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Biofuel production technologies:
status, prospects and implications
for trade and development

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Notes

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Executive summary

There is growing interest in biofuels in many developing countries as a means of “modernizing” biomass use and providing greater access to clean liquid fuels while helping to address energy costs, energy security and global warming concerns associated with petroleum fuels. This publication provides information about biofuels for use in helping to understand technology-related implications of biofuels development. It seeks to provide some context for (a) understanding the limitations of “first-generation” biofuels (made today from grains, seeds and sugar crops); (b) providing meaningful descriptions accessible to non-experts of “second-generation” biofuels (made from “lignocellulosic” biomass such as crop residues or purpose-grown grasses or woody crops); (c) presenting salient energy, carbon and economic comparisons among biofuels; and (d) speculating on the implications for trade and development of future expansion in global production and use of biofuels.

Second-generation biofuels are not being produced commercially anywhere today. They are made from non-edible feedstocks, which limit the direct food vs. fuel competition associated with most first-generation biofuels. Such feedstocks can be bred specifically for energy purposes, thereby enabling higher production per unit land area, and more of the above-ground plant material can be converted to biofuel, thereby further increasing land-use efficiency compared to first-generation biofuels. These basic characteristics of the feedstocks hold promise for lower feedstock costs and substantial energy and environmental benefits for most second-generation biofuels compared to most first-generation biofuels. On the other hand, second-generation biofuel systems require more sophisticated processing equipment, more investment per unit of production, and larger-scale facilities (to capture capital-cost scale economies) than first-generation biofuels. In addition, to achieve the commercial energy and (unsubsidized) economic potential of second-generation biofuels, further research, development and demonstration work is needed on feedstock production and conversion.

Second-generation biofuels can be classified in terms of the processes used to convert the biomass to fuel: biochemical or thermochemical. Second-generation ethanol or butanol would be made via biochemical processing. Second-generation thermochemical biofuels may be less familiar to readers, but many are fuels that are already being made commercially from fossil fuels today using processing steps that in some cases are identical to those that would be used for biofuel production. These fuels include Fischer-Tropsch liquids (FTL), methanol, and dimethyl ether (DME). Many efforts are ongoing worldwide to commercialize second-generation biofuels. In the case of biochemical fuels, breakthroughs are needed in research and engineering of microorganisms designed to process specific feedstocks, followed by large-scale demonstrations to show commercial viability. Some 10 to 20 years are probably required before commercial production could begin on a substantial basis. In the case of thermochemical fuels, since many of the equipment components needed for biofuel production are already commercially established for applications in fossil fuel conversion, and processing is relatively indifferent to the specific input feedstock, less development and demonstration efforts are needed. Commercial production of thermochemical biofuels could begin in five to 10 years.

Metrics for understanding and evaluating biofuel systems include land use efficiency, net lifecycle energy balance, net lifecycle greenhouse gas balance and economics. Among all biofuels, starch-based first-generation fuels exhibit the lowest land use efficiency (measured in km/year of vehicle travel achievable with the biofuel produced from one hectare). Sugar-based first-generation fuels provide about double the land-use efficiency, and second-generation fuels provide an additional improvement of 50 per cent or more. In terms of net energy balances, corn ethanol in the United States today requires about 0.7 units of fossil energy to produce one unit of biofuel, Untied States soy biodiesel requires about 0.3 units of fossil energy, and Brazilian sugar cane ethanol requires only about 0.1 units of fossil energy per unit of ethanol. Most second-generation biofuels will have energy balances as positive as for Brazilian ethanol. Lifecycle greenhouse gas (GHG) emission reductions associated with a biofuel replacing a petroleum fuel vary with the biofuel and production process, which itself typically generates some GHG emissions. In general, higher GHG savings with biofuels are more likely when sustainable biomass yields are high and fossil fuel inputs to achieve these are low, when biomass is converted to fuel efficiently, and when the resulting biofuel is used efficiently in displacing fossil fuel. First-generation grain- and seed-based

biofuels provide only modest GHG mitigation benefits. Sugar cane ethanol provides greater GHG emissions mitigation, and second-generation biofuels have still larger mitigation potential.

Economics are a key driver for use of biofuels. With the exception of ethanol from sugar cane in Brazil, production costs of essentially all first-generation biofuels in all countries are inherently high due to the use of high-cost feedstocks. Even the most efficient producers of ethanol (outside Brazil) are not able to compete without subsidy unless oil prices are above the $50 to $70 per barrel price range. The Brazilian ethanol industry has evolved since its inception in the 1970s to be able to produce competitive ethanol with oil prices of around $30 per barrel. Second-generation biofuels would be made from lower-cost feedstocks and so have the potential for more favourable economics than most first-generation fuels.

The technologies described in this paper imply a number of issues for the development of biofuels industries in developing countries. Key limitations of first-generation biofuels – relating to direct food vs. fuel conflict, cost competitiveness, and greenhouse gas emissions reductions – are not likely to be substantially different in developing countries than in industrialized countries. On the other hand, for second-generation fuels, many developing countries have the potential to produce biomass at lower cost than in industrialized countries due to better growing climates and lower labour costs, and so may be able to gain some comparative advantage.

The fact that second-generation biofuel technologies are primarily being developed in industrialized countries raises the question of technology relevance for developing countries. Technologies developed for industrialized country applications will typically be capital-intensive, labour-minimizing, and designed for large-scale installations to achieve best economics. Biomass feedstocks may also be quite different from feedstocks appropriate to developing country applications. Developing countries will need to be able to adapt such technologies for their own conditions, which raises issues of technology transfer. For successful technology adoption and adaptation, it will be essential to have in place a technology innovation system in a country. This includes the collective set of people and institutions able to generate fundamental knowledge, to assimilate knowledge from the global community, to form effective joint ventures with foreign companies, to formulate government policies supportive of the required research and technology adaptation needs, to implement technology-informed public policies, etc. The innovation system in Brazil is a key reason for the success of its ethanol program.

There are important roles for Government in fostering the development of biofuels industries in developing countries. The development of competitive second-generation industries will be facilitated by establishing regulatory mandates for biofuels use. Direct financial incentives could also be considered, with clear “sunset” provisions and/or subsidy caps built in from the start. Policies supportive of international joint ventures would help provide access for domestic companies to intellectual property owned by international companies. With a natural endowment of favourable climate for biomass production, developing country partners in such joint ventures might contribute host sites for demonstrations and first commercial plants, as well as avenues for entering local biofuels markets.

Finally, for there to be sustainable domestic biofuels industries, there is a need for a strong international biofuel and/or biofuel feedstock trading system, since countries relying on domestic production alone would be subject to weather- and market-related vagaries of agriculture. In the context of global trade, sustainability certification may be instrumental to ensuring that widespread biofuel production and use will be conducive to the achievement of social and environmental goals, without, however, creating unnecessary barriers to international trade.

1 Introduction

Biofuels are drawing increasing attention worldwide as substitutes for petroleum-derived transportation fuels to help address energy cost, energy security and global warming concerns associated with liquid fossil fuels. The term biofuel is used here to mean any liquid fuel made from plant material that can be used as a substitute for petroleum-derived fuel. Biofuels can include relatively familiar ones, such as ethanol made from sugar cane or diesel-like fuel made from soybean oil, to less familiar fuels such as dimethyl ether (DME) or Fischer-Tropsch liquids (FTL) made from lignocellulosic biomass.

A relatively recently popularized classification for liquid biofuels includes "first-generation" and "second-generation" fuels. There are no strict technical definitions for these terms. The main distinction between them is the feedstock used. A first-generation fuel is generally one made from sugars, grains, or seeds, i.e. one that uses only a specific (often edible) portion of the above-ground biomass produced by a plant, and relatively simple processing is required to produce a finished fuel. First-generation fuels are already being produced in significant commercial quantities in a number of countries. Second-generation fuels are generally those made from non-edible lignocellulosic biomass,[1] either non-edible residues of food crop production (e.g. corn stalks or rice husks) or non-edible whole-plant biomass (e.g. grasses or trees grown specifically for energy). Second-generation fuels are not yet being produced commercially in any country.

Figure 1 shows the substitutability of various biofuels for common petroleum-derived fuels. Alcohol fuels can substitute for gasoline in spark-ignition engines, while biodiesel, green diesel and DME are suitable for use in compression ignition engines. The Fischer-Tropsch process can produce a variety of different hydrocarbon fuels, the primary one of which is a diesel-like fuel for compression ignition engines.

While there is much attention on biofuels for the transport sector, the use of biofuels for cooking (Figure 2), is a potential application of wide relevance globally, especially in rural areas of developing countries. In all cases, combustion of biofuels for cooking will yield emissions of pollutants that are lower (or far lower) than emissions from cooking with solid fuels. Some 3 billion people in developing countries cook with solid fuels and suffer severe health damages from the resulting indoor air pollution [1, 2]. Thus, biofuels could play a critical role in improving the health of billions of people. It is noteworthy that the scale of biofuel production needed to meet cooking energy needs is far smaller than that for meeting transportation fuel needs. One estimate [3] is that some 4 to 5 exajoules[2] per year of clean cooking fuel would be sufficient to meet the basic cooking needs of 3 billion people. This is the equivalent of about 1 per cent of global commercial energy use today.

Many industrialized countries are pursuing the development of expanded or new biofuels industries for the transport sector, and there is growing interest in many developing countries for similarly "modernizing" the use of biomass in their countries and providing greater access to clean liquid fuels. Biofuels may be of special interest in many developing countries for several reasons. Climates in many of the countries are well suited to growing biomass. Biomass production is inherently rural and labour-intensive, and thus may offer the prospects for new employment in regions where the majority of populations typically reside. Restoration of degraded lands via biomass-energy production may also be of interest in some areas. The potential for producing rural income by

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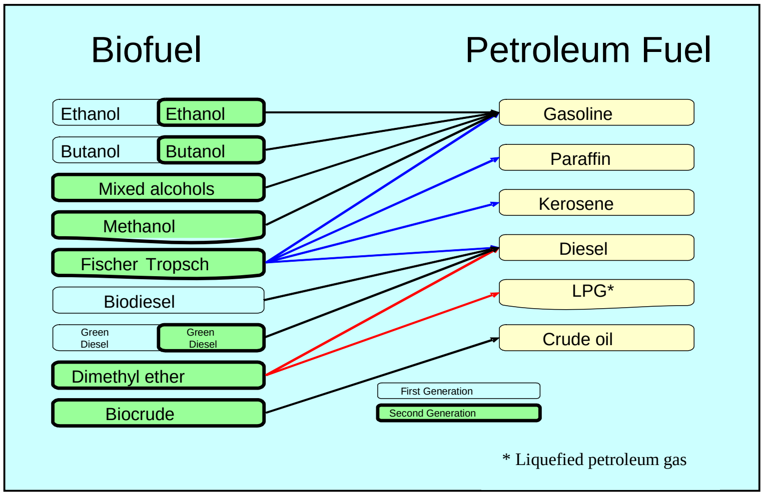
[1] Any whole-plant biomass consists of cellulose (typically about 50 per cent of the dry mass), hemicellulose (~25 per cent), and lignin (~25 per cent). The exact fractions of these components vary from one type of biomass to another.

[2] One exajoule (EJ) is 10^{12} megajoules.

production of high-value products (such as liquid fuels) is attractive. The potential for export of fuels to industrialized-country markets also may be appealing. In addition, the potential for reducing greenhouse gas emissions may offer the possibility for monetizing avoided emissions of carbon, e.g., via Clean Development Mechanism credits.

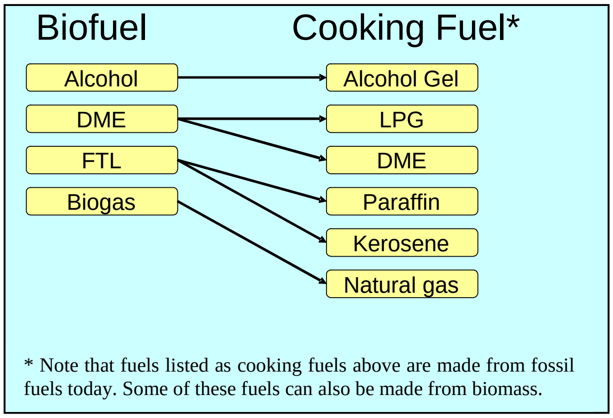
Expansion of biofuels production and use also raises some concerns, the most important among which may be diversion of land away from use for food, fibre, preservation of biodiversity or other important purposes. Added pressure on water resources for growing biofuel feedstocks is also of concern in many areas of the world.

Figure 1. Substitutability of biofuels with common petroleum-derived fuels



* Liquefied petroleum gas

Figure 2. Substitutability of biofuels for clean fossil fuels used for cooking



* Note that fuels listed as cooking fuels above are made from fossil fuels today. Some of these fuels can also be made from biomass.

This publication provides information about biofuels for use in helping to understand technology-related implications of biofuels development. It seeks to (a) provide some context for understanding the limitations of first-generation biofuels; (b) provide meaningful descriptions accessible to non-experts of second-generation biofuel technologies; (c) present salient energy, carbon, and economic comparisons between first and second-generation biofuels; and (d) finally, to speculate on the implications for trade and development of future expansion in global production and use of biofuels.

