5, 24, 46.)

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Table 4 Summary Table: Key data and figures on biofuel production technologies

Technical performance	**Typical current international values and ranges**								
Energy input	Biomass feedstock, e.g. energy crops, agriculture and forestry residues, waste oils								
Output	Liquid and gaseous biofuels								
Biofuel Variants	Bioethanol				Biodiesel				
Feedstock/Technology	Cane	Beet	Corn	Ligno cellul.	Rape	Palm	BTL	Adv. HVO	Adv. Algae
Typical yield, lde/ha	3,400	2,800	1,800	2,200	1,500	3,200	3,100	2,000	na
Co-products	bagasse	pulp	stover	lignin	glycerine	glycerine	heat	glycerine	several
Co-products, kg/l biofuel	0.25	0.25	0.3	0.4	0.1	0.1	na	0.1	na
CO$_2$ emission reduction,%	70/105	25/65	-20/60	50/110	15/85	25/80	55/120	15/84	-50/65
Energy out/input ratio	2.5-3.0	na	1.3-1.6	4.4-6.6	1.3-1.6	1.3-1.6	na	na	na
Energy conversion effic., %	12%-35% for adv. biofuels, at 20GJ/t dry mass, 110-300 l ethanol or 75-200 l biodiesel/t ligno-cellulosic material								
Major producers	Brazil	EU	US	na	EU, D	na	na	na	na
Global production, Gl/y	86.1 (2010)			0.175[a]	18.9 (2010)		(a)	na	na
Capacity under constr., Gl/y	na			1.9[a]	na		(a)	na	na
Current market share, %	about 3% of transport fuels, energy basis, using 3% arable land								
Typical plant size, Ml/y	25-150			0.1-4	25-50		0.1-4	na	na
Plant lifetime, yr	25			25	25		25		na
Global agric. & forest waste	Agriculture residues: 5Gt dry matter/yr;: Forest residues 0.5Gt dry matter/yr								

a) Incl. BTL biodiesel

Costs	**Typical current international values (2010 US$)**				
By feedstock/technology variant	Bioethanol			Biodiesel	
	Sugarcane	Corn	Adv. Ligno-cellul.	Rapeseed	Adv. BTL
Untaxed retail price, $/lge (a)	0.63	0.73	1.05	1.00	1.10
Typical cost breakdown					
Feedstock,%	60	80	40	90	35
Process,%	15	15	50	10	50
Energy, %	25	20	15	10	15
Co-products, %	0 (b)	-15	-5 (b)	-10 (b)	0
Plant invest. cost, $/litre-yr	1.7-2.5 for adv. biofuel plants with capacities between 150 and 50 Ml/yr, respectively				

* Fossil gasoline price, $/lge ~ 0.54 (oil $75/bbl)
** Assumption: bagasse used as energy input; low market value for lignin and glycerine

Data projections	**Typical projected international values and ranges**						
By feedstock/technology variant	Bioethanol			Biodiesel			
	Cane	Corn	Adv. Cellul.	Rapeseed	Adv. BTL	Adv. HVO	Adv. Algae
Typical yield (2030-2050)	4,800	2,400	3,700	2,100	5,200	3,400	na
Production	8 Glge/yr by 2015; 250 Glge/yr by 2030 (mostly advanced biofuels)						
Market share %	9% of the total transport fuel by 2030, up to 27% by 2050						
Agriculture & forest residues potential (2030)	Agriculture residues: 6.8Gt dry matter/yr;: Forest residues 0.7Gt dry matter/yr The use of 10% of such biomass could provide 120-150 Glge/yr of liquid biofuels (or 220 Glge of biogas), i.e. about 50% of the global liquid biofuel demand by 2030.						
Untaxed retail price 2020	0.60-0.70	0.70-0.80	0.90-1.05	0.95-1.10	0.95-1.05	na	na
Untaxed retail price 2030	0.60-0.70	0.65-0.85	0.80-0.95	0.95-1.15	0.80-1.00	na	na
Untaxed retail price 2050	0.60-0.75	0.65-0.85	0.75-0.90	0.95-1.20	0.75-0.90	na	na