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Sugarcane-Based Bioethanol

Energy for Sustainable Development

Coordination
BNDES and CGEE

www.sugarcanebioethanol.org

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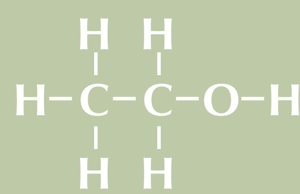

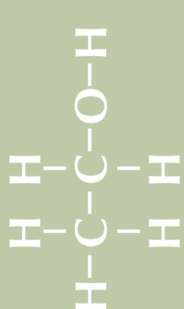

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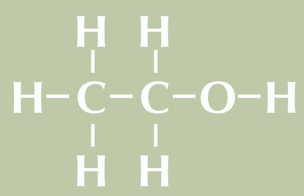

Foreword

Oil, natural gas and their derived-products account for 55% of the world's energy consumption. The fast and efficient transport facilities of our times, as well as most industrial activities are possible thanks to these fuels. Unfortunately, they will last as much as a few decades: as fossil fuels, their reserves are finite, supply safety is troublesome for many importing countries and their use is the main source of climate-changing and global warming gases.

These fuels, thus, must be substituted. The most rational way of producing the substitutes is using renewable organic matter (biomass), out of which, long ago, fossil fuels were produced by nature. One of the options is the ethanol, an excellent substitute for gasoline, the main car fuel used around the globe.

In Brazil, the sugarcane-based ethanol substitutes half of the gasoline that would be used if it did not exist and its cost is competitive without the subsidies that helped launching the program at first. That has been accomplished in 30 years since the Brazilian Ethanol Program was launched in the 1970s to reduce the dependence on oil imports. Economic considerations of the sugar industry also had a bearing on the program when it was lauched; however, environmental and social concerns did not play a significant role at that time.

In the United States, the largest world producer of corn-based ethanol, an ethanol programme has been recently launched and its justifications are eliminating additives on gasoline and cutting down on global-warming gases. In Western Europe, wheat and beet-based ethanol are also used. In these countries, the cost of ethanol is four times greater than in Brazil and internal subsidies and customs barriers protect local industries, preventing ethanol imports from Brazil.

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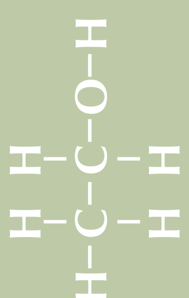

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This has caused some groups to feel quite uneasy, as they associate ethanol (and biodiesel, produced at smaller amounts) to a false dilemma: producing food versus fuels. This argument does not find grounds as we realize that ethanol production in the world, around 50 billion liters per year, takes 15 million hectares, that is, 1% of the area currently used for agriculture purposes in the world (ie, 1.5 billion hectares).

These groups also argue that, in fact, ethanol does not cut down on greenhouse gases; however, in the case of sugarcane-based ethanol that is a misconception. Actually, sugarcane-based ethanol is almost entirely renewable, since sugarcane bagasse supplies the entire energy required in the industrial phase of ethanol production. The United States is in a less comfortable position because ethanol production requires the use of energy fully derived from external fossil-fuel sources. We can say that corn-based ethanol is, in fact, fossil-fuels converted into ethanol, whereas in Brazil, it is almost fully derived from solar energy.

Sugarcane and corn production expansion involve changes in land-use, which may cause emission of greenhouse gases if expansion triggers deforestation, which is not the case of Brazil, where sugarcane expansion is taking place mostly in areas previously occupied by pasture lands. Indeed, this is a an issue related to the expansion of agriculture more than a problem associated with the expansion of ethanol (or biodiesel) production. The dilemma here, if any, could be on food production versus climate change.

What we may call "a Brazilian fix for fossil fuel problems" - the use of sugarcane-based ethanol to substitute gasoline – is not only a Brazilian phenomenon, as it is being adopted in other sugarcane producing countries (almost one hundred), such as Colombia, Venezuela, Mozambique and Mauritius Islands.

These and other issues are analyzed in depth in this book, which describes the biological characteristics of sugarcane as a plant, alcohol and other co-products and by-products production techniques, such as bioelectricity, presenting the state-of-the-art in terms of "advanced technologies".

The use of "second generation technologies" to produce ethanol based on cellulose of any other types of agricultural products (including sugarcane) is also discussed, as well as biomass gasification technologies. Social and environmental sustainability issues for ethanol production are also analyzed.

This book will certainly clear some myths around the Brazilian ethanol program and its potential expansion in the world.

Professor José Goldemberg
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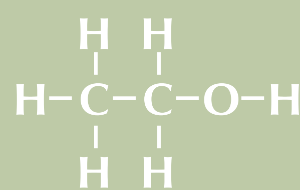

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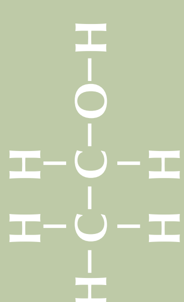

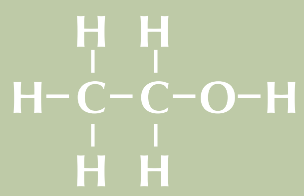

Preface

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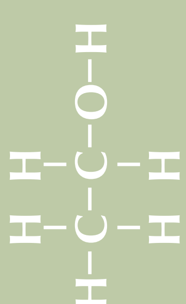

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Biofuel production started to attract growing attention in the early 2000s because of mounting interest in the development of cleaner and renewable energy sources: biofuels were seen as part of the drive to move beyond the prevalent fossil-fuel paradigm. Brazil stands out in this context, with a sugarcane bioethanol programme that has delivered remarkable results along the entire production chain, from the improvement and development of higher-yielding sugarcane varieties to the manufacture of engines that run on any gasoline and bioethanol blend.

President Luiz Inácio Lula da Silva requested the National Bank of Economic and Social Development (BNDES) and the Center for Strategic Studies and Management (CGEE) to produce this book, principally in order to share the Brazilian experience with other nations, especially with developing countries located in tropical and subtropical areas. This motivation also underlay the contributions made by the Economic Commission for Latin America and the Caribbean (ECLAC) and the Regional Office for Latin America and the Caribbean of the Food and Agriculture Organization of the United Nations (FAO).

Biofuels have been in the spotlight recently owing to the surges in food and agricultural commodity prices for which biofuel production has often been held largely responsible. This book stresses the need to distinguish between different types of biofuel production systems before making assertions regarding their impact, not only on food prices, but also on food security and energy and environmental balances. Biofuels are not all the same in terms of impacts and benefits or even in terms of the origin of their raw inputs. The book makes the point that bioethanol made from sugarcane, for example, has little to do with bioethanol made from wheat or maize. Sugarcane bioethanol is advocated as preferable to other biofuels both because of its food security impacts and because of environmental and energy aspects.

The book aims to offer a comprehensive review of biofuel issues. BNDES and CGEE coordinated the preparation of the book with the support of ECLAC and FAO. The preparation of chapters 1 to 7 and chapter 9 was coordinated by BNDES and CGEE; ECLAC and FAO coordinated the production of chapter 8 and provided insight and valuable assistance for developing the other chapters.

Chapter 1 discusses bioenergy-related concepts and describes the development of bioenergy sources, stressing their importance in today's energy context. Chapter 2 deals with ethanol as a motor-vehicle fuel, discussing its properties and performance as a fuel, as well as economic and logistical aspects of its use. Chapter 3 describes the processes used to produce bioethanol from different sugary and starchy crops, focusing on sugarcane and maize conversion routes and the energy and greenhouse gas (GHG) balances in each case. Chapters 4 and 5 look at technical aspects of the co-products and by-products obtained in sugarcane bioethanol production. Chapter 4 discusses sugar and bioelectricity, the two main co-products under current technologies, and chapter 5 analyses innovative conversion routes, such as hydrolysis and gasification, that could be used in the future to obtain biofuels from sugarcane by-products and residues. The first five chapters take a technical approach; despite occasional references to Brazil's experience, the concepts discussed are applicable in other contexts. Chapter 6 then moves on to the Brazilian experience, presenting the country's bioethanol programme — which was established in 1975 — and discussing its evolution, indicators and current perspectives. Chapter 7 addresses sustainability issues that represent major sources of concern regarding biofuels production in Brazil. Sustainability is discussed in environmental, economic and social terms, including some remarks on biofuel certification. Chapter 8 assesses the global potential for biofuel production, discusses policies adopted to foster it and evaluates the possibilities of setting up a global bioethanol market and how this would affect food security. Chapter 9 summarizes the main points made in the book and offers some recommendations.

The book aims to provide grounds for a meaningful and objective discussion on the potential and constraints of producing bioethanol from sugarcane, especially in those countries where sugarcane is already being cultivated. Policies and incentives to create a competitive market for sugarcane bioethanol are important, but the promotion of biofuels must not compromise food security, internationally agreed commitments on poverty and hunger reduction or the promotion of sustainable natural resources management.

The book also emphasizes that many developing countries — chiefly those located in tropical and subtropical zones, which includes most of the countries of Latin America and the Caribbean — have adequate natural conditions, as far as soil, water, solar radiation requirements and land availability are concerned, to expand energy-oriented sugarcane production. Recent studies stress that these comparative advantages can be exploited under *sustainable conditions by implementing strategies that balance the costs and benefits in economic, social, environmental and strategic terms. These strategies must be subject to the close analysis and monitoring of land-use changes, investment standards, GHG emissions, trade flows and food security, as highlighted in recent international forums. Many countries currently interested in biofuels may benefit from the experience accumulated by Brazil during more than three decades in the agricultural, industrial, technological and logistical aspects of the production and use of sugarcane bioethanol. This stock of know-how could constitute an important asset for other countries whose biofuel potential could be boosted through horizontal technical cooperation mechanisms.*

Tapping the potential advantages of producing bioethanol from sugarcane will require greater integration and coherence between national and international policies — especially in the areas of energy, environment, agriculture and food security — as well as between public and private action. Every effort must be made to prevent the implementation of mechanisms that could undermine the legitimate comparative advantages that many countries have in sugarcane-based bioethanol production.

As the book discusses, in designing biofuel policies, it is especially important to: (a) develop common methodologies for analysing the GHG lifecycle, given the importance of the direct and indirect emissions generated by biofuel-related changes in land use; (b) adopt internationally agreed, non-distorting standards to address the possible environmental impacts of bioenergy production; (c) set out guidelines for developing and developed countries to estimate and report GHG emissions and compliance with World Trade Organization (WTO) rules on barriers to trade; and (d) strengthen the linkages among agricultural, food and energy policies so that biofuel production does not threaten food security and farmers are not deprived of the opportunity to profit from biofuel production.

The bioethanol agenda is growing by the day. Some of the topics still open for discussion are beyond the scope of this book and will no doubt be the subject of research in the near future. One of these is the globalization of bioethanol. As in the case of petroleum, the creation of a worldwide bioethanol market will mean developing a number of complementary measures to ensure continuity and safety in production and supply. Such a process will require the formation of new alliances (public-private, private-private, multilateral) and the creation of consumer markets with clearly defined rules regarding price formation and reference product specifications.

Other significant strategic issues include the need to ensure that biotechnology developments and sugarcane variety enhancements are protected by intellectual property rights and that measures are taken to maintain the competitive advantage that developing countries currently enjoy in biofuel production.

Biofuel policies today need to be based on four pillars:

(a) a market-oriented approach *to both reduce agricultural and biofuel market distortions and avoid the creation of new restrictions;*

(b) an environmentally sustainable approach *to the development of biofuel production that results in positive net balances in terms of energy ratios (i.e., energy use versus energy production), the reduction of GHG emissions and the sustainable use of natural resources;*

(c) a development approach *that pays due attention to research, development and innovation policies that help improve the economic and physical efficiency of feedstocks and of the processes to convert them into biofuel; and*

(d) a socio-economic approach that focuses on the protection of lower-income populations and the improvement of food security *by addressing the problems created by food deficits and the dependence on fossil fuel imports, especially in poorer countries.*

The institutions involved in the production of this book maintain that, if properly designed and implemented (i.e. on the basis of the four pillars outlined above), programmes to develop the production and use of sugarcane bioethanol can foster cooperation among countries and promote sustainable development.

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FAO Regional Representative for Latin America and the Caribbean

Luz do sol
que a folha traga e traduz
em verde novo,
em folha, em graça,
em vida, em força, em luz...
Luz do sol, *Caetano Veloso*[1]

1 Light from the sun / that the leaf draws and transform/ into new green / into a leaf, into grace / into life, into force, into light…

Chapter 1

Bioenergy and biofuels

The conversion of solar energy into chemical energy by plants during photosynthesis is one of the most fascinating phenomena of nature. In plants, bathed in sunlight, the fleeting pulses of solar radiation are transformed into stable products, absolutely essential for life on our planet. Since the beginning of humanity it has been our symbiosis with the Plant Kingdom what has ensured us a supply of food, energy and widely used raw materials, allowing, across the millennia, progress in our standards of living and economic productivity. After a brief interruption of a few centuries — during which fossilized solar energy in the form of coal, oil and natural gas were greedily exploited and utilized — photosynthetic energy is gradually returning to the fore. Capable of mitigating worrisome environmental problems, photosynthetic energy promises to bring a new dynamic to agroindustry and offers an effective path for the necessary evolution of the modern industrial society towards a more rational and sustainable energy future. Without the pretence of being the only solution to the current energy problems, the capture and storage of solar power by plants may play an important role in the energy future of nations. Indeed, as Melvin Calvin — recipient of the Nobel Prize for Chemistry in 1961 for his discoveries about photosynthesis — once said, leaves are truly "silent factories".

This first chapter presents basic bioenergy concepts (Section 1.1) and describes the development of bioenergy sources (Section 1.2), especially in the form of biofuels, from a long-term perspective. Later chapters will address more thoroughly the expansion and current status of the Brazilian bioethanol market (Chapter 6) and the global market for biofuels (Chapter 8).

1.1 Bioenergy basics

Energy is — in its most basic formulation — the capacity to promote change: in any of its many forms, such as thermal, mechanical, electrical and chemical, energy always represents the capacity to cause transformations, either through natural or man-made processes. Chemical energy is energy generated through chemical reactions — ie, where a change of composition takes place — by which molecules are converted into products, usually releasing heat. For example, chemical energy is found in food and fuels, and it is used in vital animal and human processes and to provide mobility, among other purposes.

Bioenergy is one special form of chemical energy. It includes any kind chemical energy accumulated through recent photosynthetic processes. In general, natural resources that contain bioenergy and can be processed to obtain more complex energy carriers suitable for end-uses are called *biomass*. Examples of sources of bioenergy include wood and sawmill waste, charcoal, biogas resulting from the anaerobic decomposition of organic waste and other farming waste, as well as *liquid biofuels*, such as bioethanol and biodiesel, and *bioelectricity*, generated from the burning of fuels such as bagasse and wood.

In the broad context of bioenergy, the production of liquid biofuels arose specifically to meet the needs of vehicular transport. In fact, biofuels — and not all of them — are currently the only renewable alternatives with sufficient technological maturity that are economically viable as vehicle fuels. Liquid biofuels can be used very efficiently in the internal combustion engines that power automobiles. These engines are basically classified into two types, depending on how the combustion is started: spark ignition Otto-cycle engines, for which the preferred biofuel is bioethanol; and Diesel-cycle engines, in which ignition is achieved by compression and good performance is attained with biodiesel. Biofuels can be used in both types of engines, either alone or blended with conventional petroleum-derived fuels. It is interesting to note that biofuels were the preferred energy source for internal combustion engines in the early years of the automobile industry, during the second half of the 19^{th} century. Actually, pioneers of the automotive industry developed engines for biofuels: Henry Ford for bioethanol and Rudolf Diesel for peanut oil. These two biofuels were replaced in the early 20^{th} century by gasoline and diesel oil, respectively, when fossil oil distillates emerged as cheap and abundant alternatives. Technical aspects associated with the use of ethanol in engines will be discussed in Chapter 2.

The production of biomass is the result of the photosynthetic reaction, which basically depends on solar energy and the presence of water and carbon dioxide (CO_2). The reaction occurs in the plant cells of leaf stomata according to complex cycles, where water and carbon dioxide gas combine to form a glucose molecule, a simple sugar, and oxygen, according to the following formula:

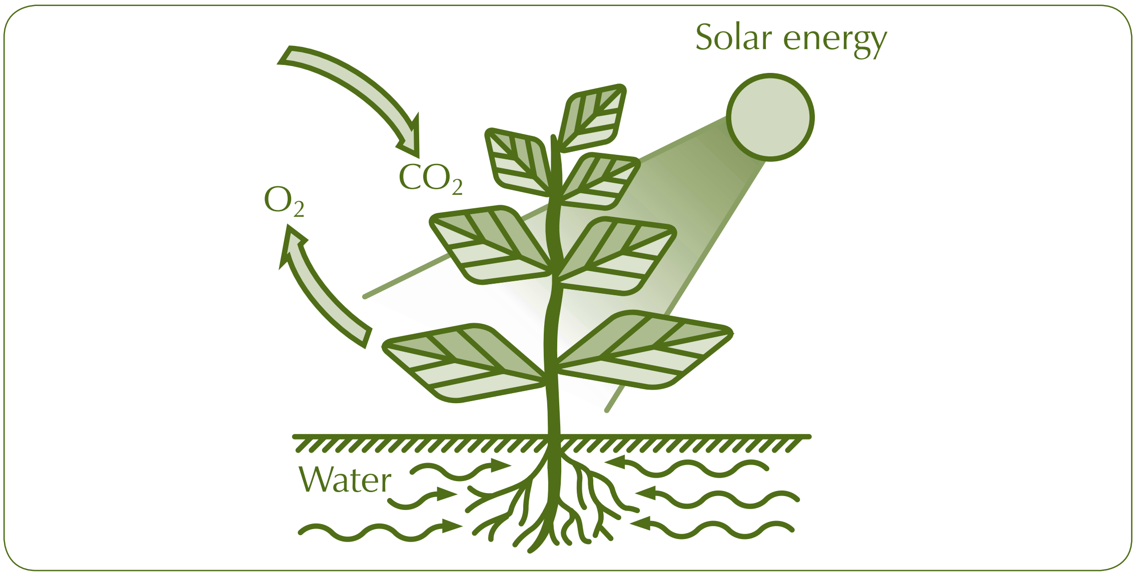
$$6\,H_2O + 6\,CO_2 \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6\,O_2 \qquad (1)$$

Ford Model A Car (1896) which used pure ethanol.

In energy terms, 1 kg (2.2 lbs) of sugar requires the fixation of approximately 17.6 MJ (megajoules) of solar energy, or the equivalent of around one-half litre of gasoline. For the mass balance of this reaction, the synthesis of 1 kg of glucose consumes around 0.6 kg of water and 1.4 kg of carbon dioxide, and releases 1 kg of oxygen into the atmosphere. Of course, this water represents only the portion used in the synthesis of sugar. Because of evapotranspiration that takes places during photosynthesis plants require hundreds of times more water than the amount actually incorporated in the plant tissue. Therefore, the fundamental conditions required for the production of biomass — and then, production of bioenergy — are the availability of solar radiation, water and carbon dioxide.

Carbon dioxide is the least problematic of the basic inputs for plant growth, as it is well distributed in the atmosphere in sufficient concentrations. However, it is worth noting that the atmospheric concentration of CO_2 has increased in recent decades, mainly associated with the intensive use of fossil fuels. In this context biofuels offer two important advantages. First, their use could reduce carbon emissions into the atmosphere on a life-cycle basis and therefore contribute to address global warming concerns caused by the increase of carbon dioxide emissions. And second, biomass production is potentially enhanced — within limits and only for some plant species — through the growing availability of carbon dioxide in the atmosphere.

Figure 1 **– The process of photosynthesis**



Source: Elaborated by Luiz Augusto Horta Nogueira.

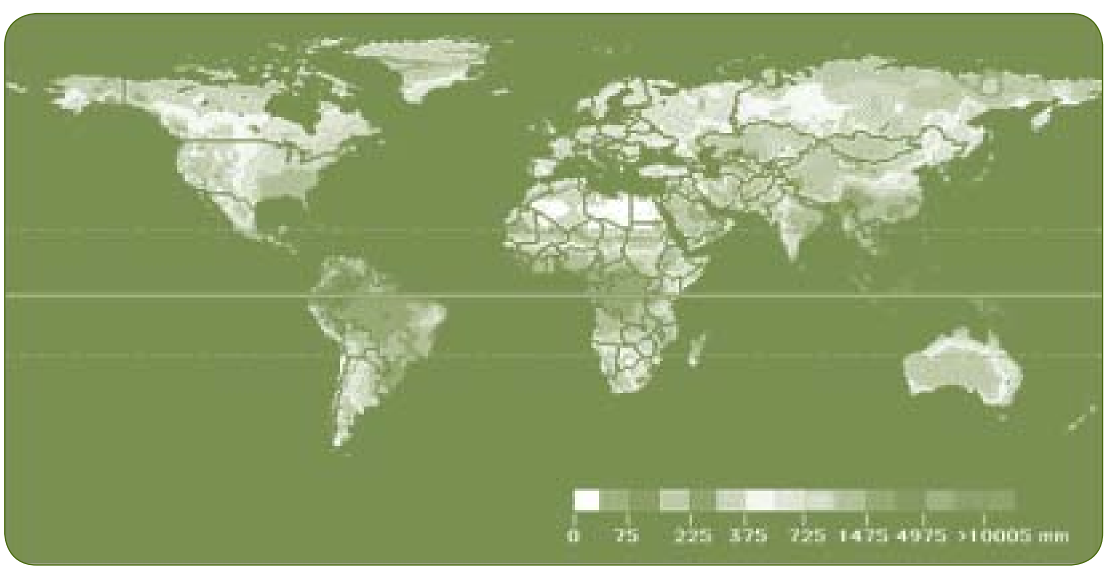
With regard to solar radiation, it is interesting to understand which portion is used by plants and how much of it is available on earth. Photosynthesis occurs through the absorption by chlorophyll of specific bands frequencies of the sunlight spectrum, especially the wavelengths between 400 and 700 nm (nanometre), ie, the red color region. In plant physiology this band is called photosynthetically active radiation (PAR) and represents approximately 50% of total solar radiation. In relation to the availability of solar radiation, the crucial factor is latitude: tropical regions receive more solar energy than regions situated at higher latitudes. According to the Solarimetric Atlas of Brazil, a square meter area situated between 10° and 15° South latitude, in Northern Brazil, receives an average of 18.0 MJ/day, whereas the same square meter located between 20° and 25° latitude in Southern Region receives 16.6 MJ/day, around 8% less energy [Cresesb/UFPE/Chesf (2000)]. Temperature, which also correlates with latitude, is another factor with direct influence on photosynthesis. Within limits, higher temperatures favour biomass production, reinforcing the bioenergy advantage of the hotter regions of the planet.

The most important constraint on plant growth, however, is water, the last of the essential inputs for photosynthesis. The limited availability of water resources of adequate quality and their heterogeneous distribution over the continents is one of the greatest challenges for the development of many countries. Extensive sunny areas in semi-arid regions will contribute very little as a source of biomass, unless irrigated with significant volumes of water. Nevertheless, large scale irrigation has costs — which often include high energy costs — that can make bioenergy production economically unviable. Globally, irrigation currently consumes over 70% of available water resources and it is used in approximately 40% of the agricultural production [(Horta Nogueira 2008)]. Moreover, as the latest IPCC report stresses, crop production could be adversely affected by human-induced climatic changes that alter rainfall and water systems and increase the frequency of catastrophic phenomena, such as droughts and flooding. This make access to water a high priority issue [FAO 2008a)], especially for biomass production in the context of climate change.

As Figure 2 shows, some tropical regions have abundant rainfall, especially those in South America and Africa. Combined with a greater incidence of solar energy and ideal temperatures, this rainfall is a significant advantage that brings together in these regions the conditions most propitious for the production of bioenergy. However, since they area also rich biodiversity regions, any biofuels development must be promoted in harmony with existing virgin tropical forests, as well as current food-production agricultural activities.

In addition to sunlight, water and carbon dioxide, other important requirements for bioenergy production are soil fertility and topography. The main mineral nutrients for plant growth are nitrogen, phosphorous and potassium. The presence of other mineral is also important, although in lower concentrations; for example, boron, manganese, zinc and sulphur, as well as organic matter, are also important factors. A fertile soil also requires an adequate structure and porosity. Generally speaking, bioenergy crops require the regular use of chemical fertilizers to achieve satisfactory yields, as well as mechanization of agricultural operations and sustainable soil and water management. In relation to topography, planted areas should not be too steep, to both minimize erosion — especially in annual crops — and facilitate planting and harvesting operations.

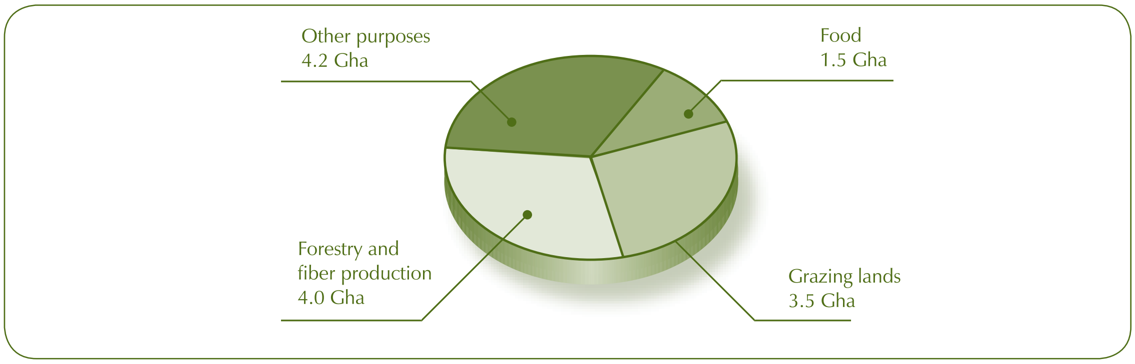
***Figure 2* – Average annual rainfall**



Source: FAO (1997).

All these factors, when considered together, define the potential areas for bioenergy cultures and other uses. Considering the entire planet, this area has been estimated to include 13.2 billion hectares, of which approximately 1.5 billion (11% of the total) are currently devoted to food production for humans and animals [Hoogwijk *et al*. (2003)]. Addressing a topic which will be discussed more thoroughly in Chapter 8, Graph 1 shows how the use of arable areas across all continents is distributed, pointing out areas available for the expansion of the agricultural frontier and the possible production of bioenergy, especially in poorly explored or overused areas, such as low productivity grazing lands.

***Graph 1* – Global use of arable lands**



Source: Based on Hoogwijk et al. (2003).

The relative efficiency of crops in capturing and storing solar energy is one of the fundamental parameters in bioenergy systems. Then, determining how and how much solar energy is actually converted into bioenergy and understanding how energy transformations and losses occur is crucial when seeking for the most favourable conditions for the plants' performance as energy collectors. It turns out, however, that the biochemical mechanisms that enable plants to synthesize sugars and other chemical products have been elucidated only in the last few decades. Carbon fixation pathways have been discovered and their different phases identified. These *photosynthetic pathways* follow a complex sequence of successive reactions, with various bifurcations and unstable compounds leading to the formation of stable substances. Such knowledge opens a new and important frontier of possibilities to understand plant behaviour and, over time, improve the productivity of species with bioenergy potential.

The photosynthetic cycles of greatest interest are the C3 cycle (Calvin cycle) and the C4 cycle (Hatch-Slack cycle), in which the molecule of the first stable product present, respectively, three carbons (phosphoglycerate) or four carbons (products such as oxaloacetate, malate and aspartate) [Hall and Rao (1999)]. While most known plants use the C3 cycle, in some tropical grassy plants, such as sugarcane, barley and sorghum, the C4 cycle is the dominant process. Such distinction is important for the development of bioenergy systems, because

C4 cycle plants have the highest productivity among photosynthetic pathways, with higher photosynthetic saturation rate (absorbing more solar energy), absence of losses by photorespiration, higher efficiency in the utilization of water, higher saline tolerance, and lower CO_2 compensation point (ie, C4 cycle plants respond better under lower concentrations of this gas). Basically, one can affirm that C4 cycle plants are more suitable for bioenergy production. Table 1 presents a comparison of some parameters of interest for C3 and C4 photosynthetic cycles [Janssens *et al*. (2007)].

Table 1 **– Parameters of vegetable performance for the photosynthetic cycles**

Characteristic	C3 Species	C4 Species
Transpiration rate (kg of evaporated water per kg synthesized)	350 – 1000	150 – 300
Optimum temperature for photosynthesis (°C)	15 to 25	25 to 35
Site of photosynthesis	Entire leaf	External part of the leaf
Response to light	Saturates at medium radiation conditions	Does not saturate under high radiation conditions
Average annual productivity (tons/hectare)	~ 40	60 to 80
Climatic aptitude	Temperate to tropical	Tropical
Examples	Rice, wheat, soy, all fruits plants, oleaginous plants, and most known vegetables	Corn, sugarcane, sorghum and other tropical grasses

Source: Janssens et al. (2007)

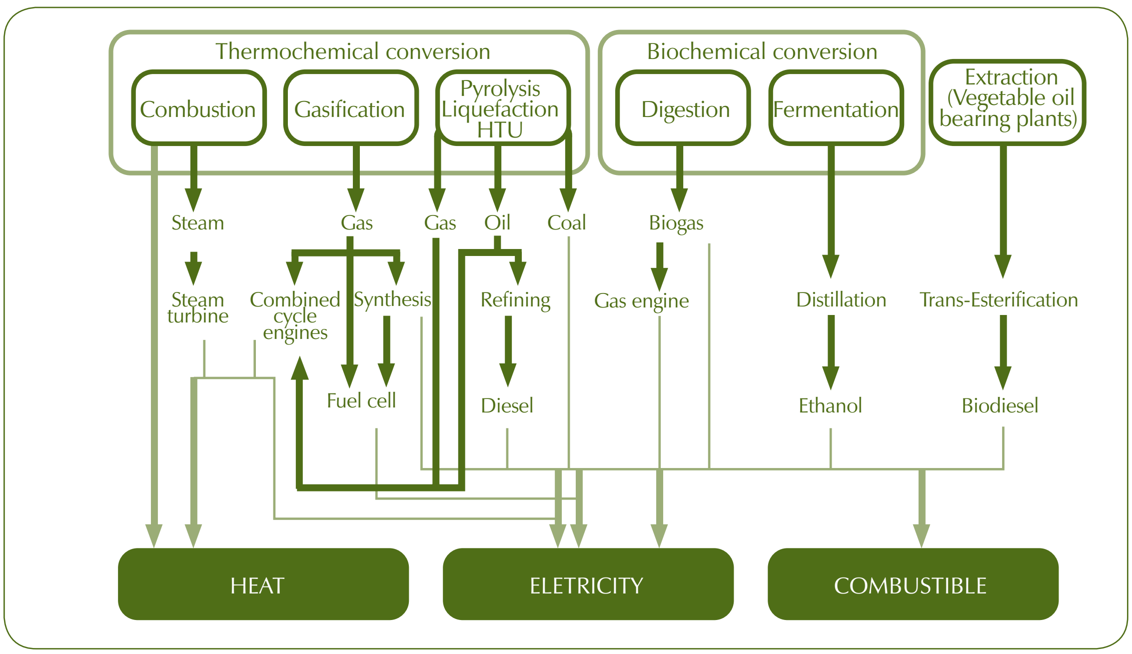
It is estimated that only about 0.1% of the solar radiation falling on Earth (ie, 180 out of 178,000 terawatts or billion kilowatts) is used in the photosynthetic processes, either natural or man-induced. The annual production of biomass on earth is approximately 114 billion tons, which on a dry basis corresponds to approximately 1.97 billion TJ (terajoules or billion kilojoules), or 314 trillion barrels of petroleum, around ten thousand times the current world consumption of this fossil fuel. In this context, average solar energy assimilation efficiency (AE) is less than 1%, although high performance plants such as sugarcane may achieve an annual AE average of 2.5% [Smil (1991)]. These values serve merely as a basis for understanding the energy magnitude of photosynthesis; it is not realistic, however, to imagine bioenergy as a substitute for all fossil forms of energy, especially in those countries with the largest energy demand.

Solar energy is fixed differently across plants. Moreover, differences in the substances and accumulation organs determine the technological paths that have to be used to convert biomass into end-use biofuels. In sugarcane, for example, energy reserves are located mainly in the stalks — as sucrose, cellulose and lignin — and have been used traditionally in the production of bioethanol and bagasse; however, sugarcane tips and leaves also attract a growing interest, for their lignocellulosic substrate. In trees and other ligneous species, by contrast, the energy content is essentially in the shaft (trunk plus branches), in the form of cellulose and lignin, and it is used basically as wood. The roots and tubers of plants such as cassava and beet accumulate starch and sucrose, while fruits and seeds such as oil palm and corn generally accumulate starch, sugar and vegetable oil, depending on the species.

Besides defining the optimal technological pathways for the conversion of biomass into biofuels, these aspects are relevant to the efficiency of global efforts to capture and use solar energy. For example, the synthesis of carbohydrates (such as cellulose and sucrose) in plants require around 60% less energy than that required for the synthesis of fats or lipids [Demeyer *et al*. (1985)], per unit of mass of final product. Theoretically, this makes biodiesel-associated pathways comparatively less efficient than bioethanol pathways using sucrose or cellulose.

Figure 3 summarizes several conversion paths that can be used to transform biomass into biofuels and useful heat. Besides purely mechanical processes for the concentration, compression or reduction of biomass humidity, two groups of chemical technologies are employed to alter the composition of the raw material to generate products that are better suited to their end uses: *thermo-chemical processes*, which use raw materials with low humidity in high temperatures; and *biochemical processes*, carried out in high water content conditions and ambient temperatures.

Figure 3 **– Technological routes for the production of bioenergy**



Source: Based on Turkenburg et al. (2000), in Seabra (2008).

1.2 Evolution of bioenergy and biofuels

Bioenergy, in its different forms, has been the main and in many cases the only exogenous energy supply used by mankind throughout history. Ligneous biomass was the quintessential energy source since the first primitive bonfires over 500 thousand years ago, meeting cooking and heating needs, while plant and animal fats used in candles and oil lamps provided a primitive source of illumination. Later on pottery and metallurgy became important sources of bioenergy demand, consumed in ovens and forges. The exploration of coal began only in the 18th century, when available wood reserves in a good part of Western Europe and, especially, England were getting exhausted. Coal exploration and the development of the steam engine were the triggering factors for the Industrial Revolution. If fossil energy — in the form of mineral coal — had not been available in abundant quantities and with relatively easy access at that time, modern history certainly had taken another course.

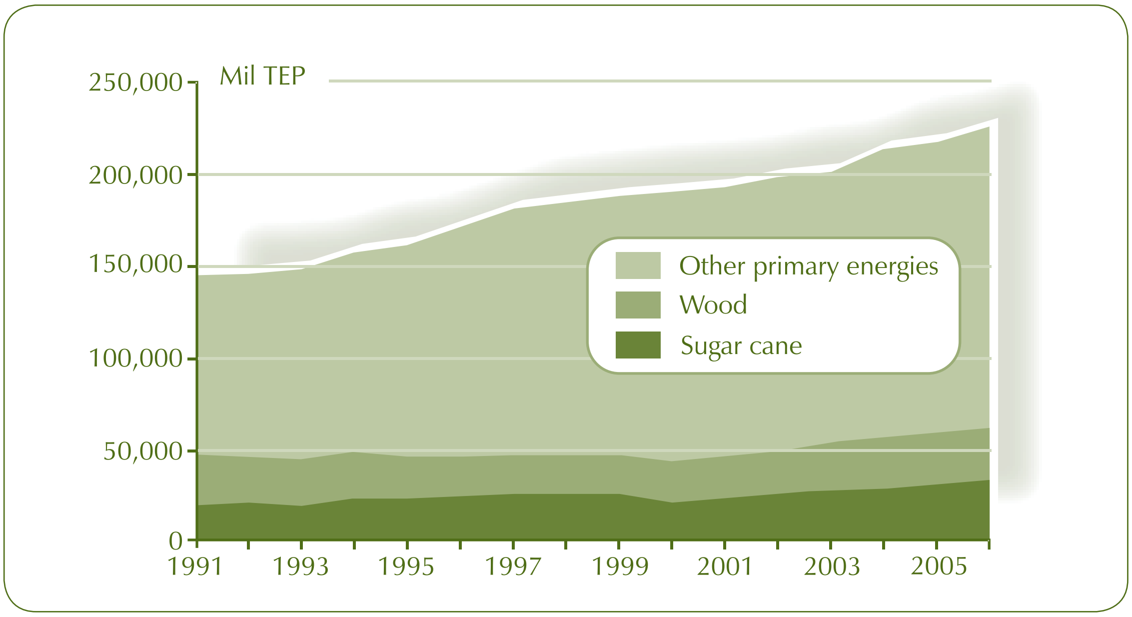
We have an interesting record of an economically important agroindustrial process sustained by biomass energy from Brazilian colonial times. According to Antonil (1982), during the 17th century the sugar mills of the *Recôncavo Baiano* had "*furnaces, burning day and night for seven months that require a lot of wood... (since) wood is feed for fire, and only Brazil could supply, with the immensity of the forest that he has, the wood that has nurtured for so many years, and will nurture in times to come, the many furnaces that burn in the sugar mills of Bahia, Pernambuco and Rio de Janeiro...* "[1]

It is curious to imagine what these sugar mills did with the bagasse from the processed sugarcane — whether they used it to feed the oxen which pulled the carts or it was destined for other purposes —, since this by-product could have constituted the basic energy source for the productive process, as it is in sugar and bioethanol plants today, even generating considerable surpluses of exportable energy.

As in other developing countries in tropical regions, the scale of bioenergy resources (eg, forests) in Brazil helps to explain why it was only after 1915 that fossil fuels began to be used in a significant way in the sugarcane industry and why wood remained a more important energy source than oil until 1964 [Dias Leite (2007)]. In fact, wood remained as the main fuel in Brazil until past the mid-20th century. It was used in railroad locomotives (which were practically the only means of transporting cargo across long distances), in boats on the Amazon River and *gaiolas* [*steamboats*] in the São Francisco River, and even to generate electricity in isolated systems using *locomóveis* (sets of simple steam engines and small furnaces). Graph 2 shows how the Brazilian domestic energy supply evolved over the past few decades and the relative contributions of sugarcane and wood as sources of bioenergy. As recently as 2007, these bioenergy sources accounted for 16.0% and 12.5%, respectively, of the total energy consumption in the country [MME (2008)].

1 As fornalhas, que por sete meses ardem dia e noite, querem muita lenha... (pois) o alimento do fogo é a lenha, e só o Brasil, com a imensidade dos matos que tem, podia fartar, como fartou por tantos anos, e fartará nos tempos vindouros, a tantas fornalhas, quantas são as que se contam nos engenhos da Bahia, Pernambuco e Rio de Janeiro...

***Graph 2* – Bioenergy's share of the Brazilian energy supply**



Source: MME (2008).

Bioenergy-related data, particularly the portion of wood in energy statistics, is determined indirectly in most sectors, based on indicators such as the industrial production of pulp and paper and the number of household firewood stoves. Recently, the Energy Research Company (EPE) started a review of this methodology, aiming at improving the reliability of Brazilian statistics. In any case, surveys by the Brazilian Institute of Geography and Statistics (IBGE) have shown that wood is still an important household fuel. Around 3.5% of Brazil's 50 million households cook exclusively with biomass and more than 14% use a mix of wood and liquefied petroleum gas [IBGE (2005)]. Wood is still the main energy source in some agroindustries (eg, dairy products, meats, sweets) and in the pottery industry, especially small and medium size firms; however, such uses come increasingly from cultivated forests, which contributes to the generation of wealth in rural areas.

Planted forests in Brazil now cover an estimated 4.1 million hectares, of which roughly half is used as an energy source, mainly in the production of charcoal [FAO (2006)]. These reforested lands have expanded approximately 250,000 hectares per year; and combined with significant advances in the development of forestry technologies, have produced important gains in energy productivity. A significant part of the charcoal production — carried out mainly in the Eastern Amazon — and part of the industrial wood-related energy demand in the North-eastern region remains based on deforestation and predatory exploitation of native forests. Nevertheless, the use of wood in Brazil, in general, is viewed as a positive example of sustainability in various respects [FAO (2007a)].

Globally, and extrapolating data from the International Energy Agency (IEA), the demand for commercial energy (ie, that which passes through energy markets) was around 470 million GJ in 2007, the equivalent to 82 billion barrels of oil [Best *et al*. (2008)]. Approximately 88% of the total came from the consumption of fossil resources (ie, coal, oil and natural gas). The rest was obtained from bioenergy, hydroelectric energy, nuclear energy and, to a small extent, from other sources such as geothermal and wind energy. Bioenergy is clearly the most important among renewable sources, with an annual consumption (commercial and non-commercial) estimated at 45 million GJ [Best *et al*. (2008)]. It is still used worldwide in domestic firewood stoves, in ovens and boiler furnaces in many agroindustries, and as liquid fuels in a growing number of vehicles, mainly in Brazil and some industrialized countries.

Bioenergy systems pose a remarkable dichotomy between two competing bioenergy paradigms.

The first is a traditional paradigm, which consists of traditional systems practiced for thousands of years, where the use of biomass resources is extractive, often without appropriate appreciation of their economic value. In general, residential and traditional industrial needs are met through low-efficiency and low-productivity systems. Examples are the use of wood for domestic cooking in rural areas and the harmful production of charcoal associated with deforestation.