Table 1. Biofuel classification

First-generation biofuels *(from seeds, grains or sugars)*	**Second-generation biofuels** *(from lignocellulosic biomass, such as crop residues, woody crops or energy grasses)*
• Petroleum-gasoline substitutes – Ethanol or butanol by fermentation of starches (corn, wheat, potato) or sugars (sugar beets, sugar cane) • Petroleum diesel substitutes – Biodiesel by transesterification of plant oils, also called fatty acid methyl ester (FAME) and fatty acid ethyl ester (FAEE) ▪ From rapeseed (RME), soybeans (SME), sunflowers, coconut, palm, jatropha, recycled cooking oil and animal fats – Pure plant oils (straight vegetable oil)	• Biochemically produced petroleum-gasoline substitutes – Ethanol or butanol by enzymatic hydrolysis • Thermochemically produced petroleum-gasoline substitutes – Methanol – Fischer-Tropsch gasoline – Mixed alcohols • Thermochemically produced petroleum-diesel substitutes – Fischer-Tropsch diesel – Dimethyl ether (also a propane substitute) – Green diesel

2 First-generation biofuels

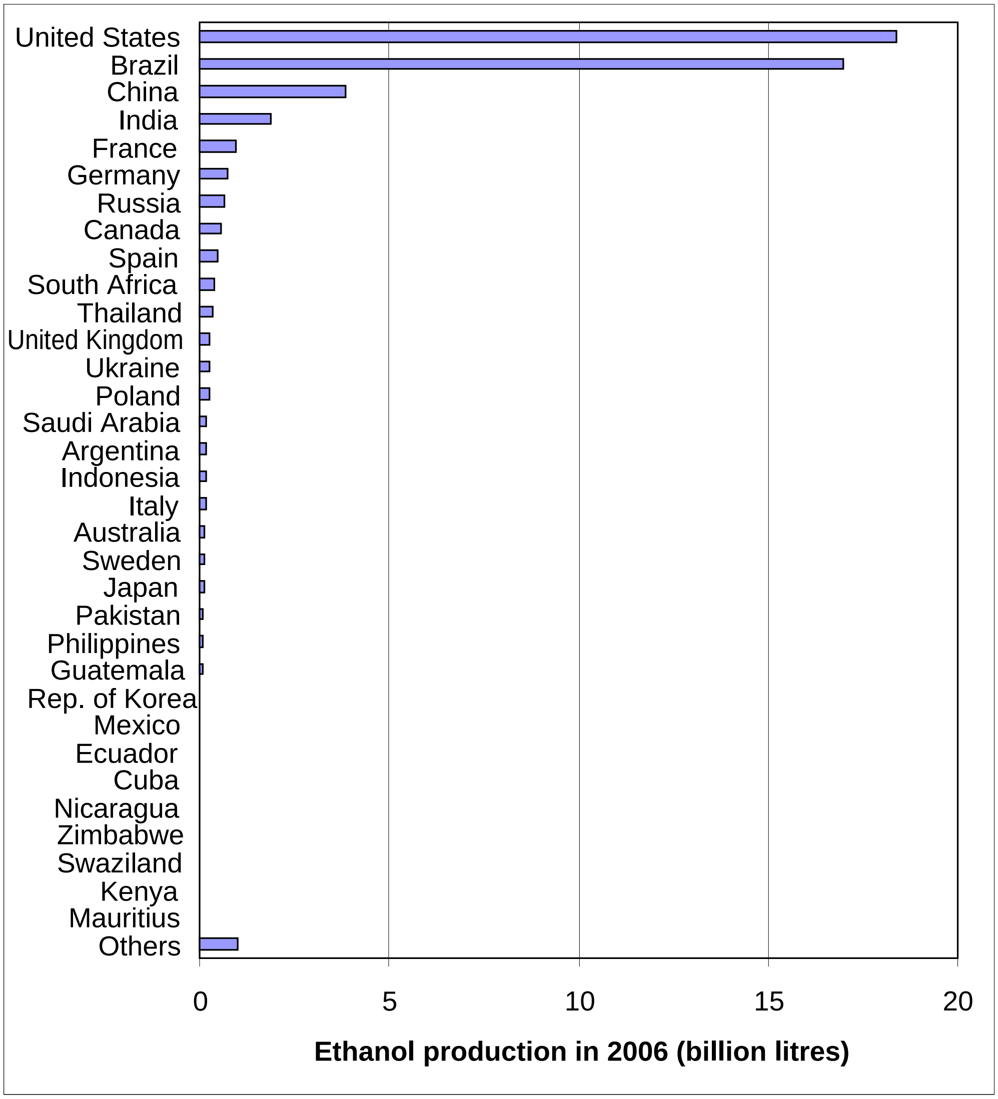
The most well-known first-generation biofuel is ethanol made by fermenting sugar extracted from sugar cane or sugar beets, or sugar extracted from starch contained in maize kernels or other starch-laden crops. Similar processing, but with different fermentation organisms, can yield another alcohol, butanol. Commercialization efforts for butanol are ongoing [4], while ethanol is already a well-established industry. Global production of first-generation bio-ethanol in 2006 was about 51 billion litres [5], with Brazil (from sugar cane) and the United States (from maize) each contributing about 18 billion litres, or 35 per cent of the total. China and India contributed 11 per cent to global ethanol production in 2006, and production levels were much lower in other countries (Figure 3), with feedstocks that include cane, corn, and several other sugar or starch crops (sugar beets, wheat, potatoes). Many countries are expanding or contemplating expanding their first-generation ethanol production, with Brazil and the United States having by far the largest expansion plans. Ethanol production is expected to more than double between now and 2013 in Brazil [6], and production capacity in the United States will double from the 2006 level once new plants currently under construction are completed [5].

From the perspective of petroleum substitution or carbon emissions mitigation efficiencies (discussed in more detail in chapter 1), the potential for most first-generation biofuels is limited. This is illustrated in Figure 4, which shows that the United States is projected to produce about 34 billion litres of ethanol in 2007 by using 27 per cent its corn crop [7]. On an energy basis, this ethanol will still account for less than 4 per cent of United States gasoline plus ethanol consumption in 2007. In addition, the significant amount of fossil fuel used to produce this ethanol substantially offsets the carbon emissions reductions from photosynthetic uptake of carbon by the corn plants.

Table 2. First-generation biofuels

Pros	Cons
• Simple and well-known production methods • Familiar feedstocks • Scalable to smaller production capacities • Fungibility with existing petroleum-derived fuels • Experience with commercial production and use in several countries	• Feedstocks compete directly with crops grown for food • Production by-products need markets • High-cost feedstocks lead to high-cost production (except Brazilian sugar cane ethanol) • Low land-use efficiency • Modest net reductions in fossil fuel use and greenhouse gas emissions with current processing methods (except Brazilian sugar cane ethanol)

Figure 3. Global fuel ethanol production by country in 2006 [5]



By contrast, the potential for sugar cane-based ethanol is much more significant from the perspective of petroleum substitution or carbon emissions reductions. In the case of Brazil, ethanol use was equivalent to nearly 50 per cent of gasoline use in 2006, and the carbon emissions reductions from ethanol use were very substantial due largely to the use of the fibre from the sugar cane itself as the energy source needed to produce the ethanol. While having the largest sugar cane-ethanol industry in the world, Brazil is not unique in its ability to produce sugar cane ethanol. More than 80 countries grow sugar cane (Figure 5), and several of these already produce some fuel ethanol.

Figure 4. United States corn-ethanol production (left axis) and fraction of corn crop devoted to ethanol (right axis) [7]

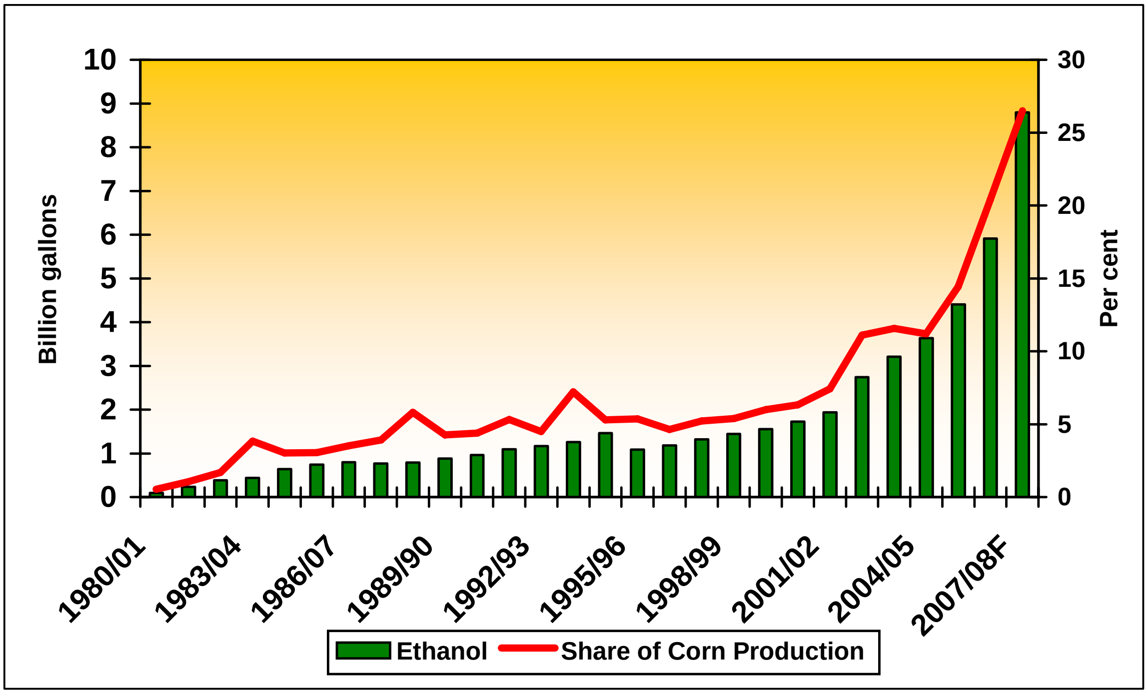
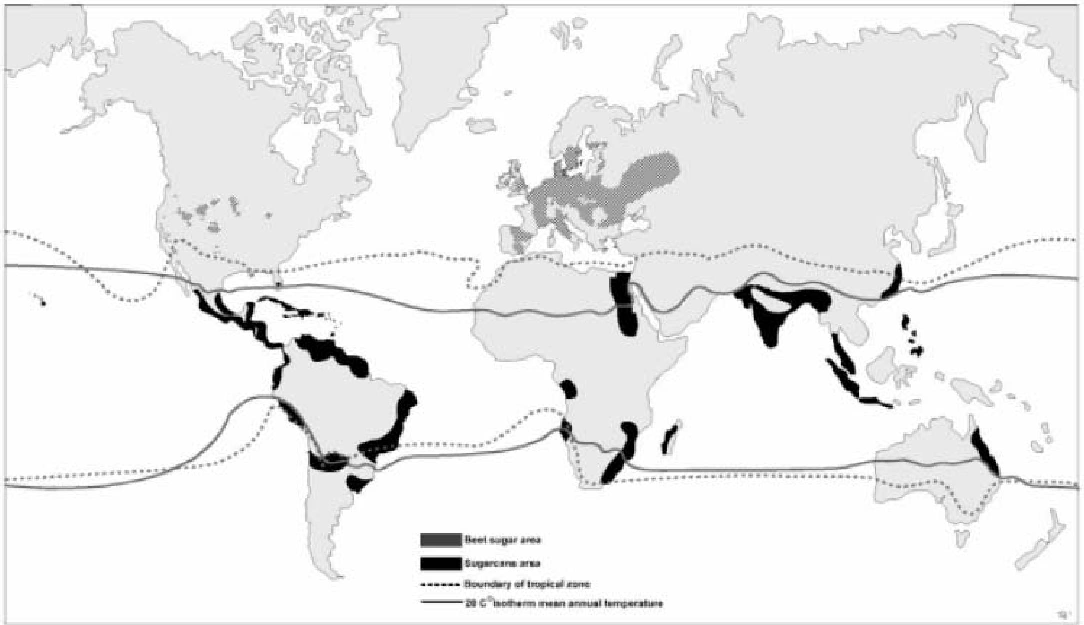


Figure 5. Sugar cane growing regions (darkest shading) and sugar beet growing areas (lighter shading) [8]

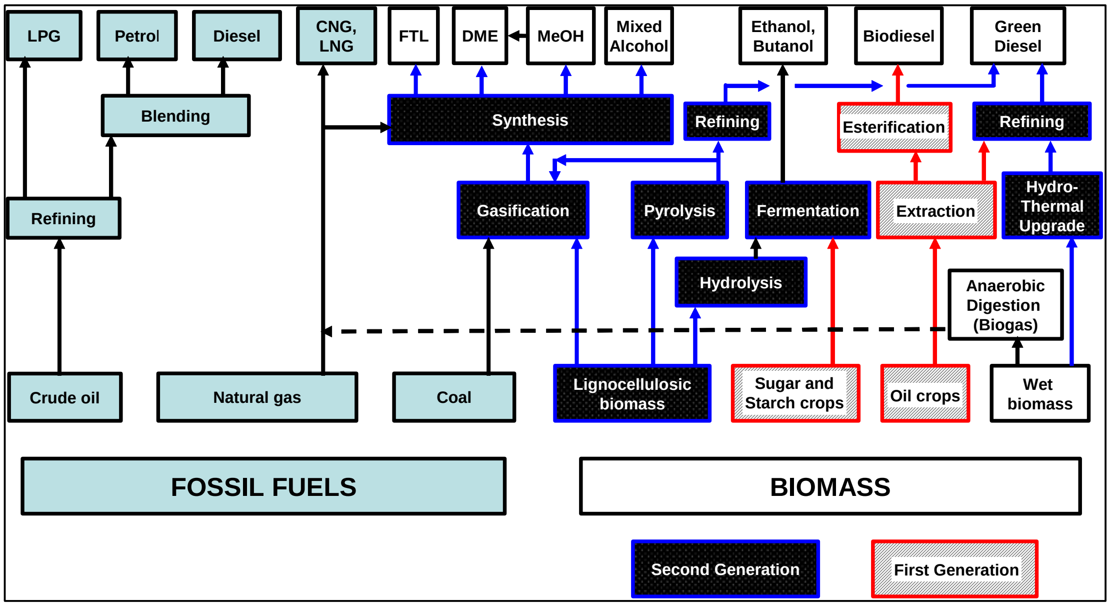


Biodiesel made from oil-seed crops is the other well-known first-generation biofuel. As of 2005, Germany led the world in production (primarily from rapeseed and sunflower) with about 2.3 billion litres produced [9]. Production worldwide has been growing rapidly since 2005. In the United States, biodiesel production (primarily from soybeans) rose from an estimated 284 million litres in 2005 to 950 million litres in 2006. In Brazil, the Government has mandated the addition of 2 per cent biodiesel to conventional diesel starting in 2008, with the percentage increasing to 5 per cent in 2013. Meeting the 2008 goal will require about 800 million litres of biodiesel. As of the end of 2006, Brazil's installed biodiesel production capacity was about 590 million litres/year, and this capacity is expected to more than double this year [10]. Interest in palm biodiesel is growing, especially in South-East Asia (Malaysia, Indonesia and Thailand) where the majority of the world's palm oil for food use is made. Jatropha, a non-edible-oil tree, is drawing attention for its ability to produce oil seeds on lands of widely varying quality. In India, Jatropha biodiesel is being pursued as part of a wasteland reclamation strategy [11]. From the perspective of petroleum substitution or carbon emissions reductions potential, biodiesel derived from oil-bearing seeds are – like starch-based alcohol fuels – limited, as discussed later.

3 Second-generation biofuels

Second-generation biofuels share the feature of being produced from lignocellulosic biomass, enabling the use of lower-cost, non-edible feedstocks, thereby limiting direct food vs. fuel competition. Second-generation biofuels can be further classified in terms of the process used to convert the biomass to fuel: biochemical or thermochemical. Second-generation ethanol or butanol would be made via biochemical processing, while all other second-generation fuels discussed here would be made via thermochemical processing. Second-generation thermochemical biofuels may be less familiar to most readers than second-generation ethanol, because there are no first-generation analogs. On the other hand, many second-generation thermochemical fuels are fuels that are already being made commercially from fossil fuels using processing steps that in some cases are identical to those that would be used for biofuel production (Figure 6). These fuels include methanol, refined Fischer-Tropsch liquids (FTL), and dimethyl ether (DME). Mixed alcohols can also be made from fossil fuels, but there is no commercial production today due to the immature state of some components of systems for producing these. The other thermochemical biofuel in Figure 6 is green diesel, for which there is no obvious fossil fuel analog. Unrefined fuels, such as pyrolysis oils, are also produced thermochemically, but these require considerable refining before they can be used in engines.

Figure 6. Production pathways to liquid fuels from biomass and, for comparison, from fossil fuels

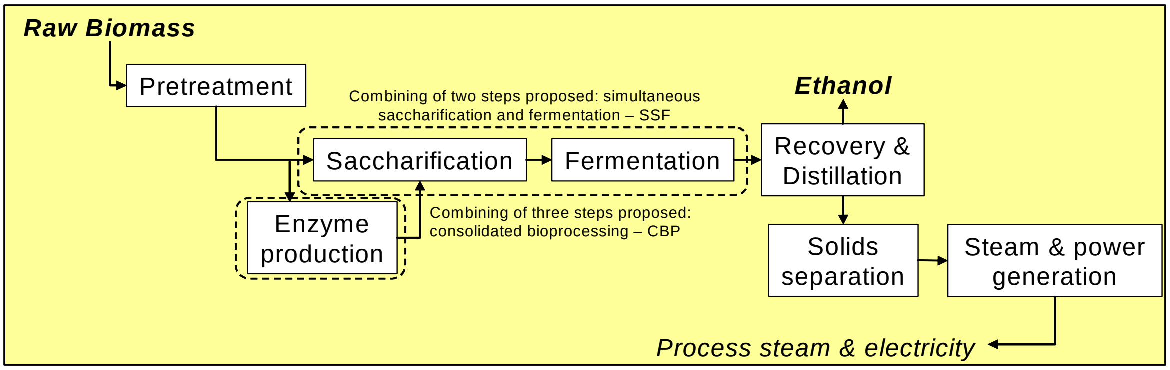


Note: Several fuels can be made starting from biomass or from fossil fuels.

3.1 Second-generation biochemical biofuels

The fuel properties of second-generation ethanol or butanol are identical to those of the first-generation equivalents, but because the starting feedstock is lignocelluose, fundamentally different processing steps are involved in producing them. Second-generation biochemically-produced alcohol fuels are often referred to as "cellulosic ethanol" and "cellulosic biobutanol". The basic steps for producing these include pre-treatment, saccharification, fermentation, and distillation (Figure 7). Pre-treatment is designed to help separate cellulose, hemicellulose and lignin so that the complex carbohydrate molecules constituting the cellulose and hemicellulose can be broken down by enzyme-catalyzed hydrolysis (water addition) into their constituent simple sugars.[3] Cellulose is a crystalline lattice of long chains of glucose (6-carbon) sugar molecules. Its crystallinity makes it difficult to unbundle into simple sugars, but once unbundled, the sugar molecules are easily fermented to ethanol using well-known micro-organisms, and some micro-organisms for fermentation to butanol are also known. Hemicellulose consists of polymers of 5-carbon sugars and is relatively easily broken down into its constituent sugars such as xylose and pentose. However, fermentation of 5-carbon sugars is more challenging than that of 6-carbon sugars. Some relatively recently developed micro-organisms are able to ferment 5-carbon sugars to ethanol [12,13]. Lignin consists of phenols, which for practical purposes are not fermentable. However, lignin can be recovered and utilized as a fuel to provide process heat and electricity at an alcohol production facility (Figure 7).

Figure 7. Simplified depiction of process steps for production of second-generation fuel ethanol



A variety of different process designs have been proposed for production of second-generation ethanol. One relatively well-defined approach for ethanol production is the use of separate hydrolysis (or saccharification) and fermentation steps (Figure 7). Other concepts (Figure 7) include one that combines the hydrolysis and fermentation steps in a single reactor (simultaneous saccharification and fermentation [13]), and one that additionally integrates the enzyme production (from biomass) with the saccharification and fermentation steps (consolidated bioprocessing [14]). Less work has been done on butanol, but similar processing ideas as for ethanol can be envisioned. The only operating commercial demonstration plant for cellulosic ethanol production in the world today is in Canada, and is owned by Iogen. It started operation in 2004, producing about 3 million litres per year of ethanol from wheat straw. Additional commercial plants have been announced, including a production facility capable of 5 million litres per year to be operated in Spain by Abengoa, starting later this year [15].

The National Renewable Energy Laboratory (NREL) of the United States Department of Energy projects that by 2030, technology developments will enable yields of ethanol to approach some 400 litres per dry metric ton of biomass feedstock converted, compared with about 270 litres per ton that can be achieved (at least on paper) with known technology today. In pursuit of such goals,

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[3] The use of acid to hydrolyze cellulose had been practiced commercially as long ago as the 1930s for ethanol production, but acid hydrolysis for ethanol production is not commercially viable today, due to high capital and operating costs and low yields of ethanol.

Department of Energy recently announced financial awards in support of the establishment of three major bioenergy research centres [16] and several major commercial-scale projects aimed at demonstrating the viability of cellulosic ethanol [17].

While cellulosic ethanol can be produced today, producing it competitively (without subsidies) from lignocellulosic biomass still requires significant successful research, development and demonstration efforts. Key research and development goals include [18]:

- Developing biomass feedstocks with physical and chemical structures that facilitate processing to ethanol, e.g. lower lignin content, higher cellulose content, etc;
- Improving enzymes (also called cellulase) to achieve higher activities, higher substrate specificities, reduced inhibitor production and other features to facilitate hydrolysis;
- Developing new micro-organisms that are high-temperature tolerant, ethanol-tolerant, and able to ferment multiple types of sugars (6-carbon and 5-carbon).

Achieving these goals may be facilitated significantly by the application of genetic engineering [12, 19]. Genetic modification of organisms appears to be generally accepted for applications involving micro-organisms contained in industrial processes, e.g. for cellulose hydrolysis or 5-carbon sugar fermentation. However, there is greater concern with the application of genetic engineering to improve biomass feedstocks, since there is the possibility of genetically modified species cross-breeding with natural species or spreading and out-competing natural species, in both cases threatening biodiversity. Care is required in the application of genetic feedstock modifications to ensure that such concerns are addressed [20].

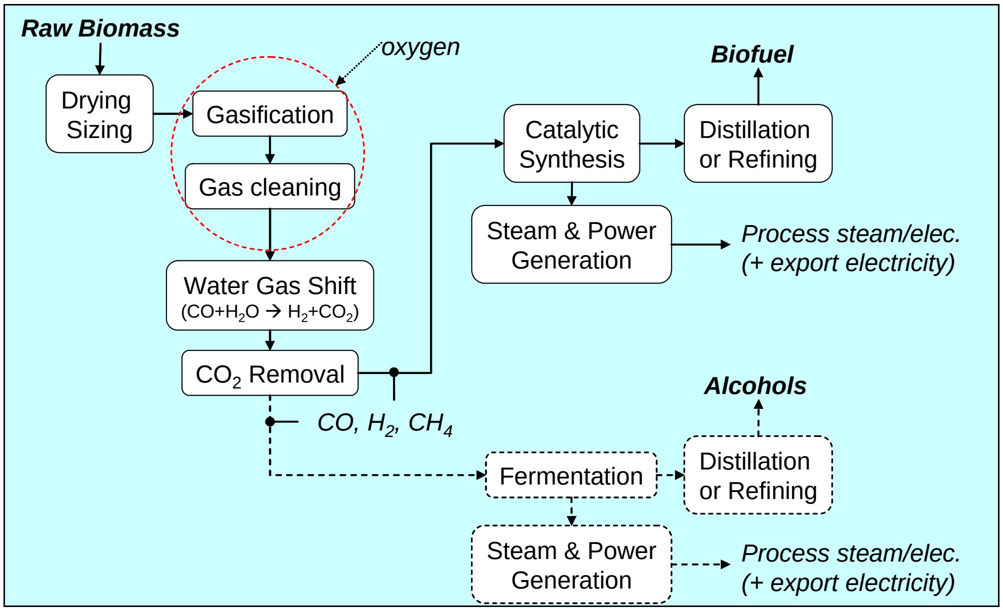
3.2 Second-generation thermochemical biofuels

Thermochemical biomass conversion involves processes at much higher temperatures and generally higher pressures than those found in biochemical conversion systems. Key intrinsic characteristics distinguishing thermochemical from biochemical biofuels are the flexibility in feedstocks that can be accommodated with thermochemical processing and the diversity of finished fuels that can be produced.

Thermochemical production of biofuels begins with gasification or pyrolysis. The former is generally more capital-intensive and requires larger scale for best economics, but the final product is a clean finished fuel that can be used directly in engines. The discussion here focuses on gasification-based processing, by which a variety of different biofuels can be produced, including Fisher-Tropsch liquids (FTL), dimethyl ether (DME), and various alcohols.

During gasification, biomass (with 10–20 per cent moisture content) is heated (typically by combusting a portion of the biomass in oxygen) to cause it to be converted into a mixture of combustible and non-combustible gases. Contaminants in the gas are removed, followed in some cases by adjustments (using the “water-gas shift” reaction) of the composition of the gas (also called synthesis gas, or syngas) to prepare it for further downstream processing (Figure 8). Carbon dioxide (CO2) is a diluent in the syngas and so is then removed to facilitate subsequent reactions downstream. The major components of the now-clean and concentrated syngas are carbon monoxide (CO) and hydrogen (H2), usually with a small amount of methane (CH4). The CO and H2 react when passed over a catalyst (the CH4 is inert) to produce liquid fuel. The design of the catalyst determines what biofuel is produced. In most plant designs, not all of the syngas passing over the catalyst will be converted to liquid fuel. The unconverted syngas typically would be burned to make electricity to provide some or all of the power needed to run the facility and in some cases to export electricity to the grid. A second option for converting syngas to liquid fuel – one that is less well-developed commercially than the catalytic process just described – is represented by the dashed lines in Figure 8. With this option, specially-designed micro-organisms ferment the syngas to ethanol or butanol.

Figure 8. Simplified depiction of process steps for thermochemical biofuels production



As a result of considerable research, development, and pilot-scale demonstration work done during the past 25 years [21, 22, 23, 24, 25], large-scale biomass gasifier technologies could be commercially ready within two or three years with concerted development efforts, but commercial-scale projects are needed to demonstrate viability. There is already extensive worldwide commercial application of gasification of fossil fuels such as coal (Figure 9) [26], and the experience being accumulated from these activities is relevant to gasification-based conversion of biomass. In fact, biomass can be co-gasified with coal, which may offer some valuable synergies [27]. Biomass is already being commercially co-gasified with coal today at one electricity-generating facility in the Netherlands, the 250 MWe Buggenum facility [28].