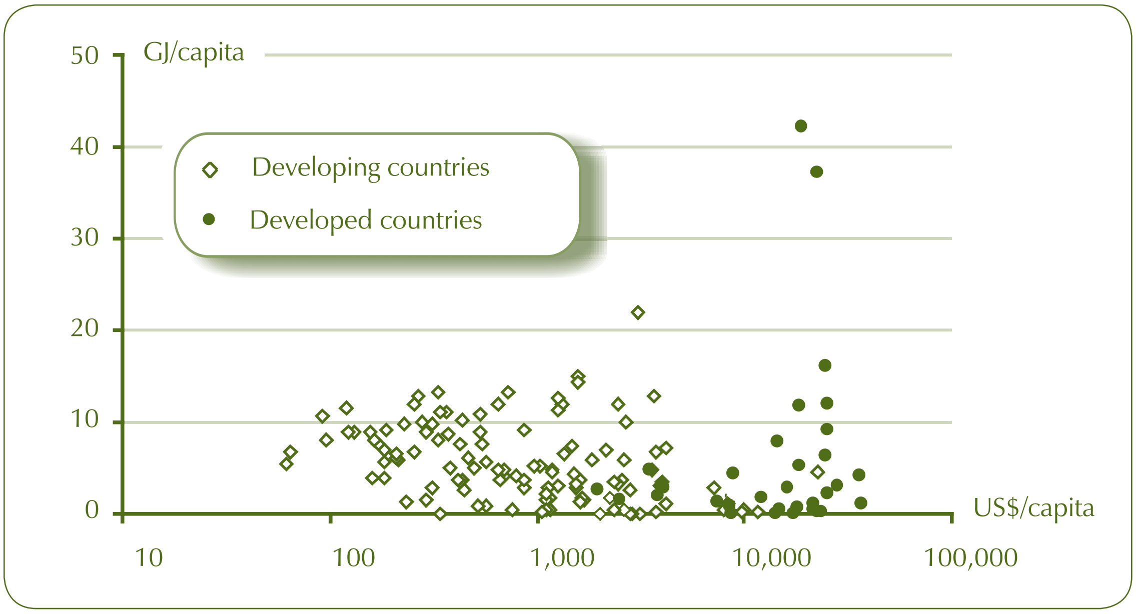
The second is the innovative paradigm of cutting-edge bioenergy systems. Production mostly occurs on a commercial basis, using environmental and economically efficient technologies to meet energy needs of the modern industry and transport sectors and to generate electricity. Some examples include the bioenergy chains of bioethanol from sugarcane, biodiesel from palm oil, oilseed and tallow, and bioelectricity from bagasse or cellulosic waste, among others.

The two paradigms now coexist and are illustrated in Graph 3, which depicts *per capita* bioenergy consumption (essentially based on ligneous resources) against *per capita* income, considering several countries. If only the clear diamonds are considered (corresponding to developing countries where traditional bioenergy is dominant), one would conclude that growth in income leads to a reduction in bioenergy use. In other words, the use of bioenergy is characteristic of poor countries. However, such hypothesis is not confirmed when high-energy use industrialized countries are included (the dark circles in the graph): the demand for bioenergy can be significant even in these countries, in many cases reaching higher levels vis-à-vis developing countries. Why is this the case? It turns out that bioenergy development differs between both groups of countries: in the first case it corresponds to the traditional paradigm; in second case it relates to the modern and innovative paradigm.

Sweden and Finland (the two dark dots in the upper right-hand corner in Graph 3) are the two most notable examples of the modern bioenergy paradigm. Both countries have high energy consumption ratios and — most notably — are located in cold-temperate regions, with low levels of sunlight and, therefore, low photosynthetic production. However, they have managed to sustainably produce significant quantities of bioenergy, achieving about

20% of their total energy requirements from biomass [Hall et al. (2005)]. Studies carried out by the US Departments of Energy and Agriculture project that by 2030 the annual production of biomass in the US for energy and industrial purposes will be of approximately one billion tons (dry base). This could reduce the estimated oil demand by 30% [DOE/USDA (2005)]. In these cases — just like in the modern production of biofuels — bioenergy is recognized as a renewable energy source obtained through modern conversion and production technologies, complying with sustainability requirements [FAO (2001)].

***Graph 3 – Per capita* bioenergy consumption vs. *per capita* income**



Source: FAO (1998).

Global bioenergy development is moving increasingly toward the reduction of traditional bioenergies within the energy supply; however, they can still be used in settings with limited energy and environmental impacts. On the other hand, modern bioenergies will expand and partially replace fossil energy sources. Bioenergy will be gradually regarded as a modern, competitive and appropriate energy source, capable of generating a new technological revolution. As Sachs (2007) predicts: *"Bioenergy is only a part of a broader concept of what is called sustainable development, a concept based on the triad of biodiversity, biomass and biotechnology, and which may serve as a starting point for the place biomass may occupy in the next decades."*

Undoubtedly, the modern innovative bioenergy paradigm is bound to replace the traditional paradigm, especially as new lignocellulosic technologies are developed (see Chapter 5 for the case of the sugarcane industry).

Chapter 2

Ethanol as vehicle fuel

No matter how it is produced — from biomass or petrochemical and carbochemical processes —, ethanol is a fuel that releases significant amounts of heat as it is burned. Nevertheless, ethanol is quite different from conventional fuels derived from petroleum. The main difference is in the high oxygen content, which represents 35% of the mass of ethanol. Ethanol's characteristics enable cleaner combustion and better engine performance, which contribute to reduce pollutant emissions, even when it is mixed with gasoline. In these cases, it behaves as a true additive for regular fuels, improving their properties. Notwithstanding the extensive experience with ethanol fuel in some countries, particularly Brazil, it is surprising how, in some countries where ethanol is not routinely used, prejudices and misleading information about the actual use conditions and the advantages associated with this fuel and additive persist.

This chapter seeks to present technical, economic, and environmental issues that are important for ethanol as a fuel in internal combustion engines, either in gasoline blends (anhydrous ethanol, that is, without water) or pure (hydrated ethanol). It discusses the main physical and chemical characteristics that define the specifications for ethanol and reviews its suitability and compatibility with the elastomers and metals most used in engines, highlighting the view of the auto industry on its use. Air emissions associated with the use of ethanol, as compared to gasoline, are analyzed. Also of interest to those considering using ethanol as a fuel, the chapter addresses generic legal terms for the use of ethanol for vehicular purposes, economic issues such as fuel pricing in markets where ethanol competes, and taxation mechanisms and logistics for fuel market incorporating ethanol.

2.1 Technical and environmental aspects of ethanol

Ethanol, or ethyl alcohol, represented by the molecular formula C_2H_6O, may be used as fuel in spark-ignition internal combustion engines (Otto cycle) in two ways, namely: 1) in gasoline and anhydrous ethanol blends; or 2) as pure ethanol, usually hydrated. Table 2 summarizes the main characteristics of ethanol and a typical gasoline. It is worth emphasizing that these properties do not refer to a strict specification covering several other properties and parameters related to safety, performance, contamination and chemical hazards. In the Brazilian case, specifications to be observed by producers and the entire distribution chain are set forth by National Petroleum Agency (ANP) Administrative Rule 309/2001 for gasoline with anhydrous ethanol, and by ANP Resolution 36/2005 for anhydrous and hydrated ethanol. In the Brazilian legislation they are referred to as anhydrous ethyl alcohol fuel (AEAF) and hydrated ethyl alcohol fuel (HEAF), respectively. According to that legislation anhydrous ethanol must contain less than 0.6% of water by mass, while for hydrated ethanol the content must be between 6.2% and 7.4%. These values correspond to a maximum content of 0.48% for anhydrous ethanol and a range of 4.02 % to 4.87% for hydrated ethanol when expressed on a volume proportion basis, at 20° C.

***Table 2* – Gasoline and bioethanol properties**

Parameter	Unit	Gasoline	Ethanol
Lower calorific value	kJ/kg	43,500	28,225
	kJ/litre	32,180	22,350
Density	kg/litre	0.72 – 0.78	0.792
RON *(Research Octane Number)*	–	90 – 100	102 – 130
MON *(Motor Octane Number)*	–	80 – 92	89 – 96
Vaporization latent heat	kJ/kg	330 – 400	842 – 930
Stoichiometric relation air/fuel		14.5	9.0
Steam pressure	kPa	40 – 65	15 – 17
Ignition temperature	ºC	220	420
Solubility in water	% in volume	~ 0	100

Source: API (1998) and Goldemberg and Macedo (1994).

In Brazil, for several decades now, the only types of fuel for internal combustion engines that can be found at all service stations are:

- regular and premium gasoline, with minimum average octane ratings of 87 and 91 (according to RON and MON methods, respectively) and both with an anhydrous ethanol content of 20% to 25%; these federal standards apply to all domestic and imported vehicles with gasoline engines, including luxury cars.
- hydrated ethanol, with an average octane rating higher than 110, for vehicles with engines suitable for this fuel or with flex-fuel engines, capable of using blends of gasoline with 20% to 25% hydrated ethanol content.

Pure hydrated ethanol must be used in engines manufactured or adapted specifically for this purpose, in particular those with higher compression ratios, which seek to use ethanol's higher octane rating (relative to gasoline) and achieve efficiencies on the order of 10%. In other words, ethanol's higher octane rating allows engines to obtain more useful energy vis-à-vis gasoline. Other modifications must be made in the fuel feed system and ignition, in order to compensate for differences in the air-fuel relationship, among other properties. Furthermore, modification of some materials that come in contact with the fuel are required, such as anticorrosive treatment of the metal surfaces of fuel tanks, fuel filters and pumps, substitution of fuel lines, and use of materials which are more compatible with ethanol. After decades of experience improving engines designed for ethanol, automotive technology has evolved to the point where vehicles using pure hydrated ethanol achieve similar performance parameters, drivability, cold start conditions and durability as gasoline engines, especially in countries with mild winters.

Incorporating extensive use of electronics in advanced systems that control fuel-air mixing and ignition, cars introduced in Brazil since 2003 use flexible or so-called "flex-fuel" engines which are capable of using, without any interference from the driver, gasoline (with 20% to 25% ethanol), pure hydrated ethanol, or mixtures of these two fuels in any proportion, while meeting standards of efficiency and drivability, and complying with the legal limits for exhaust emissions [Joseph Jr. (2007)]. Since 2005 vehicles equipped with flex-fuel engines have represented the majority of the new car sales in Brazil and cold-start systems have been improving in terms of performance and functionality. Currently there are over 60 different engine models produced by ten U.S., European and Japanese manufacturers operating in Brazil. It should be emphasized that the Brazilian approach to flex-fuel vehicles gives the driver complete discretion to choose the fuel to be used, from 100% hydrated ethanol to gasoline-ethanol blends containing 20% to 25% ethanol. In the United States, Canada and Sweden, vehicles with flexible engines are also sold, but under a different context: they use gasoline-ethanol blends ranging from pure gasoline (without ethanol) to a blend of 85% anhydrous ethanol and 15% gasoline, a product known as E85, with limited, but growing availability.

However, the simplest and fastest way of expanding the use of ethanol as a fuel is by using gasoline-ethanol blends in vehicles already on the road, without the need for modifying engines. This is an attractive option both for developing and developing countries. Developing countries because in many cases they can produce ethanol but currently depend on increasingly expensive fuel imports for their fuel supply. And developed countries because they currently have a limited capacity to produce cost-efficient ethanol with good energy and environmental balances, but can diversify their liquid fuels options by adding ethanol imported from regions with favourable conditions for biofuel production. Then, it is important to consider the consequences of adopting gasoline-ethanol blends on engine performance, drivability and durability of vehicles, as well as the associated environmental impacts.

Since the 1980s, the anhydrous ethanol content of all gasoline sold at service stations in Brazil has exceeded 20%. That same decade the United States also began using a gasoline-ethanol blend, known as E10, with ethanol content capped at 10%. The cap was favoured by the auto industry because it did not require changes in materials or components nor engine recalibrations. In recent years several countries, including China, Thailand, Australia and Colombia adopted E10 as a starting point for the introduction of ethanol in their markets. In such concentrations, ethanol acts as an octane booster and reduces pollution, replacing tetraethyl lead and other oxygenating additives facing imminent environmental restrictions (eg, MTBE), or whose use has already been banned in several countries. The experience of several countries with E10 allows us to affirm that this blend can be introduced to supply the existing vehicular fleet without requiring major changes.

Table 3 presents the modifications to vehicle engines required for different ethanol contents in gasoline [Joseph Jr. (2005)]. Note that the gasoline vehicles sold in Brazil (manufactured locally or imported) are designed to use local fuels with average contents of ethanol and already incorporate modifications in relation to a pure gasoline vehicle. In the case of flex-fuel engines, the American approach of using blends of up to 85% ethanol in gasoline is simpler than the Brazilian one, since it does not require an auxiliary cold-start system. It does, however, mean that such engines cannot use pure ethanol. In a near future, with the development of more advanced injection systems, there should be no need for auxiliary systems, and thus it may be possible for Brazilian engines to be simplified.

Table 3 **– Required modifications for vehicles using gasoline with different bioethanol contents**

% of bioethanol in gasoline	Carburetor	Fuel injection	Fuel pump	Fuel filter	Ignition system	Fuel tank	Catalytic converser	Basic Engine	Engine oil	Intake header	Exhaust system	Cold-start system
	Changes to a pure gasoline vehicle											
≤ 5%	Any vehicle											
≤ 10%		Vehicles produced from 1990 on										
≤ 25%	Brazilian gasoline vehicle											
≤ 85%	Flexible Vehicle used in the USA and in Canada											
≥ 85%	Flexible Vehicle used in Brazil											

No changes are necessary / Changes are probably necessary

Source: Adapted from Joseph Jr. (2005).

When ethanol is blended with gasoline, a new fuel is formed; some of its characteristics are distinct from the values determined by the direct measurement of the properties of each component, because of the non-linear behaviour of certain properties. While ethanol is a simple chemical substance, regular gasoline is itself a blend with over 200 different kinds of petroleum oil hydrocarbon derivatives. In the next sections we comment on the main properties of the gasoline-ethanol blends and their environmental behaviour.

Octane rating

Octane rating is a measure of a fuel's resistance to self-ignition and detonation. There are to main ratings, the Motor (MON) and Research (RON) methods, which permits to infer how engines fed with a particular fuel will behave in high load or steady load conditions, respectively. Ethanol is an excellent anti-detonating additive, and significantly improves the octane rating of the base gasoline. Brazil, the only country that adds ethanol to all its gasoline, was one of the first countries in the world to completely eliminate tetraethyl lead, and only occasionally resorted to the use of MTBE in a few regions during the 1990s. These additives are still used in some countries, but are associated with environmental problems and are being phased out.

As shown in Table 4, the addition of ethanol affects the RON octane rating more than the MON octane rating. It is also possible to see the importance of the base gasoline's composition and, consequently, its original octane rating on how the addition of ethanol impacts the octane rating. A general and clearly important rule is that the lower the octane rating of the base gasoline, the more significant the boost due to ethanol.

Table 4 **– Effect of bioethanol in the octane rating of base gasoline**

Composition of base gasoline			Increased octane rating with							
			5% de bioethanol		10% de bioethanol		15% de bioethanol		20% de bioethanol	
Aromatics	Olefins	Saturated	MON	RON	MON	RON	MON	RON	MON	RON
50	15	35	0.1	0.7	0.3	1.4	0.5	2.2	0.6	2.9
25	25	50	0.4	1.0	0.9	2.1	1.3	3.1	1.8	4.1
15	12	73	1.8	2.3	3.5	4.4	5.1	6.6	6.6	8.6
11	7	82	2.4	2.8	4.6	5.5	6.8	8.1	8.8	10.6

Source: Carvalho (2003).

Volatility

For a fuel to burn properly, it must be well mixed with air. Therefore, the vaporization capacity of a liquid fuel is an important property, which directly affects several performance parameters of the vehicle, including cold or hot start conditions, acceleration, fuel economy and dilution of lubricant oil. Thus, fuels derived from petroleum must have a balanced composition of light and heavy fractions, so as to produce a distillation curve in which the product starts to vaporize at relatively lower temperatures and ends at temperatures much higher than the ambient temperature. The addition of ethanol tends to shift the distillation curve, especially its first half, affecting the so-called T50 temperature — 50% of the mass evaporated — although the initial and final distillation temperatures are not significantly affected. In this regard, the addition of ethanol has limited impact on engine behaviour.

However, the addition of ethanol significantly affects steam pressure, an important property associated with volatility. Steam pressure determines the level of evaporative emissions and the possibility of steam forming in fuel lines, a problem which is minimized today with the use of fuel pumps inside the tank of most modern vehicles. It is interesting to note that, although the steam pressure of pure gasoline is higher than that of pure ethanol, as shown in Table 2, the addition of ethanol to gasoline raises the steam pressure of the blend. The increase typically presents a maximum of around 5% of the volume of ethanol in the gasoline, falling gradually as the ethanol content grows. For example, for a given composition of gasoline in which 5% ethanol is added, the steam pressure increased to 7 kPa, whereas, with 10% ethanol, this pressure goes to 6.5 kPa [Furey (1985)]. This effect can be easily compensated by adjusting the composition of the base gasoline, so as to ensure that the blend meets specifications. In Brazil and in other countries which have introduced ethanol as a gasoline additive, steam pressure has been specified at levels comparable to those of pure gasoline. In other words, the effect of ethanol on steam pressure can be readily controlled.

Performance

Given that gasoline-ethanol blends can be adjusted to meet the normal specifications of a pure gasoline, there are usually no performance and drivability problems, provided that the quality standards for fuels are maintained. Nevertheless, when compared to pure gasoline, a 10% ethanol blend needs 16.5% more heat to totally vaporize, which can be challenging in very low temperature conditions [TSB (1998)]. On the other hand, the higher vaporization heat required by gasoline–ethanol blends is one of the main reasons that the efficiency of an engine which uses such fuel improves 1% to 2% in comparison with the performance of pure gasoline. Therefore, even if a gasoline with 10% of ethanol contains 3.3% less power per unit volume, the final effect on fuel consumption is smaller and depends on particular driving conditions [Orbital (2002)].

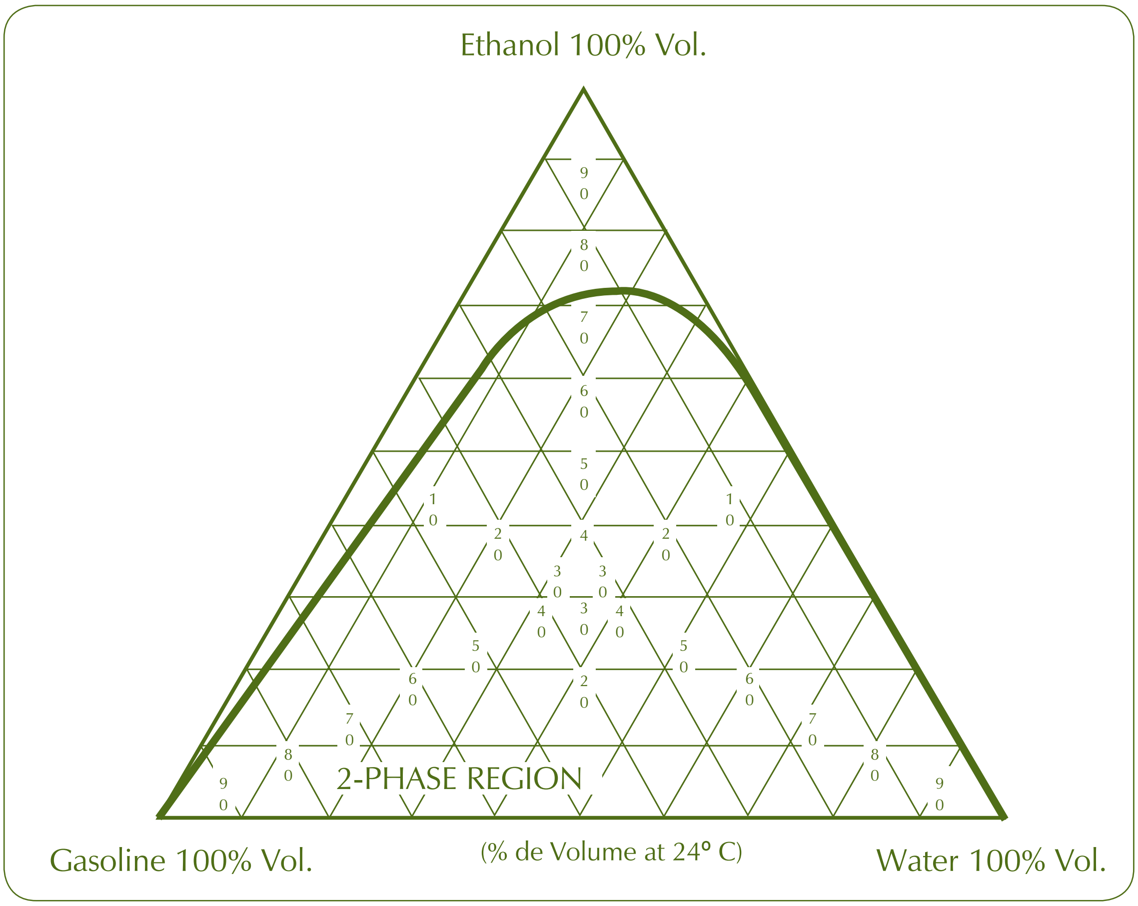
The relevant point is that in blends of up to 10% the effect of ethanol on fuel consumption is smaller than the variation in consumption from one driver to the next. Thus, in practical terms, one litre of these low ethanol content blends produces practically the same effects as a litre of pure gasoline [Salih & Andrews (1992) and Brusstar & Bakenhus (2005)]. For higher ethanol contents, such as a 25% blend, which corresponds to a 10% lower energy content per volume, one sees, on average, an increase in consumption of only 3% to 5% over pure gasoline. These results, confirmed in many field tests, suggest that ethanol, although displaying lower calorific power, allows an improvement in engine efficiency, thanks to lower intake temperature and a greater volume of combustion products. This effect is even more pronounced using pure hydrated ethanol, as long as the engine is properly adapted, by increasing its compression rate. Although it generates 40% less calorific power compared to gasoline, the final effect on contemporary engines is a 25% to 30% increase in fuel consumption relative to gasoline.

Over the intermediate term, the adoption of more advanced concepts in engine engineering, such as direct fuel injection, higher compression rates and intelligent turbo systems, may bring significant improvement in fuel economy in hydrated ethanol engines even outperforming the measures seen with pure gasoline [Szwarc (2008)].

Phase separation

The possibility of water phases separating from a gasoline-ethanol blend is frequently cited as an obstacle to greater acceptance of ethanol fuel. The concern is that somehow water is introduced with ethanol or condenses in the fuel tank of a vehicle, separating at the bottom and interfering with the normal operation of the engine. Strictly speaking, the more ethanol added to gasoline, the less this problem tends to occur. While pure gasoline basically does not absorb water, anhydrous ethanol does have an affinity for water. As shown in the ternary diagram in Figure 4, gasoline-ethanol blends have a capacity to dissolve water that is directly proportional to the ethanol content. The higher the ethanol content, the wider the range that defines the region where total solubility occurs, as observed in the upper part of the diagram. Under very low temperatures this effect is weaker but, generally speaking, ethanol acts as a co-solvent between gasoline and water, reducing the risk of separation of the water phase in gasoline.

***Figure 4* – Solubility of water in gasoline-ethanol blends**



Source: CTC (1998).

Because gasoline with ethanol presents a reasonable solubility for water and Brazil has mild temperatures, flex-fuel cars work without problems. There, cars can be filled with any blend of gasoline (with 20% to 25% of ethanol) and hydrated ethanol, whose water does not separate because of the ethanol already in the gasoline. If Brazilian gasoline did not have a high content of anhydrous ethanol, its mixture with hydrated ethanol would probably lead to phase separation, especially in temperatures lower than 18°C. Therefore, there is no reason to expect that the addition of anhydrous ethanol to gasoline will cause phase separation problems — it actually minimizes such issues.

Compatibility of materials

Some older plastic materials, such as natural rubber and butyl synthetic rubber, used in seals, hoses and filters tend to degrade more quickly when exposed to ethanol. Since 1980 these materials have been replaced by fluoroelastomers that resolve this problem. Table 5 presents the results of durability tests conducted by the British Army [Orbital (2002)], confirming the suitability of most of the plastics used today with ethanol. Still, one oil company addresses the following comment to its consumers:

> As far as our experience goes, there is no significant problem of compatibility of gasoline with oxygenates and elastomers in older cars. There was no increase in problems when gasoline with ethanol or MTBE was introduced in metropolitan areas in 1992, including regions with greater proportions of older cars [Chevron (2006)].

Table 5 **– Durability of plastic materials in bioethanol**

Plastic	Durability
Conventional Polyethylene	Acceptable
Polypropylene	Acceptable
Polymethylpentene (PMP)	Acceptable
Polycarbonate	Acceptable
Poly Vinyl Chloride (PVC)	Acceptable
High density polyethylene	Excellent
Polytetrafluorethylene (Teflon)	Excellent

Source: Orbital (2002).

As for metals, it is important to select them properly and to use protective coatings as they are always subject to corrosion under normal use conditions. Metals regarded as having low resistance to ethanol and its blends include pressure foundry alloys (Zamac type) and some aluminium alloys [Owen & Coley (1995)]. The aggressiveness of ethanol depends on its content in gasoline and it is associated, in particular, with the presence of water, organic acids and contaminants. The abrasion of metal components was extensively studied in gasoline blends with 10% ethanol and found to be no different from normal gasoline. In higher concentrations, there is a real concern about compatibility and corrosion problems. This explains why, during the 1970s, when Brazilian gasoline started incorporating higher levels of ethanol, various modifications to fuel systems were gradually introduced. Metal coating and protection processes, such as nickel and chrome plating, are currently common in the fuel tanks of Brazilian cars; the use of plastic materials in these components has increased as well.

The most effective way of reducing any compatibility problems with ethanol is by the proper specification of standards that establish maximum levels of total acidity, pH, electrical conductivity, as well as limits for some ions (chlorides, sulphates, iron, sodium and copper). That is why the proper definition and enforcement of biofuel specifications is crucial to a successful ethanol fuel program. Initiatives to standardize ethanol fuel specifications are important. A joint effort of Brazil, the European Union and the United States is underway, with promising results [Gazeta Mercantil (2008)].

Emissions of exhaust gases

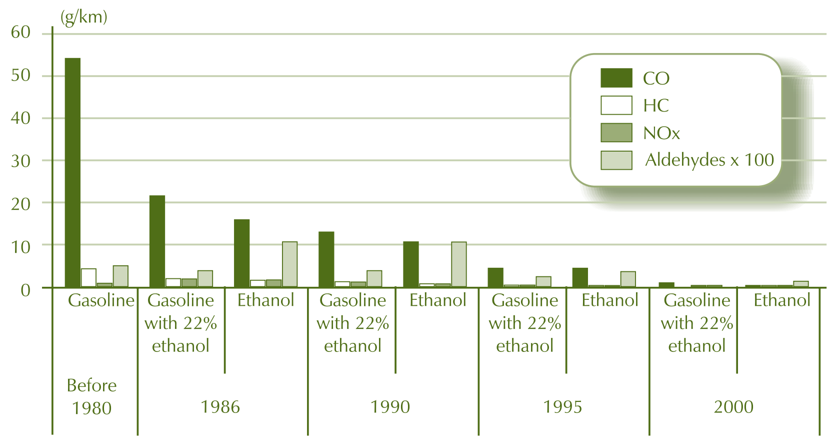
Because of its chemical composition, the combustion of pure ethanol and gasoline-ethanol blends produces lower emissions of carbon monoxide (CO), sulphur oxides (SO_x), hydrocarbons and other pollutants than regular gasoline. At the same time, there is an increase in aldehydes (R-CHO compounds) and, depending on engine features, nitrogen oxides (NO_x). Usually, car emissions are well within legal standards, a benefit of ethanol that is widely accepted.

It is important to note that the basic motivation for adding ethanol to gasoline in various regions in the United States, starting in the 1990s, was precisely the improvement of air quality associated with the oxygenation promoted by ethanol [Yacobucci & Womach (2002)]. As older car models are more polluting, the older the engine (ie, having a carburetor and no catalytic converter), the greater the environmental benefits of ethanol when compared to gasoline. Ethanol also causes less damage to the catalytic converter than gasoline, mainly because it has fewer contaminants, such as sulphur. Graph 4 displays how emissions of vehicles produced in Brazil have declined over the past decades due to technological advancements in engines and the introduction of ethanol [Ibama (2006)]. When analyzing the graph, note that aldehyde values are multiplied by 100, as they are very low.

Some studies have raised concerns about aldehyde emissions associated with the use of ethanol. These substances have carcinogenic potential and may be found in higher levels in the exhaust system of engines using ethanol. Fortunately, the use of catalytic converters — installed in US vehicles since 1975, and gradually incorporated in vehicles sold throughout the world, including Brazil since 1997 — reduce these pollutants to tolerable levels. Currently, the average emission of aldehydes in new Brazilian vehicles is 0.014 g/km for ethanol and 0.002 g/km for gasoline (the reference gasoline for emission tests contain 22% of anhydrous ethanol). Those levels are below the current limit of 0.030 g/km, as established in the Brazilian environmental regulation, as well as the stricter limit of 0.020 g/km, which will take effect in 2009 [Ibama (2006)]. Several measurements carried out in US cities, comparing air quality prior to and after large scale introductions of 10% ethanol in gasoline, did not find any significant increase in the atmospheric concentrations of aldehydes [Andersson & Victorinn (1996)].

Diesel engines are the greatest source of aldehyde emissions in urban settings [Abrantes *et al*. (2005)]. An extensive study carried out in Australia is quite conclusive: the addition of 10% ethanol to gasoline reduces CO emissions by 32%, hydrocarbon emissions by 12%, and aromatic emissions by more than 27%, reducing carcinogenic risk by 24% [Apace (1998)].

Graph 4 **– Evolution of gas emissions from new vehicles in Brazil**



Source: Based on Ibama (2006).

Use of ethanol in diesel engines

The same factors that make ethanol especially well suited for use in spark ignition engines found in most cars make it unattractive for compression ignition (diesel cycle) engines used in trucks and buses. The use of ethanol in diesel engines will require using co-solvents and additives which reduce the octane rating and increase the cetane rating and lubricating potential must be used, which often proves prohibitively expensive. Nevertheless, diesel engines adapted for ethanol are in use, particularly in Sweden, because of the environmental benefits; in fact, for over 18 years buses in Stockholm have been using 5% hydrated ethanol [Ethanolbus (2008)]. Results achieved by 600 buses operating in eight Swedish cities have been encouraging. Recently, a third generation ethanol diesel engine was launched commercially. The 270 hp 9-liter displayment, high compression (28:1) engine meets new European (Euro 5) standards for vehicular emissions [Scania (2007)]. The Bioethanol for Sustainable Transport (BEST) project is an experimental program supporting the use of ethanol in public transport in ten big cities around the world [BEST (2008)].

The use of ethanol in diesel engines has been promoted, primarily, for the environmental benefits. Thermal efficiency is comparable in diesel and gasoline engines (approximately 44%); however, diesel engines do not take advantage of a greater octane rating and consume 60% more fuel when ethanol is added to the diesel because of the calorific power difference.

Diesel cycle bus fuelled with hydrated ethanol in Madrid.

In Brazil, in the 1980s, several research projects on the use of ethanol in large engines were carried out. These projects explored whether additives could help ethanol work in diesel engines, and whether diesel engines could be "Ottolized" by adjusting the fuel system and introducing spark ignition systems. They generated a reasonable collection of studies, but without conclusive results [Sopral (1983)]. The sugar-ethanol industry's interest in developing this application is understandable. There are an estimated 100,000 diesel engines in trucks and agricultural machinery in Brazil's sugarcane fields and ethanol plants. By replacing diesel with ethanol, fuel costs could be reduced by half. The use of ethanol as an additive in high compression, electric injection engines seems to be the favoured approach [Idea (2008)].

Auto industry and users' views

Lastly, it is worth mentioning the Worldwide Fuel Chart (WWFC), a set of specifications for vehicular fuels prepared by trade associations of auto manufacturers in the United States (Alliance of Automobile Manufacturers – Alliance), Europe (Association des Constructeurs Europeens d'Automobiles – ACEA) and Japan (Japan Automobile Manufacturers Association, JAMA) and by the Engines Manufacturers Association (EMA), as well as their proposal to fuel producers [Autoalliance (2006)]. According to such proposal, the presence of up to 10% of ethanol is welcomed as an oxygenator for gasoline, with the explicit recommendation that the product fulfills quality specifications.

Today, virtually all car manufacturers — whether ethanol is present in the gasoline to be used or not — try to produce models capable of using the new fuels. To this end, car owner manuals emphasize the benefits of ethanol in gasoline: "Toyota permits the use of oxygenated gasoline with up to 10% ethanol. This fuel enables excellent performance, reduces emissions and improves air quality" [Toyota (2007)]. Although the WWFC limits its recommendation to

Ethanol in aircraft engines

Embraer Ipanema: a hydrated ethanol agricultural plane.

Hydrated ethanol is commonly used as a fuel for aircraft in the Brazilian country side, confirming the appropriateness and performance of such fuel in alternative engines. Since 2005, Embraer, the Brazilian aircraft company, has manufactured the Ipanema, an agricultural aircraft specially designed and licensed to use hydrated ethanol. Embrarer supplies kits for modifying gasoline engines to run on ethanol and it is currently developing flex-fuel systems for aircraft engines, aiming at meeting the requirements of small and agricultural piston engine aircraft. Currently, a fleet totaling 12,000 aircraft have ethanol engines [Scientific American Brazil (2006)]. The use of hydrated ethanol permits operational economies that reduce fuel costs per kilometer by 40% and increase engine power by 5% [Neiva Embraer (2008)]. This has encouraged the establishment of companies specialized in converting small aircraft to use this biofuel [Aeroálcool (2008)]. Several tests have been conducted on ethanol aircraft engines in the United States since 1980. In 1989 the Federal Aviation Authority (FAA) certified the first ethanol aircraft engine, the Lycoming IO-540 injected fuel. In subsequent years, the FAA certified the Lycoming O-235 carbureted engine and two aircraft, the Cessna 152 and the Piper Pawnee agricultural aircraft for using anhydrous ethanol with 5% gasoline (E95) [BIAS (2006)].

E10, some international initiatives in favour of blends with 20% of anhydrous ethanol (E20) are being discussed. For example, Thailand and the US state of Minnesota have proposed adopting a 20% ethanol blend. As a response to these trends, there are models already being sold in Thailand, such as the Ford Escape and the Ford Focus, compatible with E20. Ford acknowledges that the experience accumulated in the Brazilian market allowed the quick introduction of these models in the Thai market.

Broader use of ethanol as a gasoline additive faces serious misunderstandings in some countries where this technology could be implemented immediately as an alternative renewable energy and could serve as an important engine for local development. Consumer misinformation concerning the effect of ethanol on the durability and performance of their cars — devoid from any scientific foundation — has created a cultural barrier which must be overcome by providing clear and objective information to those who are interested. Ethanol is a good fuel and fuel additive, both for consumers and society. It has been unequivocally demonstrated in hundreds of studies that internal combustion engines run well on ethanol; but the main test comes from the millions of vehicles — from multiple countries, with heterogeneous fleets, and of various ages — that are currently working with renewable fuels without major problems in a variety of situations.

2.2 Economic and institutional aspects of fuel ethanol

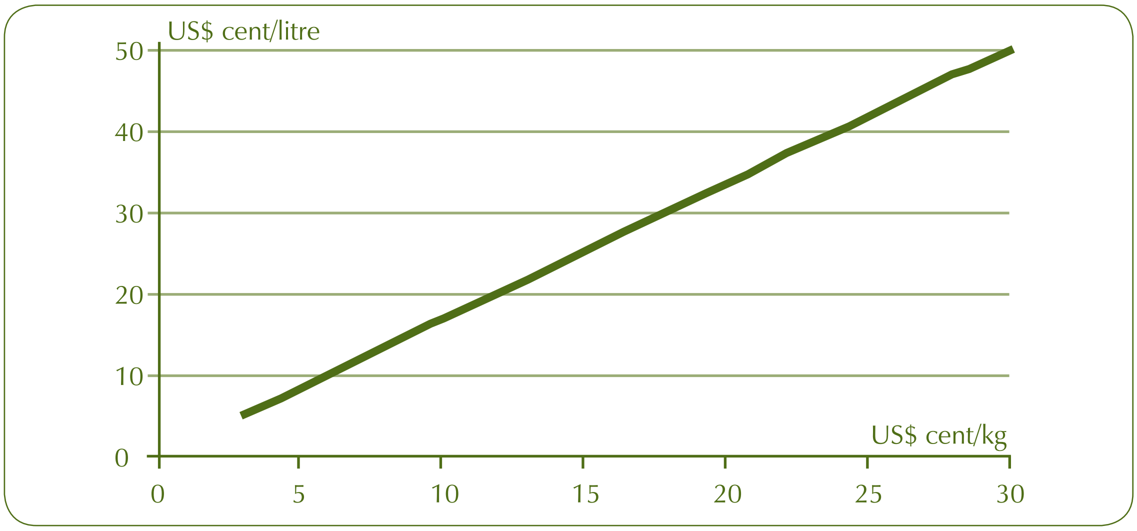
After reviewing technical aspects which make the case for ethanol as a fuel, it is important to explain how — in market terms — biofuel prices are calculated, especially bioethanol prices. In recent years and in most countries fuel markets have evolved into free markets, where prices are determined by local economic forces or mirror more competitive markets, so called parity pricing. Within this scenario, bioethanol consumer prices are determined by the producer's costs, which, in turn, are determined by production and logistics chains, including tax and sale margins. This analysis is crucial for determining if bioethanol is viable and how it would impact the market.

As we will see in the next chapter, bioethanol can be produced from a wide range of raw materials, each with its corresponding production and market opportunity cost, both used in determining bioethanol prices. Therefore, the minimum price producers will want to charge for their bioethanol should meet two conditions: a) cover production costs, which obviously include raw material and plant operational costs, as well as capital costs corresponding to production investments; and b) be equal to, or higher than the price that could be obtained if the raw materials were used in the best manufacturing alternative. Sugar and molasses are among the alternative products that sugarcane can be used for, the latter a by-product of the sugarcane industry that has value as an industrial input or as animal feed.

According to the chemical equations for transforming sucrose into bioethanol, 1 kg of sugar can theoretically produces 0.684 litres of anhydrous ethanol. Considering typical fermentation and distillation yields of 90% and 98%, respectively, we obtain the correlation indicated in equation 2 and depicted in Graph 5, a indifference curve which enables us to estimate an indifference price for anhydrous ethanol price (PIEa) for a given market price of sugar (PAç):

$$\text{PIEa (\$/litre)} = 1{,}67 * \text{PAç (\$/kg)} \tag{2}$$

Graph 5 **– Indifference price curve for anhydrous ethanol price according the price of sugar price**



Source: Elaborated by Luiz Augusto Horta Nogueira.

Equation 2 considers only the value of sucrose and excludes the costs related to other investments and operation of the production plant. Nevertheless, the indifference price is an important value for the producer: it only makes sense to produce bioethanol if it can be sold at prices higher than the price of sugar. This reasoning, however, does not always hold; for example, when the sugar market is saturated. In such scenario producing more sugar would not be as profitable as producing bioethanol because sugar prices would tend to decline due to an excess supply.

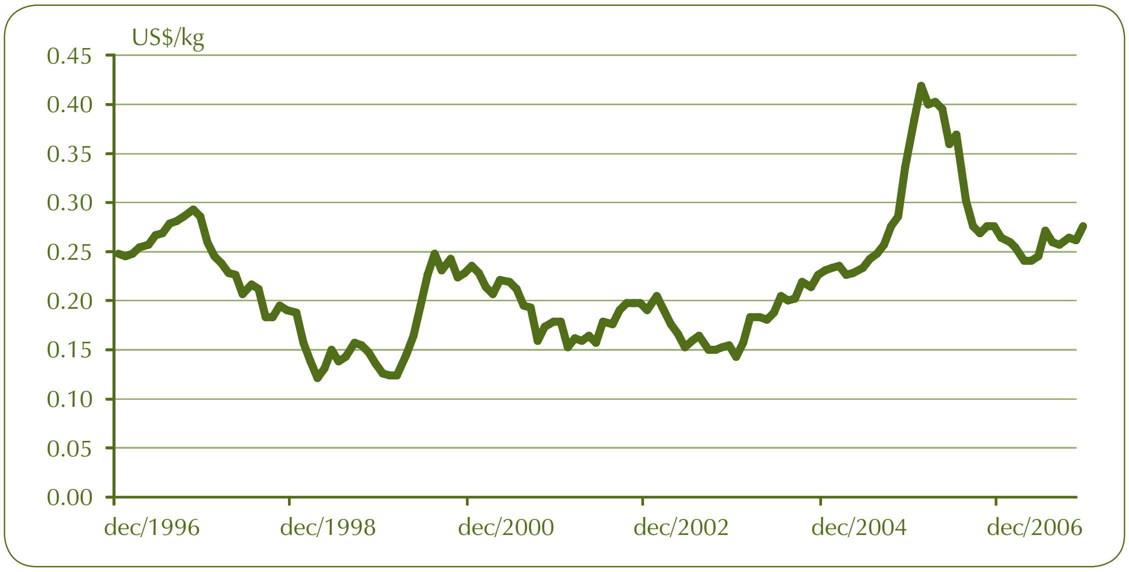
The use of molasses — a sugar by-product — for bioethanol production can be subjected to a similar analysis, which should favour bioethanol since the price of molasses is always lower than the price of sugar. The availability of molasses is directly related to sugar production and because of lower ethanol yields may be inadequate for large scale bioethanol production. While one ton of raw sugarcane juice produces 80 litres of bioethanol, one ton of molasses by-product produces 12 litres of ethanol, in addition to the sugar. Therefore, in most sugar-producing Latin American countries molasses could be an important source of bioethanol and a way for them to begin to meet domestic fuel needs. For example, Central American countries could produce — without cultivating one additional hectare of sugarcane — 22% of the bioethanol needed to introduce 10% ethanol to the gasoline currently imported by these countries, just by using molasses [Horta Nogueira (2004)].

Obviously, any viability assessment of bioethanol production should consider other factors, such as commitments and market strategies, in addition to fluctuations in the price of sugar and other commodities. Another unavoidable issue is the relative rigidity of international sugar markets, in which sizable volumes of product are traded within quotas and prices that do not reflect supply and demand pressures. Several developing countries expect that these distortions will be gradually reduced and that greater efficiency and realism will be introduced to the sugar market. A recent World Bank study modeled how sugar prices would respond if price controls were abandoned, using several market scenarios, and estimated that average sugar prices would increase by only 2.5%. The most important benefits would accrue to countries in Latin America and sub- Saharan Africa [World Bank (2007b)].

Two important factors that directly influence international sugar prices are: a) preferential contracts with the United States — ie, quotas set forth by the US Department of Agriculture — with prices determined by No. 14 Contracts of the New York Board of Trade (NYBOT), and with Europe under the terms of the Africa, Caribbean and Pacific (ACP) and Special Protocol Sugar (SPS) agreements, which set quotas to sugar-producing countries; and b) free or excess contracts, that may follow the prices of No. 5 Contracts of the London Stock Exchange or No. 11 Contracts of the NYBOT. Although these contracts determine international reference prices — based on electronic operations in such commodity exchanges — preferential contracts reflect higher prices in smaller markets. Graph 6 displays the behaviour of sugar prices according No. 11 Contracts of the NYBOT for the last ten years, when prices experienced significant volatility with a modest increase in the average price.