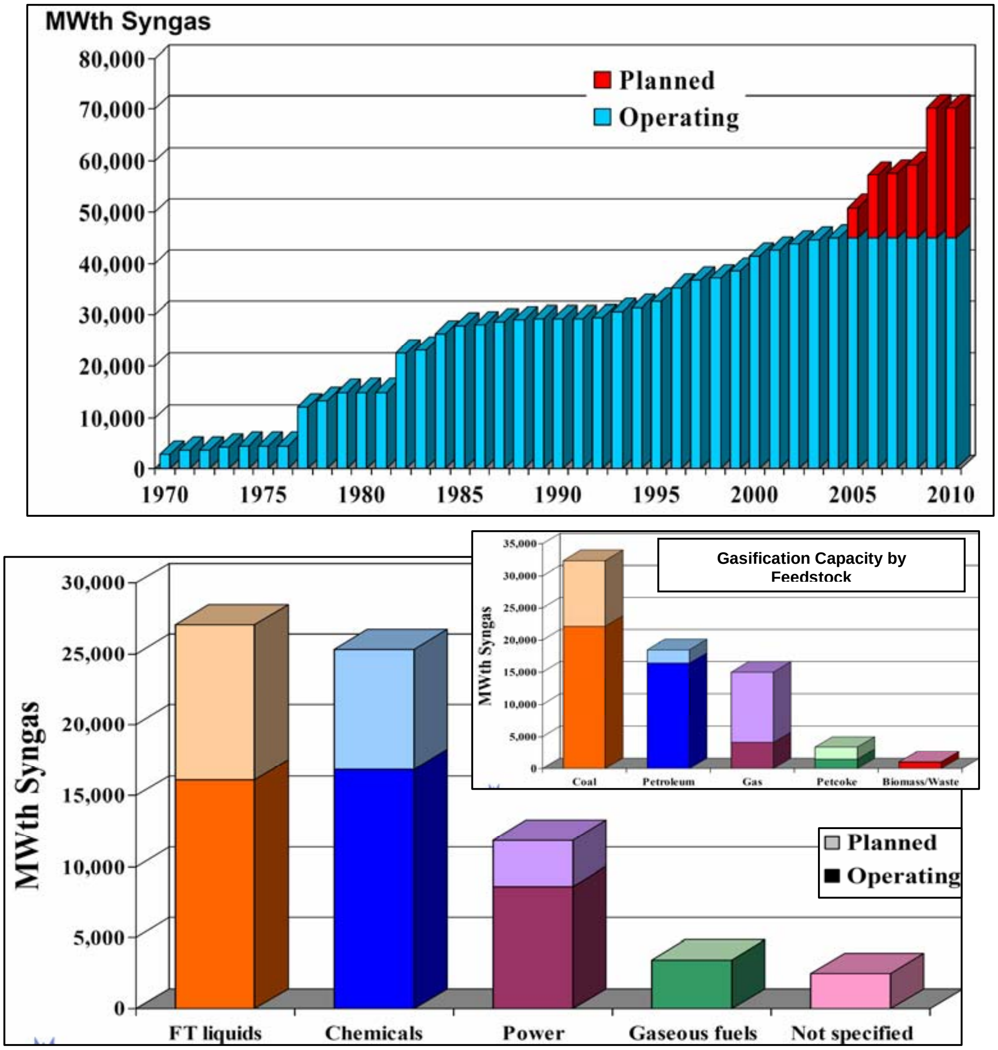
Most of the equipment components needed in a system for producing a thermochemical biofuel by the catalytic synthesis route are commercially available today. However, two areas needing further engineering development and demonstration are the feeding of biomass into large-scale pressurized gasifiers and the cleanup of the raw gas produced by the gasifier. The relatively low bulk density of biomass makes it challenging to feed into a pressurized gasifier efficiently and cost-effectively [29]. Development is needed is in the area of syngas cleanup (especially tar removal or destruction) [30] because tolerance to contaminants of downstream fuels synthesis processes is low [31, 32]. Tars have been the most problematic of syngas contaminants and have been the focus of much attention since the 1970s [32, 33, 34]. Methods for removal (or conversion to light permanent gases) are known, but still inefficient and/or costly.

The syngas fermentation option (Figure 8) is not commercial today, but research, development, and demonstration efforts are being pursued, as discussed later.

Three thermochemically-produced fuels are getting considerable attention in different parts of the world today: FTL, DME and alcohol fuel.

Fischer-Tropsch liquid (FTL) is a mixture of primarily straight-chain hydrocarbon compounds (olefins and paraffins) that resembles a semi-refined crude oil. The mixture can either be shipped to a conventional petroleum refinery for processing or refined on site into “clean diesel,” jet fuel, naphtha, and other fractions. As noted earlier, FTL is synthesized by catalytically reacting CO and H2. Thus, any feedstock that can be converted into CO and H2 can be used to produce FTL. In particular, coal, natural gas or biomass can be used as a feedstock for FTL production.

Figure 9. Global installed gasification capacity [26]



FTL fuels were first produced commercially in the 1930s in Germany from coal for use in vehicles [35]. A coal-to-fuels programme has been operating in South Africa since the early 1950s. Starting in the 1990s, there has been renewed interest globally in FT synthesis to produce liquids from large reserves of remote "stranded" natural gas that have little or no value because of their distance from markets [36, 37]. Of particular interest today is the production of middle distillate fuels (diesel-like fuels) with high cetane number[4] and containing little or no sulphur or aromatics (which contribute to tailpipe pollutant emissions). Such fuels (derived by natural gas conversion) are now beginning to be blended with conventional diesel fuels in some countries to meet increasingly strict vehicle tailpipe emission specifications.

Such environmental factors, together with today's high crude oil prices, are driving major expansion in global capacity for FTL production. In addition to Shell's gas-to-liquids (GTL, used synonymously with gas-to-FTL) plant in Malaysia (14,500 barrels per day (bpd) FTL capacity) and the PetroSA (formerly Mossgas) plant in South Africa (23,000 bpd) that started up in 1993, there are additional large commercial GTL facilities nearing startup or at advanced planning stages, including:

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[4] The cetane number is a measure of how good a fuel is for use in a compression-ignition engine.

- 34,000 barrels per day (bpd) project of Qatar Petroleum that came on line in late 2006;
- 66,000 bpd expansion of the Qatar Petroleum project to startup in 2009;
- 34,000 bpd Chevron project in Nigeria, expected on line in 2009;
- 30,000 bpd BP project in Colombia to come on line in 2011; and
- 36,000 bpd project in Algeria to come on line in 2011.

There is also a growing resurgence of interest in FT fuels from gasified coal. Coal-based FT fuel production (sometimes referred to as “coal-to-liquids” (CTL)) was commercialized beginning with the Sasol I, II and III plants (175,000 bpd total capacity) built between 1956 and 1982 in South Africa. (Sasol I is now retired.) China’s first commercial coal-FT project is under construction in Mongolia. The plant is slated to produce 20,000 bpd when it comes on line in 2007 or early 2008. Chinese companies are in discussion with Sasol for two coal-FT plants that together will produce 120,000 bpd. The United States Department of Energy is supporting a CTL demonstration project in Pennsylvania that will make 5,000 bpd of FT liquids, and there is a variety of proposals for larger-scale coal-to-liquids facilities elsewhere in the United States.

Converting biomass into FT liquids involves similar processing as for coal conversion [38, 39, 40, 41, 42, 43, 44]. Driven in part by European Union Directive 2003/30/EC, which recommends that all member States have 2 per cent of all petrol and diesel consumption (on an energy basis) from biofuels or other renewable fuels by the end of 2005, reaching 5.75 per cent by the end of 2010, financial incentives are in place in the United Kingdom, Germany, Spain, Sweden and elsewhere to encourage bio-FTL production. The Shell Oil Company, which offers one of the leading commercial entrained-flow coal gasifiers, and also has long commercial experience with FT synthesis, recently joined in a partnership with Choren, a German company with a biomass gasification system, with plans for constructing commercial biomass-to-FT liquids facilities in Germany [45, 46]. A commercial demonstration plant, with a production capacity of 15,000 tons per year of FT diesel, is currently under construction in Freiberg/Saxonia.

Dimethyl ether (DME) is a colourless gas at normal temperatures and pressures, with a slight ethereal odour. It liquefies under slight pressure, much like propane. It is relatively inert, non-corrosive, non-carcinogenic, almost non-toxic, and does not form peroxides by prolonged exposure to air [47]. Its physical properties make it a suitable substitute (or blending agent) for liquefied petroleum gas (LPG, a mixture of propane and butane). If the DME blending level is limited to 15–25 per cent by volume, mixtures of DME and LPG can be used with combustion equipment designed for LPG without changes to the equipment [48, 49]. DME is also an excellent diesel engine fuel due to its high cetane number and absence of soot production during combustion. It is not feasible to blend DME with conventional diesel fuel in existing engines, because DME must be stored under mild pressure to maintain a liquid state.

However, because DME burns extremely cleanly in an appropriately designed compression ignition engine, an attractive application is in compression ignition vehicles operating in urban areas, where vehicle air pollution is most severe. Because vehicle refuelling station equipment differs from that at conventional refuelling stations dispensing petroleum-derived fuels, and modified on-board fuelling systems are required, fleet vehicles that are centrally-maintained and centrally fuelled (buses, delivery trucks, etc.) are an excellent potential market for DME. Since many such vehicles operate in urban areas with petroleum diesel fuel today, the dramatically lower exhaust emissions with DME engines compared to diesel engines (especially of health-damaging small particles) [50, 51] provides strong public motivation for adopting DME fleets.

Until recently, the dominant use of DME was as an aerosol propellant in hair sprays and other personal care products. It was being produced globally at a rate of only about 150,000 tons per year [52]. This level is now increasing dramatically [53, 54]. From 2003 through 2006, a total of 265,000 tons per year of DME production capacity (110,000 of which is from natural gas and the rest from coal) came on line in China. An additional 2.6 million tons per year of capacity (from coal) is expected to come on line there by 2009, and plans are being developed for a further 1 million tons per year of capacity. In the Islamic Republic of Iran, a gas-to-DME facility producing 800,000 tons per year will come on line in 2008. There is also discussion of a facility to be built in Australia (with Japanese investment) to produce between 1 million and 2 million tons per year of DME from natural gas. Thus, by the end of this decade, DME production capacity globally may reach nearly 7 million tons per year.

Essentially all new DME produced this decade will be used as an LPG substitute for domestic (primarily household cooking) fuel. In China, however, some DME will also be used in buses, initially in Shanghai and subsequently elsewhere. Commercial development of DME buses is underway in China, and volume production is anticipated before the end of this decade [54]. Development of heavy-duty vehicles (trucks and buses) fuelled with DME is also underway in Sweden by Volvo, which expects to have 30 vehicles in field tests starting no later than 2009 [55] and commercial vehicles available by 2011 [56]. Major efforts in Japan are also ongoing to commercialize heavy-duty DME road vehicles [51].

Alcohol fuel that can be made via syngas processing is drawing attention in the United States at present. One such fuel is ethanol (or butanol); a second is a mixture of alcohols that includes a significant fraction of ethanol plus smaller fractions of several higher alcohols. Butanol and the “mixed-alcohol” fuel have the potential to be used much the way ethanol is used today for blending with gasoline. These are characterized by higher volumetric energy densities and lower vapour pressures than ethanol, however, making them more attractive as a fuel or blending agent.

Syngas can be converted into a mixture of alcohols by catalytic synthesis. The process steps resemble those for making FT liquids. Clean syngas is passed over a catalyst, forming a mixture of alcohol molecules. A number of different catalysts for mixed alcohol production from syngas were patented in the late 1970s and early 1980s [57], but most development efforts were abandoned after oil prices fell in the mid-1980s. High oil prices have reignited interest, and the United States Department of Energy recently awarded a substantial grant in support of one commercial-scale demonstration project [17]. Several startup companies are developing competing technologies [57, 58, 59, 60, 61, 62]. Aside from patents and patent applications, relatively little published information is available concerning these private-sector activities.

Pure ethanol (or pure butanol) can also be made from syngas by micro-organisms that ferment the gas [63]. This combined thermo/biochemical route to a pure alcohol, if it can be made commercially viable, would enable the lignin in the biomass feedstock, as well as the hemicellulose and cellulose, to be converted to fuel, unlike the case for purely biochemical “cellulosic ethanol” discussed earlier. At least one private company (BRI Energy, Inc.) is actively seeking to commercialize technology for fermentation of syngas [64]. They have announced their intention to build two commercial facilities near Oak Ridge, Tennessee, United States. One facility would convert coal-derived syngas to ethanol, and the other would convert municipal solid waste via gasification to ethanol [65]. BRI was also recently awarded a grant from the United States Department of Energy in support of a commercial-scale demonstration project [17]. Little detailed documentation is publicly available to enable an independent evaluation of BRI’s technology.