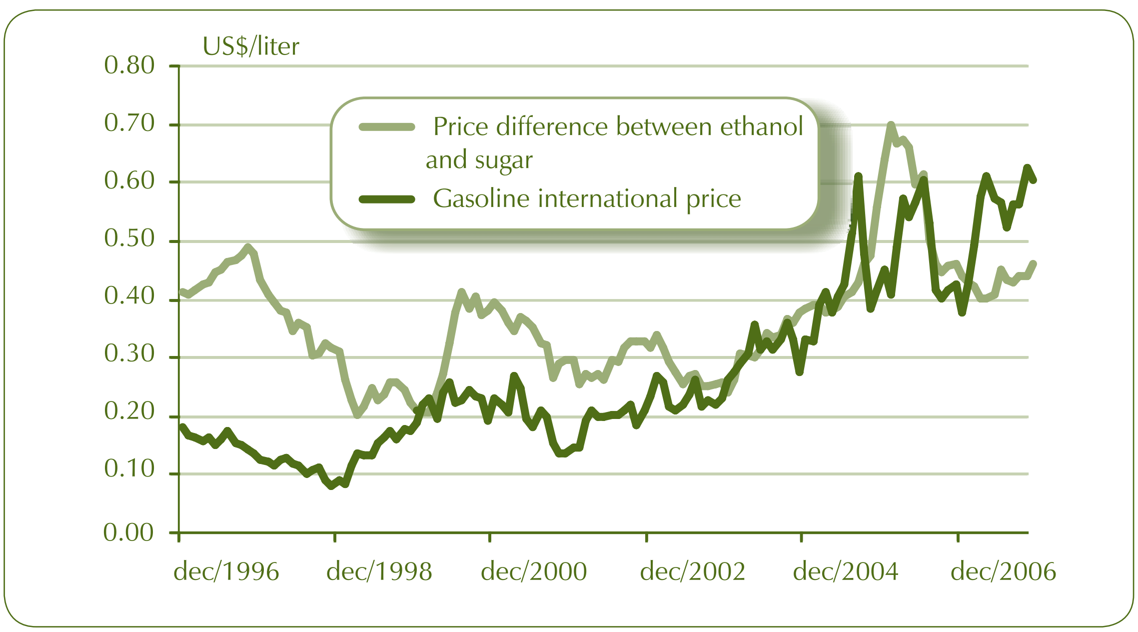
Using the prices shown in Graph 6 in the equation presented above, it is possible to estimate the minimum price that makes bioethanol attractive, ie, the price at which producers opt to use their raw materials in the production of biofuel. Considering that in blends of up to 10% one litre of ethanol produces the same effect as one litter of gasoline, as previously discussed, indifference prices can be directly compared with wholesale gasoline prices (excluding taxes) in the international market. Graph 7 displays this comparison, using the market price of regular gasoline defined by US Gulf Coast Conventional Gasoline Regular Spot Price FOB as the parameter for gasoline.

***Graph 6* – International sugar price (NYBOT Nº 11 Contracts)**



Source : NYBOT (2008).

***Graph 7* – Indifference price for ethanol vs. sugar in the international market**



Source : Calculation based on data collected by the NYBOT (2008) and EIA (2008).

The curves in Graph 7 display the evolution of the attractiveness of producing sugarcane bioethanol as a fuel additive for the ten year period between 1997 and 2006. Two stages can be identified: before and after 2003. Before 2003 gasoline prices were almost always lower than bioethanol's opportunity cost, calculated using the international price of sugar. During this period bioethanol production required subsidies most of the time to make it financially attractive. These subsidies were justified by the positive externalities provided by bioethanol: lower atmospheric emissions, the creation of jobs, and reduction of the dependency on imported energy supplies. After 2003 the two price curves have evolved more closely and, except for some months in which the gasoline price was cheaper, bioethanol production became more profitable than the production of sugar at international prices. In this context, it is expected that the costs of bioethanol production will be recovered and that bioethanol will become a profitable product.

Some important caveats must be mentioned concerning this rationale. First, most countries do not use international gasoline prices as the basis for pricing, especially countries that import gasoline. In such countries, domestic prices incorporate marine freight and additional costs of importing, which increases the gasoline price. By the same logic, international sugar prices are not the best reference for the opportunity costs of sugarcane production since they do not take into account the discounts that are often applied to sugar exports. The previous analysis did not consider low-cost raw materials such as molasses that make bioethanol production possible at lower costs. On the whole the rough comparison in Graph 7 shows that bioethanol is becoming more attractive for producers, thus attaining the necessary conditions to challenge the gasoline market, according to Baumol (1982). Furthermore, it is worth noting that the bioethanol market has a large potential for expansion, which is not true for the sugar market.

Appendix 3 presents the prices paid to producers for both anhydride and hydrated ethanol in the State of São Paulo, Brazil, from 1975 to 2006. These data show that biofuel prices, net of taxes, were similar to gasoline prices; thus, the adoption of bioethanol as an additive to gasoline did not significantly influence prices to the final consumer.

While the price floor for bioethanol producers is determined by the higher value between the production costs and the opportunity costs of alternative agroindustrial applications of the same raw materials, the price ceiling is strictly related to market conditions, in the absence of market intervention. As expected, bioethanol producers seek to maximize their profits and offer their products for the highest possible price. Their behaviour will be tempered by the other producers and possibly by importers, who will limit their margins to more reasonable levels. This highlights that bioethanol markets should be competitive, even if that means opening markets to imports, to prevent monopolistic practices and to promote lower prices.

The chances of bioethanol entering a nation's fuel market are poor without clear government support. Government officials with an understanding of the significance and benefits of bioethanol, and with a strategic vision, should define goals and coordinate efforts. The introduction of anhydrous ethanol as an additive to gasoline is an initial and essential first step to eventually using pure bioethanol as a fuel. Several points are absolutely essential for success. First, in relation to the fuel market, the Government must set forth specifications for bioethanol and define the content of bioethanol to be blended into gasoline. These measures must be implemented gradually, possibly starting with partial geographic coverage, but contemplating that over the intermediate term they will apply to all regions and all types of gasoline. The recent successful experiences in Colombia and Costa Rica, for example, provide a model for timetables and procedures [Horta Nogueira (2007)]. Often, determinations regarding the use of bioethanol in gasoline require legislative and regulatory changes; however, in many countries the removal of tetraethyl lead, addition of MTBE and reduction of benzene and sulphur contents were achieved with administrative standards and resolutions and executive decrees.

The second crucial issue requiring Government's attention is to set forth a specific taxation policy for bioethanol that, while respecting fiscal neutrality, recognizes the benefits to society of substituting gasoline with bioethanol. In this context, a differentiated form of taxation is advocated, one that provides the needed stimulus to overcome concerns and perceptions of risk, promotes a dynamic market in which agents in the fuel production and distribution sector move forward, and that makes consumers active players in the adoption of bioethanol.

Once again it is useful to describe the recent experience of countries in which bioethanol use has been implemented. All these countries successfully adopted taxation schemes that were neutral or attractive for retail consumers of bioethanol. Even though — as is observed throughout the energy sector — the significant asymmetry in the information available to sector players versus the government makes it difficult to clearly define costs, the maturity in the bioethanol market in several countries and in the fuel market, in general, makes the creation of a robust taxation system possible. In this context, it is important to highlight the importance of relating bioethanol production to local development by encouraging upstream and downstream activities in agro-industrial production, the creation of jobs and increases in disposable income, etc., as well as generating foreign currency savings for oil importing countries, or export revenue increases for ethanol exporters.

Once the decision to add bioethanol to gasoline is made and the legal conditions that make it compulsory are established, tax rate adjustments are generally unnecessary provided that the gasoline price will include bioethanol as one of its cost components, often a marginal one. Nevertheless, fuel taxes and fees can be important instruments of energy policy and should be used to foster the consistent implementation of bioethanol fuel use.

It is also important to note that in cases like Brazil, where the bioethanol market has already achieved the commercialization of hydrated ethanol and has a significant fleet of flex-fuel vehicles, regulatory and taxation mechanisms necessarily are more complex and pricing is subject to other factors and conditions. For instance, within limits, in recent months the price of bioethanol in Brazil has been defined by the price of gasoline, serving as a price ceiling that producers must respect to protect their consumer market. This market has a growing number of flex-fuel vehicles, which can switch to gasoline when the retail price per litre exceeds 70% of the price of gasoline at service stations. The price of bioethanol also constrains increases in the price of gasoline because consumers who occasionally use gasoline will abandon it if bioethanol is sold at a more appealing price. The decision exercised by the consumer considers the final costs associated with the use of fuels, which in turn reflects differences in fuel consumption per kilometre traveled. This ability to switch among substitutes acts as an effective stabilizer of fuel prices in Brazil, even during periods when petroleum prices rise.

2.3 Ethanol logistics chains

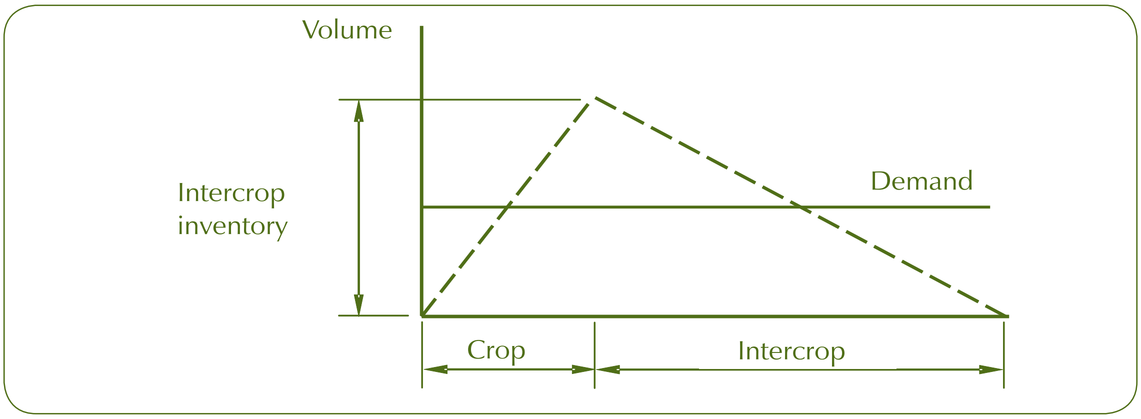
After discussing the technical and economic conditions necessary for promoting ethanol use, we turn to the infrastructure and logistics requirements for implementing ethanol effectively. Many counties understand that ethanol should and could be part of the energy matrix, but point to infrastructure barriers and a lack resources for resolving them.

In general, conditions for transporting and storing ethanol, whether pure or blended into gasoline, are not significantly different from the ones used for petroleum-made fuels. There are, however, at least three important factors to consider: the seasonality of ethanol production, the geographic distribution of this production, and the compatibility of tanks and pipeline materials that will be in contact with ethanol and its blends. These subjects will be discussed next, considering the sugarcane-based ethanol agroindustry.

Only during the months of the sugarcane harvest there is a sufficient quantity of raw material for producing ethanol. But, ethanol is consumed year-round and sugarcane has poor storage characteristics. This poses a challenge: manually collected sugarcane can be stored for only few days; mechanically harvested sugarcane, which is chopped, can be stored for only several hours. Then, the duration of the sugarcane harvest is important. More prolonged harvests are desirable as they permit better use of existing production capacity and minimize the need for storage during the intercrop period. In this regard, bioethanol production from corn or dried slices of cassava has the advantage that these raw materials can be stored.

A simple model representing the relationships between production capacity, inventories and demand for bioethanol is shown in Figure 5, demonstrating how bioethanol stocks are generated and consumed during the intercrop period. The capacity for producing in excess of consumption to supply the intercrop demand corresponds to the slope of the production curve during the harvest, and graphically demonstrates the impact of the duration of the harvest. Based on this model and considering a annual demand of one million cubic meters of bioethanol, by extending the harvest period from 150 days to 200 days, the tank storage capacity required to meet a constant demand would be reduced from 589 thousand litres to 452 thousand litres, ie, a reduction of 23% in storage capacity. Similarly, extension of the harvest would make possible the reduction of daily production capacity from 6600 litres to 5000 litres, a better match of market demand.

Figure 5 **– A model of ethanol production, storage and demand**



Source: Elaborated by Luiz Augusto Horta Nogueira.

These numbers are theoretical exercises. In fact, in addition to monthly variations in production and demand, several factors of uncertainty — notably weather-related ones — point out to the need of maintaining safety inventories to cover supply contingencies. Thus, generally, as the harvest starts there are still bioethanol inventories from the previous harvest.

An important way for dealing with uncertainty in the supply of bioethanol destined for blending with gasoline is to vary the bioethanol content according to its availability, within the range in which the combustion engines do not present problems. These procedures are used routinely by Brazilian authorities to manage bioethanol inventories by adjusting the bioethanol content in gasoline between 20% and 25%, as necessary.

Since bioethanol production is geographically dispersed in rural regions, has a distinct seasonality, is susceptible to weather conditions, and needs to be blended to gasoline, it requires a logistic infrastructure more complex than that for petroleum-related products. Handling significant amounts of bioethanol — with quality assurance (especially with regard to water content and impurities) and with no adverse impact on the facilities also used to distribute other products — requires proper planning and accurate design of systems and processes, so as to allow functionality with acceptable costs. In Brazil, bioethanol inventories maintained by distributors are enough for one or two weeks of consumption, being replenished regularly by producers, with no significant problems.

It is important to understand how bioethanol is stored and transported in Brazil, where almost two million cubic meters of the product are handled monthly. More than 350 production plants rely on a temporary storage network and several modes of transportation [Cunha (2003)]. Nine bioethanol collection terminals dot the main producing regions in the states of São Paulo, Goiás, Paraná and Sergipe, with a collective storage capacity of 90,000 cubic meters. Bioethanol from production plants is collected by trucks and then transferred via more economical modes of transportation — such as rail, ship or pipeline — to the collection terminals or distribution facilities, where it is blended with gasoline. Gasoline blended with bioethanol is then transferred to secondary distribution facilities or directly to 35,500 service stations of several national and multinational brands, again by different transportation modes, using whatever is available or most convenient, as summarized in Figure 6.

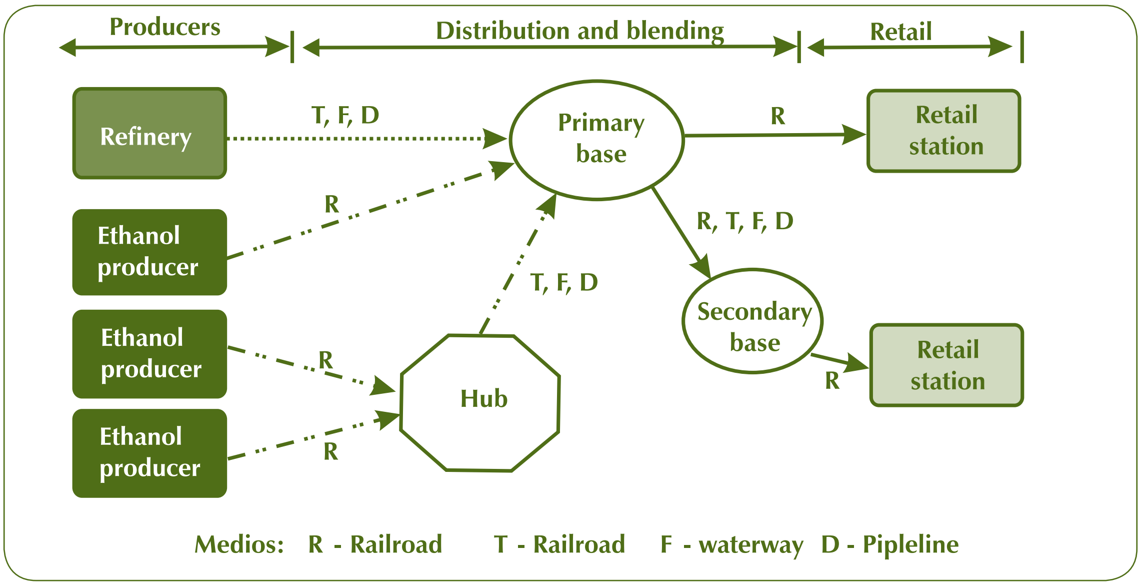
Even with so many transportation options, 70% of the bioethanol sold in Brazil (including hydrated bioethanol) is transported from production to distribution centers and from these facilities to the service stations using tanker trucks, with capacity of up to 30,000 litres. Not all anhydrous ethanol produced passes through collection terminals; part of the production is transported using more direct routes, principally in more remote regions or in minor markets. Nevertheless, it must pass through primary distribution center for blending with gasoline, an exclusive responsibility of fuel distributors.

The Brazilian option of authorizing the blending of anhydrous ethanol with gasoline only by distributors was chosen basically to simplify tax collection; nevertheless, blending could be done at production plants, refineries or even at service stations. There are, however, other important justifications, such as the decentralization of bioethanol production and the proximity of the distribution centers, as well as the need for relying on a clear and unequivocal assignment of responsibilities, a critical issue when it comes to fuel quality standards. In short, the operational model used in Brazil clearly establishes that refineries produce gasoline, *usinas* produce anhydrous ethanol and fuel distribution companies carry out the blending of these two flows. The distributors are then responsible for assessing the products they receive (gasoline and bioethanol) and ensuring the quality of the product they delivers. Other operational models may be set forth, but it is fundamental that the chain of responsibilities for fuel quality is well-defined and monitored properly by the National Petroleum Agency (ANP) [ANP (2008)].

In practical terms, the gasoline-bioethanol blend is prepared at the distribution centers in large capacity tanks — that are fed continuously with gasoline and bioethanol, with strict control of the blending process and quality — or in the tanker itself, since movement during transportation ensures the necessary homogeneity of the fuels after a few minutes of normal transit. The last way of preparing gasoline-ethanol blends is known as *splash blending* and can be carried out at low cost. Measurement of the ethanol content in the blend is performed quickly and accurately by means of a rather simple and direct method: absorption of the ethanol present in gasoline by blending it with salty water and measuring the corresponding volumes with a graduated glass tube. This quick procedure, also used in gas stations, is standardized by the Brazilian Technical Standards Association (ABNT) NBR 13,992: *Gasolina*

Automotiva – determinação do teor de álcool etílico anidro combustível (Automotive Gasoline — determination of the content of Anhydrous Ethyl Alcohol Fuel), revised in 1997.

***Figure 6* – Gasoline and ethanol logistics in Brazil**



Source: Elaborated by Luiz Augusto Horta Nogueira.

In Costa Rica the cost of adapting tanks and introducing blending and control systems at four distribution bases for the introduction 7% bioethanol in the gasoline (a production of 60 million litres of bioethanol per year) was estimated at US$ 5 million, or 3% of what the country spent to import fuels in 2006 [Ulate (2006)].

Pipelines may be the recommended means of transportation for moving large volumes of bioethanol or gasoline with bioethanol, but some operators argue they should not be used for ethanol. Ethanol is potentially corrosive, acts as a selective solvent and absorbs more water than petroleum products therefore, it requires additional measures, such as the regular inspection of pipelines and careful cleaning to avoid clogging. These problems, however, have been overcome and pipeline is a mode of transportation increasingly used for biofuels in Brazil and United States [API (2007)]. In Brazil, Petrobras has acquired considerable experience handling ethanol, transporting several million cubic meters annually. More than 200 technical reports and more than 40 operating procedures about technical issues in bioethanol logistics within the context of the oil industry have been published. According to the company, in thirty years of operating pipelines with large volumes of bioethanol stress corrosion cracking (SCC), a potential risk related to this product, has not been observed [Gomes (2008)].

Several projects are currently being developed in Brazil to expand pipeline capacity for bioethanol, foreseeing the day when there are long distance pipelines dedicated exclusively to exporting bioethanol. In the US one large operator of oil pipelines, Williams Energy Service, reports that it regularly transports gasoline with bioethanol through its lines without problems [Whims (2002)], and it is launching projects for exclusively for bioethanol pipelines [Mears (2007)].

Logistic aspects should be considered important for the successful development of bioethanol fuel programs. The issues vary from project to project, but specific solutions have been successfully implemented, always associated with detailed planning. Problems encountered in settings as different as the United States [Keese (2003)] and India [Balaji (2002)] during the introduction of bioethanol a few years ago were basically associated with logistic constraints, ie, the lack of adequate infrastructure to transport and store biofuels. The lesson of such experiences is that programs should be implemented in steps, progressively expanding capacities to gradually win the confidence of the market and consumers.

The two critical success factors that distinguish the Brazilian bioethanol experience are the wide geographic coverage and the great number of service stations that sell the product. Today, all 35,500 service stations in the country sell hydrated bioethanol and gasoline-bioethanol blends. Except for aviation fuel, pure gasoline is no longer commercialized at the retail level anywhere in the country. The development of this notable distribution infrastructure resulted from efforts initiated in the early days of the Proalcohol program and was consolidated over time. It is important to emphasize that the Brazilian experience with bioethanol would not have been successful without the political will to create such infrastructure and without the support of fuel distribution companies and Petrobras, which for many years was responsible for the purchase, blending and distribution of pure bioethanol mixed with gasoline.

Chapter 3

Bioethanol production

Biofuel production based on vegetable feedstock can be made through different technology routes — similarly to alcoholic beverages —, subject to dissimilar advantages and limitations, as shown in Table 6. Bioethanol is clearly at a more advanced development stage than biodiesel and it has been more effectively included in the energy matrix of several countries. In 2006 bioethanol represented an energy supply of around 3% of the world gasoline demand, that is, ten times the concomitant biodiesel production [EIA 2008].

This chapter reviews issues of biofuels production from different biomass sources. The chapter starts with a discussion of the main feedstocks and production technologies (Section 3.1), followed by a broad view of the agricultural and industrial stages of production in each case, addressing significant circumstances and current and prospective productivity indicators. In this regard, sugarcane (Section 3.2) and corn bioethanol (Section 3.3) production systems will be analyzed in detail, as they account for the major share of global biofuels production. The chapter also discusses, but to a lesser extent, bioethanol production systems of other feedstock, such as cassava, wheat, beet and sorghum (Section 3.4). The chapter closes with a review of productivity, emission and energy balance issues (Section 3.5), which focuses on recommendations about criteria to considered when choosing feedstock for bioethanol production; the analysis stresses the overall performance of different biomass sources for solar energy conversion into biofuels and the consequent emission of GHG per unit of existing energy. Values for these parameters are presented at the end of this chapter both for sugarcane and corn bioethanol.

3.1 Bioethanol production feedstock and technologies

Table 6, displays liquid biofuels configurations for bioethanol and biodiesel. Through biological routes, bioethanol may be produced based on any biomass containing significant amounts of starch or sugars. Nowadays, there is a slight predominance of production based on starchy materials (53% out of the total), such as corn, wheat and other cereals and grains. In such cases, conversion technology typically starts by separating, cleaning and milling the grains. Milling may be wet, where grains are steeped and fractionated before the starch conversion into sugar (wet milling process), or dry, when this is done during the conversion process (dry milling process). In both cases starch is typically converted into sugars by means of an enzymatic process, applying high temperatures. Sugars released are then yeast-fermented and the wine produced is distillate to purify bioethanol. In addition to bioethanol, these processes typically involve several co-products, which differ according to the biomass used. In Table 6, only the currently commercially implemented routes were included; other alternatives under development, such as the ones involving hydrolysis of cellulosic materials will be addressed in Chapter 5.

Table 6 **– General biofuels outlook**

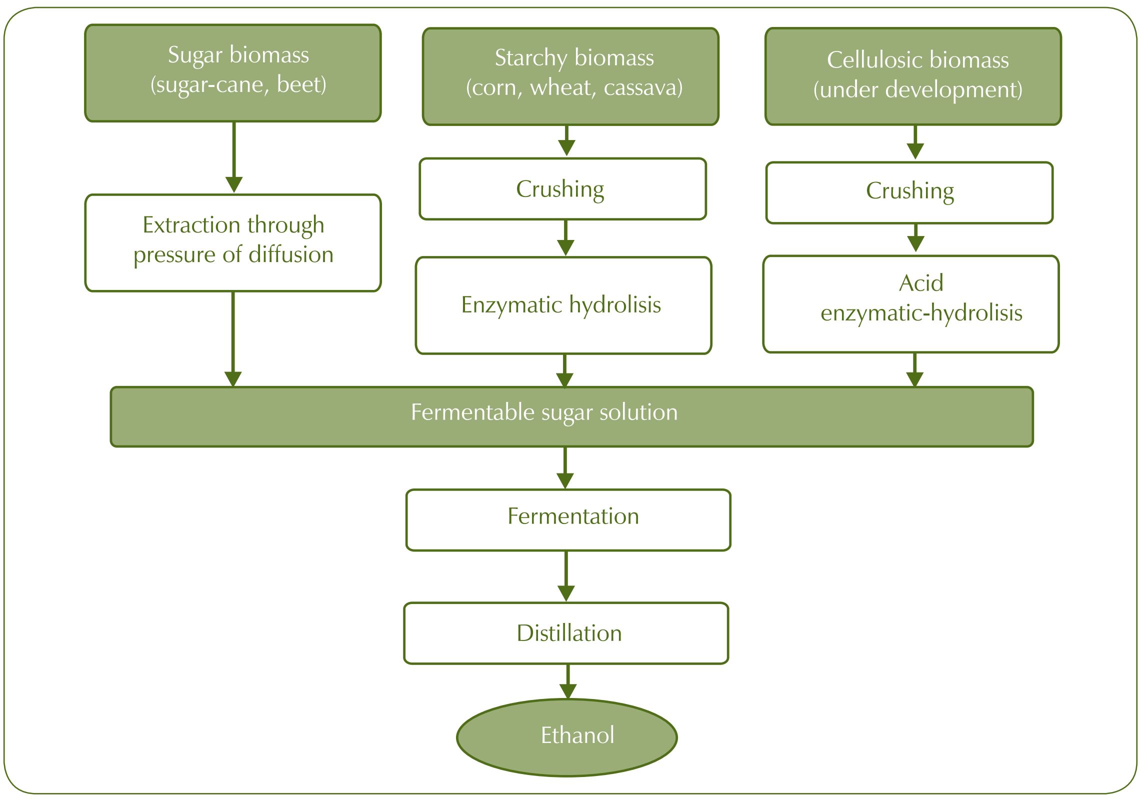
Biofuel	Feedstock	Reduction of GHG emissions	Production Cost	Biofuel production per hectare	Soil
Bioethanol	Grains (wheat, corn)	Moderate to low	Moderate	Moderate	Fertile soils
Bioethanol	Sugarcane	High	Low	High	Fertile soils
Biodiesel	Seed oils (rapeseed, soybean etc.)	Moderate	Moderate	Low	Fertile soils
Biodiesel	Palm oil	Moderate	Moderate to low	Moderate	Wet and coastal soils

Source: Adapted from IEA (2005).

Sugar-based bioethanol production — such as sugarcane and sugar beet — is a simple process and requires one step less than starch-bioethanol, since sugars are already present in biomass. Generally, the process is based on extraction of sugars (by means of milling or diffusion), which may be then taken straight to fermentation. The wine is distilled after fermentation, such as in starch-based production. Figure 7 summarizes the technology routes for bioethanol production, considering different feedstocks. It should be noted that cellulose-based bioethanol production still is in laboratory and pilot-plant stages, with technological and economic obstacles to overcome and not having yet significant presence within the energy context.

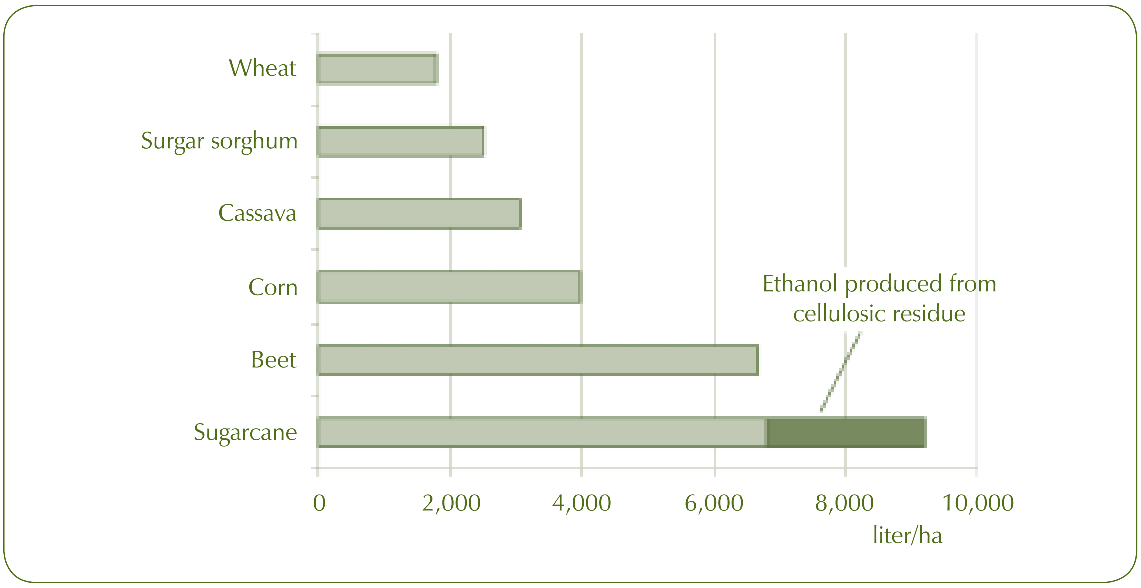
Graph 8 compares different routes for bioethanol production, illustrating the differences within productivity indexes per cultivated area. Data is from the literature [GPC (2008)] and in the cases of sugarcane and sorghum it has been modified to fit the analyses presented in this study. The results correspond to crops with good productivity, which, in some cases can imply high inputs use. Industrial technologies for sugar and starch conversion into bioethanol, underlying such graph, may be considered as well-developed and available, except those related to hydrolysis of lignocellulosic materials, currently under development (see Chapter 5). The Graph takes into account an 80-ton production of sugarcane per hectare, a productivity of 85 litres of bioethanol per ton of processed sugarcane and the use of 30% of bagasse available and half of the straw converted into bioethanol at a ratio of 400 litres per ton of dry cellulosic biomass.

***Figure 7* – Technological routes for ethanol production**



Source: Elaborated by Luiz Augusto Horta Nogueira.

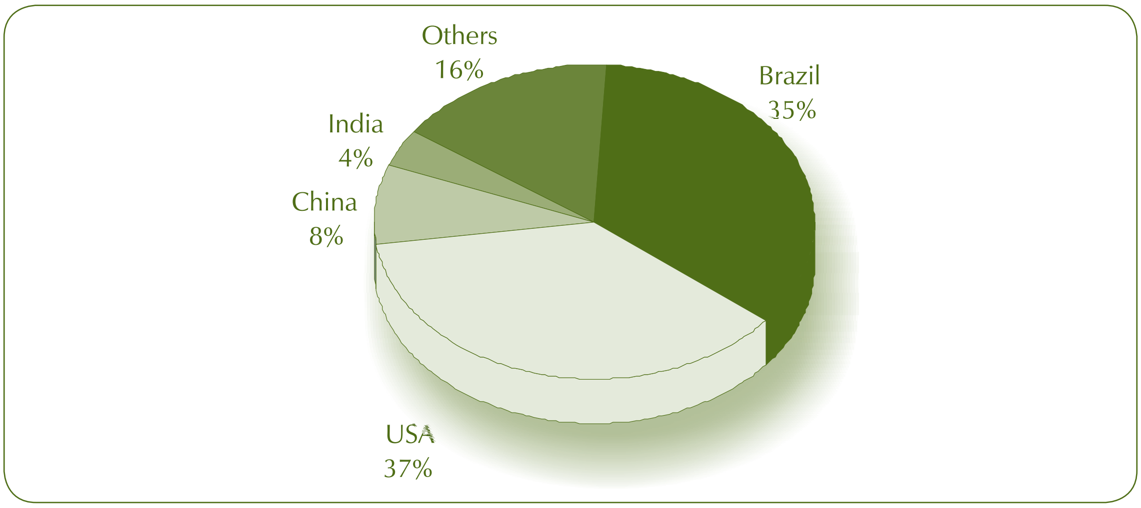
***Graph 8* – Average ethanol productivity per area for different crops**



Source: Adapted from GPC (2008).

Out of the 51 billion litres of bioethanol produced in 2006 [F. O. Licht (2006)], 72% was produced by US (corn bioethanol) and Brazil (sugarcane bioethanol), as shown in Graph 9 [RFA (2008)]. Because of their significant importance to the biofuel context, production technologies involving corn and sugarcane will be discussed at large in the following sections, addressing the most relevant agricultural aspects.

***Graph 9* – Distribution of world ethanol production in 2006**



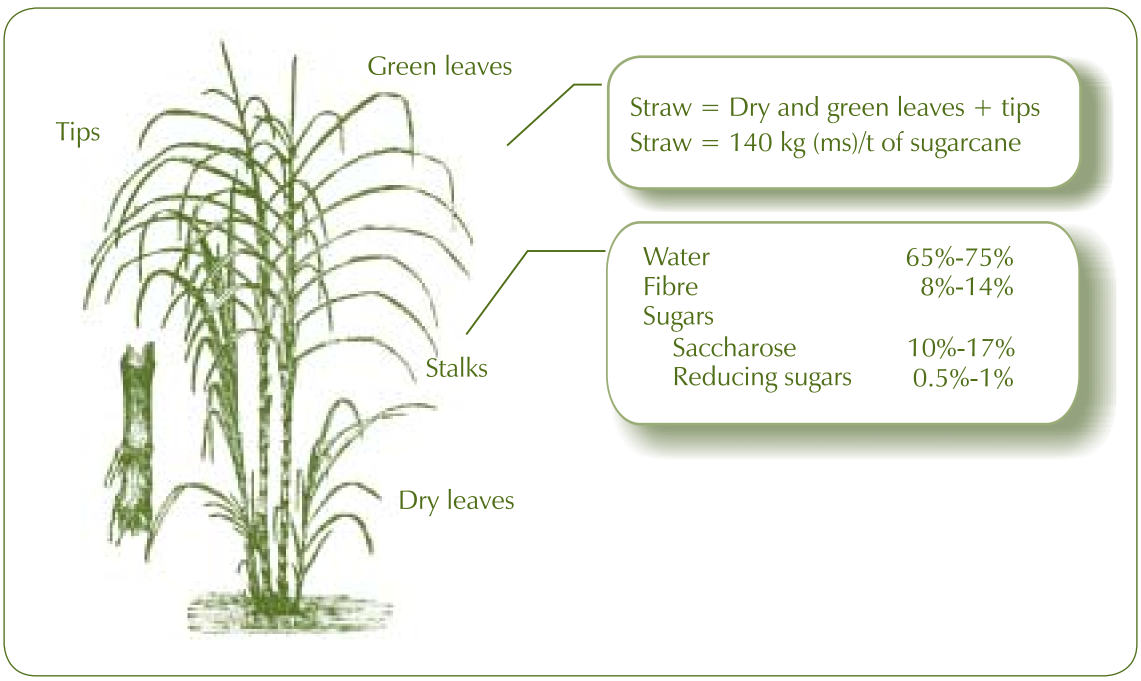
Source: Produced based on RFA (2008).

3.2 Sugarcane bioethanol

Sugarcane is a semi-perennial plant with C4-type photosynthetic cycle, genus *Saccharum*, family Gramineae, consisting of perennial tall grass species, native of warm and tropical Asian temperature zones, especially from India. The aerial part of the plant is essentially formed by *stalks*, containing saccharose, and by *tips* and *leaves*, which form the sugarcane straw, as shown in Figure 8. These components altogether sum around 35 tons of dry material per hectare.

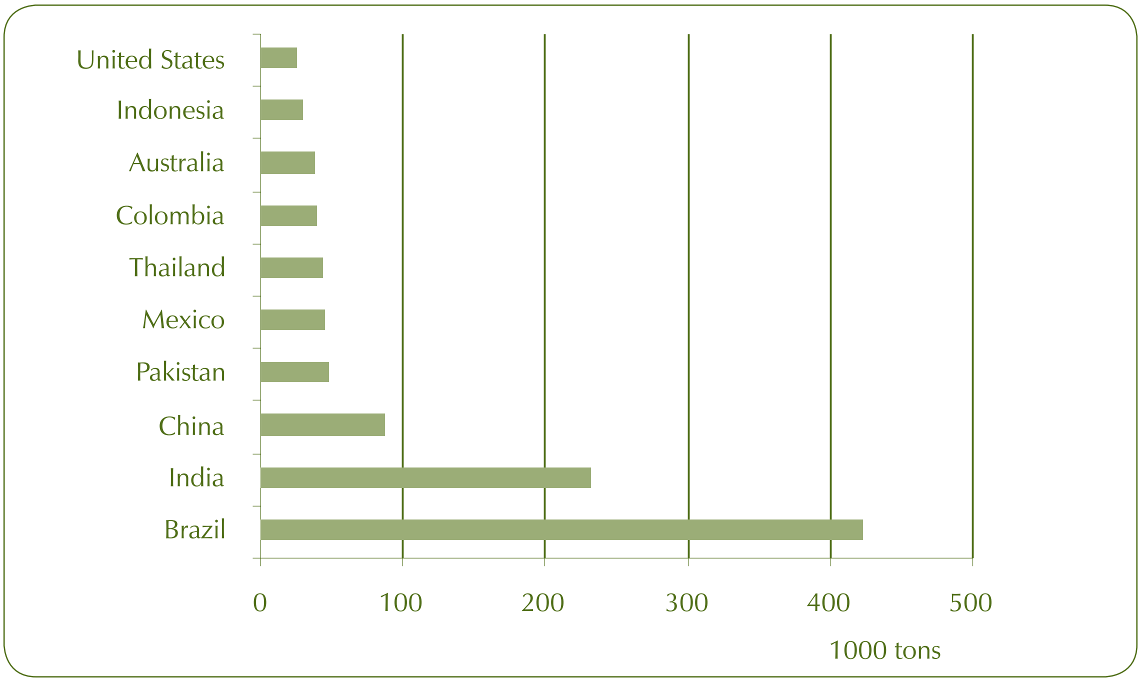
Sugarcane is the one of the most important commercial crops all over the world. It occupies more than 20 million hectares in which nearly 1,300 million tons were produced in 2006/2007. Brazil stands out as the leading producer with a cropland area of around 7 million hectares, representing close to 42% of total production. The internationally adopted sugar harvest season begins in September and ends in August of the following year. Graph 10 presents the ten leading sugarcane producers of 2005 crop [FAOSTAT (2008a)].

Figure 8 **– Typical sugarcane biomass structure**



Source: Seabra (2008).

Graph 10 – **Leading sugarcane producing countries in 2005**



Source: FAO (2007).

The ideal weather to cultivate sugarcane is one that has two distinct growing seasons: a warm and wet season, to make possible the sprouting, tilling and vegetative development, followed by a cold and dry season, which promotes the maturation and the consequent accumulation of saccharose in stems. Sugarcane does not attain good productivity in climates such as those found in wet equatorial regions; thus, it makes little sense for the Amazon forest to be used for extensive commercial sugarcane cultivation.

The complete sugarcane cycle varies, depending on the local weather, crop varieties and practices. In Brazil the cycle typically requires six years and comprises five cuts, as described below. The first cut is generally made 12 or 18 months after planting (depending on sugarcane varieties), when the so-called "cane-plant" is harvested. The other cuts, from ratoon cane (cane stalks resprouting), are harvested once a year four years in a row, with a gradual reduction of productivity. At this moment it is generally more cost-effective to reform (replant) the sugarcane plantation. The old sugarcane is then replaced by a new crop and a new production cycle begins. During sugarcane crop reform the cropland remains in fallow for some months and may receive other short-cycle crops, such as leguminous plants.

Following the sugarcane six-years production cycle, production areas must be subdivided into large planting fields at different cycle stages, with around one sixth of the total area for each stage to obtain a fairly stable production for several harvests and make appropriate use of resources and good agricultural practices (machinery and manpower). A significant consequence of this production cycle in sugarcane bioethanol production units is that agricultural activities must start two to three years before the effective industrial production, to allow for a fairly stable feedstock production within three to four years. Techniques such as direct seed cropping schemes and controlled traffic farming systems are being developed to reduce costs and preserve soil fertility. Such techniques allow increasing the number of cuts while maintaining high productivity levels [CGEE (2007b)].

Given that the typical sugarcane production cycle has five cuts during six years, average annual productivity must take into account the sugarcane crop reform period. Moreover, as part of the sugarcane produced (around 8%) is used to reform (replant) the sugarcane field, annual productivity measured in tons of sugarcane effectively processed per hectare of cropland is below the total productivity computed on the basis of sugarcane harvested.

On average, annual productivity is highly influenced by climatic variability and by specificities of producing areas, with ranges from 50 t/ha to 100 t/ha (weight of wet stem). Average productivity in Brazil is around 70 t/ha of sugarcane, which is equivalent to the figures from the best producing regions in other countries. Although there are sugarcane productivity records reaching 200 t/ha [Janick (2007)], in the Center-South Region of Brazil — where most of Brazilian mills are located — these rates range from 78 t/ha to 80 t/ha. In the State of São Paulo — the main producer — they range from 80 t/ha to 85 t/ha. [Unica (2008)]. Annex 2 presents sugarcane average productivity values in Brazil, in tons per hectare harvested.

Table 7 presents an overview of the main sugarcane crop parameters, as practiced in the Brazilian Center-South Region [Macedo (2005) and CTC (2005)]. Pol and fibre percentage based on mass of sugarcane correspond, respectively, to the saccharose apparent content and the bagasse content in sugarcane. In addition to saccharose, depending on its maturation, sugarcane contains around 0.5% of other sugars (such as glucose and fructose) not used for production of solid sugar, but possible to be used to produce bioethanol [Fernandes (2003)].

Table 7 also shows that fertilizers demand for sugarcane crops is reduced when compared to other crops, because sugarcane industrial waste returns to the cropland as fertilizer. The use of synthetic nitrogen is low, and in the areas where vinasse is applied all potassium is supplied by fertigation. In spite of being a crop with high water demand, rainfall rates higher than 800 mm (best scenario between 1,200 mm and 1,500 mm) and properly distributed (well-defined rainy and drain periods) are enough to reach good productivity. In the Brazilian Center-South typical producing units (using half of sugarcane to produce sugar and the other half to produce bioethanol) the application of vinasse represents around 15 mm to 20 mm in 30% of the sugarcane cropland area and virtually eliminates the need for irrigation. The values shown for vinasse and cake filter application refer to values recommended in typical conditions for the State of São Paulo, according to the environmental laws.

Table 7 – **Main sugarcane agricultural parameters in the Brazilian Center-South**

Indicator	Percentage
Productivity	87.1 tc/ha
Harvest of green sugarcane (without burning)	30.8%
Mechanized harvest	49.5%
% sugarcane pol (content of saccharose)	14.22
% sugarcane fibber (content of bagasse)	12.73
Fertilizers	
P_2O_5	
Cane-plant	120 kg/ha
Ratoon cane without vinasse	25 kg/ha
K_2O	
Cane-plant	120 kg/ha
Ratoon cane without vinasse	115 kg/ha
Nitrogen	
Cane-plant	50 kg/ha
Ratoon cane with vinasse	75 kg/ha
Ratoon cane without vinasse	90 kg/ha
Limestone	1.9 t/ha (only in planting)
Herbicide	2.20 kg/ha (recommended value)
Insecticide	0.12 kg/ha (recommended value)
Other agrochemicals	0.04 kg/ha
Application of filter cake	5 t (dry milling process)/ha
Application of vinasse	140 m^3/ha

Source: Macedo (2005a) and CTC (2005).

(a) (b)

Sugarcane harvest: (a) manual with burning and (b) mechanized without burning.

Sugarcane harvest periods vary according to rainfall to allow cutting and transportation operations while reaching the best maturation point and maximizing sugar accumulation. In the Brazilian Center-South Region harvest goes from April to December, while in the Northeast Region harvest takes place from August to April. The traditional harvest system — which is still used in nearly 70% of sugarcane crops in Brazil and involves the previous burning of the sugarcane crop and the manual cut of the whole stalk sugarcane — is being progressively replaced by the mechanized harvest of green chopped sugarcane (without burning), due to environmental restrictions on burning practices. Recent agreements between the government and producers made for an estimate of all sugarcane to be mechanically harvested by 2020, without previously burning the sugarcane crop.

After it is cut sugarcane is promptly transported to the mill to avoid saccharose losses. Except for a few companies that use some sort of waterway transport, the transportation system is based on trucks — single-trailer truck, twin-trailer truck, triple trailer truck, road train — with cargo capacity between 15 and 60 tons. In recent years sugarcane logistics has undergone significant development, involving integrated operations of cutting, shipment and transportation, to cut costs and diminish soil compaction.

***Figure 9* – Distribution of the 350 sugarcane processing mills in Brazil**

Source: CGEE (2006).

Sugarcane cannot be stored for more than a few days and mills operate only during the harvest period, irrespective of the type of facility. The initial processing stages for bioethanol are basically the same as for sugar production, as shown in Figure 10. Once in the mill sugarcane is generally washed (only the whole stalk sugarcane) and sent to the preparation and extraction phases. Extraction is made by roll-mills — arranged in sets from four to seven successive three-roll mills — that separate the sugarcane juice containing saccharose from the bagasse, which is sent to the mill's power plant to be used as fuel. In some new units implemented in Brazil extraction by diffusion is being adopted and expected to deliver some advantages as far as energy is concerned. In that process chopped and shredded sugarcane is repeatedly washed with hot water inside diffusers, where it releases sugars through a leaching process. Then the product is pressed through a drying roller, which generates the bagasse to be used in boilers. Produced in the mill or diffuser, the juice containing sugars can be then used in sugar or bioethanol production.

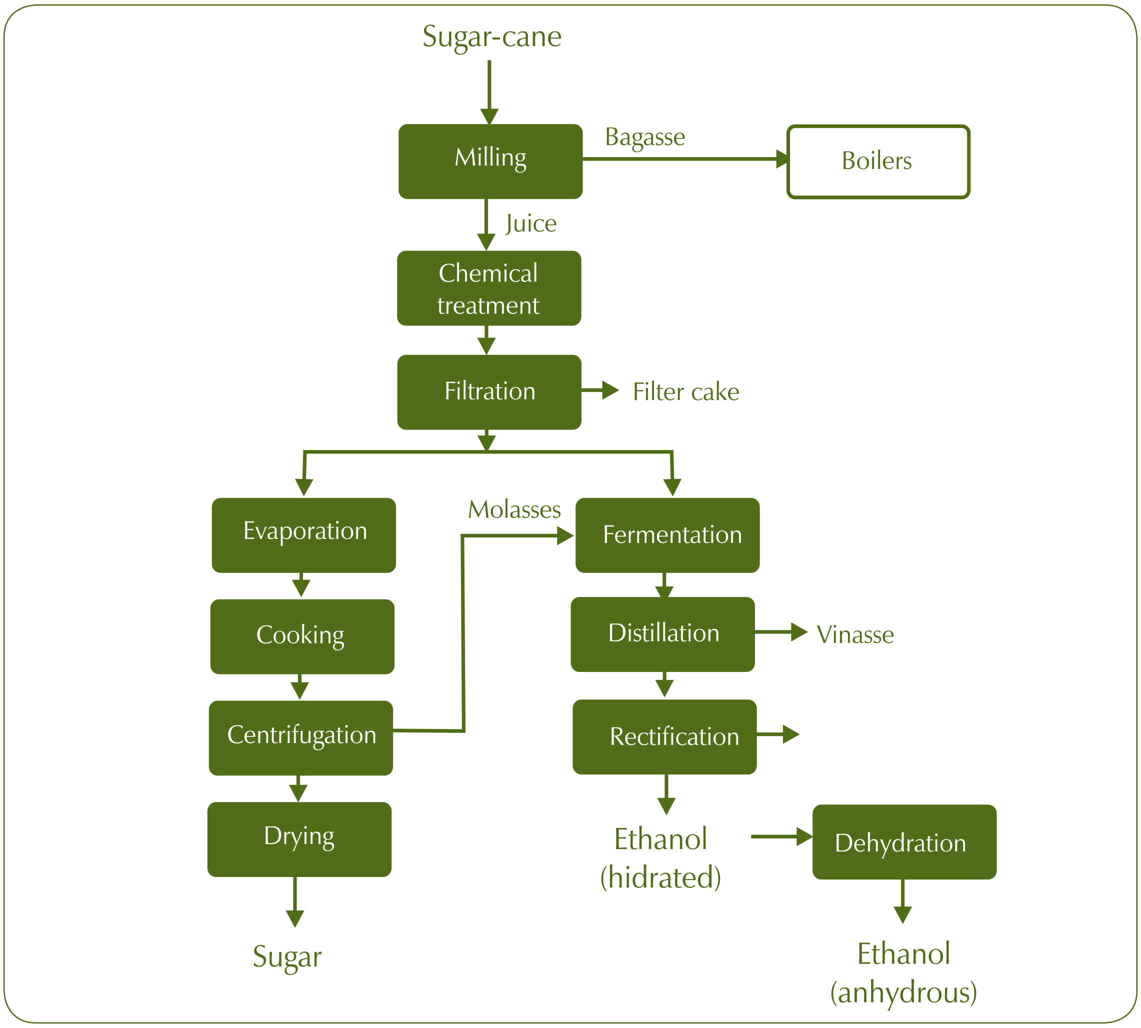
Sugarcane transport by triple trailer truck in Brazil.

In sugar production the juice is initially screened and chemically treated for coagulation, flocculation and precipitation of impurities, which are eliminated through decanting. The filter cake, used as fertilizer, is generated by recovering sugar out of the decanted slurry by means of rotary vacuum filters. The treated juice is then concentrated in multiple-effect evaporators and crystallized. In such process only part of the saccharose available in the sugarcane is crystallized and the residual solution with high sugar content (honey) can be used in the process once again to recover more sugar. The honey produced — also called molasses — does not return to the sugar manufacturing process but can be used as an input for bioethanol production through fermentation, because it still contains some saccharose and a high amount of reducing sugars (such as glucose and fructose, resulting from saccharose decomposition).

Thus, sugarcane bioethanol production may be based on fermentation, whether using the sugarcane juice alone or using a mix of juice and molasse, the latter being more frequently practiced in Brazil. In sugarcane-juice bioethanol the first stages of the manufacturing process, from sugarcane receipt to initial juice treatment, are similar to the sugar manufacturing process. In a more well-rounded treatment the juice is limed, heated and decanted as in the sugar process. After treatment the juice is evaporated to balance its sugars concentration and, in some cases, it is mixed to molasse, generating sugarcane mash, a sugary solution which is ready to be fermented.

The mash is sent to fermentation reactors, where yeasts are added to it (single-celled fungi of *Saccharomyces cerevisae* species) and fermented for a period ranging from 8 to 12 hours, generating wine (fermented mash, with ethanol concentration from 7% to 10%). The most common fermentation process in Brazilian distillery is Melle-Boinot, characterized by the recovery of wine yeasts by means of centrifugation. Then, after fermentation yeasts are recovered and treated for new use, while the wine is sent to distillation columns.

Figure 10 **– Sugar and sugarcane-based bioethanol production flowchart**



Source: Seabra (2008).

In distillation bioethanol is initially recovered in hydrated form. Nearly 96° GL (percent in volume) corresponds to around 6% of water in weight, producing vinasse or stillage as residue, generally at a ratio of 10 to 13 litres per litre of hydrated bioethanol produced. In this process, other liquid fractions are also separated, producing second generation alcohols and fusel oil. Hydrated bioethanol can be stored as final product or may be sent to the dehydration column. Nevertheless, as it is an azeotropic mixture, its components cannot be separated by distillation only. The most commonly-used technology in Brazil is dehydration with addition of cyclohexane, forming a ternary azeotropic mixture, with boiling point lower than that of anhydrous bioethanol. In the dehydration column, cyclohexane is added on top, and the anhydrous bioethanol is removed from the bottom, with nearly 99.7° GL or 0.4% of water in weight. The ternary mixture removed from the top is condensed and decanted, while the part with high water content is sent to the cyclohexane recovery column.

Sugarcane processing mill in Brazil.

Bioethanol dehydration also can be made by adsorption with molecular sieves or by means of extractive distillation with monoethyleneglycol (MEG), which stand out as providers of lower energy consumption, as well as by their higher costs. Due to increasing requirements in foreign markets several bioethanol producers in Brazil and in other countries have been choosing molecular sieves, since they allow producing anhydrous bioethanol free from contaminants.

The possibility of using sugars from sugarcane exclusively or non-exclusively to produce bioethanol represents a significant adaptation technology in this agroindustry, which sugar mills can use to arbitrage — within certain limits — a cost-effective production program, depending on price conditions, existing demand and other market perspectives. Actually, to take advantage of such flexibility several Brazilian mills have sugar and bioethanol manufacturing lines, each one capable of processing 75% of the juice produced, allowing a margin of 50% of the total processing capacity against the extraction capacity of the mill.

Water discharges in bioethanol production are relatively high. Currently, considering the Brazilian Center-South scenario, around 1.8 m^3 of water are collected per ton of processed sugarcane; however, such figure is significantly going down as a result of recycling initiatives, which allow reducing both the water collection level and treated water disposal. This aspect will be analyzed in-depth in Chapter 6.

Considering the entire sugarcane bioethanol production cycle, the residues generated in the process are vinasse (from 800 to 1,000 litres per ton of processed sugarcane for bioethanol), filter cake (around 40 kg of wet output per ton of processed sugarcane) and boiler ashes [Elia Neto (2007)]. As said before, in the Brazilian mills such residues are well appreciated by-products that once recycled can be used as fertilizers, contributing to both significantly reduce the need for mineral fertilizers and avoid the need for irrigating sugarcane crops.

As bioethanol production involves significant water elimination, the energy demand is high, particularly concerning thermal power, as shown in Table 8. Steam demand in hydrated bioethanol considers the conventional technology consuming 3.0 kg to 3.5 kg of steam per litre of bioethanol produced; in anhydrous ethanol demand is estimated considering an azeotropic distillation process using cyclohexane that consumes 1.5 kg to 2.0 kg of steam per litre of bioethanol produced. As far as electric power demand is concerned, there are slight distinctions between processes, but all of them are around 12 kWh per ton of processed sugarcane.

***Table 8* – Energy demand in sugarcane processing**

Energy	Unit	Sugar	Hydrated bioethanol	Anhydrous bioethanol
Thermal Steam saturated at 1.5 bar (manometric method), for heaters, evaporators and distillation	kg/tc	470-500	370-410	500-580
Mechanical Driving of sugarcane preparation and milling systems and motopumps	kWh/tc	16	16	16
Electric Various electric engines, lighting and other charges	kWh/tc	12	12	12

Source: Pizaia (1998).

In the sugarcane-based bioethanol agroindustry all energy consumed in the process can be supplied by a heat-and-power production system (cogeneration system) installed in the mill, using only bagasse as an energy source. Actually, many sugarcane mills all over the world produce a significant part of the energy they consume. Particularly in Brazil, mills are energy self-sustained and they often manage to export increasing amounts of electric power surpluses to the public grid, thanks to the growing use of energy-efficient equipment. More details on the arrangement of power facilities in mills and their energy-production potential is discussed in Chapter 4.

Regarding industrial yield, one ton of sugarcane used exclusively for sugar production generates around 100 kg of sugar as well as over 20 litres of bioethanol using molasses. Data for Brazil is presented in Table 9, using average figures from nearly 60 mills in the State of São Paulo (figures adapted from CTC, 2005); losses refers to an average sugarcane with a 14% saccharose content. One ton of sugarcane may produce 86 litres of hydrated bioethanol in bioethanol-only production; or 100 kg of sugar plus 23 litres of hydrated bioethanol out of molasses in sugar production. Figures in the last case correspond to a sugar production process with two masses (successive crystallization processes), in which honey is not depleted but sent with relative high content of saccharose for bioethanol production, which allows enhancing the product quality and reducing energy consumption to produce sugar. In a nutshell, synergies and complementary relationships between the sugar and bioethanol production help cutting costs and increasing the efficiency of agroindustrial processes.

***Table 9* – Average losses and yields of sugarcane mills**

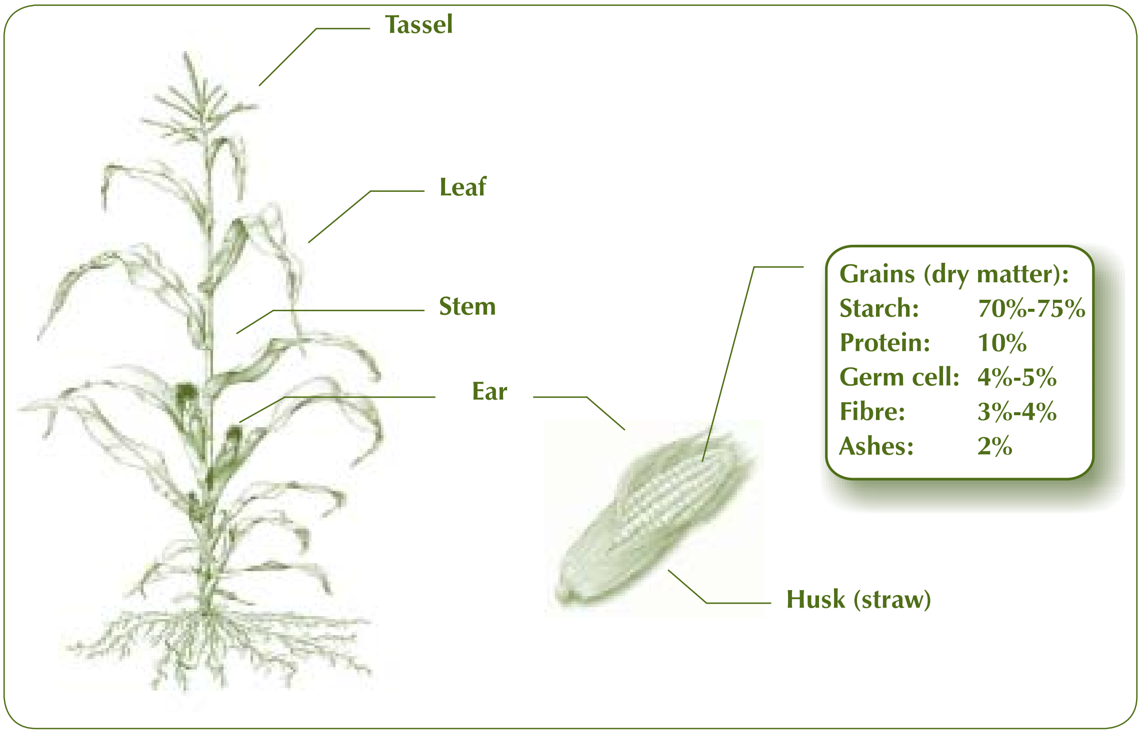
Item	Sugar or yield loss
Sugarcane washing	0.7%
Extraction	3.9%
Filter cake	0.5%
Not defined	3.5%
Distillation	0.2%
Fermentation yield	90.0%
Overall yield	
Sugar	100 kg/t cane (+ 23 litres/t cane)
Hydrated bioethanol	86 litres/t cane

Source: Figures adapted from CTC (2005).

3.3 Corn bioethanol

Similarly to sugarcane, corn (*Zea mays spp.*) is a C4 plant from the grass family, with annual production cycle. Originated in Mesoamerica, corn is currently cultivated in all continents and occupies nearly 147 million hectares, producing around 725 million tons in 2004 [Faostat (2008a)]. It is an important food item in several countries, as human and animal food.

Figure 11 – **Typical structure of corn biomass**

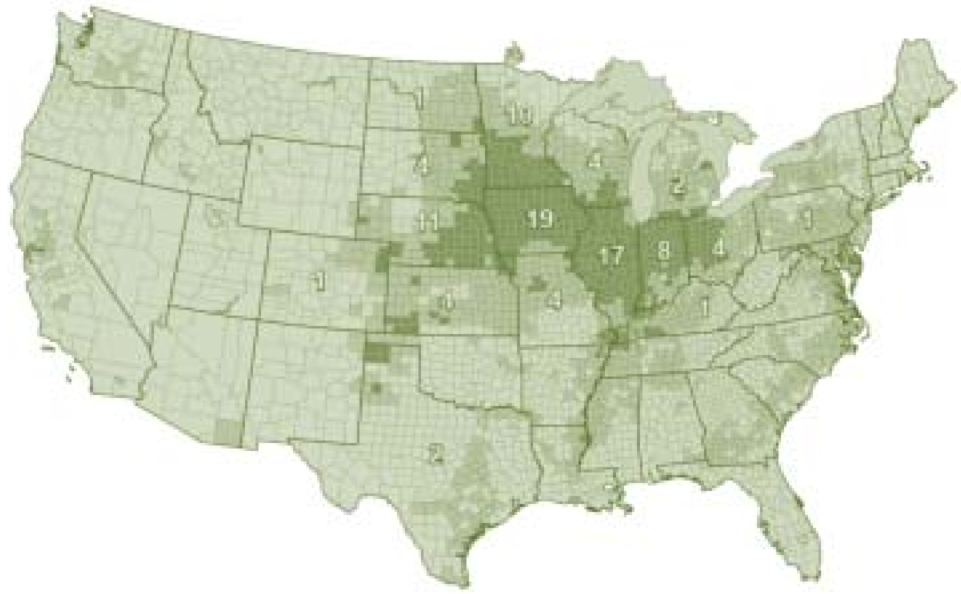


Source: Seabra (2008).

The United States is the leading world's corn producer, responsible for nearly half of the total global production. In 2006 US corn production was over 267 million tons of grains from a cropland area of over 28 million hectares [USDA (2008)]. Out of that total, more than 50% was used in animal feeding, while less than 20% went to the bioethanol industry [Iowa Corn (2008)]. Most production comes from the so-called Corn Belt region, especially the States of Iowa and Illinois, where it is the main crop, as shown in Figure 12. Corn is also the main feedstock in US bioethanol production: more than 98% of bioethanol produced in the US is from corn.

In temperate zones corn is planted in the Spring (April and May in the Northern Hemisphere) because it is a plant that cannot endure cold weather. Corn crops typically involve a crop rotation with some sort of nitrogen-fixing plant, generally alfalfa or soybean (in long-summer regions), and occasionally a third crop may be used, such as wheat. In the traditional model soil is ploughed every year, but minimum tillage is becoming increasingly common. In the US the harvest season goes from September through November and it generally performed by a harvesting machine. In mechanical harvesting the ear is separated from the stem and the kernels are extracted from the ear; the straw and corncob are left on the field.

Figure 12 – **Distribution of corn production in the United States***



Source: Seabra (2008).
* Map numbers indicate percent contribution of each State.

Corn harvest.

US average productivity is around 9 tons of kernels per hectare [USDA (2008)]. Actually, kernels account for around 50% of plant dry matter, which also includes the stem, leaves, straw and corncob [Pordesimo et al. (2004)], amounting to 15 tons of dry matter per hectare.

Although this biomass is expected to be used as an energy alternative, it is important that most of it remains on the field after harvest to preserve soil fertility [Blanco-Canqui and Lal (2007)].

As compared with sugarcane, corn demands a relatively larger amount of fertilizers, as shown in Table 10. Results are weighted for irrigated and non-irrigated areas [Pimentel and Patzek (2005)]. When it comes to water consumption, total demand is around 5.6 thousand m^3 per hectare, although less than 10% of the cropland in the United States needs irrigation [NGCA (2008)].

***Table 10* – Fertilizers and agrochemicals demands for corn production in the USA**

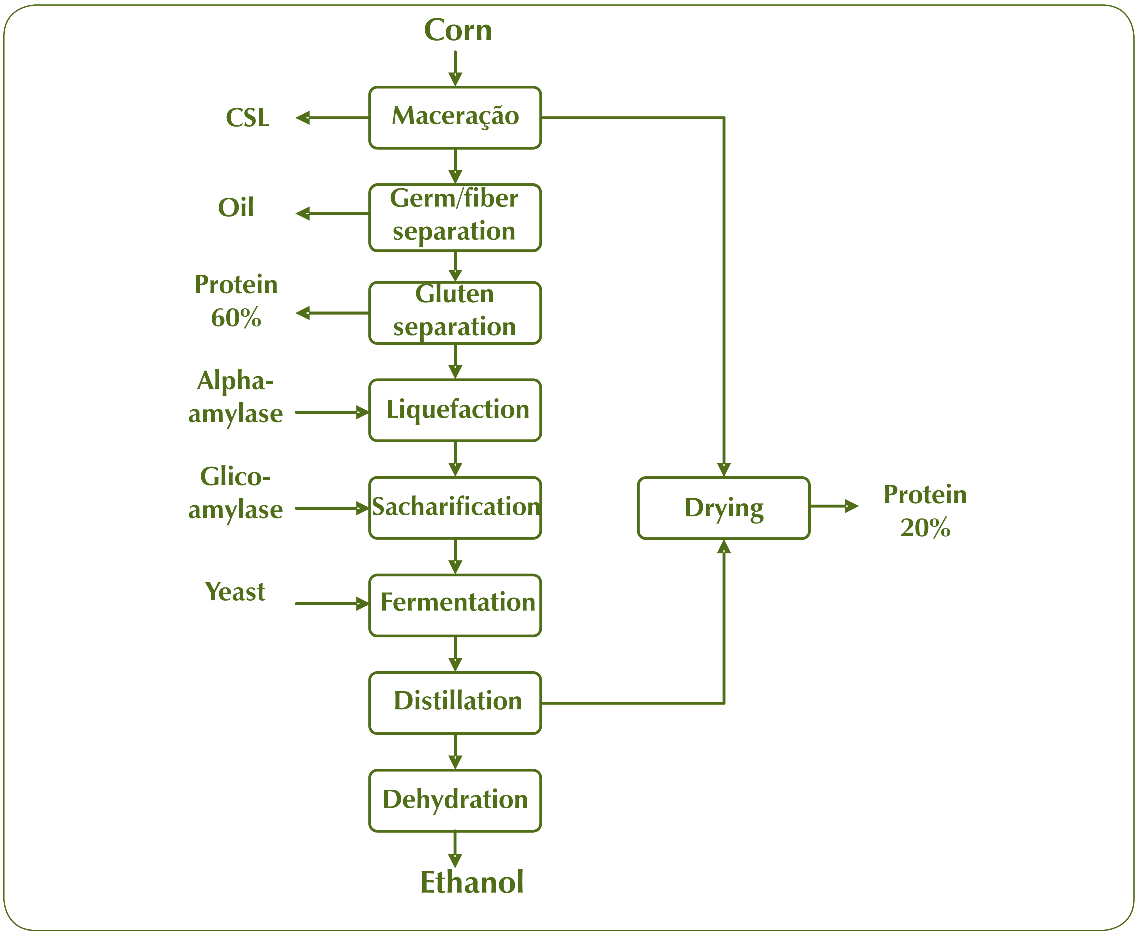
Inputs	Demand
Nitrogen	153 kg/ha
Phosphorus	65 kg/ha
Potassium	77 kg/ha
Limestone	1,120 kg/ha
Seeds	21 kg/ha
Irrigation (in 10% of cropland)	8.1 cm/ha
Herbicide	6.2 kg/ha
Insecticide	2.8 kg/ha

Source: Pimentel and Patzek (2005).

Bioethanol may be produced using corn by means of wet or dry milling. Wet milling was the most common option until the 1990s, although nowadays dry milling has become the preferred process. Wet milling provides a large variety of products; however, improvements have made dry-milling processing the best option considering its lower investment and operation costs that enable substantial cuts in bioethanol final cost [Novozymes (2002)].

In wet processing (Figure 13) the corn kernel portions are separated and several products, such as proteins, nutrients, carbon dioxide (CO_2, used in soft drink plants), starch, and corn oil are recovered. While corn oil is the golden product, starch (and consequently bioethanol) is the one produced in larger amounts yielding about 440 litres of bioethanol per dry ton of corn, as shown in Table 11.

Figure 13 – **Flowchart of wet-milling corn-based bioethanol production**



Source: Wyman (1996).

In dry milling (Figure 14) the only bioethanol co-product is a protein supplement for animal feeding called DDGS (Distillers Dried Grains with Solubles). In this process ground corn kernels are blended with water and enzymes (alpha-amylase) to hydrolyse the starch into smaller sugar chains. In the next stage the chains are saccharified by glucoamylase and the solution produced is then fermented. In some units, during these liquefaction/saccharification operations, a part of fine vinasse is recycled (backsetting process) to reduce the pH and provide nutrients for fermentation.

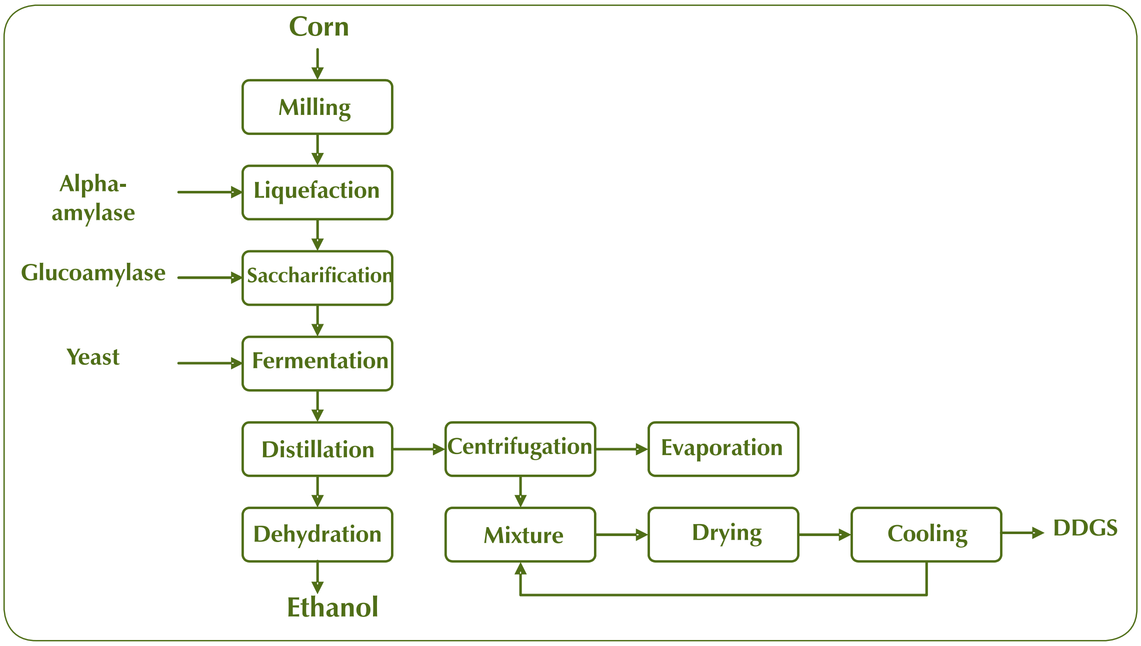
The sugar release process, although rapid in the initial stages, quickly slows down, which may require remaining 48 to 72 hours in the reactors to get maximum starch saccharification. In order to reduce such time and contamination risks, several units develop saccharification and fermentation simultaneously. In this case, the conversion to glucose is also reduced. However, in processes using backsetting recycling permits to re-use sugars not converted initially.

Table 11 **– Yield of co-products in wet milling**

Product	Yield
Corn oil	34–38 kg/t corn
Protein 20%	306 kg/t corn
Protein 60%	68 kg/t corn
CO_2	308 kg/t corn
Bioethanol	440 litres/t corn

Source: Wyman (1996).

Figure 14 **– Flowchart of dry-milling corn-based bioethanol production**



Source: Wyman (1996).

As in the case of sugarcane bioethanol, in the fermentation phase glucose is transformed into bioethanol by the action of *Saccharomyces cerevisiae* yeast, and the wine produced is then sent to distillation. Vinasse produced in this stage is sent to a set of centrifuges where fine vinasse is separated. The remaining vinasse is usually concentrated in evaporators, producing syrup with approximately 50% of humidity. The syrup is combined with solid elements removed from the centrifuge and nearly 10% of humidity to obtain DDGS. Other distillation stages are equivalent to the sugarcane bioethanol process used in Brazil. The only difference is that in the US dehydration with molecular sieve is already the most used process to produce anhydrous bioethanol. As for yields, typically around 460 litres of anhydrous bioethanol and 380 kg of DDGS are obtained per dry ton of corn [Wyman (1996)].

Corn bioethanol production mill in the USA.

3.4 Bioethanol based on other feedstocks

As mentioned already, any feedstock with enough content of sugar or starch may be converted into bioethanol. Therefore, in addition to sugarcane and corn, some countries have considered other starchy of sugary crops, such as cassava, wheat, sugar beets and sweet sorghum. These alternatives are briefly addressed below.

Cassava (*Manihot esculenta*) is native to Brazil and largely grown in tropical regions of Africa and Asia. In addition to its broad use as basic food in human and animal diet, in Thailand and China cassava is semi-processed for export (as *tapioca*) and used locally to produce bioethanol for beverages. The main advantage of cassava is the high content of starch in its roots, ranging from 20% to 30%; in addition, it is a annual crops simple to cultivate and has low edafoclimatic requirements. These characteristics stirred up actual attempts to use cassava during the first stage of the Brazilian Ethanol Program (Proálcool), in the 1970s. Nonetheless, such projects were not successful, mainly because the high price of cassava bioethanol vis-à-vis sugarcane bioethanol and interruptions in the supply of roots to the industry. In recent years some Asian countries have been fostering bioethanol fuel production based on cassava [Howeler (2003)], with good results in Thai distillation plants [Koisumi (2008)].

In bioethanol production cassava roots are peeled off, washed and grounded to get a mix that in successive stages is put into kilns and tanks for starch saccharification, in processes similar to those used for corn bioethanol. With industrial productivity rates similar to those for corn, one ton of non-processed cassava with around 25% of starch allows producing 170 litres of bioethanol. On the agricultural side, average agricultural productivity in well-managed crops in Brazil yield around 18 tons per hectare [Mandioca Brasileira — Brazilian Cassava (2008)]; that is, 3,060 litres of bioethanol per hectare. Significant co-products have not been identified in cassava-based biethanol production, apart from vinasse from the distillation process [Trindade (1985)]. Sweet potato could be processed in a similar way as cassava for bioethanol production; however it has higher costs and results so far have been limited.

Wheat (*Triticum spp.*), another starch-producing crop, has been effectively applied in recent years to produce bioethanol in some European countries, such as England and Germany, by means of an industrial process rather similar to that used in corn bioethanol. Typical agricultural and industrial productivities are, respectively, of 7.5 tons per hectare and 240 litres of bioethanol per ton of processed grains [LowCVP (2004)], which yield 1,800 litres per hectare. In addition, around 320 kg of co-products are obtained per ton of processed wheat, which can be used for animal feeding — as in the case of corn . Barley and rye crops are also being adopted to produce bioethanol fuel in several European countries, but at a lower scale.

Sugar beet (*Beta vulgaris*) is another sugar crop — in addition to sugarcane — that is used to manufacture bioethanol, using residual honey (molasse) always available in saccharose industrial production [Tereos (2006)]. This vegetable has a tuberous root that accumulates high amounts of sugar, delivering outputs of 50 and 100 tons per hectare and saccharose contents around 18% [RIRDC (2007)]. It may reach rather high agroindustrial productivity levels, of around 7,500 litres of bioethanol per hectare, which is quite similar to sugarcane productivity levels. Industrial processing begins by cleaning and fractioning the beet in fine slices that are then sent to a diffuser, in which they are successively washed under hot water to induce sugar release. The liquid resulting from this operation contains around 16% of soluble solids extracted from the beet, which are then processed in similar way to sugarcane juice, into crystallized sugar or into bioethanol. One ton of tubers usually produces 86 litres of bioethanol and 51 kg of a fibrous cake that may be used as animal feed [El Sayed et al. (2005)]. In spite of presenting high productivity, beet depends on external power (electricity and fuel) to be processed.

Sweet sorghum (*Sorghum bicolor (L.) Moench*) is often pointed out as a potential bioethanol feedstock; however, there is no current significant bioethanol production based on it. Particularly, the use of sorghum to produce bioethanol may be even integrated to the sugarcane agroindustry, extending the usual crop season with a crop relatively simpler than sugarcane, with several similarities when it comes to processing. Sweet sorghum stems may be processed in mills, producing a sugary juice — with saccharose content lower than the one found in sugarcane juice — that may then be subject to a similar industrial process to produce molasses and bioethanol.

Sweet sorghum can deliver more than 2,000 litres of bioethanol per hectare, considering an industrial productivity of 40 litres of bioethanol per ton of processed sorghum [Icrisat (2004)] and an agricultural productivity of 50 tons per hectare. Such productivity has been observed in BR 505 sorghum croplands developed by Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Company — Embrapa) at Centro Nacional de Pesquisa de Milho e Sorgo (Brazilian National Corn and Sorghum Research Center), aiming at producing bioethanol [Teixeira et al. (1997)]. Nonetheless, using sweet sorghum still poses difficulties that must be overcome before its effective adoption, especially regarding its weak resistance to degradation after harvest, limited germplasm base, low environmental friendliness and low resistance to pests and diseases [Venturi and Venturi (2003)]. Actually, sorghum experiments in the State of São Paulo mills did not achieve significant results, even when intercropped with sugarcane [Leal (2008)].

There are currently high expectation on fast-growing and high-yield grasses, especially in light of the development of innovative ethanol production routes in the near future, by means of hydrolysis of cellulosic materials (see Chapter 5). In addition to forestry species (such as eucalyptus) and some leguminous trees (particularly, *Leucaena spp*.), the new bioethanol routes based on cellulosic biomass will allow using grasses such as Elephant grass (*Pennisetum purpureum*), generally used as forage plant in Brazil, switchgrass (*Panicum virgatum*), native to North America, which could produce several annual cuts, as well as tallgrass genus *Miscanthus*, of high interest in Europe.

In choosing bioethanol feedstock crops it is crucial to consider overall efficiency requirements. Thus, among other aspects, it is worth prioritizing crops that minimize soil, water and external agrochemical addition requirements, as well as economic feasibility considerations. It is senseless to propose the use of sophisticated crops with good alternative market value as bioenergy sources. Feedstock represents typically 60% to 70% of bioethanol final cost; thus, pursuing low-cost feedstock alternatives is critical. Co-products and by-products of nutritional, industrial or energy value, are equally important to the extent that they may provide a desirable flexibility in bioenergy production, associating biofuels to other sources of economic value.

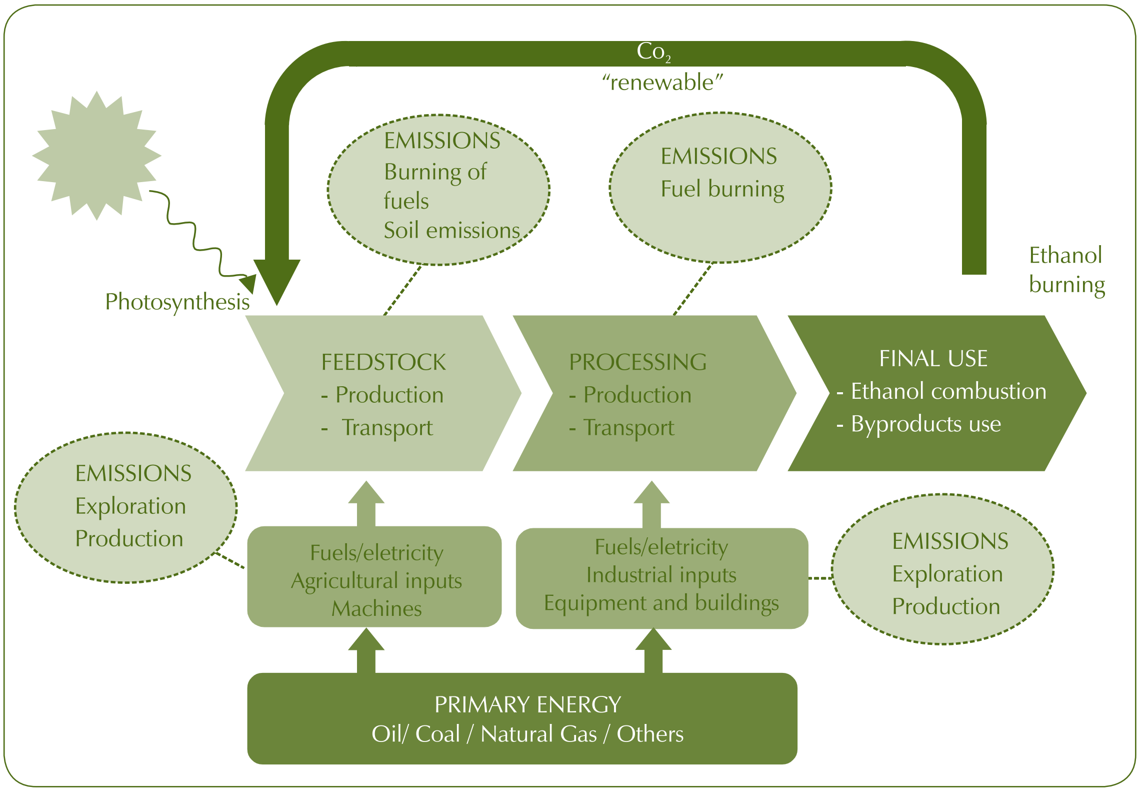
Another important issue for properly choosing biomasses with potential to produce bioethanol is the energy balance, ie, the relationship between the direct and indirect energy used to produce a bioethanol vis-à-vis the energy delivered by the biofuel produced. It is therefore desirable to use crops with high productivity and low demand of external energy inputs. This subject will be addressed in the next section.

The need of understanding clearly what is that makes a crop an innovative option for bioethanol production stresses the importance of more in-depth agronomic, economic and technology studies that allow more sound recommendations. As knowledge on such crops increases, diversification of the supply of feedstock to produce bioethanol will eventually take place, relying on stronger and more sustainable grounds. Production of such crops could eventually will become possible in environments where there is currently high interest, such as saline soils with low water requirements. Irrespective of the scenario, bioethanol production will not be deemed as substituting current agricultural production; however, it can become a new activity designed to use marginal lands, expanding and diversifying agricultural practices.

3.5 Productivity, emissions and energy balances

Notwithstanding the biomass used, the main purpose of bioethanol production is substituting oil derivatives, which allows diminishing the dependency on such fossil resources and reducing GHG emissions. However, the extent to which biofuel may replace a fossil fuel essentially depends on how it is produced. As all production technologies directly or indirectly involve the use of fossil resources, the benefit associated to the use of a biofuel depends on effectively saving the non-renewable energy it delivers when compared to its fossil equivalent. Proper calculation of the energies involved in the agroindustrial production process requires consideration to the lifecycle GHG emissions, from farm to final use, as shown in Figure 15.

Figure 15 **– Biofuel lifecycle diagram**



Source: Seabra (2008).

As seen in Figure 15, the boundaries of the system to be analyzed may change, depending on the study carried out; however, lifecycle analyses generally aim at determining energy consumption and GHG emissions from feedstock production through final fuel use. Energy consumption and emissions associated with the production of inputs and equipment used in the fuel production chain are also considered. It is worth noting that, in principle, all CO_2 released when burning biomass products in one period is recycled by means of photosynthesis during biomass growth in the next production cycle, but the share corresponding to fossil fuels consumed in bioethanol production means a net increase of these gases in the atmosphere.

Some questions on the impact of land-use changes have arisen recently, especially regarding GHG emissions. It is asserted that — depending on the previous vegetation in the area used for biofuel-related feedstock production — the disturbances caused by land-use changes could release to the atmosphere an amount of carbon previously "restrained" in vegetation and soil, high enough to jeopardize the positive environmental benefits of biofuel production. This issue is yet rather controversial, mainly because there is a lack of sufficient data on the effect to anticipate conclusions.

In any case, land-use related emission is a subject matter that deserves attention; further research is then necessary to consistently estimate the actual share of such emissions in the biofuels lifecycle. Nevertheless, at least in Brazil, forest cover losses and bioethanol production associations are least probable, as expansion of sugarcane production has taken place mainly in areas previously occupied by low productivity pastures or by annual crops usually designed for export, which generally have lower carbon retention than sugarcane-raising activities. Another aspect to considered is the effect of increasing green sugarcane harvest, with higher amount of straw and, therefore, of carbon incorporated to the soil.

Without examining in detail such issue, several studies were already carried out to assess energy and environmental impacts of biofuels. In the case of sugarcane bioethanol production in Brazil several environmental advantages are already known, especially considering the replacement of gasoline and GHG emissions reductions, since the disclosure of first detailed studies on the subject [Macedo and Horta Nogueira (1985) and Macedo (1992)]. Since then, updating studies have been published [Macedo (1998) and Macedo et al. (2004)], following up the development of agroindustrial practices and the improvement of knowledge on environmental aspects of the sugarcane industry in general.