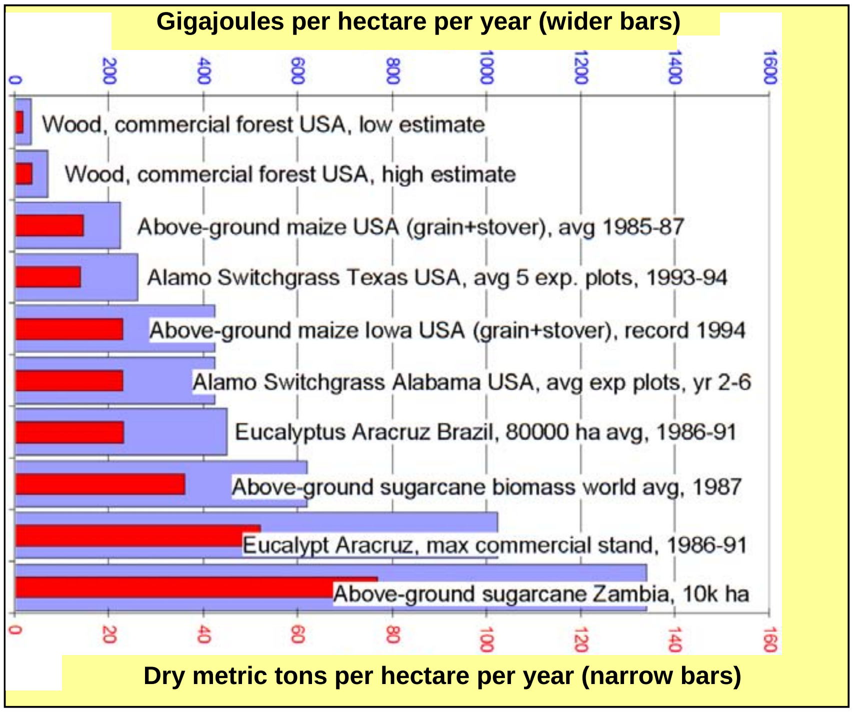
4 Perspectives on first- and second-generation biofuels

Metrics that can be useful for understanding and evaluating first- and second-generation biofuel systems include land use efficiency, net life cycle energy balance, net life cycle greenhouse gas balance and economics.

4.1 Land-use efficiency for providing transportation services

Land is ultimately the limiting resource for biofuels production. There is a wide variation in the total amount of biomass that can be produced on a unit area of land, depending on species chosen, soil and climate conditions, and agronomic treatments (Figure 10). The high productivity per hectare of sugar cane, a first-generation biofuel feedstock, rivals the highest productivities that have been achieved with plantations of eucalyptus, which could be a second-generation biofuel feedstock (Figure 10). However, only a fraction of the sugar cane biomass is used for liquid fuel production in a first-generation biofuel facility, whereas nearly all of the above-ground eucalyptus plant would be used for production of a second-generation biofuel. (A second-generation ethanol fuel could be made from the lignocellulosic fractions of the sugar cane, such as bagasse and other fibrous material, which would then make sugar cane ethanol one of the most land-efficient of all biofuels.)

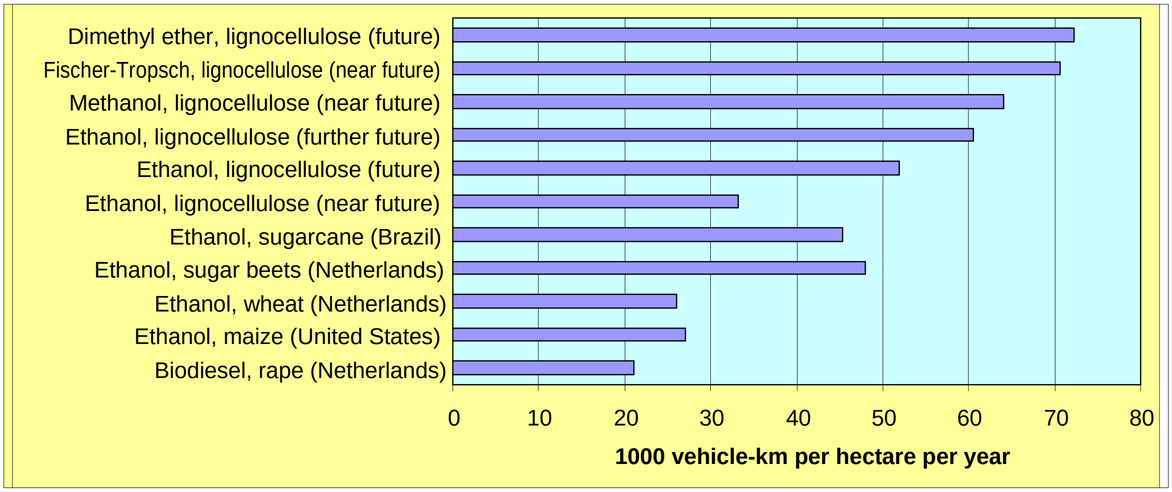
Figure 10. Biomass production rates in dry metric tons per hectare per year or gigajoules per hectare per year [66] **(one gigajoule is one million (10^6) kilojoules)**



An informative measure of land-use efficiency is the level of transportation service that can be provided from a hectare of land. Taking into consideration the rate of biomass feedstock production per hectare, the efficiency of converting the feedstock into a biofuel, and the efficiency of using the biofuel in a vehicle, one can estimate the vehicle-kilometres of travel that can be provided by a hectare of land. Among all biofuels, starch-based first-generation fuels give the lowest yield of vehicle-kilometres/hectare/year (Figure 11), since only a fraction of the above-ground biomass is used as input to a biofuel production facility.[5] By this land-use efficiency measure, sugar-based first-generation fuels are about twice as good as starch-based fuels. Second-generation fuels, because they utilize much more of the available above ground biomass than first-generation fuels, can provide an improvement of 50 per cent or more in land-use efficiency over sugar-based first-generation fuels.

The comparison in Figure 11 does not provide any information regarding the net energy balance of producing the biofuel, the associated net lifecycle greenhouse gas emissions, nor economic considerations. These additional factors, discussed below, must also be considered in evaluating any particular biofuel system.

Figure 11. Estimates of vehicle-kilometres per year light-duty automobile travel per hectare for various first- and second-generation biofuels



Note: Ethanol and methanol are used in spark-ignition engine vehicles (8.7 litres per 100 km fuel use). The other fuels are used in compression-ignition engine vehicles (6.2 litres per 100 kilometres fuel use).

4.2 Net energy balances

Energy balances for biofuels production can be viewed from several different perspectives. Figure 12 illustrates this with a comparison (based on United States conditions) of the energy balance for gasoline production from petroleum, ethanol production from corn, and second-generation ethanol production from corn stover. While there are differences among the energy balances for various first-generation biofuels and among those for different second-generation biofuels, the two ethanol fuels in Figure 12 can be considered to be broadly representative of the spectrum of first-generation and second-generation biofuels, with one important exception – sugar cane ethanol, discussed below. In this figure, the energy inputs include all energy sources associated with producing the raw material used for fuel production (crude oil, corn or corn stover), transporting it to the conversion facility and converting it into liquid fuel.

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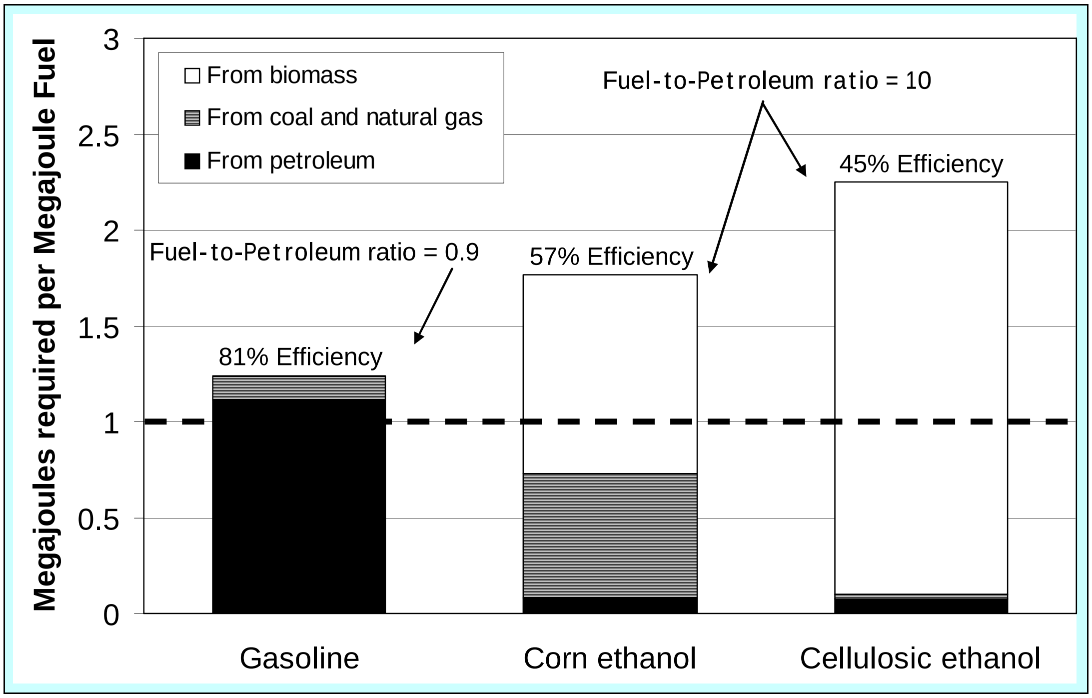
[5] Figure 11 was developed assuming fuel economy values representative of those for light-duty vehicles, as indicated in the figure caption. If lower fuel economies were assumed, e.g. representing those for SUVs or trucks, the relationship between the sizes of the bars would not be significantly different, but the absolute levels of transportation service provided per unit area would be lower than shown.

Figure 12. Comparison of energy ratios for a petroleum fuel, a first-generation biofuel and a second-generation biofuel ("cellulosic ethanol" made from corn stover) [84]



Three observations are worth making from Figure 12. First, the overall energy ratio (OER), defined here as the energy in the liquid fuel divided by the sum of all energy inputs to the process, is highest for gasoline and lowest for cellulosic ethanol. However, a large portion of the energy input for the latter is biomass (or, indirectly, solar energy), a renewable energy input. Therefore, a second energy ratio, the fossil energy ratio (FER), is more meaningful. This is the liquid fuel energy output divided by the total non-renewable fossil energy input. For gasoline, the FER is the same as the OER, about 0.8. For corn ethanol, the FER is about 1.4, and for cellulosic ethanol, the FER is about 5. A final energy measure – one relevant to oil security discussions – is the amount of liquid fuel produced per unit of petroleum used, the petroleum energy ratio (PER). Gasoline has a PER of about 0.9, while the ethanol options have PER values of about 5. Table 3 summarizes these numbers and shows the same metrics for first-generation soy biodiesel in the United States and Brazilian sugar cane ethanol. The latter gives the highest FER and PER values among all fuels shown in Table 3, because most of the energy input to produce the ethanol comes from the fibre in the sugar cane itself.

Table 3. Energy ratios for gasoline and some first- and second-generation biofuels

	Overall Energy Ratio (OER)	**Fossil Energy Ratio (FER)**	**Petroleum Energy Ratio (PER)**
Liquid Fuel*	*Liquid fuel output* *Fossil+biomass Input*	*Liquid fuel output* *Fossil Input*	*Liquid fuel output* *Petroleum Input*
Gasoline (United States)	0.81	0.81	0.91
Corn ethanol (United States)	0.57	1.4	5.0
Soy biodiesel (United States)	0.45	3.2	not available
Cellulosic ethanol (United States)	0.45	5.0	5.0
Sugar cane ethanol (Brazil)	0.30	10	10

* Estimates from Figure 12 for gasoline, corn ethanol and cellulosic ethanol; [67] for biodeisel; [68] for sugar cane ethanol.

4.3 Greenhouse gas emissions

The effectiveness with which greenhouse gas emissions (GHGs, including CO_2, CH_4, and others) can be avoided using biofuels is related to the amount and carbon intensity of the fossil fuel inputs needed to produce the biofuel, as well as to what fossil fuel is substituted by use of the biofuel. A proper GHG accounting considers the full life cycle of the biofuel, from planting and growing the biomass to conversion of the biomass to biofuel, to combustion of the biofuels at the point of use. (In the case of vehicle applications, this full life cycle analysis is sometimes referred to as a "well-to-wheels" analysis.) If the harvested biomass is replaced by new biomass growing year-on-year at the same average rate at which it is harvested, then CO_2 is being removed from the atmosphere by photosynthesis at the same rate at which the already-harvested biomass is releasing CO_2 into the atmosphere – a carbon-neutral situation. However, typically some fossil fuel is consumed in the course of producing or converting the biomass or delivering the biofuels to the point of use, resulting in net positive GHG emissions on a life cycle basis. These emissions will offset to some degree the emissions that are avoided when the biofuel is used in place of a fossil fuel.

There could also be net GHG emissions associated with converting land from its current use to use for biomass energy feedstock production. The net emissions might be positive if existing forests were to be removed to establish energy crops. The net emissions might be negative if perennial energy crops (which can build soil carbon) are established, replacing annual row crops that were being grown on carbon-depleted soil. Emissions associated with land use change can be significant, but are very much dependent on local factors [69]. Therefore, as a simplifying assumption for the discussion presented in this publication, no GHG emissions associated with such land use changes are considered.