The last assessment study published analyzes the energy and GHG emission balances for the current situation and for a 2020 scenario, considering an approach "from sugarcane crops to the mill gate" [Macedo et al. (2008)]. The study concludes that nowadays — based on the average rates of key agricultural and industrial parameters of 44 mills in the Center-South Region of Brazil — for each fossil energy unit used to produce sugarcane bioethanol, more than nine renewable energy units are produced, in the form of bioethanol and surpluses of electric power and bagasse, as shown in Table 12. Moreover, the ratio of energy production to energy consumption is expected to increase above 11 by 2020, even in a scenario of higher mechanization and use of agricultural technologies that increase the energy demand by 12%, mainly because of the increase in bioethanol production per unit of processed sugarcane and the significant increase of electric power production. The estimates assume electric power surpluses of 9.2 kWh and 135 kWh per ton of sugarcane in 2005/2006 and 2020, respectively; and thermal rates in cogeneration systems of 9 MJ/kWh and 7.2 MJ/kWh, in the same periods. These values are consistent with technologies available and those under development, which in the case of cogeneration consider the use of sugarcane straw (40% of recovery) as a supplemental fuel to bagasse in systems with high pressure extraction-condensation turbines and processes with reduced consumption of steam (340 kg of steam per ton of processed sugarcane) [Macedo et al. (2008)].

Regarding GHG, current production of sugarcane anhydrous bioethanol involves emissions of almost 440 kg CO_2eq/m^3 of bioethanol, with prospective reduction in the years to come, as shown in Table 13. In addition, bioethanol use in 25% gasoline blends — as adopted in Brazil — results in a net GHG emission reductions of around 1,900 kg CO_2eq/m^3 of bioethanol, in current conditions, and it will possibly reach levels above 2,260 kg CO_2eq/m^3 of bioethanol by 2020, as shown in Table 14. The net increase in emissions reduction will be associated to the use of bagasse and electricity surpluses and net emissions avoided (resulting from the difference between emissions in production and emissions avoided). This is because, when gasoline is replaced by bioethanol all emissions associated to the use gasoline are mitigated, and only emissions related to bioethanol production are then taken into account. The calculations also assume that surplus bagasse must replace fuel oil in boilers and that electric power produced in the bioethanol agroindustry becomes the electric power generated, using world average emission factors (579 and 560 t CO_2eq/GWh for 2005 and 2020, respectively) [Macedo et al. (2008)].

***Table 12* — Energy balance of sugarcane bioethanol production in Brazil (MJ/tc)**

Energy balance component	2005/2006	2020 Scenario
Sugarcane production and transport	210.2	238.0
Bioethanol Production	23.6	24.0
Fossil Input (total)	233.8	262.0
Bioethanol	1,926.0	2,060.0
Bagasse surplus	176.0	0.0
Electricity surplus	82.8	972.0
Renewable *Output* (total)	2,185.0	3,032.0
Energy production/consumption		
Bioethanol + bagasse	9.0	7.9
Bioethanol + bagasse + electricity	9.3	11.6

Source: Macedo et al. (2008).

***Table 13* – Emissions from sugarcane bioethanol production in Brazil (kg CO_2eq/m^3)**

	2005/2006		2020 Scenario	
Bioethanol				
Total emission	417	436	330	345
Fossil fuels	201	210	210	219
Vegetation Fires	80	84	0	0
Soil	136	143	120	126

Source: Macedo et al. (2008).

***Table 14* – Net emissions from sugarcane bioethanol production and use in Brazil (kg CO_2eq/m^3)**

	2005/2006		2020 Scenario		
Form of bioethanol use	E100	E25	E100	E100-FFV*	E25
Avoided Emissions	2,181	2,323	2,763	2,589	2,930
Use of surplus biomass	143	150	0	0	0
Electricity surplus	59	62	784	784	819
Use of bioethanol	1,979	2,111	1,979	1,805	2,111
Net emissions	-1,764	-1,886	-2,433	-2,259	-2,585

Source: Macedo et al. (2008).
* FFV: flex fuel vehicles

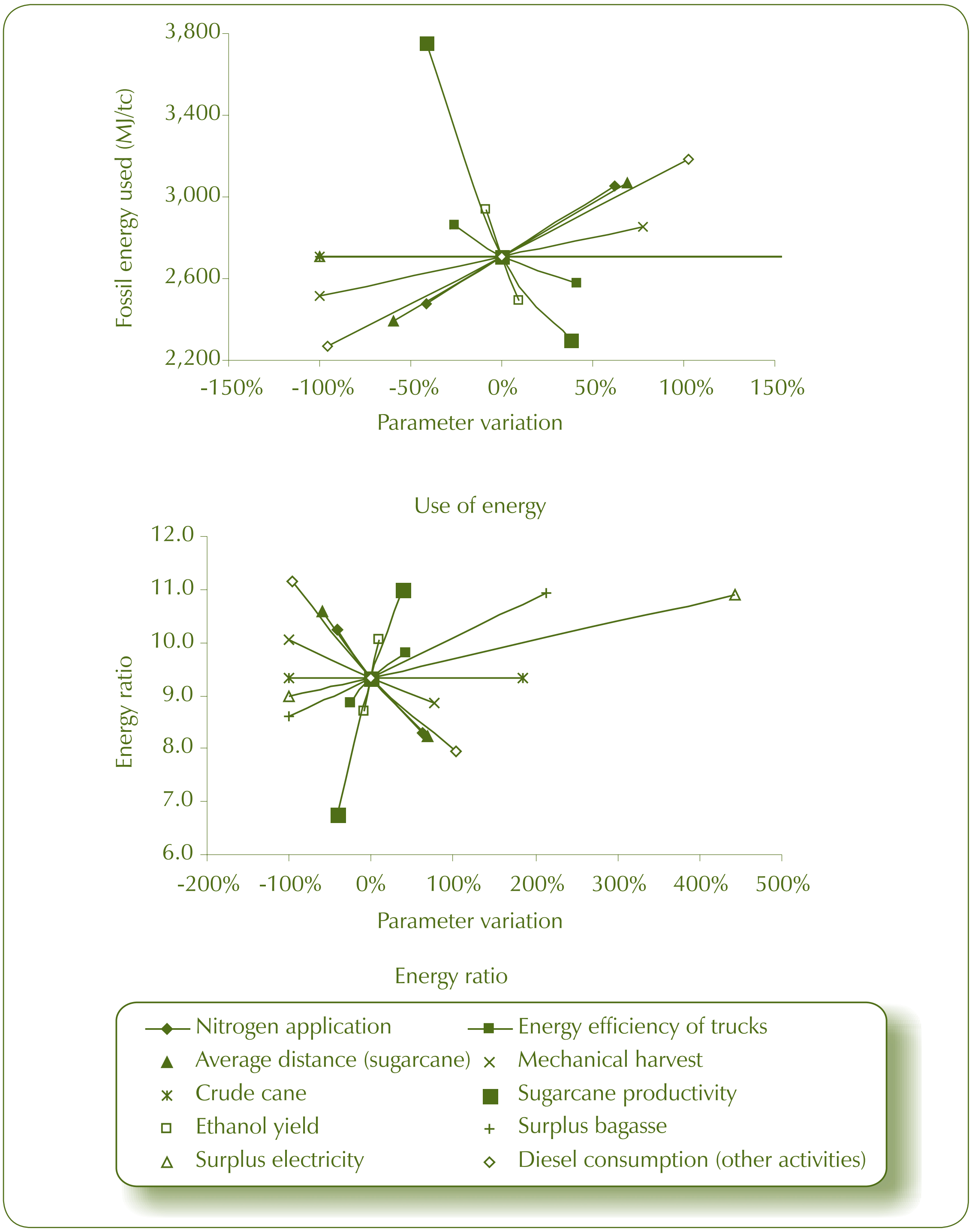
It is also important to keep in mind that these results are based on sample average conditions of Brazilian Center-South mills, which may present varying energy balances as agricultural and industrial parameters of each mill are considered. Figure 16 illustrates the individual influence of these varying parameters on energy use in mills and on the energy production to energy consumption ratio. Figure 17 presents the sensitivity of GHG gross and net emissions, considering the change intervals for these mills. Within such limits, the results may be considered typical for the energy agroindustry based on sugarcane with good performance indicators, such as practiced in several tropical countries with proper climate for the crop.

Bioethanol production based on sugarcane is already a developed technology, and there is not much room for major increases in productivity, particularly at the industrial stage. However, perspectives are different for bioethanol production based on sugarcane lignocellulosic materials, such as bagasse and straw. Current trends show that mills are very likely to turn into producing units, not only of sugar and bioethanol, but also of significant amounts of electricity, an energy of higher quality and economic value than fuels, per unit of energy produced. Advanced new cogeneration options, combined with lower energy demand processes are steps in that direction. In the near future a significant part of the straw will be added to bagasse as supplemental fuel, producing electric power at levels even higher than electric power surpluses, higher than 100 kWh per ton of processed sugarcane. Bearing this in mind, it is reasonable to expect that by 2020 the ratio between production of renewable energy and consumption of fossil energy in sugarcane bioethanol will be close to 12, with net emissions avoided around 2,600 kg CO_2eq/m^3 of bioethanol [Macedo et al. (2008)].

There is also controversy on the environmental benefits of using corn bioethanol to replace gasoline. In any case, there is no doubt that, even in the best scenario, the benefit is far below that of sugarcane bioethanol. This is because although processing corn into bioethanol demands significantly lower amounts of energy than sugarcane to be converted into bioethanol, in corn processing all energy comes from external fossil sources. The steam required (10.6 MJ/litre) is produced in natural gas boilers, and electricity (0.4 kWh/litre) is supplied by the public grid, which in the US depends on fossil-fuel sources to a large extent [Pimentel and Patzek (2005)].

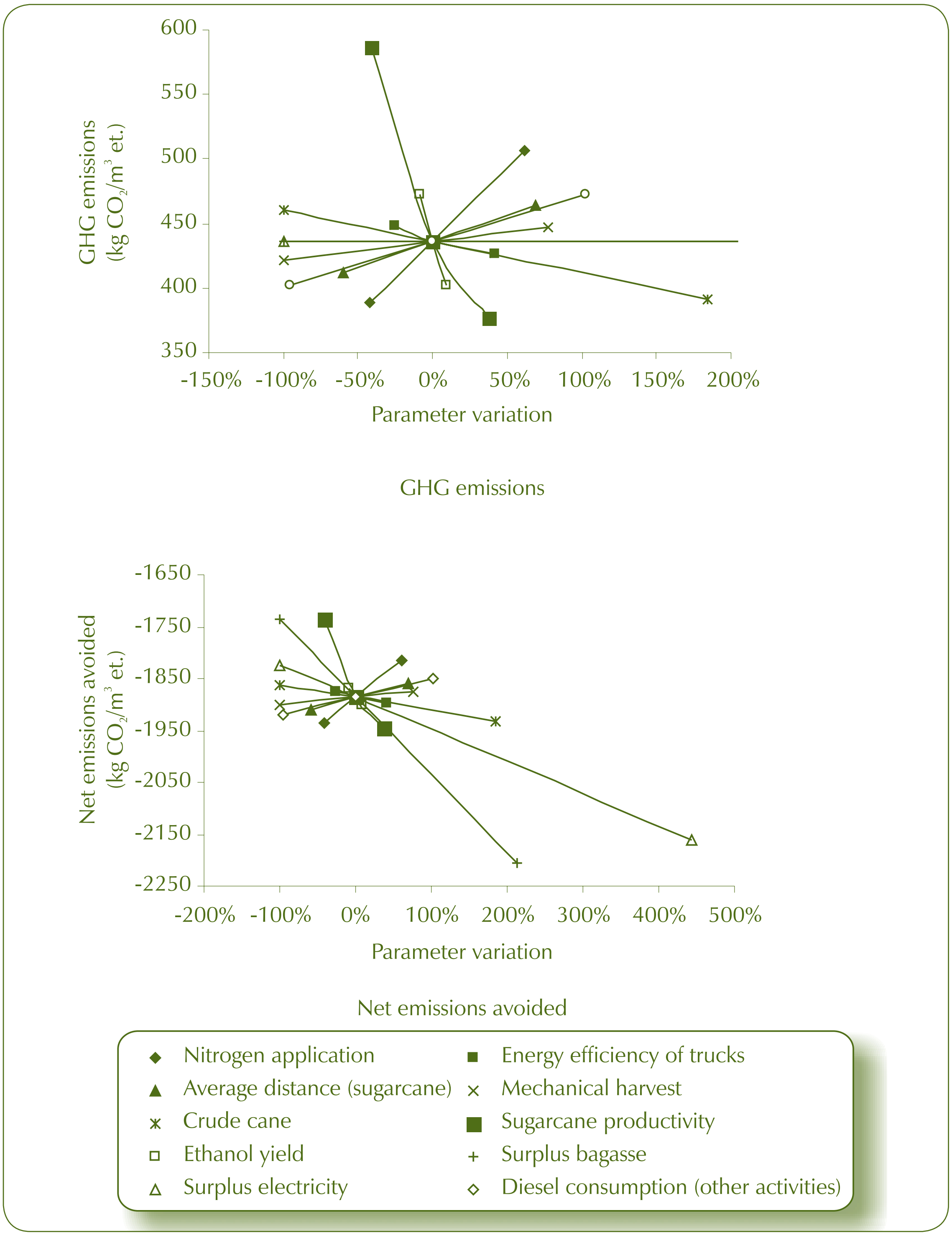
A recent comparative study that analyzed several studies [EBAMM (2005)] concludes that the most representative energy ratio for corn bioethanol in the US is 1.3, considering co-product credits, such as DDGS. As for emissions, corn bioethanol production involves total emissions of around 1.700 kg $CO_2\,eq/m^3$ of bioethanol (also considering co-product credits), with avoided net emissions of 130 kg CO_2eq/m^3 of bioethanol, considering its final use, as shown in Table 15. Note that this value is almost 15 times lower than the value observed in sugarcane bioethanol.

Figure 16 **– Analysis of sensitivity for sugarcane bioethanol in 2005/2006: use of energy and energy ratio**



Source: Macedo et al. (2008).

Figure 17 **– Analysis of sensitivity for sugarcane bioethanol in 2005/2006: GHG emissions and GHG net avoided emissions**



Source: Macedo et al. (2008).

Table 15 **– Energy and GHG emission balances for corn bioethanol in the USA**

Energy flows	Value
Consumption at agricultural stage	5.59 MJ/litre
Consumption at industrial stage	15.24 MJ/litre
Total consumption	20.83 MJ/litre
Bioethanol production	21.20 MJ/litre
Co-products energy value	4.13 MJ/litre
Total *output*	25.33 MJ/litre
Energy ratio (production/consumption)	1.2
Balance of emissions	
Agricultural stage	868 kg CO_2eq/m^3
Industrial stage	1,353 kg CO_2eq/m^3
Co-products	-525 kg CO_2eq/m^3
Emission in bioethanol production	1,696 kg CO_2eq/m^3
Bioethanol emissions	81 g CO_2eq/MJ
Gasoline emissions	94 g CO_2eq/MJ
Net emissions	134 kg CO_2eq/m^3

Source: Farrell et al. (2006) and EBAMM (2005).

Just like sugarcane bioethanol, corn bioethanol production is also a developed technology. Then, we must expect the next improvements in the pursuit of a better environmental performance to come from using the remaining biomass (straw) as fuel or input to increase bioethanol production, possibly by means of hydrolysis. However, the use of this biomass is quite limited, given the significant role it plays in soil quality preservation.

The situation is not that different for other bioethanol feedstocks, at least for beet, wheat and cassava, as shown in Table 16; that is, the energy ratio and avoided emissions values are rather low [Dai et al. (2006), EBAMM (2005), IEA (2004), Macedo et al. (2007) and Nguyen et al. (2007)].

***Table 16* – Comparison of different feedstock for bioethanol production**

Feedstock	Energy ratio	Avoided emissions
Sugarcane	9.3	89%
Corn	0.6 – 2.0	-30% a 38%
Wheat	0.97 – 1.11	19% a 47%
Beet	1.2 – 1.8	35% a 56%
Cassava	1.6 – 1.7	63%
Lignocellulosic residues*	8.3 – 8.4	66% a 73%

Source: Produced based on Dai et al. (2006), EBAMM (2005), IEA (2004), Macedo et al. (2007) and Nguyen et al. (2007).
*Theoretical estimate, process under development

Therefore, with the exception of sugarcane bioethanol, the energy and GHG emission balances of most bioethanol feedstock are not encouraging. That is why expectations for improvement lay in the production of biofuel based on lignocellulosic materials, taking into account both environmental criteria and production potential. Nonetheless, cellolosic ethanol is not yet a commercial technology and many research efforts and evidences are still needed for this option to be effectively feasible in the future. This subject will be addressed in Chapter 5.

Thus, the reduction of GHG emissions is possibly one of the most important positive effects associated with sugarcane bioethanol. According to the Brazilian First Communication to the United Nations Framework Convention on Climate Change, the use of sugarcane energy reduced by 13% the carbon emissions of the whole energy sector, based on values for 1994. Bioethanol replacement of gasoline and energy production from bagasse reduced CO_2 equivalent emissions by 27.5 million and 5.7 million tons, respectively, in 2003. [Goldemberg et al. (2008)]. Moreover, for every 100 million tons of sugarcane used in energy production purposes, emissions of 12.6 million tons of CO_2 equivalent could be avoided, considering bioethanol, bagasse and surplus of electric power supplied to the grid [Unica (2007)].

Chapter 4

Co-products of sugarcane bioethanol

Besides bioethanol, the sugarcane agroindustry produces an expanding range of products and intermediate feedstock, which are extending the economic importance of the sector, and by means of interesting synergies, adding value to the entire process. These products include sugar – the original and traditional product of the industry – and more recently, electric power, produced using cogeneration systems which have existed for decades, but whose output is now generating surpluses for the public electricity grid. These trends are increasingly important for the profitability of the sugarcane agroindustry and for the supply of electricity in many countries, like Brazil. This chapter discusses the manufacture of other sugarcane-based products that already enjoy well established technologies and functioning markets, while the next chapter analyses new possibilities that are at an initial phase of commercialization or still in development.

4.1 Sugar and derivates

A staple in the modern human diet, sugar is composed essentially of sucrose and was introduced in the western world during the Middle Ages by the Arabians as a highly valued spice. Sugar from sugarcane began to be produced by Portugal from its crops in its Atlantic colonies, and with the enormous expansion of sugarcane cultivation in the tropical New World, was transformed from a product whose consumption was largely restricted to society's elite, into a widely-used global commodity. Sugar was extremely important for the early development of the Brazilian economy, more important than gold or any other product and, as scholars Gilberto Freyre and Câmara Cascudo reported, it helped shape the society and personality of the Brazilian people. Such importance can also be observed in many other countries, where sugarcane agroindustry was and still is a central element of economic activity.

Today, more than 130 countries produce sugar; worldwide production in the 2006-2007 harvest reached 164.5 million tons. Roughly 78% of this total is produced from sugarcane, cultivated mainly in tropical and subtropical regions in the southern hemisphere. The remaining is produced from sugar beets, grown in temperate zones in the northern hemisphere. Because the cost of cultivating sugarcane is lower than the cost for sugar beets, the fraction of global sugar production occurring in developing countries is increasing as trade barriers impeding the free trade of this product are removed. Thus, these countries will likely account for almost all of the future growth in production, boosting their share of the worldwide supply of sugar from 67% in 2000 to 72% by 2010. Table 17 lists the leading producers and exporters of sugar according to data from the 2006-2007 harvest [Illovo (2008)].

Table 17 **– Main sugar producing and exporting countries for 2006/2007 harvest***

Country	Production (million tons)	Export (million tons)
Brazil	33.591	22,200
India	27.174	1,341
European Union	16.762	1,228
China	11.630	–
United States of America	7.661	–
Thailand	7.011	4,528
Mexico	5.543	380
South Africa	5.419	2,339
Australia	5.156	3,958
Pakistan	3.813	–

Source: Illovo (2008).
*Preliminary figures.

Considering this harvest, five major exporters – Brazil, Thailand, Australia, South Africa and Guatemala – supplied roughly 80% of all free trade exports in the world (excluding the contribution of preferred and quota markets which were discussed in Chapter 2). It is interesting to note that the portion traded in international markets is small in relation to overall production, because 69% of worldwide production is consumed in the country of origin [FAO (2007b)]. In this way, any variations in the volume produced in each country, due to weather conditions, may provoke significant changes in product availability and, consequently, in price. India's climb to the top among sugar-producing countries is a case in point. Some years it has exportable surpluses, and in others, it has become a significant importer.

In addition to the natural volatility of a market with variable supply and relatively low price elasticity, market conditions of other sweeteners such as high fructose corn syrup (HFCS) and low calorie sweeteners – that, in 2005, accounted for 18% of the global market for sweeteners – also contribute to price fluctuations in the international sugar market. In the past few years, high fructose corn syrup, used extensively by the food industry, has been losing market share to the sugarcane due to increases in the price of corn.

The worldwide consumption of sugar has been growing steadily at an annual rate of 2% through the last decades, which means an increase in demand of approximately 3 million tons each year. Such growth is taking place chiefly in developing countries, reflecting increases in consumer income and changing eating habits. Today, these markets already account for over 60% of current worldwide sugar consumption, with projections that Asian countries will account for a major portion of the growth in sugar demand [FAO (2007b)]. Such tendencies can be observed in the Indian market, where over the past 25 years the *per capita* consumption of sugar increased from 6 kg/year to 17 kg/year, while the consumption of other traditional sweeteners (*gur* and *khandsari*, handcrafted sweeteners produced from sugarcane) declined from 14 kg/year to 9 kg/year [India Infoline (2008)]. China, another key Asian market, is expected to consume 14 million tons of sugar per year by 2010, representing a *per capita* consumption of 10 kg/year, a level that will still keep the country well below the worldwide average of approximately 24 kg/year [FAO (2007b)]. Graph 11 presents the annual *per capita* consumption of sugar in several countries.

Besides granulated and refined sugar, higher value sweeteners targeted at specific segments of the consumer market have emerged in the sugarcane industry, with better prices for the producer. These include organic sugar, produced from sugarcane cultivated without agrochemicals or artificial additives, and sugars blended with low calorie sweeteners, such as aspartame or sucralose, the latter itself derived from sugarcane sucrose.

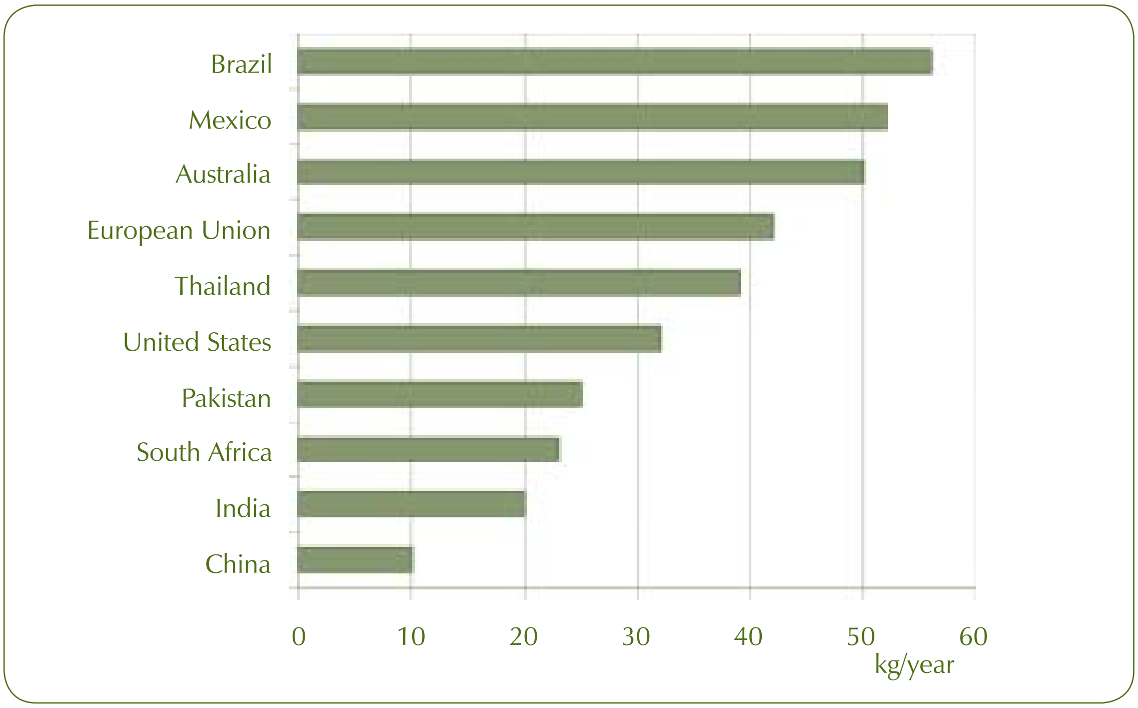
Organic sugar possibilities

Changes in consumer behaviour, favouring products considered healthy or those with fewer chemical additives, have opened a lucrative market for the sugarcane agroindustry with positive environmental implications for sugarcane processing and production. A good example is the case of Grupo Balbo, which began its Projeto Cana Verde (Natural Cane Project) in 1986, pioneering the integration of advanced technologies with traditional methods for cultivating sugarcane, in order to offer a line of organic food. Among its leading products is its Native brand of sugar, produced since 2000 by Usina São João (São João Mill) and sold in 40 countries, accounting for almost 22% of Grupo Balbo's revenue.

For an agricultural product to be considered organic, not only must the feedstock be cultivated without pesticides, the entire production system must be reconsidered and adjusted. Organic production also implies conservation and sustainable management of natural resources, such as soil and water, in an environmentally friendly manner, certified by independent third parties. These concepts were applied to 13,400 hectares of sugarcane fields, certified for organic farming in the following ways: Varieties of sugarcane that are naturally resistant to pests were selected; weeds and insects were managed using manual, mechanical, and biological techniques; organic fertilizers, including recycled by-products from sugarcane processing were used; and the sugarcane was harvested without burning. In these ways, the ecological potential of sugarcane is valued and the soil fertility is preserved, boosting yields that, after some years of adjustment, have been significantly above the average of other growers. Organic production establishes high standards for environmental protection in the industrial phase of production, with minimal use of chemicals and sophisticated procedures for process control, monitoring of operations, and safety. Likewise, energy efficiency has been accomplished by implementation of efficient cogeneration systems, with the acquisition and trade of carbon credits under the Kyoto Protocol.

Another important element of the production of organic sugar is the protection of faunal and floral biodiversity in agricultural areas, which has been promoted with good results. Significant efforts were undertaken to establish and replant forests with native species. According to a Fauna Inventory conducted in the region, the São João Mill has six times as many bird species as neighbouring farms, and a good variety of mammals, including carnivores such as puma and maned-wolf, suggesting recovery of ecological chains. The entire agroindustrial process and its environmental impact are periodically monitored by several International Certifying Institutions from Brazil, the United States, Europe and Japan [Native (2008)].

Graph 11 – Per capita **consumption of sugar in several countries**



Source: Illovo (2008).

Given the variety of plant feedstocks and different production contexts, the cost of sugar production varies widely. Among sugar-producing countries, Brazil stands out as the country with the lowest cost of production, followed by several African countries [F. O. Licht (2007)]. From a bioenergetic perspective, it is important to note that the low cost of Brazilian sugar is largely related to the development of agricultural and industrial technology associated with the expansion of bioethanol production. Morever, this low cost is because sugar production is integrated with bioethanol manufacturing, as was explained in the previous chapter, which confers significant operational and product quality advantages. In other words, Brazil managed to became the biggest producer of sugar and have the lowest cost, because it associated its sugar production with bioethanol.

4.2 Bioelectricity

In sugarcane, about one third of solar energy that is absorbed is fixed as sugar, while the rest is incorporated in the plant fibre, composed of cellulose, hemicellulose and lignin, which form the bagasse and sugarcane straw. The use of such biofuels is gaining increasing interest, with bagasse routinely used as a source of energy, especially within the sugarcane agroindustry.

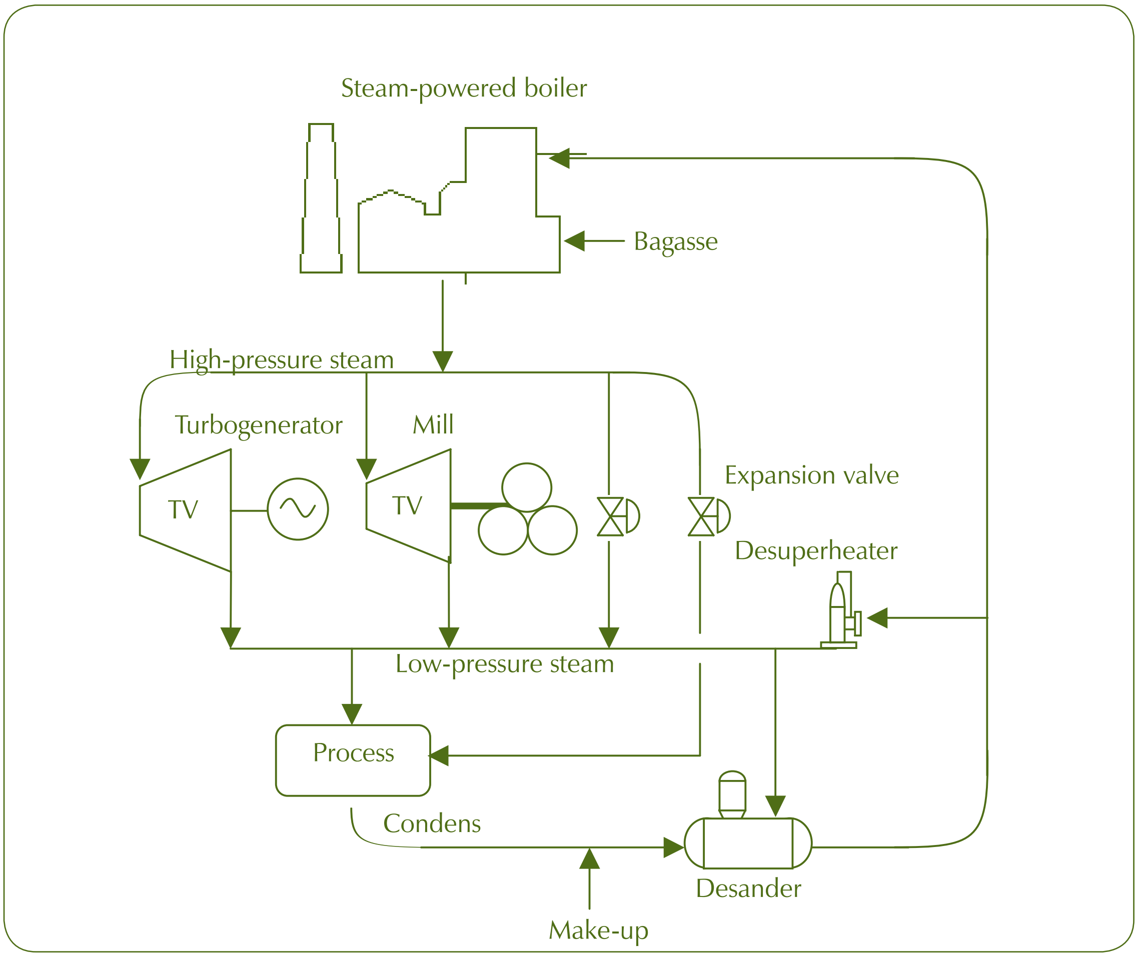
In the industrial processing of cane, three kinds of energy are required: thermal energy for heating and concentration processes; mechanical energy for milling and other mechanically driven systems, including pumps and large fans; and electric power for powering pumping, control systems and lighting, among others needs. In order to meet these energy requirements, sugar and bioethanol plants simultaneously produce these different energy forms using bagasse as their sole fuel. This technological approach, called cogeneration, represents a key distinguishing feature of sugarcane in relation to the other feedstocks used to produce sugar or bioethanol, which require external energy input for the industrial process.

Figure 18 illustrates the typical arrangement used in cogeneration systems in the sugarcane agroindustry throughout the world, where the main differences lie in the steam pressure produced in boilers [Seabra (2008)]. Briefly, high-pressure steam produced by the heat released by burning bagasse in boilers drives steam turbines for electric power production and mechanical drivers. The low-pressure exhaust steam meets the thermal energy requirements. This basic approach allows for several constructive variations, which, with the necessary investments, can increase electric power production per ton of processed sugarcane. While historically only bagasse was used as a fuel in the sugarcane agroindustry, increasingly part of the harvesting residue, the sugarcane straw, is also being used.

In typical conditions, the steam circuit of the plant is generally balanced, which means that the steam supply sufficiently meets the plant's own requirements. Over the course of its development, the industry has made improvements while maintaining this equilibrium, accommodating increases in the volume of sugar processed -- a consequence of improvements in the quality of the sugarcane crop -- with efficiency gains in cogeneration systems which generate and use steam. Using figures from current Brazilian plants, which are similar to those of other countries, the processing of one ton of sugarcane, yields about 250 kg of bagasse (with a moisture level of 50%), which can generate 500 kg to 600 kg of steam, close to the 400 kg to 600 kg of steam consumed in the processing [Leal (2007)]. By careful management of steam requirements and by installing more efficient boilers, it is possible to achieve a surplus of bagasse. In any case, the most interesting gains are achieved during power production, before the steam is used.

Such gains are possible because, in the production of electric and mechanical energy, in the sugarcane agroindustry there is a degree of flexibility in the way steam is produced in boilers and used to power steam turbines. While the steam pressure coming out of the turbines must -- because of requirements of the industrial process -- be close to 2.5 bar, the incoming pressure can be within a wide range, in accordance with the boiler used. The power that can be generated is proportional to the thermal energy, a function of the pressure and temperature in the boiler. Almost without varying the quantity of fuel, it is possible to increase the electric power generated by the sugarcane agroindustry by installing boilers and turbines that operate with steam at higher pressures and temperatures.

Figure 18 – **Common setup of cogeneration system in the sugarcane agroindustry**



Source: Seabra (2008).

During the past few decades, the operating parameters for steam boilers have increased in Brazil, an evolution that has been replicated in other countries [Horta Nogueira (2006)]. Until 1980, plants in the state of São Paulo had boilers with pressure between 12 and 22 bar and purchased 40% of the electric power they consumed. By 1990, with the replacement of old boilers and turbines, the average steam pressure in these plants had reached 22 bar, with temperatures of 300°C (572°F), levels which made the plants self-sufficient with regard to their electric power needs and in cases produced a surplus for sale. Under typical conditions, Brazilian plants consume the useful energy equivalent of 16 kWh per ton during the preparation and milling of the sugarcane, which is added to the electric power demand, on the order of 12 kWh per ton of sugarcane [Macedo et al. (2006)]. Thus, plants with generating capacities exceeding 28 kWh per ton of processed sugarcane are usually able to offer surplus energy for sale to the public electricity grid.

The recent appreciation in prices for these surpluses and the prospect of selling electric power to public utility concessionaires, has stimulated a new cycle of modernization of cogeneration systems in the sugarcane agroindustry in many countries, with plants installing high pressure systems that permit them to generate significant bioelectricity surpluses. The factors considered important for stimulating electric power production in the sugarcane sector include the demand for greater efficiency and less environmental impact in the energy sector, regulatory reform in the electric sector, and the development of technologies which better manage medium-sized cogeneration systems.

In terms of efficiency, cogeneration is intrinsically superior to conventional thermoelectric generation. Conventional thermoelectric technologies generally convert into useful power about 30% -- and under extreme conditions up to 50% -- of the energy provided by the fuel, inevitably dissipating a significant portion of the thermal energy into the environment. Cogeneration systems, by directing the otherwise wasted heat to meet thermal needs of the industrial process, achieve efficiencies by exploiting 85% of the fuel's energy, with clear benefits in the economy and in the reduction of environmental impact. Despite these advantages, the monopolistic behaviour of electric companies and the rigidity of regulatory frameworks virtually block these self-reliant producers from being connected to the grid and selling their available surpluses. Fortunately, attitutdes have evolved in a positive way and in several countries the sugarcane agroindustry is increasingly an important player in the supply of electric power. In this way, the Brazilian case is emblematic: in the first five years of this decade, the supply of electric energy from sugarcane to the public grid grew at an annual rate of 67% [Moreira e Goldemberg (2005)].

With the possibility of selling their bioelectricity surpluses, sugar and bioethanol plants began to also value solid residues of the harvest, which could further increase the availability of electric power. Of course, the use of sugarcane straw in boilers, which could approach 140 kg per ton of harvested cane, raises new issues of a practical nature regarding the harvest, handling and operation of boilers with this biofuel (ie, sugarcane straw). Such issues, however, are being gradually addressed successfully, permitting these solid biofuels to be harvested and hauled to the industrial plants at attractive prices (from US$ 0.80 to US$ 1.80 per GJ). Nevertheless, it is recommended that half of the straw be left as a soil covering for agronomic reasons: to minimize erosion, return nutrients to the soil, and to maintain a minimum level of humidity in the soil [Hassuani et al. (2005)]. Another issue related to the generation of bioelectricity for sale is the operation of the boilers in periods when no sugarcane is being harvested, when there is no demand for process heat, and which requires the storage of bagasse. This approach has been implemented in plants of several countries with favourable results, depending on the energy supply and particular opportunities for sale.

Table 18 demonstrates how the steam boiler parameters directly affect the production of energy surplus in sugar and bioethanol plants. To estimate these potential surpluses, the following assumptions were made: production of 280 kg of bagasse (with a moisture content of 50%) per ton of sugarcane; process steam pressure at 2.5 bar; and the use of back-pressure steam turbines, except in cases when operation occurs between harvests or with limited consumption of process steam, situations which impose the use of condensing turbines, with the condenser operating at 0.12 bar. In the two instances in which straw is used, 50% remains in the field, which means an effective contribution of 70 kg of this biofuel per ton of harvested cane.

Table 18 **– Electric power and bagasse surplus in cogeneration systems used by the sugarcane agroindustry**

Cogeneration system parameters	Consumption of process steam kg/tc	Production period	Straw use	Electric power surplus kg/tc	Bagasse surplus kg/tc
21 bar, 300° C	500 kg/tc	harvest	no	10.4 kg/tc	33 kg/tc
42 bar, 400° C	500 kg/tc	harvest	no	25.4 kg/tc	50 kg/tc
42 bar, 450° C	500 kg/tc	harvest	no	28.3 kg/tc	48 kg/tc
65 bar, 480° C	500 kg/tc	harvest	no	57.6 kg/tc	13 kg/tc
65 bar, 480° C	350 kg/tc	harvest	no	71.6 kg/tc	0 kg/tc
65 bar, 480° C	500 kg/tc	entire year	50%	139.7 kg/tc	13 kg/tc
65 bar, 480° C	350 kg/tc	entire year	50%	153.0 kg/tc	0 kg/tc

Source: CGEE (2005).

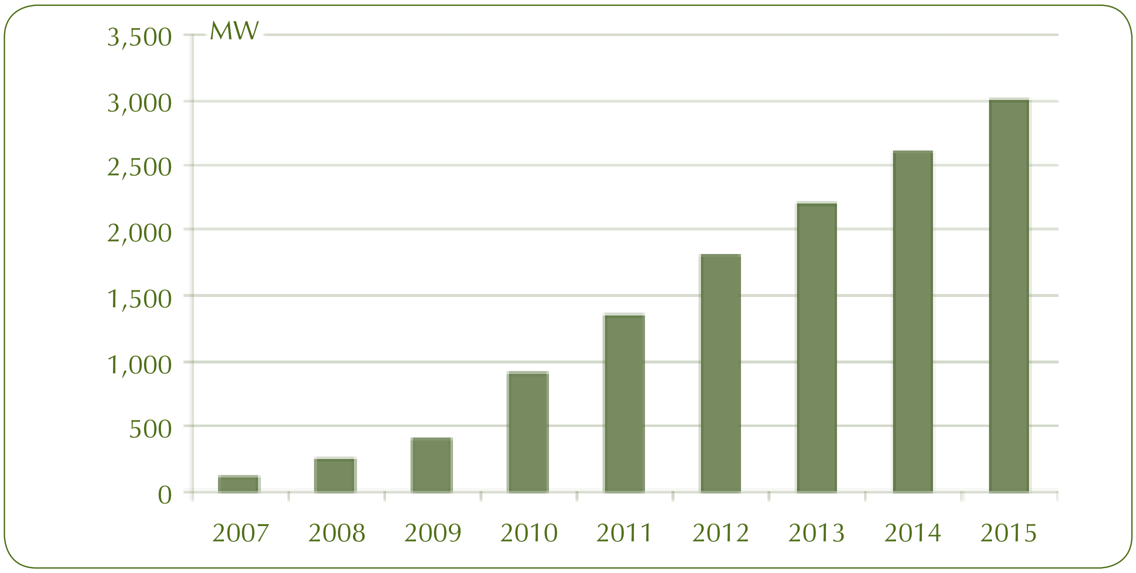
As shown in Table 18, there is an important increase in the surplus electric power as the boiler pressure is increased. Furthermore, reducing process steam consumption from 500 kg to 350 kg per ton of processed cane (kg/tc), increased the surplus electric power by 24%, and with partial use of sugarcane straw the surplus increases 141%. It is worth mentioning that recent cogeneration systems are being implemented in Brazil with boilers that operate above 90 bar, with an estimated production of 146 kWh per ton of cane for the public electric grid [Seabra (2008)]. Another study suggests that by considering the most efficient technology available for steam systems in sugar plants – generating steam at 105 bar and 525°C (977°F), reducing the demand for process steam to 280 kg per ton of cane, using all the bagasse and 50% of the tips and leaves, and operating year-round – it would be possible to deliver a surplus of 158 kWh per ton of processed sugarcane to the electric grid [Walter e Horta Nogueira (2007)].

The operation of a sugar and bioethanol plant under typical conditions in Central-South Brazil, milling 2 million tons of sugarcane annually using conventional cogeneration systems at 65 bar and 480°C (896°F), would translate into an installed production capacity of 31 MW. If the cogeneration systems are optimized to operate at 90 bar and 520°C (968°F), the power output increases to 82 MW for operations during the harvest [Seabra (2008)]. It is possible to achieve significant energy gains by using high steam parameters in these cogeneration systems. However, the use of higher pressures to increase the generation of surplus electric power implies proportionately larger investments, whose amortization will depend on other factors, including tax rates, the regulatory framework, and other prospects for increased supply in the electric sector, all issues which are essentially removed from the normal operation of the plants. Despite these issues, the pace of expansion of energy generating capacity by Brazilian sugar and bioethanol plants has been remarkable [CGEE (2005)].

According to the figures compiled by the Brazilian National Electric Power Regulatory Agency (Aneel) as of March 2008, the installed capacity for electric power generation from sugarcane bagasse reached 3,081 MW, with another 460 MW under construction or awaiting regulatory authorization to operate [Aneel (2008)]. Considering the figures for 2006, these plants account for the generation of 8.357 GWH, approximately 2% of the Brazilian electricity production [MME (2008)]. The state of São Paulo, which is responsible for approximately 60% of Brazilian sugar and bioethanol production and whose 131 plants processed 264 million tons of cane in 2006-2007 harvest, has an installed capacity of 1,820 MW with surpluses of 875 MW offered to the public electric grid [Silvestrin (2007)]. As demonstrated in Graph 12, the projected expansion for the generation of electric power surpluses by the sugarcane agroindustry just in the state of São Paulo is substantial. And for all of Brazil, the electric power generating capacity based on bagasse could reach 15 GW by 2015, equivalent to 15% of the current power capacity of Brazilian electric plants. There are prospects that the economic value of bioelectricity production may approach that of sugar production in the most modern plants, including the production of bioethanol, sugar and electric power [F. O. Licht (2008a)]. Taking a long-term view, considerating projected demand for bioethanol and the bagasse that would be available from such production, Walter and Horta Nogueira (2007) estimate that, in 2025, the installed capacity could reach 38.4 GW (if by then bagasse is used to produce bioethanol by means of hydrolysis and if boilers use 60% of available straw) or 74.7 GW (if all bagasse and 60% of the straw are used to produce bioelectricity).

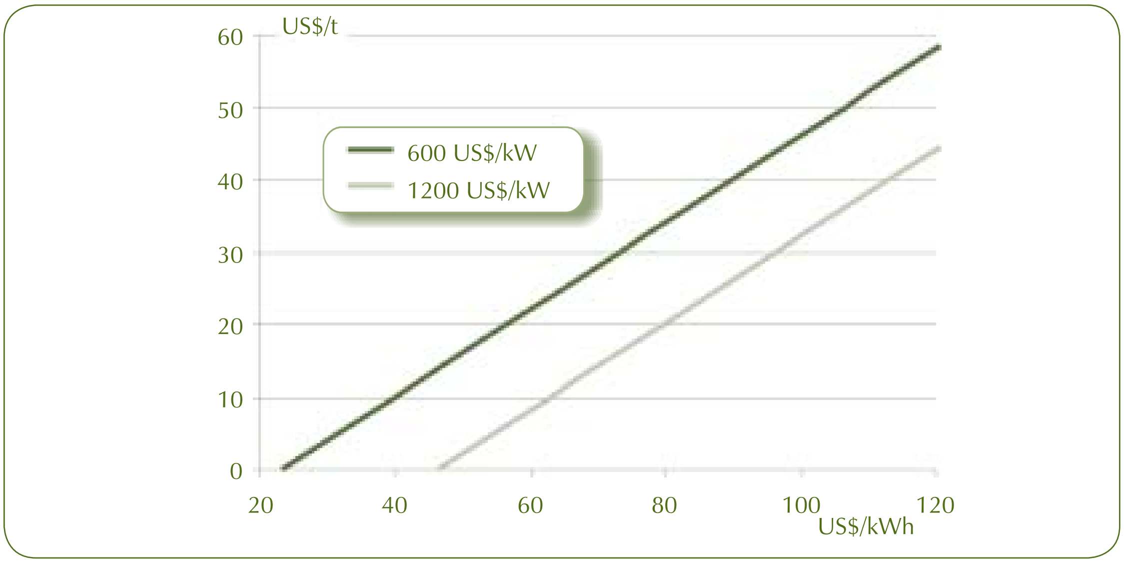
With the likely development of processes for the production of bioethanol from bagasse, there is interest in the analysis of the competitive prospects for this biomass, or in other words, figuring out the ways to maximize its economic prospects. In this context, a preliminary assessment comparing the economic value of the two alternative products of bagasse – bioelectricity and bioethanol produced by means of hydrolysis – is presented in the two graphs below. In Graph 13, bagasse's economic value is defined by the price at which electric power is sold, using two hypothetical unit costs for a given electric generation capacity. In Graph 14, bagasse's value is estimated when it is used for bioethanol production by means of hydrolysis (which will be detailed in the next chapter), producing 378 litres of bioethanol per ton of dry bagasse. In this scenario, the costs of capital and of operating the industrial facility were taken from the literature, varying, according to the maturity of the technology, from US$ 0.26 to US$ 0.13 per litre of bioethanol produced in the short-term and in 2010, respectively [IEA (2005)].

Graph 12 – Electric power generating capacity of cogeneration systems expected to be installed in sugar and bioethanol mills in the State of São Paulo in coming years



Source: Silvestrin (2007).

Graph 13 – Value of used bagasse for electricity production



Source: Elaborated by Luiz Augusto Horta Nogueira.

The evolution of electricity production at a Brazilian sugarcane mill

Usina Vale do Rosário (Vale do Rosário Mill).

A good example of the changes which ethanol and sugar mills in Brazil are undergoing in their search for ever greater electric power surplus is the Vale do Rosário Mill [Heck (2006)]. Located in Morro Agudo, São Paulo, this plant currently processes roughly five million tons of sugarcane per harvest. After modifications to the plant's energy system were initiated in 1986, the plant met all of its energy needs, but generated no surplus. The motivation for making further improvements was the potential for producing more electric power (great expansion of direct steam to take advantage of the exhaust steam and bagasse surplus) and the willingness of the public utility concessionaire (CPFL) to purchase the surplus. In the first phase, with the boilers operating at 22 bar and 280°C (536°F), more efficient steam turbines were installed, and new procedures to optimize steam use were introduced. By the 1993 harvest, the plant was producing 4.7 kWh per ton of processed sugarcane and a 10 year contract with CPFL was signed for the sale of 4 MW during the harvest. In a second phase, implemented between 1995 and 1997, two new boilers, operating at 44 bar and 430°C (806°F), and a 12 MW turbogenerator were acquired, which increased the surplus production to 16.5 kWh per ton of sugarcane. A new contract with CPFL, for sale of 15 MW starting in 1998, stimulated the construction of a new substation and a 16 km 138 kV transmission line. In the next phase, completed in 2001, new turbogenerators, which use extraction/condensation turbines, were installed. This permitted renewal of the contract with the concessionaire with delivery of 30 MW. In the most recent phase, concluded in 2005, a boiler that produces 200 tons of steam per hour at 65 bar and 515°C (959°F) was installed, which took the plant's electric power generation to 65 MW, or 60 kWh per ton of processed cane.

Graph 14 – **Value of used bagasse for ethanol production**

Source: Elaborated by Luiz Augusto Horta Nogueira.

Graphs 13 and 14 permit one to arrive at an interesting conclusion. The opportunity cost of bagasse for electric power production, considering the prevailing rates for electric power (more than US$ 60 per kWh in 2005) and market prices for bioethanol (usually close to US$ 0.50 per litre), clearly point to the greater economic attractiveness of bioelectricity production compared to the bioethanol production, at least for scenarios with these prices. This conclusion, in principle, does not take weigh strategic considerations associated with energy planning, which reinforce the attractiveness of supplying electricity, in the Brazilian case, and liquid fuels, in the US case.

The use of bagasse for generating electric power could reduce carbon emissions into the atmosphere, as it would substitute fuel oil burned in conventional thermoelectric plants, and would add electricity during the harvest period, which happens to coincide with the months when reservoir levels and hydroelectric generating capacity are at their lowest. The reduction of emissions is estimated to be about 0.55 tons of CO_2 equivalents per ton of used bagasse. Such reductions in greenhouse gases emissions qualify for carbon credits if they constitute "additionality" (the reduction of greenhouse gases emissions should exceed those that would occur in the absence of the activity), and use an approved consolidated baseline methodology (Method AM0015 – "Bagasse-based cogeneration interconnected to the electric grid"), for the quantification and certification of these Certified Emission Reduction (CER) credits within the terms of the Clean Development Mechanism (CDM) established by the Kyoto Protocol.

In Brazil, the Interministerial Commission on Global Climate Change (CIMGC), which is tied to the Ministry of Sciences and Technology, is responsible for the compliance and follow-up of CDM projects. As of March 2008, 24 Brazilian cogeneration projects using sugarcane bagasse were registered with the United Nations Framework Convention on Climate Change (UNFCCC), corresponding to a total reduction of 461,000 tons in annual emissions of CO_2. Emission factors used depend on the region where the projects are located. For the years 2004 to 2006, in the Northeast and Central-South regions, these factors, respectively, were 0.136 and 0.2826 tons of CO_2 equivalent per kWh generated [MCT (2008) and Ecoinvest (2008)].

To conclude the discussion concerning bioelectricity as an important by-product of the sugarcane agroindustry, it is worth noting the enormous potential for further technological development in this field. A process for gasification of bagasse, which could significantly increase electric power generation, with projected yields exceeding 180 kWh per ton of processed sugarcane, will be discussed in detail in the next chapter. Another process that has stimulated new research is the biodigestion of vinasse, which, without reducing its fertilizing potential, could provide additional surpluses of electric power to bioethanol plants. It is estimated that the vinasse by-product from the production of one cubic meter of bioethanol, treated anaerobically (in the absence of oxygen), produces 115 cubic meters of biogas, which, in turn, can generate 169 kWh of bioelectricity, already deducting the energy consumed in the process (2006)]. For now, the elevated costs associated with biodigestion of vinasse have limited the interest in this process.

In an assessment of future possibilities for energy conversion in the sugarcane agroindustry, considering different products and technological approaches that could become available in the next 20 years, Macedo (2007) estimates that up to 59% of the total energy content of sugarcane may be recovered as biofuel and bioelectricity, a much better yield than the current 38%. And more specifically concerning electric power, within an exploration of the thermodynamic limits of electric power production based on sugarcane using the most advanced technologies, Lora et al (2006) considered various complementary and related alternatives, in two basic scenarios: maximization of fuels production and maximization of bioelectricity generation. In this context, using technologies that are either still in development or diffusing gradually, such as the gasification of bagasse associated with gas-powered turbines, vinasse biodigesters, and hydrogen fuel cells that use reformed bioethanol, it would be possible to reach more than 510 kWh of electric power per ton of processed sugarcane. It should be remembered that this potential represents only about 25% of the energy potential of sugarcane, considering the energy available in the sugar and in the fibre is on the order of 7,200 MJ per ton of sugarcane. In other words, the upper limit for producing electric power from sugarcane is dozens of times higher than the average generation currently observed in Brazilian plants, which, in fact, is only now beginning to be developed.

4.3 Other co-products of sugarcane bioethanol

As with corn, the source for a diversified range of products, sugarcane produces much more than bioethanol, sugar and electricity. The traditional co-products of sugarcane, molasses, *aguardente* (a distilled beverage), yeast, filter cake and vinasse, are being joined by a growing and varied list of new products ranging from flavour enhancers for the food industry to packing plastic. This section in based on an extensive study published in Brazil in 2005, which identified more than 60 technologies in several industrial sectors that use sugarcane as a raw material [IEL/Sebrae (2005)]. Short commentaries about traditional products are presented first, followed by innovative products, most of which are related to the food industry. Products that are still in development are discussed in the next chapter.

Molasses – the liquid or residual honey of sugar manufacturing – is widely used as a feedstock for bioethanol production in distilleries attached to sugar mills. It can also be used for animal feed or for the culture of bacteria and fungi in other fermentation processes used for manufacturing chemical and pharmaceutical products, as well as the production of yeast used in baking. In this context, yeast is the dry extract obtained by three alternative processes: separating the liquid from concentrated yeast, dredging the vat bottom, or from the vinasse. This yeast serves as a low cost protein supplement used as a component of animal feed and in the food industry. Each litre of bioethanol produces an estimated 15 to 30 grams of dry yeast [Leal (2008) and Pesquisa Fapesp (2002)].

Bagasse is chiefly valued as a fuel, and it constitutes a source of cellulose for the paper and cardboard industries. In São Paulo, bagasse has an actual market value due to its energy capacity, and is used routinely by the ceramic industry and in orange processing, among other applications. In addition, bagasse is treated to enhance its digestibility and to incorporate sources of nitrogen for its use in bovine feed. Vinasse and filter cake add value as fertilizers, as they are used within the sugarcane agroindustry itself. Many plants send most of the vinasse they produce to reform and maintain the fertility of their sugarcane fields.

Carbon dioxide produced in the fermentation vats is usually washed to recover the bioethanol, and then released into the atmosphere, but may be purified, deodorized, liquefied, and stored under pressure for other purposes, such as the production of carbonated beverages and dry ice, sodium bicarbonate manufacturing and the treatment of effluents. From the fermentation mass balance, 760 kg of carbon dioxide are produced during the manufacturing of one thousand litres of anhydrous bioethanol. Some Brazilian bioethanol plants have installed equipment to process this carbon dioxide. During the harvest season the JB Sugar and Alcohol Mill, in the city of Vitória de Santo Antão, in the state of Pernambuco, produces 528 tons of food grade carbon dioxide [Carbogás (2008)].

While these traditional products can add value in a limited way to the production of bioethanol (that is why they are called by-products), innovative products are the result of highly complex and costly technologies that usually impose an additional processing step, as in the production of acids and amino acids by fermentative pathways. Table 19 (adapted from IEL/Sebrae, 2005) provides an overview of new products derived from sugarcane that are commercialized or about to be. This market is quite promising because, among other reasons, it is comprised of environmentally friendly products and, in some cases, products that are used in economically important sectors.

Citric acid has been produced for decades in Brazil through the fermentation process, using cultures of the fungus *Aspergillus niger* in molasses substrate dissolved in water. Citric acid is used extensively as a food preservative, and adds flavour as well. It is also used for cleaning industrial equipment and in the manufacturing of detergents and other hygiene and cleaning products. It is challenging to produce it economically because of the maintenance of production strains and accurate control of fermentation conditions.

Among the amino acids that can be produced by fermentation of sugar, lysine stands out. Its main market besides pharmaceutical applications, is as an ingredient in animal feed for poultry and swine, a growing market. Lysine is considered an essential amino acid because neither animals nor humans have an enzymatic pathway to synthesize it; thus its ingestion is required. Because the major part of an animal's diet is composed of plant carbohydrates, which are deficient in absorbable lysine, the addition of lysine to animal feed is required. That is the reason for the great interest in lysine; Brazilian imports in the past few years have been on the order of 10,000 tons per year.

It is worth examining the ways in which the sugarcane agroindustry has been diversifying in Brazil, within an environment of great technological complexity and profitability, in which the implementation of processes to develop new products from sugarcane is moving in two directions. In the first approach, the sugar-alcohol agroindustry is diversifying its product line. In late 2003 the Zillo Lorenzetti Group established Biorigin, a biotechnology company specialized in the production of natural ingredients for the human and animal food industry. Dozens of companies, which include the mills of Santa Adélia, São Martinho, Santo Antônio, São Francisco, Viralcool, Usina Andrade, São Carlos, Galo Bravo, Cresciumal, Santa Cruz OP, Jardest, São José da Estiva, Cerradinho, Equipav, Nova América, Pitangueira and Bonfim have implemented yeast-drying processes for its commercialization [IEL/Sebrae (2005)]. Approximately 50% of the yeast produced is destined for the domestic market, chiefly used in poultry (roughly 50%) and swine (roughly 30%) feed. The remaining 50% of production is destined for export, mostly (80%) to countries in Southeast Asia, where the yeast is used as feed at fish and shrimp farms. Using as a reference price US$ 12.5 per kg of dry yeast [IEL/Sebrae (2005)], yeast products could generate revenues of US$ 187 to US$ 375 per thousand litres of bioethanol produced, a phenomenal result in terms of economic yield from an agroindustrial process.

Table 19 – **New products from the sugarcane agroindustry**

Family	Feedstock	Products
Biotechnology: Materials produced based on the biological functions of living organisms	Molasses	a) Citric acid b) Amino acids: lysine c) Agrochemicals: Growth regulator or phytoregulators (indolacetic acid, jasmonic acid), pesticide (biofungicide, biological controller, biological Insecticide, biological pesticide) d) Nitrogen fixer e) Silage inoculum
Chemical: Products resulting from chemical reactions carried out with or without a catalyst	Molasses, bagasse, and vinasse	a) Industrial inputs (technical dextran, calcium gluconate, mannitol, sorbitol and biodegradable surfactants) b) Furfural (xylose liquor, furfural, furfuryl alcohol, furano-epoxy compounds, wood preservative, casting resin) c) Plastics (PHB and PHB/hl, PHA mcl/PHB hpe). d) Inputs for the industry of paper and cellulose (corrugating means, chemothermomechanic pastes, filtering materials) e) Concentrated vinasse
Veterinary-drugs: Chemical, biological, biotechnological substances or manufacturing preparations, given directly or mixed to the food, to prevent and treat animal diseases	Molasses and bagasse	a) Anti-diarrheic syrup b) Ferrous-dextran complex c) Probiotic
Food	Molasses, bagasse, and vinasse	a) Yeast, fructose and glycose by-products b) Fructooligosaccharides c) Inverted syrups by enzymatic pathway d) Edible mushrooms of the species *Pleurotus ostreatus*.
Biologics	Bagasse	a) Fertilizing compound
Structural: Materials whose properties make them useful in structures, machines or consumable products	Bagasse	a) Bagasse/cement pellets b) MDF pellets

Source: Amended from IEL/Sebrae (2005).

In the second approach to diversification, other industrial sectors, such as the food and chemical sectors, are increasingly incorporating sugarcane by-products as raw materials. In this context, Alltech, a multinational animal feed company, opened a joint yeast production unit with *Usina Vale do Ivaí*, in the state of Paraná, in 2005. The unit has capacity to produce 50,000 tons per year and it is considered one of the largest yeast factories in the world, and sells 80% of its production to foreign markets [JornalCana (2005)]. In a similar way, the Japanese company Ajinomoto and South Korean Cheil Jedang established lysine production facilities in Brazil taking advantage of existing technology and the low cost of sugar, a feedstock that replaces the corn and the soybean used to make lysine in other countries. When completed, these two factories together will produce 180,000 tons per year. The economic advantages are enormous: transformed into lysine, a 50 kg bag sells for US$ 50, seven times the price of sugar [Inovação Unicamp (2008)]. The growing integration between the sugarcane agroindustry and food production represented by these industries is highlighted by these examples.

Finally, in relation to these new products, it is important to note, that given the significant value they add, the necessary investments in plant infrastructure are relatively minor, especially in the context of the overall cost of a bioethanol plant. Perhaps, the greatest challenge to appropriately promote and diffuse these processes is an adequate understanding of the technologies involved, which requires the applied knowledge of modern biotechnology and all the instrumentation and control of infrastructure that it implies.


5
Silmara

Chapter 5

Advanced technologies in the sugarcane agroindustry

The range of products that can be made from sugarcane is not limited to those discussed in the previous chapter. This chapter presents innovative technologies for using sugarcane as an industrial and energy input. These technologies link the production of bioethanol to novel processes such as hydrolysis of lignocellulosic residues (Section 5.1) or gasification for fuels and electricity (Section 5.2) — which will increase the value of lignocellulosic materials — and the production of biodegradable plastics (Section 5.3). A review of the ways bioethanol can be used as a basic input in the petrochemical industry — or the alcohol-chemical industry as it will come to be known — is also included (Section 5.4) in this chapter, including reference to alcohol-chemical projects developed some decades ago and to renewed initiatives in the field in recent years. The chapter closes with a discussion of the potential of biorefineries (Section 5.5). It is argued that because the entire cane of the sugarcane plant — with its sugars and fibres — is a source of valued materials, sugar mills and bioethanol plants will increasingly be configured as "biorefineries," a concept that mimics the refineries of the oil industry, but using new inputs that are renewable and more environmentally friendly. Biorefineries will allow to transform sugarcane biomass into a wide range of products through integrated and interdependent processes.

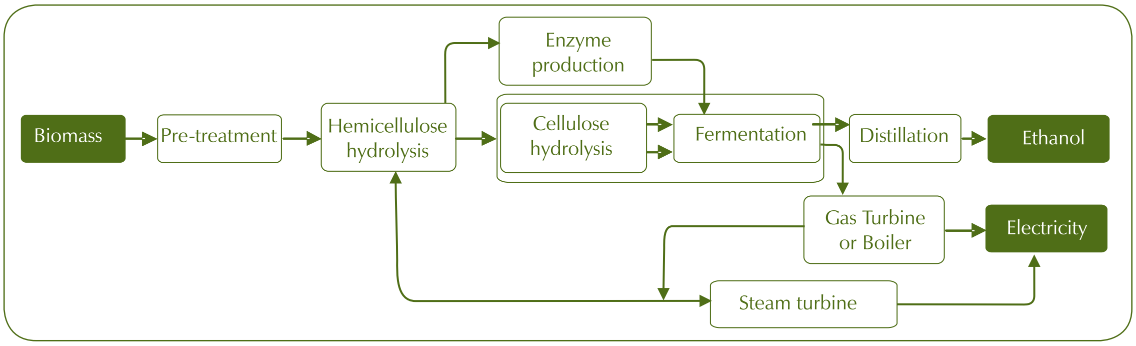
5.1 Hydrolysis of lignocellulosic residues

As discussed in Chapter 3, with the exception of sugarcane, the technologies commercially available for bioethanol production from starch and sugars, such as those derived from corn and sugar beet, involve modest energy and environmental gains. Furthermore, the use of these inputs offer limited economic benefits, when there are more profitable alternative markets (eg, food markets). On the other hand, despite its outstanding advantages as a bioethanol feedstock, sugarcane is not a viable option in all regions of the planet. Partially for those reasons, countries in the Northern Hemisphere have been searching intensely for technological approaches that would permit the production of biofuels that are attractive both from an economic and from an environmental perspective. Today, the prevailing view is that, in the future, in five to ten years, bioethanol production using hydrolysis of cellulosic materials will come to represent the realization of this long awaited alternative. Nevertheless, there are great obstacles to overcome and it is not easy to forecast how long such development will take.

Bioethanol has been produced through hydrolysis and fermentation of lignocellulosic materials since the end of 19th century, but it is only in the last 20 years that this technology has been proposed to serve the fuels market. The main research and development programs are being conducted in the United States and Europe, basically in experimental production scales. Their success could transform bioethanol into a viable biofuel that could be produced in almost all regions of the world, using available organic waste from various sources [Macedo (2005b)]. In fact, almost all biomass waste produced in agricultural and industrial activities — and even urban trash — contain substantial lignocellulosic material that can be converted into bioethanol through the new expected technologies.

Technologies for producing bioethanol from lignocellulosic materials involve the hydrolysis of biomass polysaccharides into fermentable sugars, and their subsequent fermentation to produce bioethanol. Hydrolysis uses complex and multiphase technologies based on acid or enzymatic routes, or both, in order to separate the sugars and remove the lignin. A simplified version of the generic sequence of this process is illustrated in Figure 19.

Figure 19 **– Schematic of the process of ethanol production by hydrolysis of biomass**



Source: Seabra (2008).

Unlike thermochemical processes, the composition and structure of the biomass employed have strong influence on the course and yield of the processes of hydrolysis and fermentation. Indeed, a considerable research effort should be exclusively focused on better understanding the formation of structural components of plants and how to modify them, to increase the yields from hydrolysis [DOE (2006)], as hydrolysis is really efficient only after the separation of the biomass fractions.

Lignocellulosic biomass is composed of polysaccharides (cellulose and hemicellulose) and lignin, a complex polymer of methoxy and phenylpropane groups that keep cells joined. The cellulosic fraction (40%-60% of dry matter) is a linear polymer of glucose-glucose dimers (cellobiose), rigid and difficult to break. Its hydrolysis produces glucose, a six-carbon sugar whose fermentation by *Saccharomyces cerevisiae* is well known. The hemicellulosic fraction (20%-40%), in general, is composed of a main chain of xylose (with β-1,4 bonds), with various branches of mannose, arabinose, galactose, glucuronic acid, etc. Hemicellulose is easier to hydrolyze than cellulose, but the fermentation of five-carbon (pentose) sugars is not as developed as the processes for glucose. The biochemical structure of the lignin fraction (10%-25%) is not related to simple sugar molecules, thus is not suited for bioethanol production using fermentation. The lignin fraction, however, still has an important role to play in the success of hydrolysis technology. Although it is possible to use lignin to produce several products, the focus of ongoing studies is the use of this material as a source of energy for such processes, which will ensure self-sufficiency and, perhaps generate surplus electric power which can be sold. Of course, this situation is attractive not only for the economic viability of the technology, but also from an environmental perspective, if it reduces dependence on external fossil energy resources.

In general, the first step consists of mechanical pre-treatment of the feedstock to clean and "crush" the material in order to break its cellular structure and make it more susceptible to subsequent chemical or biologic treatments. The next step, which is also considered pre-treatment, consists of lignin removal and hydrolysis of the hemicellulose. For this step there are several types of processes, with different yields and distinct effects on the biomass, which in turn have implications on the subsequent steps. Table 20 presents the most used methods.

Table 20 – **Processes to pre-treatment biomass for hydrolysis**

Process	Description	Reaction time	Xylose yield	Cost*
Physical				
Vapour explosion	Crushed biomass is treated with vapour (saturated, 160°-260°C) followed by a rapid decompression.	1-10 min	45%-65%	–
Thermohydrolysis	Uses hot water at high pressure (pressure above the saturation point) to hydrolyze the hemicellulose.	30 min	88%-98%	–
Chemical				
Acid hydrolysis	Uses concentrated or diluted sulphuric, hydrochloric or nitric acids,	2-10 min	75%-90%	+
Alkaline hydrolysis	Uses bases, like sodium or calcium hydroxides.	2 min	60%-75%	++
Organosolv	A mixture of an organic solvent (methanol, bioethanol and acetone, for example) and acid catalyst (H_2SO_4, HCl) is used to break internal bonds of lignin and hemicellulose.	40-60 min	70%-80%	
Biologic	Fungi (molds) are used to solubilize the lignin. Generally used in conjunction with other processes.			
Combined				
Catalyzed Vapour Explosion	Addition of H_2SO_4 (or SO_4) or CO_2 in the vapour explosion may increase the efficiency of enzymatic hydrolysis, reduce the production of inhibitor compounds, and promote a more complete removal of hemicellulose.	1-4 min	88%	–
Afex (ammonia fibre explosion)	Exposure to liquid ammonia at high temperature and pressure for a period of time, followed by a rapid decompression.		50%-90%	
CO_2 Explosion	Similar to the vapour explosion		75%	

Source: Based on Hamelinck, et al. (2005).
* The + symbol indicates advantageous effect (lower cost).

In the actual hydrolysis step, cellulose is converted into glucose, according to the following reaction, which may be catalyzed by a diluted acid, concentrated acid, or enzymes (cellulase):

$$n\ C_6H_{10}O_5 + n\ H2O \rightarrow n\ C_6H_{12}O_6 \qquad (3)$$

The acid hydrolysis (both the concentrated and diluted one) occurs in two stages, to exploit differences between hemicellulose and cellulose. The first stage involves the hydrolysis of hemicellulose, which follows the pre-treatment process described above. In the second stage, high temperatures are applied to optimize the hydrolysis of the cellulosic fraction [Dipardo (2000)]. Hydrolysis with diluted acid employs high temperatures and pressures. Reactions that take only seconds to a few minutes permit a continuous process. In contrast, processes that use concentrated acid are conducted under milder conditions, with longer reaction times [Graf and Koehler (2000)]. A comparison of the different hydrolysis processes is presented in Table 21.

Table 21 **– Comparison of different options for cellulose hydrolysis**

Process	Input	Temperature	Time	Saccharification
Diluted Acid	$< 1\%\ H_2SO_4$	215° C	3 min	50%-70%
Concentrated Acid	30%-$70\%\ H_2SO_4$	40° C	2-6 h	90%
Enzymatic	Cellulase	70° C	1.5 day	75%-95%

Source: Based on Hamelinck, et al. (2005).

In the enzymatic process, hydrolysis is catalyzed by enzymes that are generically referred to as cellulases. Cellulase, in fact, is an enzymatic complex composed of endoglucanases (that attack the cellulose chains to produce shorter polysaccharide chains), exoglucanases (that attack the non-reducer terminals of these short chains and remove the cellobiose) and β-glucosidases (that hydrolyze the cellobiose and other oligomers into the glucose) [Philippidis and Smith (1995)]. As in the acid processes, pre-treatment is required to expose the cellulose to the attack of enzymes.

As the enzymatic process is conducted in mild conditions (pH 4.8 and temperature between 45° and 50° C), the cost of processing is relatively low [Sun and Cheng (2002)]. Additionally, it allows larger yields and simultaneous saccharification and fermentation (SSF), and has lower maintenance costs (because there is virtually no corrosion). Because of its great potential for development and lower costs, many experts consider enzymatic hydrolysis as the key to cost-competitive bioethanol production over the long-term [Dipardo (2000) and Lynd, et al. (1996)].

Hydrolysis by diluted acid is currently at a more advanced stage in comparison to the others processes, but it has serious limitations in terms of yield (50%-70%). Hydrolysis with concentrated acid offers better yields and fewer problems in terms of the production of inhibitors, but the need to recover the acid and for equipment that is resistant to corrosion diminishes profitability of the process. Enzymatic hydrolysis, on the other hand, offers high yields (75%-85%) and further improvements are expected to get yields up to 85% to 95%. Furthermore, the non-use of acids may represent not only economic advantages (equipment with low operating cost and cheaper materials), but also environmental advantages (there is no production of residues). In most cases, these processes still are at early stages of development, with experiments conducted on reduced scales. In real systems with large volumes yields will be lower.

Regardless of the method, the fermentation of sugars from the hydrolysate into bioethanol basically follows the same principles as those observed in the production based on starch or sugars. In the case of hydrolysis, however, a good part of the hydrolysate is composed of five-carbon sugars, which cannot be fermented by wild lines of *S. cerevisiae*. Currently, most fermentation processes exclude this fraction of the sugars, or carry out the fermentation in two steps, significantly compromising profitability.

The expectation is that in the future these transformations could happen simultaneously in a smaller number of reactors, requiring, therefore, micro-organisms capable of fermenting both sugars with high yields. For this, researchers have turned to genetic engineering to insert pentose metabolic routes into yeast and other bioethanologenic microorganisms, as well as to improve the performance of micro-organisms that already have a capacity to ferment both sugars. Even though there have been successes in this area, fermentation of mixtures of biomass sugars still has not achieved commercial viability [Galbe and Zacchi (2002), Lynd, et al. (2005) and Gray, et al. (2006)]. In addition, it is important to consider harmful inhibitors of fermentation present in the hydrolysate (acids, furans, phenolic compounds, etc.), which should be removed when their concentrations are high, or which require the use of robust lines of resistant micro-organisms.

Within the context of enzymatic hydrolysis, the process with simultaneous saccharification and fermentation (SSF) — although not yet optimized — is viewed as a real option that could reduce substantially the problem of inhibition. One development in this process is the inclusion of co-fermentation of substrates with multiple sugars, which permits the conversion of pentoses and hexoses in the same reactor. Currently this approach — simultaneous saccharification and co-fermentation (SSCF) — is being pilot tested and will be a focus of development in the medium term. The endpoint of this technologic development could be the establishment of consolidated bioprocessing (CBP), in which the four biologic conversions employed in bioethanol production (enzymatic hydrolysis, saccharification, fermentation of hexoses, and fermentation of pentoses) occur in a single step. In this case, thermophilic micro-organisms would anaerobically produce enzymatic complexes with better cellulolytic activity than typical mold-derived enzymes and would ferment all the sugars released in the same reactor [Wyman (2007)].

In view of the long-term outlook for all these possibilities, some increase in bioethanol yield is expected, but the main outcome should be a reduction in the costs of production. A large prospective study carried out recently [Hamelinck, et al. (2005)], projected that enzymatic hydrolysis with diluted acid pre-treatment would be feasible on a commercial basis in the near future. In this scenario the process could recover approximately 35% of biomass energy in the form of bioethanol, and a total of 38% if surplus electricity is included. Bioethanol cost would be € 22 per GJ, assuming a biomass cost of € 3 per GJ and an investment of € 2100 per kW of bioethanol (using 2003 prices). In the long-term, using consolidated bioprocessing, the energy recovery with bioethanol could reach 47%, and a total of 52% counting surplus electricity. But the main expected advantage is a great reduction in the cost of producing bioethanol. The cost could drop to as low as € 9 per GJ, if the cost of biomass could be reduced to € 2 per GJ and investments requirements decline to € 900 per kW of bioethanol. In all estimates the energy considered always refers to the superior calorific power (SCP).

Table 22 summarizes the main results of studies concerning processes in development for bioethanol production by means of hydrolysis. It should be noted, however, that time frame forecasts in the last column should be taken cautiously, as they were generated at the time of the studies. Yields refer to the bioethanol produced per ton of dry biomass. The cost of biomass refers to its use as an input in bioethanol production and it is defined exogenously to such production process.

***Table 22* – Comparison of yield and cost estimates for bioethanol production by means of hydrolysis**

Reference	Process	Yield (litre/t)	Biomass cost	Ethanol cost	Availability
Hamelinck et al. (2005)	SSF with diluted acid pre-treatment	~300	3 €/GJ	0.98 €/litre	Short-term
	SSCF with vapour explosion pre-treatment	~340	2,5 €/GJ	0.58 €/litre	Medium-term
	CBP with thermohydrolysis	~400	2 €/GJ	0.39 €/litre	Long-term
Aden et al. (2002)	SSCF with diluted acid pre-treatment	374	33 US$/t	0.28 US$/litre (Minimum price)	Short-term
Wooley et al. (1999)	SSCF with diluted acid pre-treatment	283	44 US$/t	0.38 US$/litre	Short-term
	SSCF with diluted acid pre-treatment	413	28 US$/t	0.20 US$/litre	Long-term

Sources: Seabra (2008).

Regardless of the technological approach, it is important to note the great influence that biomass cost has on the final cost of bioethanol. In general, in estimates for countries in the Northern Hemisphere biomass cost represents approximately 40% of bioethanol costs and a large part of future reductions of biofuel prices depend on reductions of biomass costs. Therefore, high expectations are created when the situations in other regions are considered, especially those that can produce biomass at lower costs. One example is sugarcane biomass in Brazil. Sugarcane straw has a cost initially estimated at around US$ 1 per GJ [Hassuani, et al. (2005)], while bagasse — considered a residue — has no cost, in terms of what it takes to produce it; however, bagasse is indeed highly valued for electric power production, as discussed in the previous chapter.

In Brazil, hydrolysis technology also has been developed, with applied research already at a reasonably advanced stage. A process for producing bioethanol from bagasse (and eventually from straw) using an Organosolv treatment combined with diluted acid hydrolysis has been tested on a pilot scale for some years, as part of a project involving the Research Support Foundation of the State of São Paulo (Fapesp), the Sugarcane Technology Center (CTC), and Dedini S/A Indústrias de Base, a manufacturer of bioethanol plant equipment. The project has in operation an unit with an installed capacity to produce 5,000 litres of bioethanol per day, located next to a sugar and bioethanol plant; the objective is to determine process engineering parameters for the fabrication of large scale units [Dedini (2008)].

In the process, Dedini Rapid Hydrolysis (DHR – Dedini Hidrólisis Rápida) — a Dedini patented solvent (ethanol) — is used to break the cellulose-hemicellulose-lignin matrix, dissolving the lignin, hydrolyzing the hemicellulose, and exposing the cellulose to diluted sulphuric acid, which rapidly promotes (in 10 to 15 minutes) the hydrolysis of this fraction at temperatures of 170°C to 190°C and pressures of around 25 bar. It is a continuous process that has been uniformly and routinely operating since 2003. Although there are still aspects to fine-tune, complex challenges have been already overcome, such as how to continuously feed bagasse into high-pressure reactors, and the selection of materials which can be handled under demanding mechanical specifications in highly corrosive environments. Since the pentose fraction is not used in the process, yields are relatively low, on the order of 218 litres of bioethanol per ton of dry bagasse. However, it is expected that using this fraction of sugar will increase yields close to 360 litres per ton of bagasse [Rossell and Olivério (2004)].

More recently, Petrobras installed a reactor for enzymatic hydrolysis at *Cenpes,* its Research Center in Rio de Janeiro. And supported by the Ministry of Science and Technology, another pilot scale platform for enzymatic hydrolysis of bagasse is being implemented at the newly established Bioethanol Science and Technology Center in Campinas, São Paulo. This pilot reactor is the result of laboratory experiments that have involved about a hundred researchers from twenty research groups at universities and research centers throughout Brazil, many with international partners.

Dedini plant-pilot for producing bagasse-based ethanol.

In general, we can say that significant progress has been achieved in the development of hydrolysis technology; however, there are still important challenges to overcome for the implementation of commercially competitive units based on this technology. Given that resources are limited, it is essential to determine what critical issues need to be addressed for the consolidation of this technology. In recent years modified micro-organism were developed, and the main operations of industrial hydrolysis were modeled and optimized, but basically still on the limited scale of experimental reactors, in which it is easier to control temperature and contamination by other micro-organisms. Despite there is no consensus about the best technological approach for bioethanol production through these innovative routes, researchers around the world are nevertheless calling for the construction of the first commercial plants, which would permit to realize the expected rewards usually associated to *learning from experience* [Lynd, et al. (2005), Zacchi (2007), and Wyman (2007)].

5.2 Gasification for fuels and electricity production

Gasification is a process of thermochemical conversion of biomass carried out at high temperatures, in which solid or liquid organic substances are converted into gassy products, chiefly CO, H_2, CO_2 and water vapour, along with the formation of light hydrocarbons and other volatile and condensable compounds as secondary products [Grabowski (2004)]. The inorganic components of biomass are discharged in the form of ashes. The process can be carried out by means of a reaction of organic material with oxygen from the air or from vapour, or even with pure oxygen, using reactors at atmospheric pressure or pressurized. Heating of the gasifier can be done directly, by partial oxidation of the biomass, or indirectly, using heat exchange mechanisms. Fixed, fluidized, or entrained bed gasifiers may be used in the reactor. The choice of the gasification approach will depend on the biomass to be processed, the type of product sought, and the size of the plant.

The reactions that take place in a gasifier are extremely complex and the efficiency of the process depends on how properly they are carried-out. To give a simplified idea of the gasification process that follows the volatilization of the solid fuel, the following reactions occur simultaneously [Rauch (2002)]:

$$C + \frac{1}{2} O_2 \rightarrow CO \quad (4)$$

$$C + H_2O \rightarrow H_2 + CO \quad (5)$$

$$C + O_2 \rightarrow CO_2 \quad (6)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (7)$$

$$C + CO_2 \rightarrow 2\,CO \quad (8)$$

Using gasification, an heterogeneous material such as a biomass can be transformed into a gaseous fuel suited to various applications; sometimes the gas must be properly cleaned to the specifications required by the particular use. Cleaning can occur at low temperatures, for example by filtering (at around 200°C) and washing for removal of particulates and condensable materials after cooling. Cleaning may be also carried out at medium-high temperatures (350°-400°C) for use in gas turbines and fuel cells. Hot cleaning is usually done using ceramic filters [Macedo, et al. (2006)].

Biomass gasification has been evolving since the 1940s, with the creation of different types of gasifiers, process arrangements and applications. Contemporary gasifiers range from small systems that supply gas for automotive internal combustion engines to small stationary units that produce combined heat and power (CHP). In addition, larger scale gasifiers have been developed to generate power with gas turbines, at thermal power ratings of 10 MW to 100 MW and, more recently, to produce clean gas for the synthesis of liquid fuels (methanol, Fischer-Tropsch liquids, bioethanol, DME, etc).

Many of the obstacles to the development of this technology were identified and partially resolved in the 1990s, including how to feed large quantities of loose biomass into pressurized reactors, the development of systems to clean the gas to meet required quality standards, and other specific requirements so that the gas can be used in gas turbines designed for gases with low calorific power or in synthesis reactors which convert them into liquids fuels. Fuels synthesis can benefit from the experience of the fossil fuel industry, but the high complexity of the processes involved will certainly require further development.

The expectation is that biomass gasification could lead to the production of both liquid biofuels, mainly for automotive use, and bioelectricity on a large scale, as described in the following paragraphs. The main factor driving this technological development is the desire to reduce greenhouse gases emissions and substitute the consumption of petroleum-derived products. Despite promising previous experience with several demonstration plants, research and development efforts have not been consistent over the years; therefore, it is expected that these technologies will only become mature commercial options in the medium to long term (ie, in a period probably longer than ten years). But for those developments to actually take place a major commitment to research and development is needed, as well as the definition and implementation of encouraging public policies.

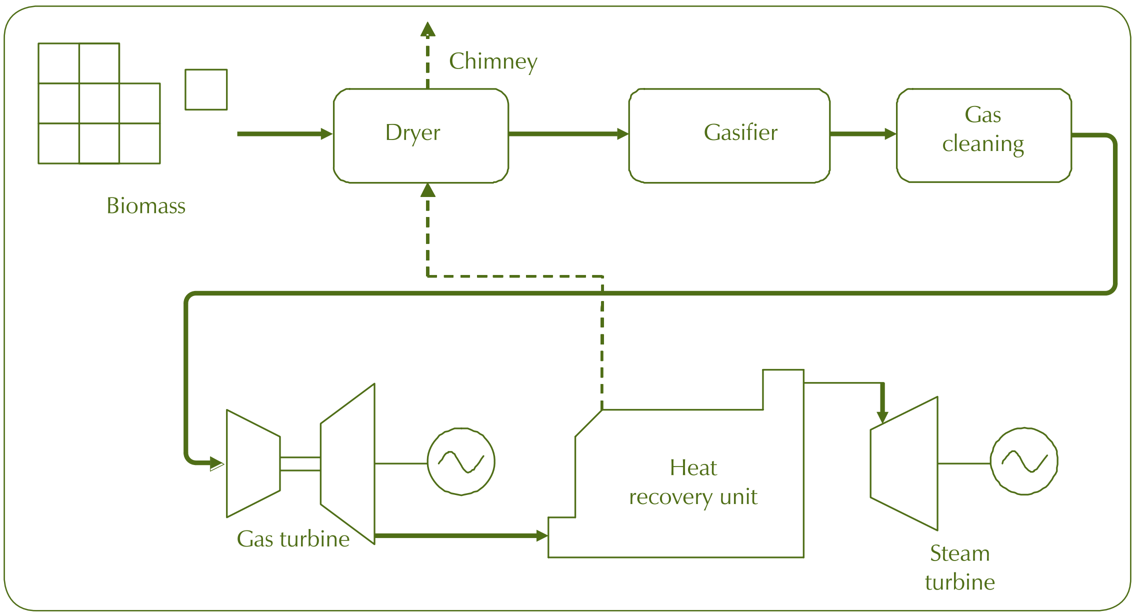
Gasification of biomass integrated with combined cycles (BIG/GT-CC technology)

Gasification is considered a critical technology to facilitate the efficient, clean and low cost conversion of biomass into bioelectricity. Gasification enables to implement the use of biomass in gas turbines, which have a thermal power cycle where working fluid operate at average temperatures considerably higher (above 1200°C) than in conventional steam cycles (below 600°C), reducing thermodynamic losses and maximizing performance. In this regard, it is expected that the biomass integrated gasification / gas turbine combined cycle (BIG/GT-CC) technology will become viable, creating a broad field for using solid biomass in the generation of electric power. In the case of gasifiers, smaller volumes of gas should be clean when compared with the direct combustion of biomass; and gas turbines associated with steam cycles (combined cycle) offer great efficiency in the generation of electricity with low capital costs.