There is a rich literature on GHG life cycle analyses (LCAs) of biofuels [70]. Most published LCAs have been undertaken in a European or North American context, with an excellent study of Brazilian sugar cane ethanol being an exception [68]. There is considerable context-specific variability and uncertainty around input parameter values in LCA analysis, which may explain the wide-ranging results from different studies for the same biofuel and biomass source.[6] For example, Figure 13 shows results from LCAs carried out as part of a major European study. The estimated range in reductions of GHG emissions per vehicle kilometre (v-km) for rape methyl ester (RME) compared to conventional diesel fuel (for which RME can substitute) is 16 per cent on the low end and 63 per cent on the high end – a range of a factor of four. The range in reduction indicated for SME (soy methyl ester) is 45 per cent to 75 per cent. The range for ethanol from sugar beets is somewhat smaller (but complicated by three alternative sets of assumptions about how GHG emission credits are assigned to the residual pulp co-product of ethanol production). Ethanol from wheat shows anywhere from a 38 per cent GHG emissions benefit to a 10 per cent penalty relative to gasoline.

Understanding such diversity in LCA results requires examining details of each analysis, including analytical boundaries, numerical input assumptions and calculation methodologies. However, without delving into that level of detail, it is possible to draw a few firm conclusions [70]. Higher GHG savings with biofuels are more likely when sustainable biomass yields are high and fossil fuel inputs to achieve these are low, when biomass is converted to fuel efficiently, and when the resulting biofuel is used efficiently. Conventional grain- and seed-based biofuels can provide only modest GHG mitigation benefits by any measure (per megajoule of fossil fuel displaced, per v-km

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[6] Factors that can significantly affect calculated GHG emissions include (a) the type of biomass and its sustainable yield level; (b) competing uses for the biomass; (c) competing uses for the land (what would have been the GHG impact if land were used for a "business as usual" purpose); (d) agronomic practices, including fertilizer and herbicide application (and their method of production); biomass harvesting and transportation methods; climate; soil type and prior use of the land (which affects soil carbon dynamics and other factors); what products any biofuel co-products will substitute for; performance of specific technologies for biomass conversion to fuel and fuel use in vehicles; what fuel/vehicles will be replaced by the biofuel; and how GHG reductions will be measured.

driven, or per hectare of land use) and will be able to provide only modest levels of fuel displacement in the long term in any case due to the relatively inefficient land use associated with these fuels.

The fundamental reason for the poor performance of grains and seeds is that they represent only a portion (typically less than 50 per cent of the dry mass) of the above-ground biomass [71], so they are disadvantaged from the yield point of view. Higher efficiency in converting seeds/grains to fuel compensates the lower biomass yield to some extent. For example, some 380 litres of ethanol can be produced from a dry ton of corn grain using current technology [72].[7] This compares to today's known technology for cellulosic biomass conversion to ethanol, which can only yield some 255 litres/dry ton (at least on paper – no commercial-scale plant has been built) [73]. Future improvements in cellulosic ethanol production are expected to eliminate the conversion efficiency advantage currently enjoyed by corn ethanol: yields from lignocellulose of 340 litres/ton are projected for 2010 [73] and 437 litres/ton for 2030 [74]. Technology for production of Fischer-Tropsch fuels from lignocellulose (which could be commercially ready in the 2010/2015 timeframe) can yield some 280 litres of diesel equivalent [38], which corresponds to 471 litres of ethanol equivalent.[8]

More efficient land use in mitigating GHG impacts can be achieved in the longer term by dedicated high-yielding lignocellulosic energy crops. Decades of experience with development of food crop yields, together with recent experience with developing lignocellulosic energy crops, suggests that major yield gains can be expected (probably with lower inputs per ton of biomass produced) with concerted development efforts [74]. While historically there have been relatively low levels of research and development support provided for energy crop development, recent major private sector investments in research and development (e.g. see [75]) are likely to accelerate the pace of progress in improving yields. Assuming high yields are sustainable and acceptable from biodiversity and other perspectives, land requirements to achieve GHG emission reductions with biofuels will be reduced. There is also the possibility for some by-product CO_2 to be captured (for long-term underground storage) during the process of making biofuels, especially via thermochemical conversion, which could lead to negative GHG emissions for a biofuel system [38]. Proposals have also been made for thermochemically co-processing coal and biomass to make carbon-neutral liquid fuels by capturing and storing some CO_2 produced during the conversion process [27].

Finally, it is worth noting that biomass can be converted into heat or electricity as well as into liquid fuel. GHG emissions per unit land area that are avoided in this way may be greater than when making liquid fuel (Figure 14). However, for electricity or heat production, a variety of renewable resources is available (hydro, solar, geothermal, wind, etc.). Biomass is the only renewable source of carbon, which makes it the only renewable resource for producing carbon-bearing liquid fuels.

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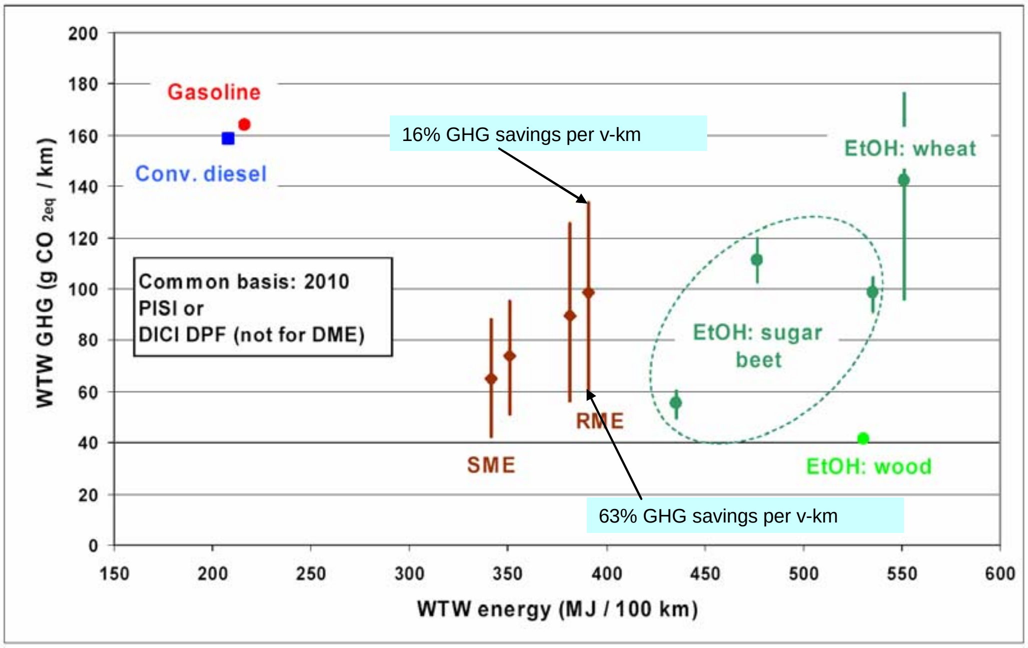
[7] The use of lignocellulosic residues of grain or seed production to provide energy for the biofuel production process (substituting for fossil fuels) could improve the GHG performance of biofuels from grains or seeds to some extent, but residue use is not practiced today. Residues are used routinely to fuel the processing of sugar cane into ethanol (as discussed earlier), and the quite favorable GHG impacts of this biofuel pathway can be attributed largely to this.

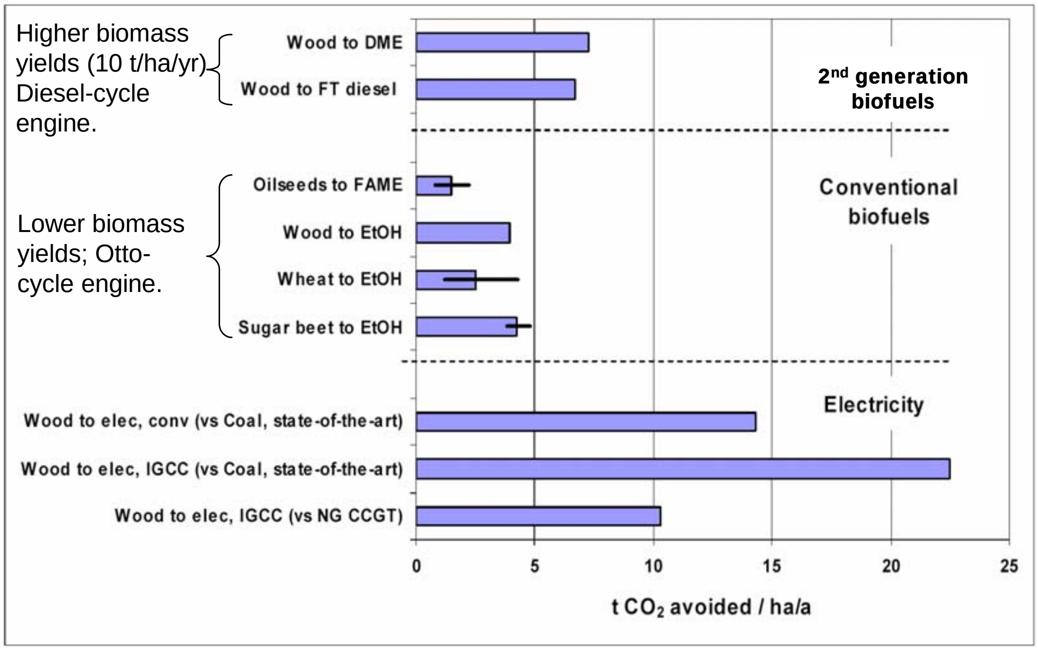
[8] One litre of ethanol contains 21.1 megajoules, and one litre of diesel contains 35.7 megajoules.

Figure 13. Well-to-wheels energy requirements and greenhouse gas emissions for conventional biofuel pathways compared with gasoline and diesel pathways, assuming 2010 vehicle technology [76]



Notes: EtOH = ethyl alcohol (ethanol); SME = soy methyl ester; RME = rape methyl ester; PISI = port injection spark ignition; DICI DPF = direct injection compression ignition with diesel particulate filter.

Figure 14. Comparison of GHG emissions avoided per hectare for biofuels vs. biomass-derived electricity [76]



Note: When biomass electricity substitutes for coal-fired electricity, the GHG emissions avoided per unit land area used for biomass production are larger than when the biomass is converted to liquid fue**l.**

4.4 Economics

With the exception of ethanol from sugar cane in Brazil, production costs of essentially all first-generation biofuels in all countries are subsidized. In most countries, including Brazil, demand is driven by regulatory mandates. The Brazilian ethanol industry has evolved since its inception in the 1970s to be able to produce ethanol that is competitive with gasoline at oil prices much lower than today's levels (Figure 15). In contrast, even the most efficient producers of ethanol (outside Brazil) are not able to compete without subsidy unless oil prices are above the $50 to $70 per barrel price range (Figure 16). The relatively high cost of the edible crops used as feedstocks for first-generation biofuels accounts for the high production costs outside of Brazil. In some cases, as with corn in the United States, prices for the feedstocks have increased dramatically recently because of the rapidly growing demand for feedstocks for biofuels production (Figure 17). The United States Department of Agriculture expects corn prices to continue rising through the end of this decade and acreage devoted to corn planting to reach unprecedented levels (Figure 17). Such market impacts highlight sharply the food vs. fuel issue associated with first-generation biofuels.

Figure 15. Historical cost reductions for ethanol production in Brazil shown as a function of cumulative ethanol production by the Brazilian industry [8]

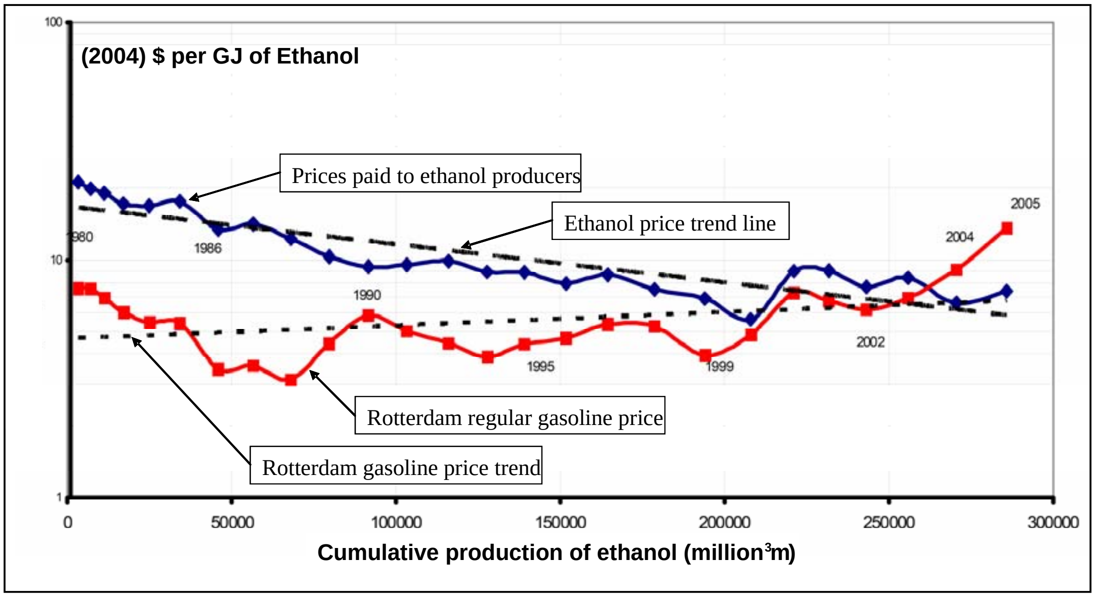
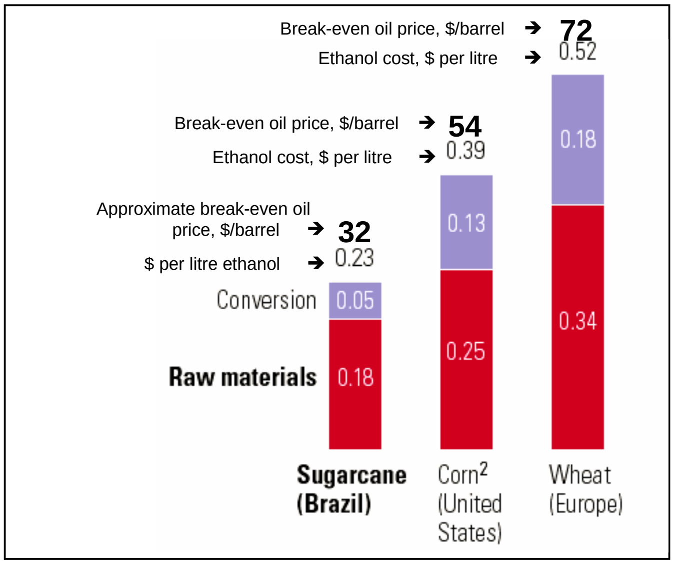
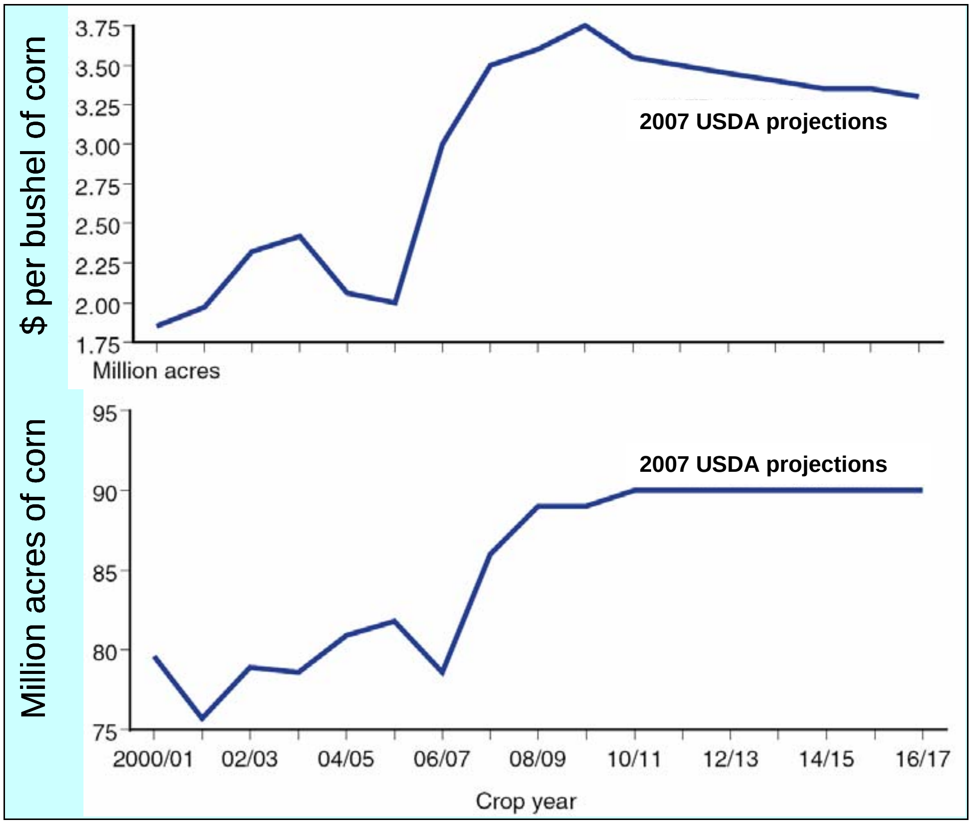


Figure 16. Representation of production costs for first-generation ethanol in Brazil, the United States and Europe [77]



Note: Estimate of the corresponding break-even world oil price is approximate and assumes 20 per cent engine efficiency advantage for a pure ethanol engine relative to gasoline [78].

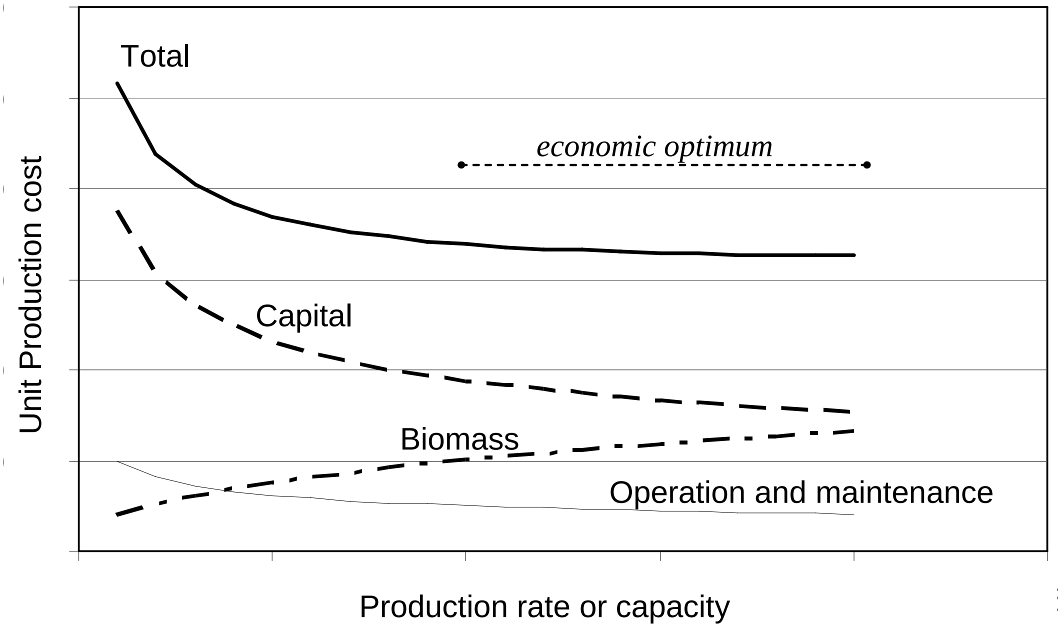
Figure 17. Historical and projected corn prices and corn area planted in the United States [79]



A general characteristic distinguishing second-generation biofuels production from first-generation technologies is the larger capital cost per unit of production. Lower-cost feedstocks will offset this greater capital intensity to yield lower total production costs. However, high capital intensities will drive implementation to be at larger scales to capture scale economies. Capital costs per unit of production capacity fall with increasing plant size and, up to relatively large plant sizes, this cost reduction will generally more than offset the increased biomass costs that arise from longer average transportation distances associated with the larger scale of production [80] (Figure 18). Thus, there will be a strong economic driver to build second-generation systems that are larger than most first-generation systems. Due to the intrinsic nature of the technologies involved, economies of scale likely will be more significant for thermochemical conversion than for biochemical conversion. However, a more important factor in achieving low cost for either system will be the extent to which cost learning takes place after commercial introduction (akin to that seen in the Brazilian sugar cane ethanol industry – Figure 15).

For second-generation biochemical ethanol production, advances in engineering of biological organisms and processes, and in lower-cost production of lignocellulosic feedstocks such as switchgrass, are projected by the National Renewable Energy Laboratory (NREL) in the United States to lead to commercial competitiveness of biological fuel ethanol (at crude oil prices below mid-2006 levels) sometime in the next 10 to 20 years (Figure 19). A near-term NREL goal is that with technological understanding available by 2012, commercial ethanol production costs (assuming a relatively low cost of biomass feedstock) will be competitive with ethanol from corn [12]. Cellulosic ethanol costs (if a plant were built using today's known technologies) are far from this target (Figure 19). In the longer term, both low feedstock costs and large production scales are projected to be needed to reach costs below corn-ethanol costs (Figure 19). The achievability of supplying large volumes of biomass at an average cost of $30/ton or less (as assumed in Figure 19) will be challenging in the temperate climate conditions found in most of the continental United States. However, many developing countries may have a comparative advantage due to natural climatic conditions, and there is a greater probability that sustainable low-cost biomass production can be achieved in such places.

Figure 18. Representation of the impact of process scale on the unit cost of production



For second-generation thermochemical systems, since many of the equipment components needed for biofuel production are already commercially established from applications in fossil fuel conversion (as described earlier), with relatively modest further development and demonstration efforts, thermochemical biofuels could be in commercial production within a few years. With the present understanding of technology, a large-scale biomass-FTL production facility in the United States (processing, say, 5,000 dry tons per day of biomass, costing an average of $50 to $60 per dry ton delivered) would require an oil price in the neighbourhood of $70/barrel to be competitive without subsidy [81]. Where thermochemical biofuel production can be integrated with a facility producing biomass by-products usable for energy – e.g. the pulp and paper industry – thermochemical biofuel production can be competitive at much lower oil prices (~$50/barrel of oil) and/or at smaller scale [82]. Production costs competitive with ~$50/barrel of oil are targeted for stand-alone thermochemical fuel production systems (not integrated with any other industrial process) in the longer term by NREL [83]. In countries where biomass production costs are lower than in the United States (due to better growing climates) and where construction and labour costs are also lower, thermochemical biofuels will compete at oil prices lower than the levels discussed here.

Figure 19. Costs and cost targets for cellulosic ethanol production projected by analysts at the United States National Renewable Energy Laboratory [84]

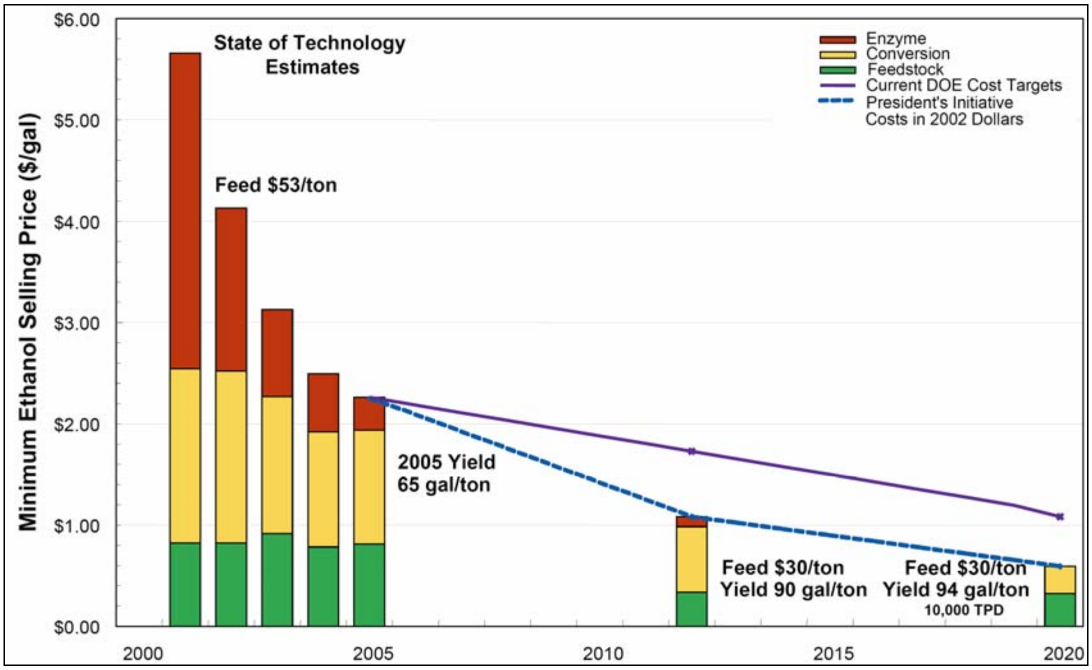


Table 4. First- vs. second-generation biofuels

	1st Gen.	**2nd Gen.**
Biofuels readily usable in existing petroleum infrastructure	Yes	Yes
Proven commercial technology available today	Yes	No
Relatively simple conversion processes	Yes	No
Markets for by-products of fuel production needed	Yes	Yes/No
Capital investment per unit of production	Lower	Higher
Feedstock cost per unit of production	Higher	Lower
Total cost of production	High*	Lower
Minimum scale for optimum economics	Modest	Large
Land-use efficiency	Low	High
Direct food vs. fuel competition	Yes	No
Feasibility of using marginal lands for feedstock production	Poor	Good
Ability to optimize feedstock choice for local conditions	Limited	High
Potential for net reduction in petroleum use	Good*	Better
Potential for net reduction in fossil fuel use	Modest*	High
Potential for net reduction in greenhouse gas emissions	Modest*	High

* Except for first-generation Brazilian sugar cane ethanol, which would get a more favourable mark.

5 Implications for trade and development

There exists today a significant demand in industrialized countries for biofuels, driven largely by regulatory mandates for blending of biofuels into petroleum fuels. This demand is likely to grow considerably in the years ahead, driven by increasingly ambitious regulatory mandates, sustained high oil prices, and energy security concerns. Biofuel demands in many developing countries will also grow, driven by similar factors. Opportunities for trade in biofuels or biofuel feedstocks will be expanding [85]. The technologies described in this publication imply a number of issues relating to the development of biofuels industries in developing countries supplying domestic and/or global markets.