The basic concept of BIG/GT-CC technology involves pre-treatment of biomass, followed by gasification, cooling and cleaning of the gas, and its combustion in a turbine. The hot gases that leave the gas turbine are transformed into steam using a heat recovery system, and steam is then used in a steam cycle to generate more electricity. Furthermore, after they are used to produce steam, the exhaust gases at low temperature can still be used in biomass drying, completing integration of the system [Faaij, et al. (1998)]. Figure 20 presents a basic schematic representation of a BIG/GT-CC system.

Given the basic concept of gasifying biomass and using the gas in gas turbines, there are three variations that may be used, which differ mainly in terms of how the gasifier is designed. One approach is based on circulating fluidized bed (CFB) technology, where the gasifier operates at atmospheric pressure with air injection to supply the oxygen that is needed for the gasification reactions. A Swedish company, Termiska Processer AB (TPS), with extensive experience in biomass gasification using this technology, proposes to insert a reactor in BIG/GT-CC systems immediately after the gasifier, for cracking of tar, a substance that hampers gas cleaning systems. The second approach is based on a gasifier with indirect heating and operating close to atmospheric pressure. The most relevant project on this gasification approach is conducted at the Battelle Columbus Laboratory (BCL), in Columbus, Ohio, and involves the use of sand to enable heating of organic material. The third approach involves CFB gasification technology, but operating at high pressures (20-30 bar, 900°-1000° C). Foster Wheeler (US) and Carbona (Finland) are two companies that have gained prominence with this technology [Consonni & Larson (1996) and Larson, et al. (2001)].

Figure 20 **– Schematic exhibition of a BIG/GT-CC system**



Source: Based on Larson, et al (2001).

In terms of yields, several studies have been carried out to estimate the efficiency and costs of bioelectricity, under the assumption that all technological problems have been resolved. However, the fact is that there are some significant obstacles to overcome, such as feeding and operation of high capacity pressurized gasifiers, gas cleaning with complete tar cracking, separation of alkali and particulates from the gas produced, modification of gas turbines for using gas with low caloric power obtaining a performance comparable to turbines that burn natural gas, and a significant reduction of capital costs through the learning effect. It is estimated that efficiency for generating electric power could be around 45%, for electric power costs in the range of US$ 40 to US$ 60 per MWh, as shown in Table 23, depending on the cost of biomass and the gasification technology used [Jin, et al. (2006)].

In the past 15 years there have been considerable research and development efforts in biomass gasification technologies associated with the use of gas turbines. Various projects were considered during this period; however, only one facility was actually built and operated for a significant time, in Värnamo, Sweden, using TPS technology. In Brazil there were plans for a BIG/GT-CC system generating 30-32 MW of electric power, in the interior of Bahia, using eucalyptus wood as fuel, but it was never built. The most plausible alternative —yet still highly unlikely— would be the use of BIG/GT-CC systems integrated with sugar mills and bioethanol plants, because the low cost of biomass would favour viability of the project. This alternative has been investigated since 1997 by the Copersucar Technology Center (now called the Sugarcane Technology Center) in partnership with TPS. At the moment, however, there is only speculation regarding the possibility of constructing a demonstration unit, in a future phase of the project [Hassuani, et al. (2005)].

***Table 23* – Comparison of yields and costs estimates of BIG/GT-CC systems**

Study	Gasification Technology	Efficiency Relative to PCI	Investment (US$/kW)	Biomass Cost (US$/GJ)	Electric Power Cost (US$/MWh)
Jin et al. (2006)	Atmospheric pressure with indirect heating	43.8%	968	3.0	55
	Pressurized with oxygen injection	45%	1,059	3.0	52
Faaij et al.* (1998)	Pressurized CBF	54%	1,950	4.0	80
Consonni & Larson (1996)	Atmospheric pressure with direct heating	41.9%	1,500	2.0	49

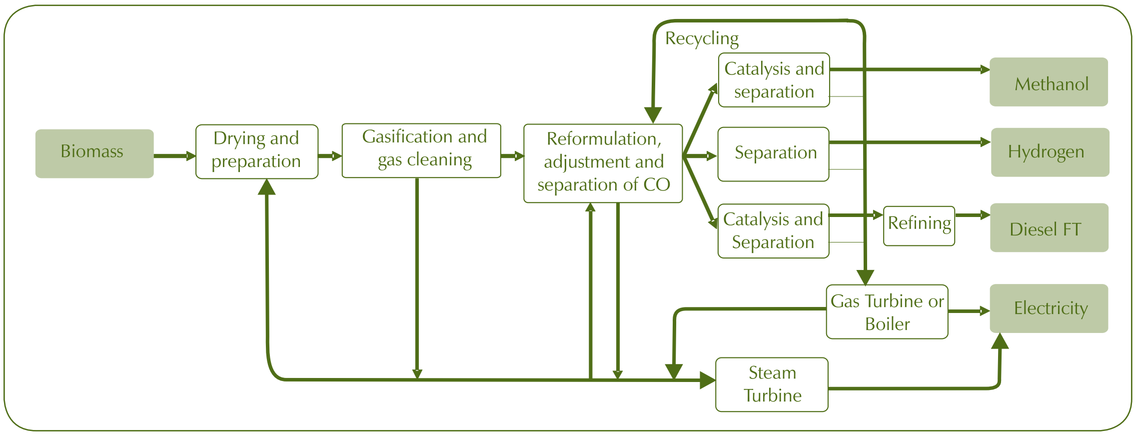
Source: Adapted from Seabra (2008).
* Original values in Dutch florins were converted at an exchange rate of US$ 1.00 = Dfl 2.00.

Synthesis fuels

Various biofuels, such as Fischer-Tropsch liquids (FT gas and FT diesel), hydrogen, methanol, ethanol, and dimethyl ether (DME) may be obtained out of synthesis gas (syngas) produced from biomass. In this process, biomass gasification generates synthesis gas, which must pass through cleaning and reforming processes and, if necessary, adjustment of its composition, so that it can be converted into fuel in a reactor. Given that not all the gas is converted into fuel, the unconverted portion can be re-circulated (to maximize fuel production), or it can simply be burned to generate electric power (in a BIG/GT-CC system, for example). The last option is known as *once-through* and it is considered the most economically viable approach when the electricity can be sold [Hamelinck, et al. (2001), Hamelinck, et al. (2003) and Larson, et al. (2005)]. Figure 21 presents a general diagram of the production of several fuels.

The scale of production is a determinant factor of the economic viability of liquid fuels produced using gasification technology, and a reason why the pressurized CFB gasification technology is favoured by some authors [Hamelinck, et al. (2003), Larson, et al. (2005) and Hamelinck, et al. (2001)]. The gasification process should be such that the gas produced is rich in CO and H_2, the two main reactants in liquid fuel production. Air injection should be avoided because it is not desirable that the gas produced is diluted in nitrogen.

Figure 21 – **General flowchart of methanol, hydrogen and diesel production through the biomass gasification (Fischer-Tropsch)**



Source: Adapted from Hamelinck (2004).

Because gas produced by gasification may contain considerable quantities of methane and other light hydrocarbons, one option is converting these compounds into CO and H_2 at high temperature and in the presence of a catalyst (generally nickel). Another important factor is the H_2/CO ratio, which should be adjusted for each type of biofuel, with less hydrogen in heavy fuels like diesel. This adjustment is done by the water-gas shift reaction, carried out in the presence of an iron-based catalyst [Van der Laan (1999)]:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (9)$$

The basic reactions involved in the production of each fuel are the following [Larson, et al. (2005)]:

For Fischer-Tropsch liquids: $CO + 2H_2 \Leftrightarrow CH_2 + H_2O$ (10)

For dimethyl ether (DME): $3CO + 3H_2 \Leftrightarrow CH_3OCH_3 + CO_2$ (11)

For methanol: $CO+2H_2 \Leftrightarrow CH_3OH$ (12)

There are three basic reactor designs: fixed bed (gas phase), fluidized bed (gas phase), and mud bed (liquid phase) [Larson, et al. (2005)]. The first design provides low conversions with only a single passage and it is still difficult to extract heat. The second design offers greater conversions, but it involves a more complex operation. The last is the one that offers the highest conversion rates for processes with simple passage.

Looking into the current state of this technology, significant development has been observed, especially in Europe, with the construction and operation of demonstration projects and even some commercial units. Based on the experience with biomass gasifiers and in the oil synthesis industry, in recent years some analyses have been conducted to evaluate the possibilities and costs of these biofuels in the future. In the case of FT liquids (gasoline and diesel), for example, if all technological problems were resolved, the overall efficiency could surpass 57%, considering the combined production of fuels (with an efficiency of 34%) and electricity (efficiency of 23%). The cost of biofuel would be around US$ 15 per GJ, given biomass costs of US$ 50 per ton and an investment of about US$ 1,770 per kW of fuel produced [Larson, et al. (2006)]. For the sake of comparison, conventional diesel costs around US$ 7 per GJ when the barrel of oil is at US$ 30 [Macedo (2005b)]. Table 24 presents some values from the literature, including yields and costs of liquid biofuels produced by means of synthesis processes associated with biomass gasifiers.

***Table 24* – Comparison of yields and costs for fuel production from synthesis gas**

Reference	Fuel	Yield (litre/ dry ton)	Investment	Biomass cost	Fuel cost
Phillips et al. (2007)	Ethanol	303	0.82 US$/litre/year	35 US$/t	0.26 US$/litre
Larson et al. (2006)	FT liquids	138	1,774 US$/$kW_{comb, PCI}$	50 US$/t	15.3 US$/$GJ_{PCI}$
	DME	468	1,274 US$/$kW_{comb, PCI}$	50 US$/t	13.8 US$/$GJ_{PCI}$
Hamelinck et al. (2002)	Methanol	280-630	930-2,200 US$/$kW_{comb, PCS}$	2 US$/GJ	8.6-12.2 US$/$GJ_{PCS}$

Source: Seabra (2008).

As previously stated, concerns about greenhouse gas emissions and oil costs are stimulating research into alternative ways of producing liquid fuels from biomass, reducing the use of fossil energy and even sequestering carbon emissions. A recent proposal [Williams, et al. (2005)] is the use of biomass gasification in conjunction with coal in a "hybrid" system, in which biomass would be used at a level that would significantly reduce greenhouse gases emissions of the thermal cycle.

Analyses of all innovative gasification bioenergy systems showed that assigning a value to their ability to mitigate climate change is essential to promote their economic viability, assuming the price of oil is US$ 30 a barrel. However, the recent increases in oil price, combined with renewed efforts to develop and demonstrate gasification technology, could lead to commercial systems in less time than originally predicted.

In addition to the hydrolysis and gasification approaches, which are reasonably well-known and have good prospects for economic viability improving in the medium term, other possibilities have emerged that could open new frontiers for the use of sugarcane in energy production, if their technical feasibility on commercial scales is confirmed. One of those possibilities, still being studied, is the production of butanol (C_4H_8O) — a widely-used industrial solvent currently manufactured in petrochemical plants — through biochemical processes that use lignocellulosic materials as inputs. Butanol can then be used as a gasoline additive in elevated concentrations without affecting mileage [DuPont (2008)]. Another approach that has been suggested is the production of biodiesel through biochemical processes that use sugars as the substrate. Projects to establish such industrial units have been proposed by the company responsible for such technology and its Brazilian partners [Amyris (2008)]. Such possibilities are certainly interesting and have a significant volume of applied technology; however, their economic feasibility has not been demonstrated and there is little knowledge of their performance and costs, both fixed and variable.

5.3 Using bioethanol as a petrochemical or alcohol-chemical input

Plastic materials — a generic term that designates a diversified family of artificial polymers — play an important role in our modern life, with a wide range of applications, whether replacing traditional materials like glass and wood, or creating new products (eg, packaging, coating and structural materials, among other possibilities). The main inputs to produce plastics in the petrochemical industry are natural gas and petroleum- naphtha. Production processes involve complex reactions that are usually grouped into three categories: a) first generation industries, which supply basic petrochemical products, such as ethene (or ethylene, C_2H_4), propene (or propylene, C_3H_6) and butadiene; b) second generation industries, which transform the basic petrochemicals into so-called final petrochemicals, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyesters and ethylene oxide; and c) third generation industries, in which the final products are chemically modified or built-in final consumer products, such as films, containers, and objects.

Bioethanol is an homogeneous and reactive substance that can be used as an input in various traditional petrochemical processes, which in this case could be called alcohol-chemical. The most important processes used in the transformation of bioethanol are classified as shown in Table 25. Prominent among them is ethane — produced by the dehydration of bioethanol — the precursor of a wide range of second generation products, such as polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). According to the equation for the dehydration of bioethanol, and assuming a conversion efficiency of 95%, 1.73 kg or 2.18 litres of bioethanol are consumed for each kilogram of ethane produced.

Based on the dehydrogenation of bioethanol into acetaldehyde, it is possible to generate another important class of intermediate butadiene and polybutadiene basic components of synthetic rubber used for various applications, including tires. Almost all products listed in Table 25 have widespread use in the industrial (paints, solvents and adhesives), agricultural (fertilizers and agrochemicals) and final use (for example, in textile fibres) sectors. Therefore, bioethanol can be considered an input for a wide range of traditional petrochemical products, by means of first and second generation conversion processes.

Table 25 – Basic processes of the alcohol-chemical industry

Processes	Main products	Typical application
Dehydration	Ethene Propene Ethylene-glycol	Plastic Resins Solvents Ethyl Ether Textile Fibres
Dehydrogenation Oxygenation	Acetaldehyde	Acetic Acid Acetates Dyes
Estherification	Acetates Acrylates	Solvents Textile Fibres Adhesives
Halogenation	Ethyl chloride	Cooling Fluids Medicine Products Plastic Resins
Ammonolysis	Diethylamin Monoethylamine	Insecticide Herbicide
Dehydrogenation Dehydration	Butadiene	Synthetic Rubbers

Source: Adapted from Schuchardt (2001).

The markets for these uses of bioethanol are important. Bioethanol demand by the Brazilian chemical and petrochemical industries could reach 7 million cubic meters [Apla (2006)], roughly one-third of the production in the 2006-2007 harvest. As the production of these sectors in Brazil represents only around 3% of global production, it is evident that there is large potential to expand the use of sugarcane bioethanol as a input on a global scale. Considering just that worldwide ethylene demand in 2005 was 105 million tons [CMAI (2005)], the use of bioethanol to replace 10% of other inputs would result in a demand of 23 billion litres, which is on the same order of magnitude as current Brazilian bioethanol production. With the basic technologies well understood, the critical factor for the development of this market is the relative price of bioethanol vis-à-vis other relevant inputs.

First steps of ethanol-chemical industry in Brazil

Projects to promote the use of ethanol to substitute fossil inputs in the Brazilian petrochemical industry were successfully implemented by Oxiteno and Coperbo, during the 1980s. These production routes were discontinued in 1985 because unfavourable prices, but there is renewed interest out of the recent increase in the cost of fossil inputs.

Oxiteno — the petrochemical branch of Grupo Ultrapar — used sugarcane bioethanol regularly as an input at its unit in Camaçari, Bahia, during the first half of 1980s, with an annual production of ethylene estimated at 230,000 tons. Today, the company is investing considerably on the development of technologies for petrochemical and alcohol-chemical processes, and has obtained several international patents, especially for the production of catalysts, which are essential components for converting ethanol into ethylene and other precursors. Furthermore, Oxiteno is working to develop the production of ethanol by hydrolysis of cellulose and to implement biorefineries, explicitly acknowledging its interest in supplying the inputs it needs for ethylene and ethylene-glycol production units [Inovação Unicamp (2006) and BNDES (2007)].

Coperbo — a Pernambuco Rubber Company — has an even longer history tying bioethanol to the production of chemical inputs. In September 1965, this company started the production of its butadiene unit in the city of Cabo, Pernambuco, to manufacture 27,500 tons per year of synthetic rubber based on ethanol. The objective was to meet the growing demand for this elastomer, which was only partially met by the domestic production of natural rubber. However, the approval by the Government of exports of molasses and imports of natural rubber created a shortage of ethanol to produce rubber, hampering the company's operations. In 1971 shareholder control of Coperbo was transferred to Petroquisa. This improved its financial situation and gave it a new impulse to increase its ethanol production, starting in 1975. The inclusion of acetic acid and vinyl acetate in its product line led to the creation of the National Alcohol-Chemical Company, which was later controlled by Union Carbide, a company that is currently managed by Dow Chemical [Jornal do Comércio (1999)]. No further details were obtained about its current industrial processes, but it is a fact that for several years this company produced ethanol-based butadiene, which was mainly used to manufacture tires on a commercial scale.

5.4 Biodegradable plastics production

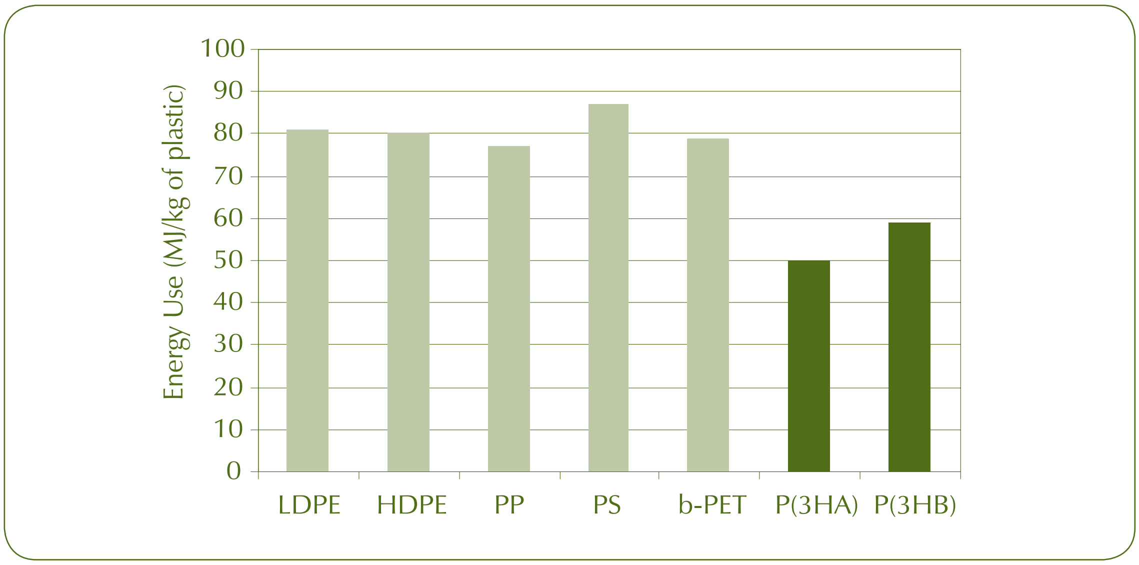
The global production of plastics was 230 million tons in 2004 and it is expected to increase to nearly 300 million tons en 2010 [Dröscher (2006)]. This enormous and growing market is a source of increasing environmental concern, because most plastic products are rapidly discarded and they have slow decay rates. Once used, less than 10% of plastics are recycled; the vast majority ends up in landfills [Waste-online (2008)], where complete decomposition can take from 100 to 500 years. The use of biodegradable plastics — besides increasing recycling — would be an effective solution to circumvent the problem.

Biodegradable plastics are polymers that, under appropriate environmental conditions, decompose completely in a short period of time due to microbial action. Bioplastics have an added important advantage: they are produced from renewable sources, like starches, sugars or fatty acids. One example of a bioplastic is polylactic acid (PLA), which is composed of lactic acid monomers obtained from microbial fermentation. Another possibility is to obtain the biopolymers directly from micro-organisms as in the case of polyhydroxybutyrate (PHB), polyhydroxyalkanoate (PHA) and their derivatives; in these cases the biopolymer is biosynthesized as energy reserve material of micro-organisms.

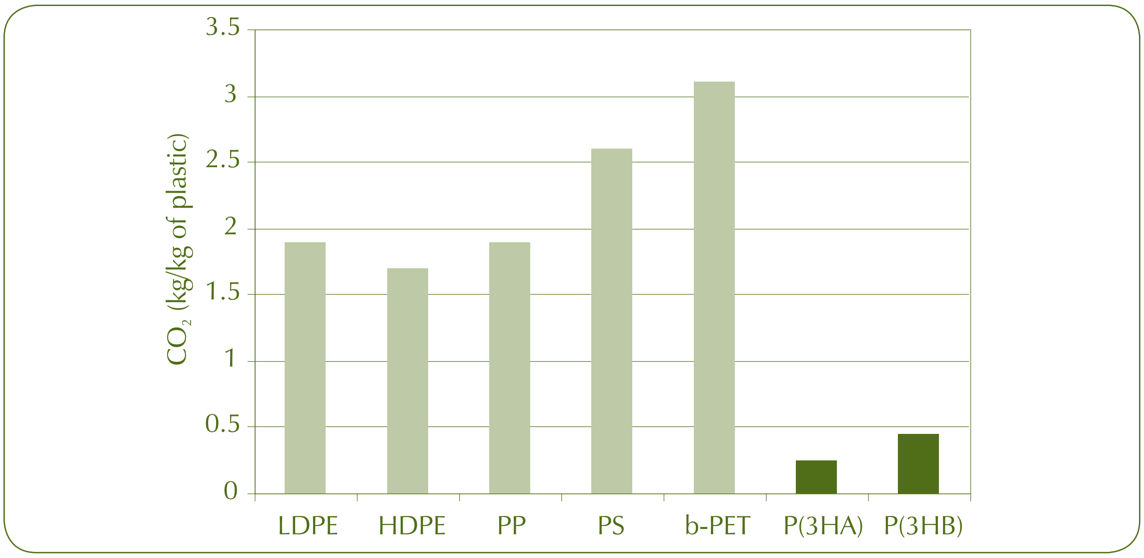
The first report about bioplastics was published in the 1920s, but the subject remained dormant until the 1970s, when the oil crisis revived research in alternative sources of materials and energy. Today, structures and biosynthetic routes and applications of many bioplastics are well understood, but there are still important limitations for large-scale production; for example, special growth conditions required for the synthesis of these compounds, the difficulty of synthesizing them through low cost precursors, and the high cost of their recovery. Even using recombinant micro-organisms capable of fermenting low cost sources of carbon (eg, molasses, sucrose, vegetable oils, and methane), these processes are still not competitive with the conventional production of synthetic plastics [Luengo, et al. (2003)].

Besides economic issues, it is also important to have a positive energy balance over the life cycle of these polymers, as they are intended to replace petrochemical materials. Normally, energy gains are small, since the energy supply, in general, is based on fossil fuels. In this case, once again the materials derived from sugarcane are favoured, thanks to the use of bagasse as an energy input in the process. Graph 15 presents a comparison between the energy consumed and greenhouse gases emitted in the production of 5 plastics of fossil origin — low density polyethylene (LDPEP), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (b-PET) — and two co-polymeric polyesters produced with biomass: P(3HA), based on soybean oil, and P(3HB), based on glucose [Akiyama, et al. (2003)].

Graph 15 **– Energy use (a) and Emissions of Greenhouse Gases (b) in the production of various types of plastics**



(a)



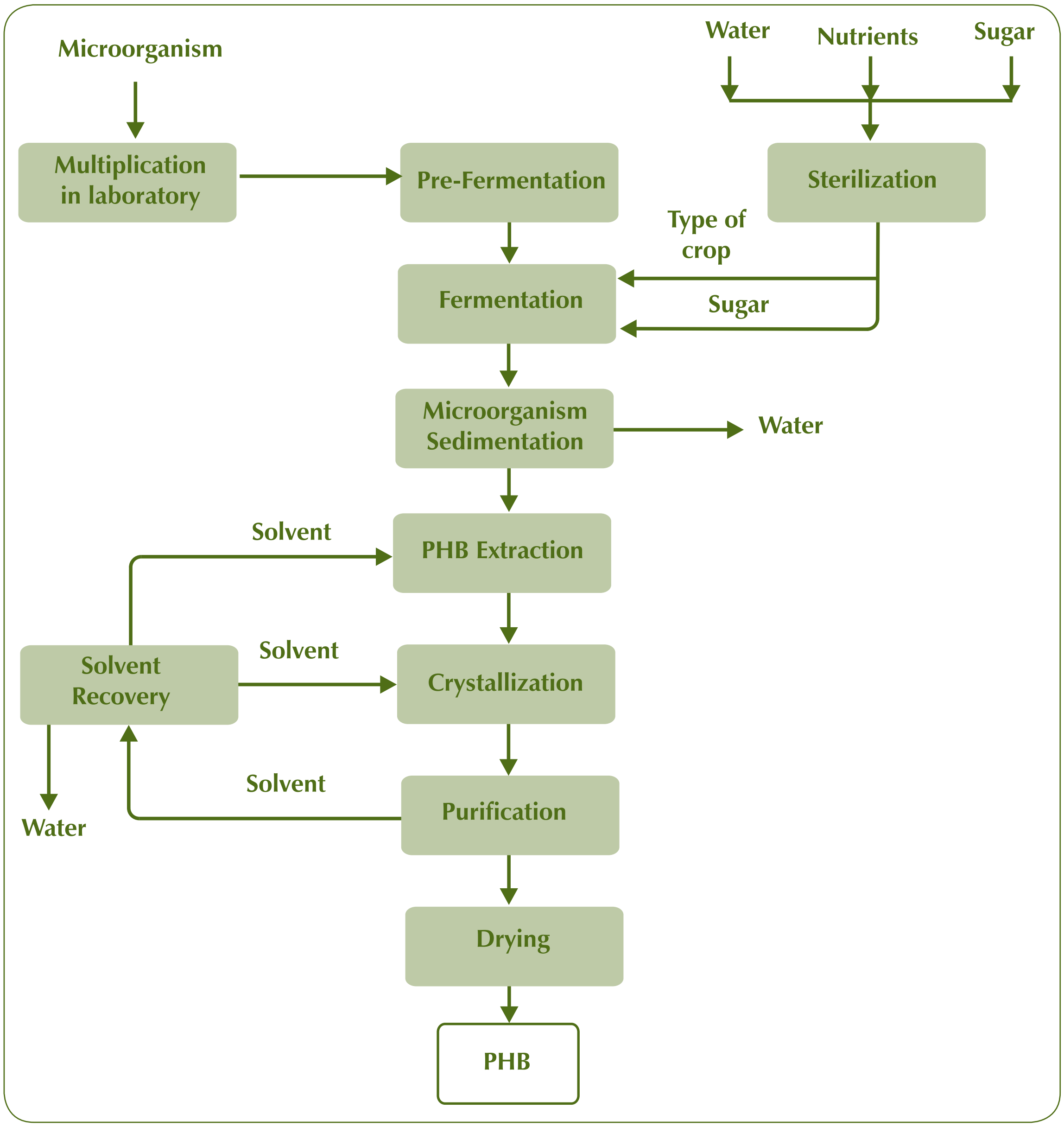
(b)

Source: Akiyama, et al. (2003).

In Brazil, there is already one PHB (polyhydroxybutyrate) production unit operating on a pilot basis with capacity to produce 60 tons per year. PHB Industrial S.A., in the city of Serrana, São Paulo, is attached to the *Usina da Pedra*, a sugar and bioethanol plant which supplies the sugar input and all the steam and electric power required by the plant. Industrial scale production is scheduled to start in 2008, beginning with 10,000 tons per year, destined mainly for the foreign market [Biocycle (2008)]. The production process is illustrated in Figure 22. Fermentation is carried out by micro-organisms cultivated anaerobically in a medium composed of sugarcane sugar and inorganic nutrients [Nonato, et al. (2001)]. Given this production design, it is estimated that only 10% of all the energy consumed in the life cycle of PHB comes from non-renewable sources, since bagasse provides the entire energy needed in the process [Seabra and Macedo (2006)]. Thus, it is reasonable to imagine considerably better performance in terms of non-renewable energy use and greenhouse gas emissions vs. polymers synthesized from other sources.

Pilot plant of PHB Industrial S.A. for biodegradable plastic production based on sugarcane sugar.

Figure 22 – **Flowchart of PHB production from sugarcane sugar**



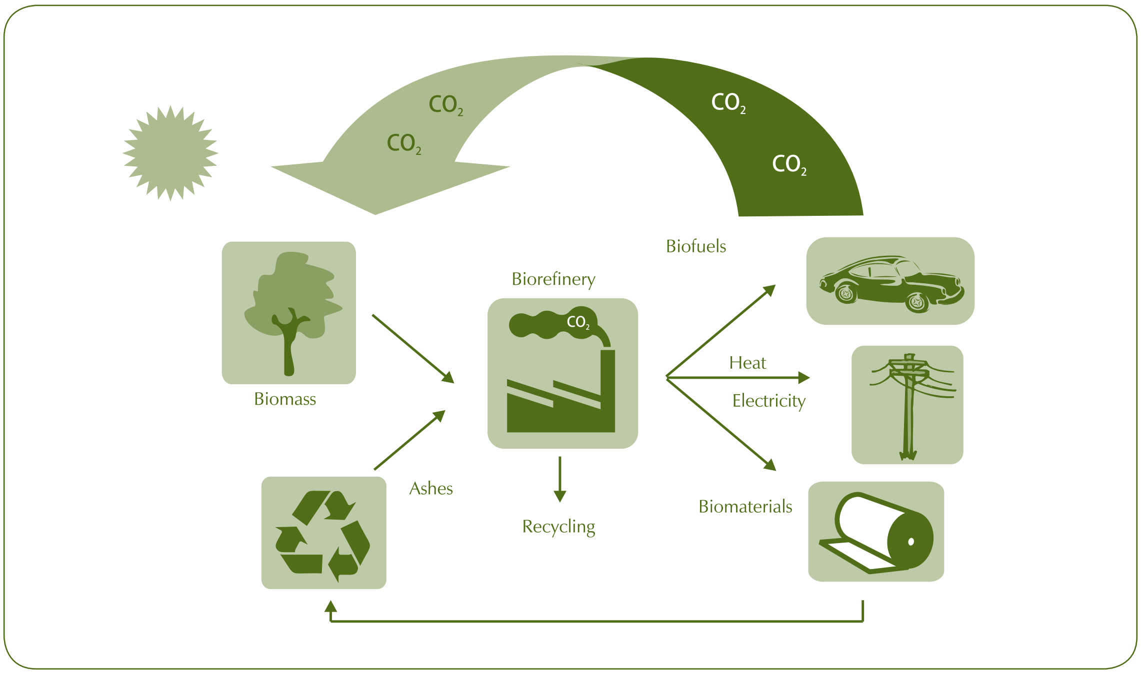
Source: Nonato (2007).

5.5 Biorefinery: multiple products and integral use of raw materials

A true biorefinery, as it is in the case of oil, can be defined as an integrated complex capable of producing various products — fuels, chemicals and power — using different types of biomass [Ondrey (2006)], in a model that would permit reaching greater efficiencies in thermodynamic, economic and environmental terms. Sugarcane bioethanol production can already be considered an example of a biorefinery, with its combined production of sugar, bioethanol and other chemical products, as well as power and heat generation from biomass residues [Macedo (2005b)].

Ragauskas, et al. (2006) provide a broad discussion of biorefineries and argue that they represent an optimized option for using biomass in the sustainable production of bioenergy, biofuels and biomaterials, both in the short and long term. Because of these attributes, large investments in development have been made in the past few years, both by governments and large private companies [Genencor (2004) and Ondrey (2006)]. Those investments create the expectation for competitive commercial plants in a not very distant future.

Figure 23 **– Complete integrated biomass-biofuel-biomaterial-bioenergy cycle**



Source: Adapted from Ragauskas, et al. (2006).

Some analyses of hypothetical "biorefineries" have contemplated the use of technologies that are expected to be "mature" in the future. Lynd et al. (2005) visualize the future self-sufficient production of power, Fischer-Tropsch fuels, and hydrogen, based on lignocellulosic materials, as well as scenarios involving the co-production of bioethanol-power, FT bioethanol-power-fuels, bioethanol-hydrogen or other combinations of products in conjunction with the production of protein. In the analysis, some scenarios demonstrate global energy efficiency on the order of 70% and economic competitiveness with conventional processes based on fossil fuels prices of the last few years.

A similar process of productive diversification and by-products valorization is taking place in forest-based industries. Analyses of the process envision the production of paper and cellulose, energy and a variety of chemical products, contributing to increase process efficiency, improve the benefit/cost ratio, and reduce environmental impacts [Karlsson (2007)]. The forest-based industry presents growth prospects which are similar to those in the sugarcane agroindustry, as well as interesting synergies between both industries in the development of technologies and markets.

Throughout this chapter it was possible to perceive the enormous potential associated with gasification technology as well as the possibilities of technologies for producing energy and different fuels. As a final point, and illustrating the potential of hydrolysis, it is important to bear in mind that when that technology becomes commercial and competitive, all biochemical sugar-processes for producing plastics, organic acids and solvents, among others, will no longer be restricted to the conventional sugar industry, but could be derived from any other source of biomass.

Chapter 6

Sugarcane bioethanol in Brazil

Sugarcane bioethanol has been used as a fuel in Brazil for almost 100 years. Its evolution traces an interesting history, from the progressive construction of institutional infrastructure and the evolution of agroindustrial technology (which in themselves shows an exemplary trajectory of gains in productivity) to the steadily increasing importance of environmental aspects, such as the need to reducing water consumption and recycling it. In the paragraphs that follow, the Brazilian experience will be discussed in depth. The analysis starts with an overview of the historical use of bioethanol as fuel, stressing the crucial role played by a legal and institutional infrastructure created along the process, which has paved the way for this alternative energy source to become a vital component of the Brazilian energy matrix. The second section presents the current situation of bioethanol production in Brazil, especially regarding the issues of production facilities and perspectives for development of production. The last section explores the evolution of bioethanol technology innovations, focusing on the research and development of methods, equipment and processes that have enabled the sugarcane agroindustry to consolidate itself as a sustainable energy source.

6.1 Evolution of bioethanol fuel in Brazil

In 1903, the *I Congresso Nacional sobre Aplicações Industriais do Álcool* (First National Congress on Industrial Applications of Alcohol) recommended the development of infrastructure to produce automotive bioethanol in Brazil [Goldemberg et al. (1993)]. The *Estação Experimental de Combustíveis e Minérios* (Fuel and Mining Experimental Station) — which later became known as the *Instituto Nacional de Tecnologia* (INT) (National Technology Institute) — was created in 1920 and many successful tests on bioethanol driven vehicles (called «motor alcohol» at the time) were conducted there at that time. The stated objective was to substitute petroleum-derived gasoline, a product that had always been scarce and whose price tended to increase over time [Castro and Schwartzman (1981)]. Several pioneers at that time promoted the use of bioethanol to power vehicles: Heraldo de Souza Mattos, who took part in car races using pure hydrated bioethanol as fuel, in 1923; Fernando Sabino de Oliveira, author of a book entitled *O álcool-motor e os motores a explosão* (Bioethanol and the internal combustion engines), published in 1937; and Lauro de Barros Siciliano, author of dozens of studies on the use of bioethanol in engines, who conducted bench and road tests, in an attempt to spark the interest of government and entrepreneurs [Vargas (1994)].

Ford vehicle adapted by INT in 1925 for demonstrations of the use of bioethanol as fuel.

Based on these experiences, in 1931 the Brazilian government implemented a compulsory blend of at least 5% anhydrous bioethanol in gasoline (Decree 19.717, signed by President Getúlio Vargas), aiming to reduce the impacts of total dependence on petroleum-derived fuels and take advantage of excess production in the sugar industry. Initially, the mandate applied only to imported gasoline, but later it was also requested for domestically produced gasoline. The responsibility of establishing prices, production quotas per mill and fuel blends was assigned to the *Instituto do Açúcar e do Álcool* (IAA) (Sugar and Alcohol Institute). Therefore, the use of bioethanol as automotive fuel (already known to the automotive industry for over century) has been a regular practice in Brazil since 1931, practically contemporaneously with the introduction of the automobile as a means of transportation in the country.

The amount of bioethanol in Brazilian gasoline varied over successive decades, reaching an average of 7.5% in 1975, when the effects of the first petroleum crisis imposed the need to expand the use of this biofuel in cars. Due to high international petroleum prices, import expenditures expanded from US$ 600 million in 1973, to US$ 2.5 billion in 1974, triggering a US$ 4.7 billion trade balance deficit. These results came to weigh heavily on Brazilian foreign debt and inflation over the course of the following years. In today's energy market context, with different countries considering bioethanol as an energy option, it is worth looking at the main historical influences that have enabled the consolidation of bioethanol fuel production in Brazil.

In the mid-1970s, aiming to address the post-oil-crisis energy situation, a proposal was developed to reduce to dependence on imported oil. The proposal involved visionary entrepreneurs like Lamartine Navarro Jr. and Cícero Junqueira Franco and combined the preferences of the Sugar and Alcohol Institute for the exclusive production of bioethanol in independent distilleries, as well as the interests of Copersucar (the main sugar producers cooperative), which intended to take advantage of unused capacity of sugar mills. After discussions between the private sector and the government, a document with recommendations was submitted to the *Conselho Nacional de Petróleo* (National Petroleum Council) in March 1974 [Bertelli (2007)].

Another relevant factor that encouraged a positive government stance for increasing the use of bioethanol was a visit by the then President Ernesto Geisel, in June 1975, to the *Centro Tecnológico da Aeronáutica* (Aeronautical Technology Center). During that visit he was shown successful results from research carried out by Professor Urbano Ernesto Stumpf on bioethanol use in engines, utilizing gasoline with high levels of anhydrous bioethanol, and also from testing the use of pure hydrated bioethanol in specially adapted engines. It was clear that Brazil could provide itself with a good solution to the oil dependency problem: On the supply side, it could increase the production of bioethanol using the idle capacity of sugar mills; on the consumption side, it could increase the amount of ethanol in gasoline, and eventually use pure bioethanol as a fuel.

Based on these premises, and after new studies and debates, in November 14, 1975 the Federal Government instituted the *Programa Nacional do Álcool* (National Alcohol Program – Proálcool), through Decree 76.593 signed by President Geisel. The decree established special lines of credit, formalized the creation of the National Alcohol Commission (CNA) responsible for managing the program, and determined a price parity between bioethanol and standard crystal sugar. The objective was to stimulate the production of this biofuel, which had been, until then, an undervalued by-product. In this context, production goals were set of 3 billion litres of ethanol for 1980, and 10.7 billion litres for 1985. Several incentives to expand the production and use of bioethanol fuel were implemented, initially by increasing the addition of anhydrous bioethanol to gasoline. The oversight of Severo Gomes, Minister of Industry and Trade, and the support of José Walter Bautista Vidal, Secretary of Industrial Technology, were decisive in the early years of Proálcool implementation, when the initial program took shape. Later on, during the most important expansion phase, which started in 1979 under Minister João Camilo Pena, the commitment to bioethanol fuel became evident and the foundations for its consolidation were put in place. Serving as a message from this pioneering generation, the book *Energia da biomassa – Alavanca de uma nova política industrial* (Biomass Energy: In praise of a New Industrial Policy) points to the need to transcend conventional energy systems in order to become a «photosynthesis civilization» [Guimarães et al. (1986)].

With a decidedly favourable legal climate, the production of bioethanol expanded significantly. Between 1975 and 1979, bioethanol production (anhydrous and hydrated) grew from 580 thousand m^3 to 3.676 million m^3, surpassing the goal established for that year by 15%. In 1979, with the oil crisis worsening and prices reaching new heights, the Proálcool program gained new force, stimulating the use of hydrated bioethanol in engines adapted or specially made to work with it. At that time, Brazil's dependence on imported oil was around 85%, accounting for 32% of all Brazilian imports. This had serious impacts on the national economy and justified the ambitious goal of producing 10.7 billion litres of bioethanol in 1985. To this end, via Decree 83.700 of 1979, the federal government increased its support for alcohol production with the creation of the *Conselho Nacional do Álcool* (National Alcohol Council – CNAL), which oversaw Proálcool and the National Executive Commission for Alcohol (Cenal), responsible for implementing the program [CGEE (2007a)]. Under this scenario, bioethanol production reached 7.7 billion litres in 1985, exceeding the intended goal by 8%.

The combination of incentives adopted by Proálcool (which had shown itself to be capable of effectively influencing economic agents) at the time included: a) establishing higher minimum levels of anhydrous ethanol in gasoline (progressively increased to 25%); b) guarantying lower consumer prices for hydrated ethanol relative to gasoline (at the time, fuel prices throughout the entire production chain were determined by the federal government); c) guarantying competitive prices to the bioethanol producer, even in the face of more attractive international prices for sugar than for bioethanol (competition subsidy); d) creating credit lines with favourable conditions for mills to increase their production capacity; e) reducing taxes on new cars and on annual registration fees for hydrated bioethanol vehicles; f) making the sale of hydrated bioethanol at gas stations compulsory; and g) maintaining strategic reserves to ensure supply out of season.