The limitations of first-generation biofuels in terms of direct food vs. fuel conflict, cost-competitiveness, and greenhouse gas emissions reductions are not likely to be substantially different in developing countries than in industrialized countries. While the climate in many developing countries is better suited than in many industrialized countries to growing first-generation biofuel feedstocks, agricultural productivities are generally lower. Higher agricultural productivities thus would help mitigate food vs. fuel conflicts to some extent, and targeting biofuel feedstock production on lands less suited to food crop production also would be helpful. In any case, the economics of first-generation biofuels may not be much better than can be achieved in industrialized countries, because global commodity markets may set prices for first-generation biofuel feedstocks. In addition, smaller scales of production that might be favoured in developing countries (to reduce investment capital needs) would tend to raise unit costs for biofuels production. Clean Development Mechanism credits may help improve economics, but credits for first-generation biofuels (other than for sugar cane ethanol on the Brazilian model) will be modest without innovation in production techniques that reduce fossil fuel use compared to current industrialized-country norms.

Considering second-generation biofuel technologies, given that they are primarily being developed in industrialized countries, issues concerning technology relevance for developing countries are important. Technologies developed for industrialized country applications will typically be capital-intensive, labour-minimizing, and designed for large-scale installations to achieve best economics. In addition, the biomass feedstocks for which technologies are designed may be quite different from feedstocks that are suitable for production in developing countries. To capitalize on their comparative advantages of better growing climates and lower labour costs, developing countries will need to be able to adapt such technologies. Tailoring feedstocks to local biogeophysical conditions will be important for maximizing biomass productivity per hectare and minimizing costs. In addition, adapting conversion technologies to reduce capital intensities and increase labour intensities will be important for providing greater employment opportunities and reducing the sensitivity of product cost to scale. If such adaptations can be made successfully, second-generation biofuel industries in developing countries should be competitive with those that will be established in industrialized countries.

The sustainable application in developing countries of technologies developed in industrialized countries also raises issues for technology transfer. For successful technology adoption and adaptation, it is essential to have a technology innovation system in place in a country. For smaller countries, regional innovation systems may serve this purpose. An innovation system refers to people involved in a broad set of activities and institutions, including (a) research universities/institutes generating fundamental knowledge and assimilating knowledge from the global community; (b) industries with the capacity to form joint ventures with foreign companies and to introduce innovation and learning into shared technologies; (c) government agencies able to recognize and support the required research and technology adaptation needs; and (d) a technology-informed public policymaking system. Technology innovation ideally would begin with involvement in the earliest (pre-commercial) stages of technology development. Such an innovation system is one of the key reasons for the success of the Brazilian ethanol program [86], and such systems are in place in a few other large developing countries, including India [87] and China.

There are important roles for Government in fostering the development of biofuels industries in developing countries. Given that first-generation biofuel technologies are already relatively well developed but still face economic and other limitations, emphasis of government efforts on second-generation biofuels may be appropriate. The development of competitive second-generation industries will be facilitated (especially in larger countries or regional clusters of smaller countries) by establishing regulatory mandates for biofuels use. Direct financial incentives – including grants for research, development and demonstration, or biofuel price subsidies – could also be considered, but clear "sunset" provisions and/or subsidy caps (e.g. tied to oil prices and with finite durations) should be designed into such provisions. Policies supportive of international joint ventures would also help provide access for domestic companies in developing nations to intellectual property owned by international companies. With a natural favourable climate for biomass production, developing country partners in such joint ventures might contribute host sites for demonstrations and first commercial plants, as well as avenues for entering local biofuels markets.

Even with effective government support and an effective technology innovation system in place, time will be needed before second-generation biofuels will be able to make a significant impact in any developing country. To quantify this, consider Macedo's estimates for the time that will be required before a commercial second-generation biofuel industry could be established (defined by Macedo as having 5 to 15 commercial production facilities operating) in Brazil using the lignocellulosic portion of sugar cane [6]. Considering all of the steps needed to reach that point (including research, development, pilot-scale demonstration and commercial-scale demonstration), he estimates that a competitive thermochemical biofuel industry (producing FTL or DME) could be in place by 2020, while a competitive biochemical biofuel industry (producing ethanol by consolidated bioprocessing) might be established between 2020 and 2030. Considering the Brazilian context for these estimates – one of the lowest-cost lignocellulose production systems in the world, a well-established and competitive first-generation biofuels industry, major sugar cane production expansion plans that provide opportunity for rapid introduction of innovations, an established technology innovation system in the country and supportive government polices – the time to establish second-generation biofuels industries in an "average" developing country will likely be at least this long. On the other hand, with today's unprecedented level of global activity aiming at commercial development of biofuel technologies, research and development surprises could shorten these time estimates.

Finally, for there to be sustainable domestic biofuels industries, there is a need for strong international biofuel and/or biofuel feedstock trading systems, since countries relying on domestic production alone would be subject to weather- and market-related vagaries of agriculture [86]. In the context of global trade, sustainability certification may be instrumental to ensure that widespread biofuel production and use will be conducive to the achievement of social and environmental goals, without, however, creating unnecessary barriers to international trade.

Given the still-early point in commercial development of second-generation biofuel technologies, it is difficult to project the role that developing countries will take in a global biofuel economy in the long term. One possibility is that they will simply become exporters of second-generation feedstocks, taking advantage of their favourable natural climates and low labour costs for growing biomass. A more attractive evolution would be their becoming producers, users and exporters of finished biofuels, thereby retaining domestically more of the considerable added value involved in the conversion of the feedstocks to finished fuels.

Table 5. Second-generation biofuels and developing countries

Technology relevance

- Most conversion processes being developed for industrialized country applications will typically be capital-intensive, labour-minimizing, designed for large-scale installations, and designed for temperate-climate feedstocks.
- To capitalize on comparative advantages of better growing climates and lower labour costs, developing countries will need to be able to adapt such technologies to reduce capital intensities, to increase labour intensities and to develop optimal feedstocks for local conditions.

Technology transfer

- Successful technology adoption and adaptation require a technology innovation system: research capacity, private sector companies with the capacity for joint ventures, government agencies that can recognize and support requisite research and technology adaptation needs, and a technology-informed public policymaking system. (The Brazilian technology innovation system is a key reason for the success of sugar cane ethanol there.)

Government support

- Establish regulatory mandates for biofuels use to help launch biofuel industries.
- Consider direct grants for research, development and demonstration.
- Consider financial incentives (e.g. biofuel price subsidies), but include “sunset” provisions.
- Implement policies supportive of international technology joint ventures.

Technology commercialization timeframe

- Competitive second-generation biofuel industries could be established in developing countries before 2015–2020 for thermochemical biofuels and before 2020–2030 for biochemical biofuels.

Trade

- Any sustainable global biofuel industry requires strong international biofuel and/or feedstock trading systems to help insulate domestic industries from inherent weather- and market-related vagaries of agricultural systems.
- In the context of global biofuels trade, sustainability certification may be instrumental to ensure socially and environmentally responsible production.
- Will developing countries’ role in a global second-generation biofuel industry be limited to being exporters of feedstocks, taking advantage of their favourable natural climates and low labour costs for growing biomass, or will they retain more value added by becoming producers, users and exporters of finished biofuels?

6 Summary

This publication has reviewed a variety of biofuels and biofuel production processes. The discussion has been set in a "supply-side" context – i.e. how biomass can provide increased liquid fuel supplies or fossil fuel substitution. The "demand-side" context – i.e. how efficiently the biofuels are utilized (in vehicles, cooking, etc.) – has been addressed only indirectly. It is worth stating that the more efficiently a biofuel can be used, the greater the energy services it will provide per hectare of land. In fact, improving biofuel end-use energy efficiencies – e.g. through introduction of vehicles with high fuel economies, efficient mass transit, energy-conscious urban land-use design, etc. – should be part of any comprehensive energy supply planning. Given the inherent inefficiency of photosynthesis, improving end-use efficiency is essential if biofuels are to make more than modest contributions to meeting energy-service demands [74].

Regarding the multitude of biofuel technologies that are in use or that have been proposed, the preference for one biofuel pathway over another in any given national or regional context may be determined by the extent to which broader development and sustainability objectives would be satisfied. Such objectives may include increasing the availability of liquid fuels, reducing imports of liquid fuels, providing rural employment, developing new world-scale industrial activities, developing smaller-scale "home-grown" industries, reclaiming degraded lands, earning export revenues, or reducing greenhouse gas emissions. Different biofuels and biofuel feedstocks will measure up differently, depending on the criteria applied. In this publication, the focus has been on describing the technology, economic status and prospects for a broad (but not complete) range of first-generation and second-generation biofuels, and on providing some perspective on energy, greenhouse gas emission, and economic trade-offs among biofuels.

First-generation biofuels have some attractions, but more limitations. Positive attributes include relatively simple and well-known processing technologies, relatively low unit investment requirements for production, scalability to relatively small production capacities, and fungibility with existing petroleum-derived fuels. Limitations include (a) direct competition with food production; (b) the use of feedstocks optimized for food production, rather than for energy production; (c) utilization of only a portion of the total biomass produced by a plant, so that land-use efficiency is low from energy supply and/or greenhouse gas mitigation perspectives; and (d) relatively high production costs in most cases due to the competition for feedstocks with food.

Sugar cane ethanol stands out among first-generation biofuels as suffering fewer limitations, in large part because energy for processing the cane into ethanol is provided by biomass from the cane itself. This, coupled with the extensive learning-by-doing that has been achieved by the Brazilian sugar cane-ethanol programme, leads to favourable metrics, including those relating to fossil fuel substitution, greenhouse gas emissions abatement and production cost.

There is a broad spectrum of second-generation biofuels. Their common defining feature is that they are made from lignocellulosic feedstocks. By comparison to feedstocks for first-generation biofuels, lignocellulosic biomass is generally (a) not edible and therefore does not compete directly with food production; (b) can be bred specifically for energy purposes, thereby enabling higher production per unit land area; and (c) represents more of the above-ground plant material, thereby further increasing land-use efficiency. These basic characteristics of lignocellulosic materials translate into substantial energy and environmental benefits for second-generation biofuels compared to most first-generation biofuels.

However, for essentially the same reason that lignocellulosic biomass is not used for food (indigestibility), it is more challenging to convert into liquid fuels than are edible feedstocks. In general, second-generation biofuel production systems require more sophisticated processing equipment, more investment per unit of production capacity, and larger-scale facilities (to capture economies of scale). Second-generation biofuel production facilities can be (and a few are being) built today. Subsidies and "niche" markets offer the possibility for competitive economics for these facilities, but to achieve their full commercial (unsubsidized) energy and economic potential, further research, development and demonstration efforts are needed on both feedstock production and feedstock conversion.

Second-generation biofuels include those made by biological processing ("cellulosic ethanol") and those made by thermochemical processing (e.g. Fischer-Tropsh fuels), two fundamentally different approaches. Thermochemical processing has the important advantage of greater feedstock flexibility than biological processing, but the economically optimum production scale may be larger than for biological processing. Many efforts are ongoing worldwide to commercialize second-generation biofuels made by both routes. Some research and development breakthroughs, followed by commercial-scale demonstrations, are needed to prove the viability of unsubsidized cellulosic ethanol. In contrast, because thermochemical biofuels are identical to some fuels that are already being made from fossil fuels, little or no fundamental research and development breakthroughs are needed, but commercial-scale demonstrations are still needed.

The technologies described in this publication imply a number of issues relating to the development of biofuels industries in developing countries. The limitations of first-generation biofuels in terms of direct food vs. fuel conflict, cost-competitiveness, and greenhouse gas emissions reductions are not likely to be substantially different in developing countries than in industrialized countries for reasons that have been elaborated earlier. Considering second-generation biofuel technologies, given that they are primarily being developed in industrialized countries, issues around technology relevance for developing countries are important. Developing countries will need to be able to adapt second-generation conversion technologies to local conditions and local feedstocks. To fully capitalize on their comparative advantages of better growing climates and lower labour costs, it will be important that agricultural productivities be raised, both for conventional agriculture (to reduce land requirements for food production) and for production of second-generation biofuel feedstocks (to better compete with second-generation feedstocks in industrialized countries that are the focus of significant productivity improvement efforts). Technology adaptations that reduce capital investment requirements for conversion systems in favour or greater labour inputs will also be of value. In addition, successful technology adoption and adaptation will require effective technology innovation systems in a country (or in a region in the case of clusters of smaller countries). Such an innovation system is one of the key reasons for the success of the Brazilian ethanol programme.

There are important roles for Governments in fostering the development of biofuels industries in developing countries. The development of competitive second-generation industries will be facilitated by establishing regulatory mandates for biofuels use. Direct financial incentives could also be offered, but clear "sunset" provisions and/or subsidy caps should be designed into such provisions. Policies supportive of international joint ventures would help provide access for domestic companies in developing countries to intellectual property owned by international companies.

For there to be sustainable domestic biofuels industries, there will be a need for strong international biofuel and/or biofuel feedstock trading systems, since most countries that rely on domestic production alone would be subject to weather- and market-related vagaries of agriculture. In the context of global trade, sustainability certification may be instrumental to ensure that widespread biofuel production and use will be conducive to the achievement of social and environmental goals.

Even with supportive policies and infrastructure, time will be needed before second-generation biofuels will be able to make an impact in any developing country, because of the research, development and demonstration requirements needed to reach the commercial implementation stage. The time frame for establishing a commercial second-generation biofuel industry in terms of years is likely to be a minimum of 5-to-10, but less than 10-to-20.

Given the still-early point in commercial development of second-generation biofuel technologies, it is difficult to project what role developing countries are likely to take in a global biofuel economy in the long term. One possibility is that they simply become exporters of second-generation feedstocks, taking advantage of their favourable natural climates and low labour costs for growing biomass. A more attractive evolution would be their becoming producers, users and exporters of finished biofuels, thereby retaining domestically more of the considerable added value involved in the conversion of the feedstocks to finished fuels.

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