Around 1985 the situation began to change because of falling crude oil prices and strengthening of sugar prices. These events made ethanol production unattractive and created difficulties to the bioethanol industry that led to the end of the expansion phase of Proálcool. In addition, in 1986 the Federal Government reviewed incentive policies to bioethanol thereby reducing the average sugarcane agroindustry returns and stimulating even more the use of the available raw sugarcane to produce sugar for export. An important consequence of the reduced attention given by the government to bioethanol and of the absence of specific policies to support its production was that in 1989 consumers began facing sporadic supply shortages of this biofuel. The mechanisms to create safety reserves failed and emergency measures became necessary, such as reducing the level of bioethanol in gasoline, importing bioethanol and using gasoline-methanol mixes as a substitute for bioethanol.

A tough consequence of the bioethanol supply crisis — by the way, a national product whose advertising campaign suggested «use what you need because there will be no shortage» — was the loss of confidence by Brazilian consumers, which then led to the inevitable fall in sales of pure-bioethanol-powered cars. Thus, having accounted for 85% of new car sales in 1985, sales of bioethanol-powered vehicles accounted for only 11.4% in 1990 [Scandiffio (2005)]. It was not until the middle of 2003, with the launch of flexible fuel vehicles, that consumption of hydrated bioethanol started to grow again significantly.

Paradoxically, even during the period of apparent lack of direction regarding the future of bioethanol, independent studies concluded that it was necessary to maintain the program in operation. The studies proposed realigning the rate of bioethanol growth to the new conditions, but ensuring continuity of the program, not only for its environmental and social benefits, but also for the gains in productivity underway, which made bioethanol competitive compared with crude oil at US$ 30 a barrel [Scandiffio (2005)].

By the beginning of the 1990s, after decades of strict state control, the basic structure of the Brazilian sugarcane industry was characterized by the following elements: agricultural and industrial production under the control of the sugarmills; heterogeneous production, especially in sugarcane; underutilization of by-products; and competitiveness driven largely by low salaries and mass production. Technical differences among firms in the North Northeast and Midsouth were significant and, even within a given region there existed sharp differences in productivity and scale of production [CGEE (2007a)].

During the early 1990s the Brazilian Government implemented a series of administrative changes, as part of a significant review of its role in the economy. Within that context, a process of liberalization and institutional reshaping of the sugar alcohol sector was unleashed. The Sugar and Alcohol Institute was closed and the administration of bioethanol related matters were transferred to the *Conselho Interministerial do Açúcar e do Álcool* (Interministerial Sugar and Alcohol Council Cima), which was headed by the Ministry of Industry and Trade until 1999, when management was assumed by the Ministry of agriculture. A move towards a free-market pricing in the sugar-alcohol sector started in 1991, with the progressive removal of subsidies and a reduction of the government's role in fixing bioethanol prices, a process that was completed only in 1999. The result of those changes was the creation of a new set of rules to organize the relationships between sugarcane producers, bioethanol producers, and fuel distributors. The only feature of the original framework of legal and tax measures — which provided the foundation for the consolidation of bioethanol fuel in Brazil — currently in place is the differential tax on hydrated bioethanol and bioethanol vehicles, in an attempt to maintain approximate parity for the consumer vis-à-vis the choice between hydrated bioethanol and gasoline.

In this context, anhydrous bioethanol and hydrated bioethanol are traded freely between producers and distributors. Within the sphere of agroindustry, the price of sugarcane is also free, but for the most part it is determined according to a contractual voluntary model jointly coordinated by the sugarcane planters and bioethanol and sugar producers. According to the model, the sugar content of sugarcane that arrives for processing, as well as sugar and bioethanol produced by the mills, are all converted using a common basis for comparison, ie, *Açúcares Totais Recuperáveis* (ATR - Total Recoverable Sugars). Under this concept, sugarcane is paid according to its effective contribution to production, which is measured in terms of the ATR content of the raw material delivered to the agroindustry. Prices are determined by the economic results from the production of sugar and bioethanol, taking into account sales both in internal and foreign markets. In the State of São Paulo and surrounding regions the model is run by the *Conselho dos Produtores de Cana, Açúcar* e *Álcool do Estado de São Paulo* (São Paulo State Council of Sugarcane, Sugar and Alcohol Producers), founded in 1997 and constituted by representatives from all the private sectors involved in bioethanol production [Scandiffio (2005)].

The process of reassigning the roles and functions of economic agents was neither smooth nor consensual. Rather, there were significant discrepancies between the conservative players and those more progressive. The first group intended to maintain the interventionist apparatus and keep their guaranties in terms of market share and profits. The second group was for a freer market, in which investment potential and profits earned were based on advantages obtained in production and not on government granted conditions. The latter group eventually prevailed. The existence of a favourable institutional framework was essential to consolidate the changes implemented.

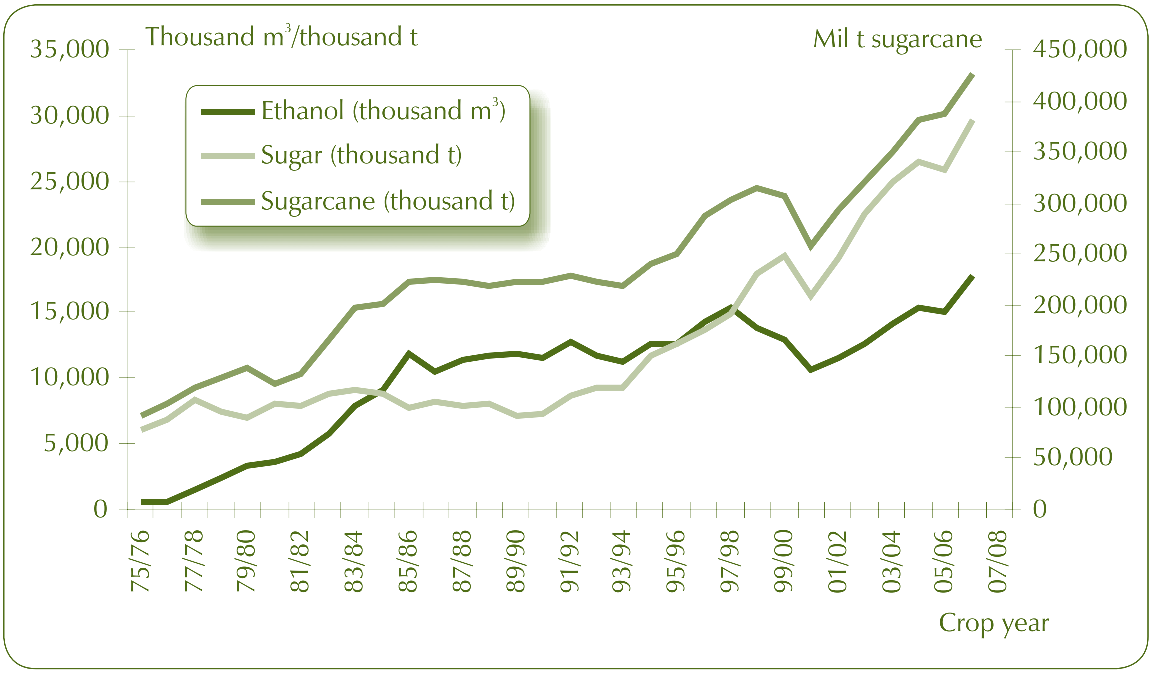
The institutional restructuring in the sphere of the bioethanol industry continued in 1997 with the creation of two important institutions, through Law 9.478: The *Conselho Nacional de Política Energética (CNPE* - National Energy Policy Council); and the *Agência Nacional do Petróleo (ANP* - National Petroleum Agency), later renamed the *Agência Nacional do Petróleo, Gás Natural* e *Biocombustíveis* (National Agency for Petroleum, Natural Gas and Biofuels), in accordance with Law 11.097, of 2005. The CNPE main responsibility is establishing directives for specific programs for biofuels use. On the other hand, ANP oversees the regulation, contracting, and inspection of biofuel-related economic activities, and implements national biofuel policy, with emphasis on assuring supply throughout the country and protecting consumer interests with respect to product price, quality and supply. More specifically, ANP's responsibilities include: inspecting and applying administrative and pecuniary sanctions pursuant to laws or contracts; enforcing good conservation practices, the rational use of biofuels, and environmental preservation; organizing and maintaining the archive of information and data relative to the regulated activities of the biofuels industry; and specifying quality standards for biofuels. The last attribution is of major importance, and it relies on adequate technical support as well as the establishment of communication channels between biofuel producers, engine manufacturers and environmental agencies. As seen in Chapter 2, specifications for anhydrous bioethanol and hydrated bioethanol for fuel purposes are defined by an ANP resolution.

The process of institutional review within the bioethanol sector concluded in 2000 with the creation of the *Conselho Interministerial do Açúcar e do Álcool* (CIMA – Interministerial Sugar and Alcohol Council) through Law 3.546. The purpose of this agency is to deliberate on policies related to the activities of the sugar-alcohol sector, taking into account aspects such as the following: a) an adequate share of sugarcane products in the national energy matrix; b) economic mechanisms necessary for the sector self-sufficiency; and c) scientific and technological development of the sector. CIMA is integrated by the Ministry of Agriculture, which heads it, as well as the Ministries of Finance, Development, Industry, Foreign Trade, and Mines and Energy. One of CIMA's more important responsibilities is to specify and periodically revise the bioethanol content of gasoline, within the 20% to 25% range. In recent years this level has been pegged at 25%; however, it can be reduced (and effectively it has been) contingent upon market availability conditions.

In 2003 flex-fuel cars appeared in the market and had a very good acceptance by consumers, because the owners have the option of using gasoline (with 25% anhydrous bioethanol), hydrated bioethanol, or both, depending on price, autonomy, performance or availability conditions. As a result, the consumption of hydrated bioethanol in the domestic market made a comeback, opening new perspectives for the expansion of the sugarcane industry in Brazil, as well as possibilities for meeting the demands of the international anhydrous bioethanol market for its use in gasoline blends. Ever since then, the Brazilian sugarcane industry has been expanding at high rates, consolidating itself economically and achieving positive indicators for environmental sustainability, as will be seen later in this chapter.

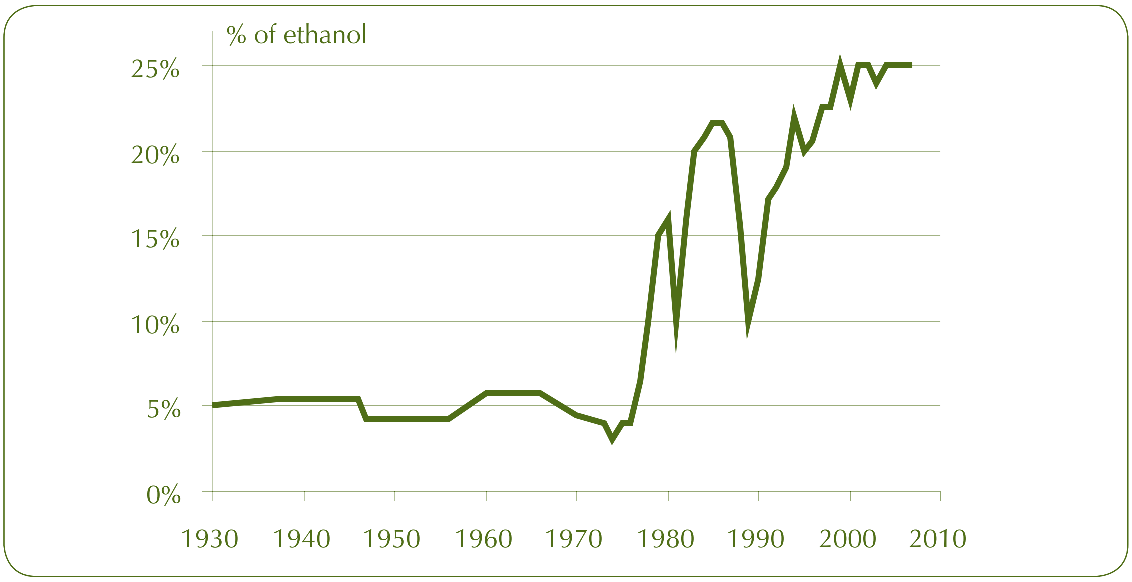
Graphs 16, 17 and 18 summarize the process described above regarding the expansion of bioethanol production in recent decades. In Graph 16, one can see how the production of sugarcane and bioethanol (anhydrous and hydrated), accompanied by the increase in sugar production, adequately attended the expansion in demand for this biofuel [Unica (2008)]. Graph 17, in turn, shows the evolution of anhydrous bioethanol levels in gasoline, from the very beginning of bioethanol use in Brazil [MME (2007) and Mapa (2008)]. Graph 18 depicts the growth in production of hydrated bioethanol vehicles. By the end of the first phase of Proálcool, in 1985, the bioethanol fleet numbered 2.5 million vehicles, accounting for 90% of sales of new cars; this share was only regained in 2003 with the launch of flexible vehicles [Anfavea (2008)]. Currently, this biofuel can be used by 5.5 million Brazilian vehicles (including cars with hydrated bioethanol and flex-fuel engines), an amount equivalent to a little over 20% of the fleet on the road (25.6 million vehicles).

Graph 16 **– Evolution of the production of sugarcane, ethanol and sugar in Brazil**



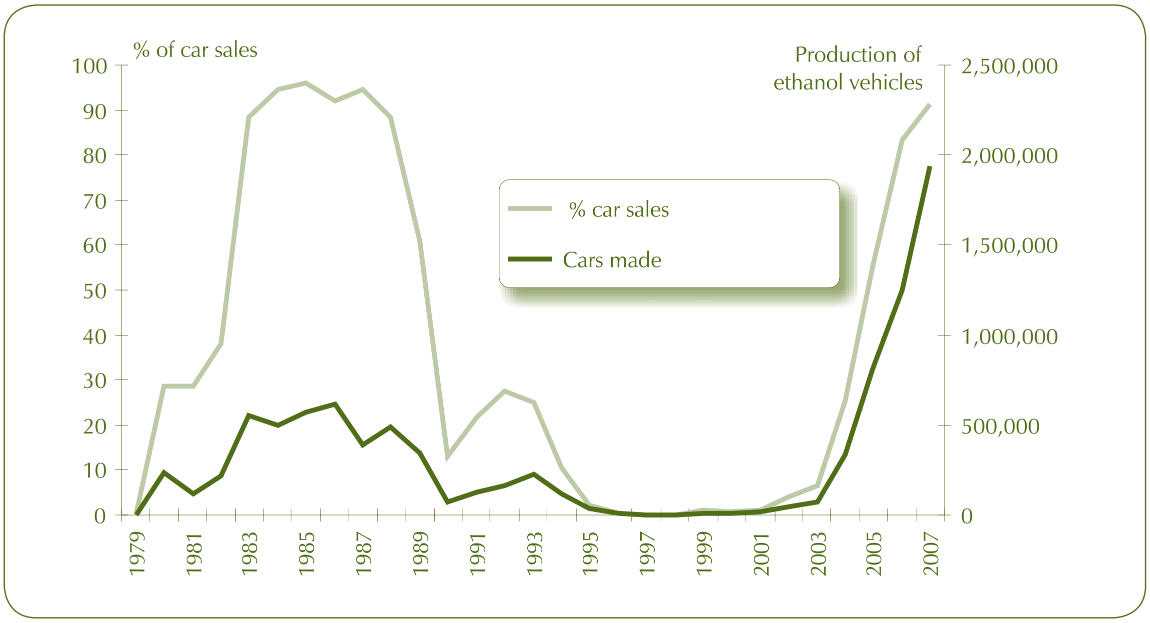
Source: Unica (2008).

Graph 17 **– Average levels of anhydrous ethanol in Brazilian gasoline**



Source: MME (2008).

Graph 18 – **Evolution of production of hydrated ethanol vehicles and share in new vehicle sales**



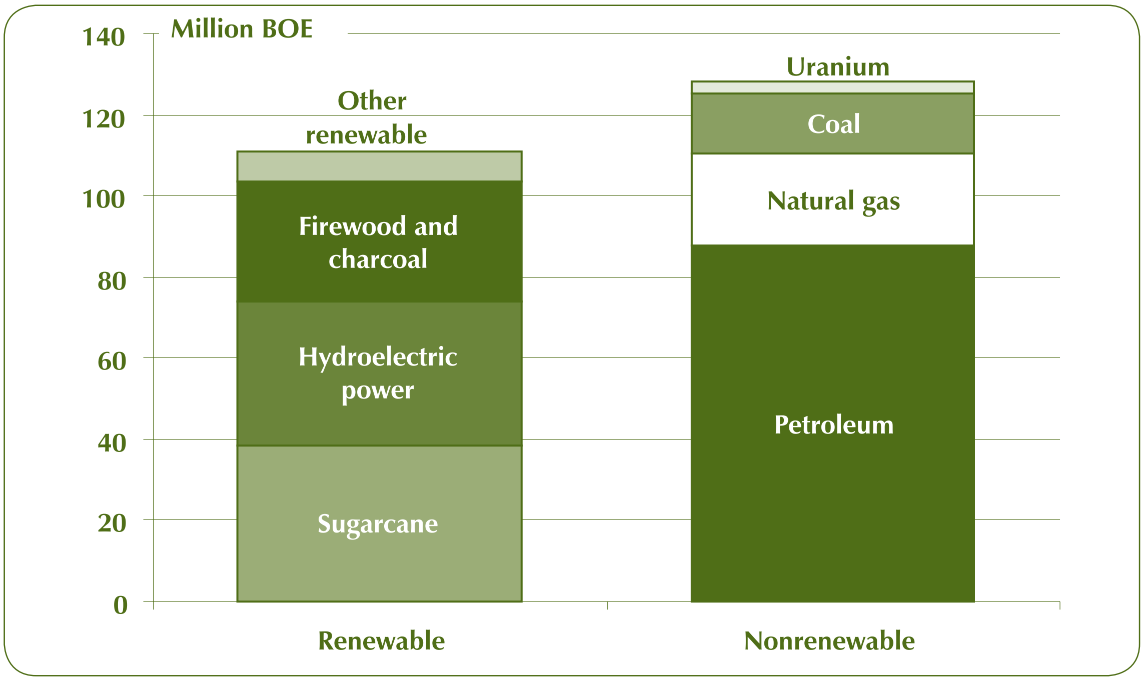
Source: Anfavea (2008).

Graphs 16, 17 and 18 show clearly that the demand for this biofuel remained quite constant during the 1990s, despite sagging sales of hydrated bioethanol vehicles, thanks to its use in gasoline blends. This allowed to keep production units in operation at relatively stable levels until the beginning of the present decade, when a new cycle of growth got underway. Thus, since the 1970s, bioethanol has been regularly used in significant volumes in Brazil and was not significantly affected by the fall in sales of hydrated bioethanol cars. The only exception to this trend was in the last years of the past decade, when sugarcane harvests were impacted by adverse weather conditions. Short-term perspectives indicate that the internal demand for hydrated bioethanol will growth significantly, with current forecasts for 9 million vehicles capable of using this fuel by 2010, which will be equivalent to 32% of the fleet forecasted for that year [Pires (2007)].

From an economic point of view, the estimated cost of the implementation of Proálcool, between 1975 and 1989, is of approximately US$ 7.1 billion, of which US$ 4 billion were financed by the Brazilian government and the rest by private investments [Dias Leite (2007)]. Valuing the volume of bioethanol fuel consumed between 1976 and 2005 at gasoline prices in the world market (adjusted for inflation) yields an estimate of US$ 195.5 billion in foreign-exchange savings, US$ 69.1 billion in avoided imports and US$ 126.4 billion in avoided foreign debt interest [BNDES (2006)].

The importance of the sugarcane bioenergy chain in Brazil is well illustrated by the fact that in 2007 it accounted for 16% of the national energy matrix, slightly above the contribution of hydroelectric power (responsible for 90% of Brazil's electric power), and 36.4% of the national energy supply derived from renewable sources (see Graph 19). In short, energy derived from sugarcane is a significant pillar of the Brazilian energy supply.

Graph 19 **– Primary energy sources utilized in Brazil in 2007**



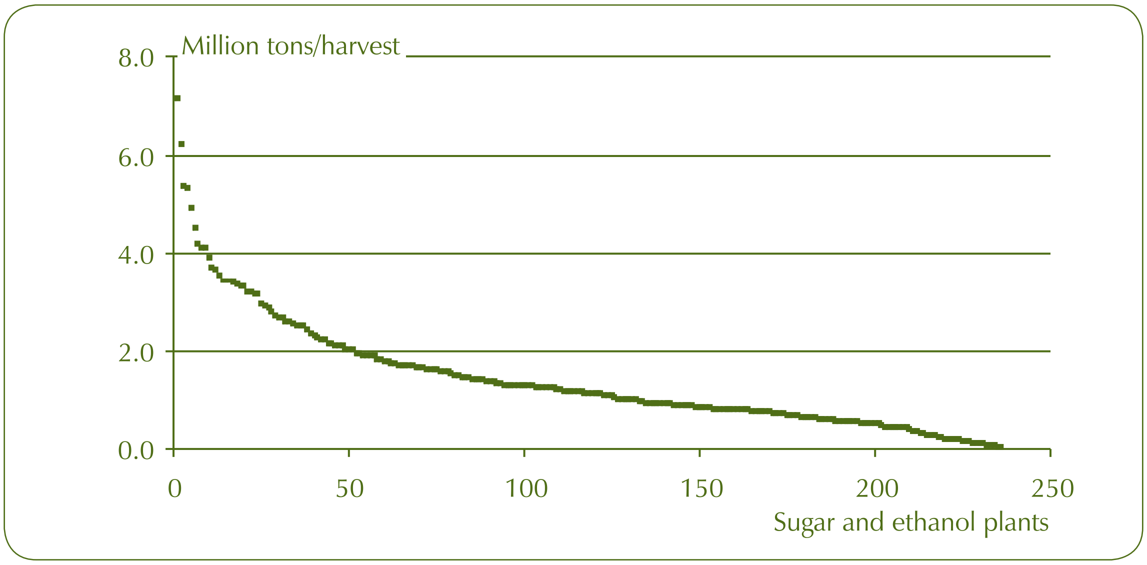
Source: MME (2008).

6.2. Sugarcane agroindustry in Brazil

Sugarcane has been cultivated in Brazil since 1532, when it was introduced by Martim Afonso, the first Portuguese colonizer, who intended to build sugar mills such as those already existing at the time on the Azores Islands. The species adapted well to Brazilian soil and during the entire colonial period was extensively and successfully cultivated along the Brazilian coast. Dozens of mills were built there, especially in the Bahian Recôncavo and Pernambuco, providing a foundation for the sugar economy in Brazil, which lasted almost two centuries. With the expulsion of the Dutch from the Northeast and the expansion of the sugar agroindustry in the Antilles region, around the middle of the 17th century, production in Brazil decreased in relative terms, though it remained an important activity in the Brazilian economy. The creation of the Sugar and Alcohol Institute, in 1933, when the use of automotive bioethanol was already a blossoming reality, provided new life into the industry. Also, from that time onwards, the sugar industry began to expand in the Southeast, first in association with the decline of coffee plantations, and later driven by the growth of the domestic market [Szmrecsányi (1979)].

Currently, sugar cane is grown in almost all states in Brazil and occupies close to 9% of the cultivated land, being the third most important crop in terms of land occupied, after soybeans and corn. In 2006, the cultivated area was of the order of 5.4 million hectares and total production was 425 million tons [Carvalho (2007)]. The biggest producing area is the Mid-South-Southeast, accounting for more than 85% of production; the largest national producer is the State of São Paulo, which contributes close to 60% of the production. The production system involves more than 330 mills, each capable of processing between 600 thousand and 7 million tons of sugarcane per year; an average mill processes close to 1.4 million tons per year. Graph 20 shows the distribution of annual milling capacity (2006/2007 harvest). As can be seen, the 10 biggest mills are responsible for 15% of the raw material processed, whereas the 182 smallest units process half of all sugarcane. Economically speaking, these numbers demonstrate the low concentration within this agroindustry, as typically seen in bioenergy systems.

***Graph 20* – Distribution of the annual processing capacity of sugar and ethanol plants in Brazil**

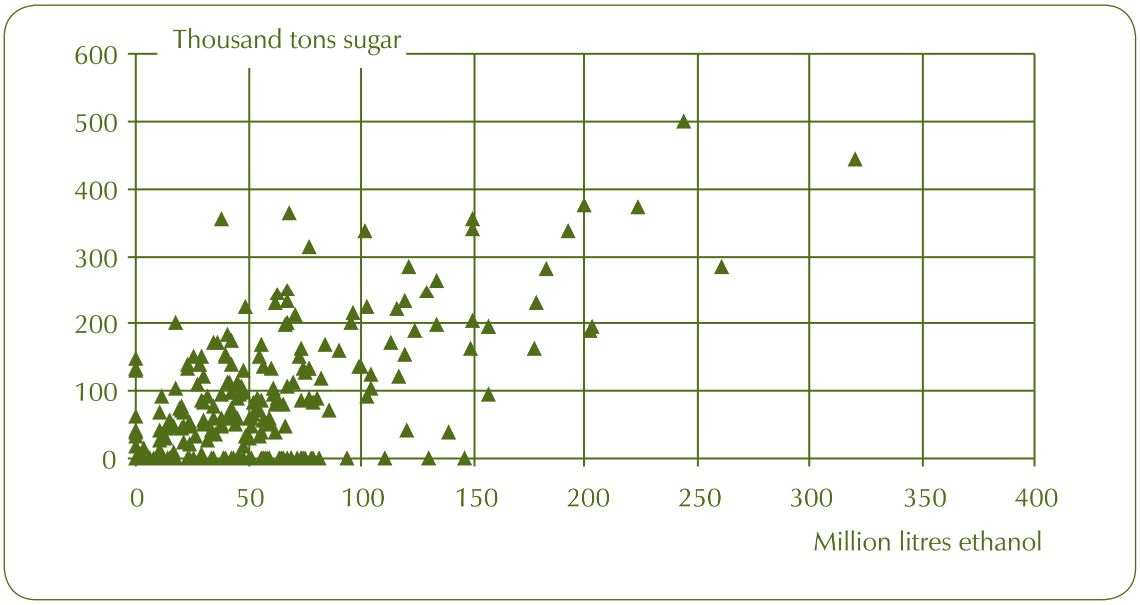


Source: Based on Idea (2007).

Brazilian plants, on average, receive 80% of sugarcane from land owned, rented, or belonging to shareholders and agricultural businesses linked to the plants. The remaining 20% is supplied by close to 60 thousand independent producers, the majority working with less than two agricultural *módulos (*an agricultural *módulo* corresponds to the smallest parcel of farmland that can sustain a family and varies by region). A large proportion of sugarcane producers can be described as small farmers, who produce sugarcane along with other farm products, not only for economic purposes but also for self-consumption, and generally rely on technical support from the mills [CGEE/NAE (2005)].

Brazilian plants can be classified in three categories: Sugar mills that only produce sugar; sugar mills with distilleries, which produce sugar and bioethanol; and independent distilleries that only produce bioethanol. The largest group is the one that combines sugar mills and distilleries (close to 60% of the total), followed by a considerable quantity of independent distilleries (close to 35%) and then by units that only process sugar (see Graph 21). Nationally, during the 2006/2007 harvest an average of 55% of available sugar content from processed sugarcane was used to produce bioethanol [Unica (2008)].

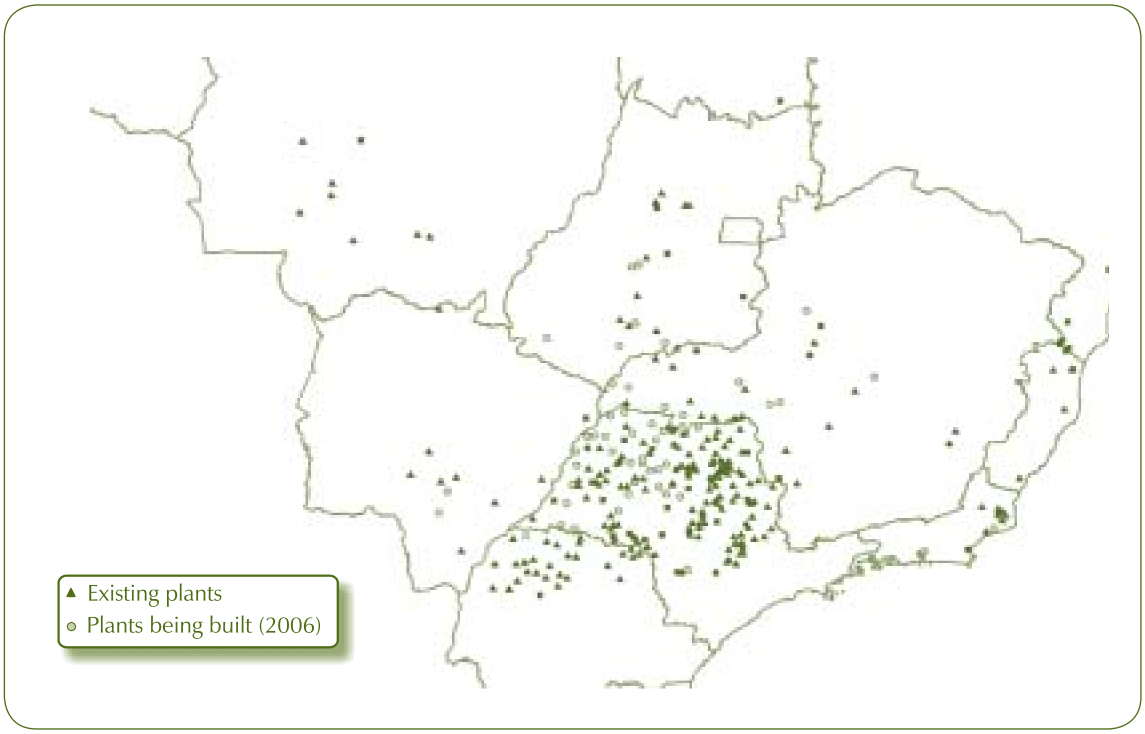
***Graph 21* – Production profiles of sugar and ethanol plants in Brazil during the 2006/2007 harvest**



Source: Based on Idea (2007)].

Geographically, sugar and bioethanol plants are located close to sugarcane producing regions, mostly in the State of São Paulo, as Graph 9 shows. In that state there is a confluence of excellent soil and climate conditions, adequate transportation infrastructure, proximity to consumer markets and an active science and technology base that has been fundamental to expand production with increased productivity. In recent years, with the relative reduction of the area available in São Paulo and rising land prices, new production units have been occupying areas previously used for pasture and, to lesser extent, for annual crops in the Triângulo Mineiro, south of Goiás and southeast of Mato Grosso do Sul. These areas are adjacent to the traditional sugarcane-producing areas of central southern Brazil (as showed in Graph 24), which make it possible to develop production systems similar to those that exist in São Paulo.

Figure 24 – **Locations of new sugar and alcohol plants in Brazil**



Source: CGEE (2006).

According to harvest figures for 2006/2007, the sugarcane agroindustry (which includes sugarcane, sugar and bioethanol production) generated close to R$ 41 billion in direct and indirect sales. The 420 million tons of raw sugarcane processed produced 30 million tons of sugar and 17.5 billion litres of bioethanol. Out of that, 19 million tons of sugar (US$ 7 billion) and 3 billion litres of ethanol (US $ 1.5 billion) were exported, representing 2.65% of the Gross National Product (GNP). In addition, R$ 12 billion in taxes and fees were collected and annual investments of R$5 billion in new agroindustrial units were made. These strong results were accomplished by a range of productive units characterized by wide variations with respect to production scale, size, geographic location, production structures and financial and business profiles. There are, therefore, differences in costs of production and levels of efficiency, particularly as a result of the significant evolution of the sugar-alcohol sector during recent decades, not just in terms of capacity and production profiles, but also in the loosening of regulations.

Brazilian sugar and bioethanol plants currently in operation can be classified into three groups, taking into consideration their financial situation, productivity indicators, and the introduction of new technologies (based on IEL/Sebrae, 2006):

Stagnated companies: Plants in critical or pre-critical conditions because accumulated debt and outdated technology with little possibility of acting independently in a highly competitive sector. Only with new resources and specific lines of credit can the outlook be changed; old technologies must be updated to enable increased agroindustrial productivity.

Profitable companies: Plants that were able to successfully adapt to sector deregulation and the lack of definition on energy policy in Brazil during the 1990s. They have expanded production capacity and invested in new technologies, resulting in reduced costs and increase productivity. Either individually or in groups, some of these companies have diversified their activities to handle international logistics and sales of their products.

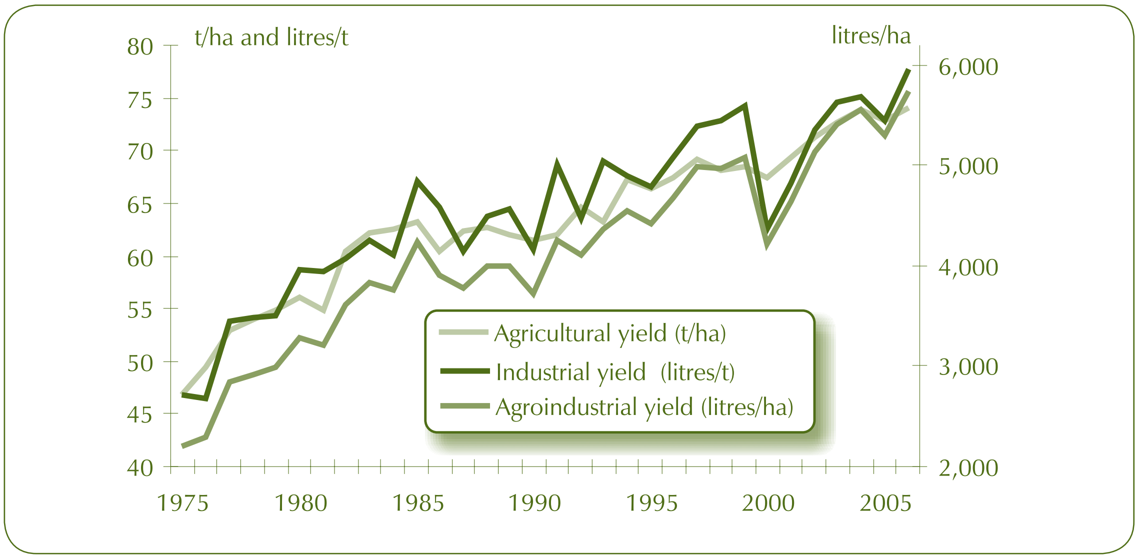
Innovative companies: Profitable companies that, by themselves or in partnerships with multinationals, stand out from the previous group. They have diversified their technological base for producing sugarcane-based products and opened up new perspectives for adding value to sugarcane.

Associated with the expansion of sugar-alcohol production, there has been significant diversification in the composition and origin of the capital invested in this agroindustry. Originally almost exclusively based on family businesses, they were often founded and run by Italian immigrants and their descendents in the Center South Region, or by regional families in the case of Northeast plants. Currently, in addition to family business, capital investments are being made by a range of companies (Cosan, Costa Pinto, Guarani, Nova America, São Martinho) as well as by strategic national (Votorantim, Vale, Camargo Correa, Odebrecht) and foreign investors. The latter group includes investors from a variety of nations, such as France (Tereos, Sucden, Louis Dreyfus), Germany (Sudzucker), United States (Bunge, Comanche Clean Energy, Cargill, Global Foods), Spain (Abengoa), Guatemala (Ingenio Pantaleón), India (Bharat Petroleum, Hindustran Petroleum, India Oil), England (ED&F Man, British Petroleum), Malaysia (Kouk) and Japan (Mitsui, Marubeni).

Another innovation has been the increasing presence of both national and foreign financial investors such as Goldman Sachs, Merryll Lynch, Adeco (George Soros), Tarpon, UBS Pactual and Cerona, individually or in consortium with sugarcane operators. In the latter case it is worth mentioning the investment groups formed specifically to implement platforms for the production and sale of sugarcane bioethanol, such as Infinity Bio-Energy, Brenco (Brazil Renewable Energy Company) and Clean Energy Brazil. Typically, the business model based on foreign capital includes Brazilian partners, with an important participation of foreign companies in dozens of mergers and acquisitions that have taken place in recent years. Although this diversification is very important, and reflects the confidence of foreign investors and the introduction of new management and governance concepts, foreign capital still represents a small portion of total investments in the sector; it is estimated that those investments accounted for 12% of processing capacity in 2007 [Nastari (2007)].

It is important to understand that the expansion of bioethanol and sugar production in recent decades has occurred not only because the increase in cultivated area, but also because the significant productivity gains in agricultural and agroindustrial activities. During the last 32 years productivity grew at an average cumulative annual rate of 1.4% in agriculture and 1.6% in agroindustry, resulting in a cumulative average annual growth rate of 3.1% in the per-hectare yield of bioethanol. Graph 22 shows this growth over the course the last three decades, in average values, for all Brazilian production units. In this graph, the data for the area planted and sugarcane production are from the *Ministério da Agricultura, Pecuária e Abastecimento* (Ministry of Agriculture, Livestock and Supply) [Mapa (2007)]; bioethanol production data was obtained from *União da Indústria de Cana-de-Açúcar* statistics. [Unica (2008)]. Thanks to these gains in productivity, the area currently dedicated to the cultivation of sugarcane for bioethanol production, close to 3.5 million hectares, is only 38% of the area that would have been required to obtain such production with the yields of 1975, when Proálcool began. This noteworthy gain in productivity — 2.6 times the volume of bioethanol for a given area — was obtained through the continuous incorporation of new technologies, as will be described in the next section.

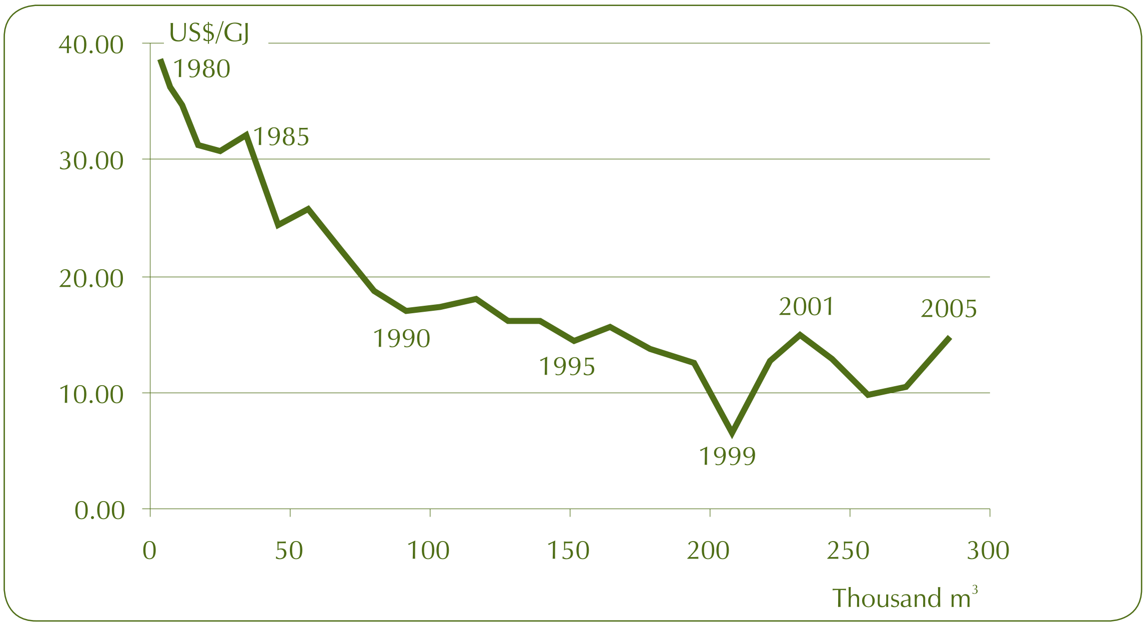
***Graph 22* – Evolution of agricultural, industrial and agroindustrial productivity in sugar and ethanol plants in Brazil**



Source: Based on Mapa (2007) and Unica (2008).

A direct consequence of the gain in productivity was the progressive reduction in costs, which is reflected in the values received by producers (See Graph 23). Sometimes referred to as the *learning curve*, this phenomenon clearly reflects a process of learning and consolidation, similar to what has been experienced by other new energy technologies such as wind power [Goldemberg et al (2004)]. The graph shows how experience and skill have translated into a progressive fall in prices (2002 US dollars), which decreased at a cumulative annual rate of 1.9% during the last 25 years. Something to note in the graph is the asymptotic tendency of prices, which have remained practically constant for the last 10 years. The stabilization of prices is usually a signal of maturity in the sphere of conventional technologies; therefore, it would reveal technological maturity in the bioethanol industry.

***Graph 23* – Evolution of prices paid to ethanol producers in Brazil**



Source: Adapted from Goldemberg et al. (2005).

According to the same logic of growth with gains in productivity and efficiency, the evolution of the sugar-alcohol sector has witnessed the formation of consortia and clusters as ways to rationalize costs, particularly with respect to the adoption of new technologies. Furthermore, the sector has enlarged the scale of production in plants and ensured the strategic occupation of contiguous agricultural areas [CGEE (2005)]. The growth in processing capacity — more than 7 million tons of sugarcane per year in the largest new units — has allowed to hold sugarcane transportation costs at competitive levels through the use of more efficient practices and greater cultivation of areas close to the plants. It is interesting to see that these larger agroindustrial units correspond, in energy terms, to an oil refinery with a 35 thousand barrel a day processing capacity, ie, they operate on a scale well below that seen in the petroleum industry.

The appendixes provide historical data on bioethanol (anhydrous and hydrated) and sugarcane production and cultivated area for the main producer states, as well as information on prices paid to bioethanol producers.

6.3 Technological research and development

During the expansion of bioethanol production by Brazilian plants, as described in the previous section, the incorporation of innovative processes and technological development played an essential role, resulting in increased production efficiency and progressive lowering of environmental impacts. On the other hand, new possibilities for sugarcane-based bioenergy production, such as employing lignocellulosic by-products to produce bioethanol and electricity, are highly dependent on processes still under development.

The existence of public institutions, Federal, and State, as well as private businesses providing know-how to the sugarcane bioethanol production chain (especially agricultural aspects), was and it will always be of critical importance with respect to genetic improvement, agricultural mechanization, management, biological pest control, recycling of wastes and better-performing agricultural-conservation practices [CGEE (2005)]. These institutions are mostly located in the State of São Paulo, where the majority of sugarcane in Brazil is grown and processed. This State is also home to the most productive Brazilian university complex, one responsible for close to half of all scientific studies produced annually in the country. Within this realm, an interesting synergy has come about based on the need for technological support and the availability of human resources well trained to provide it. The two most important promoters of this process of innovation have been the Government of the State of São Paulo and the private sector, working in partnership.

São Paulo State-funded institutions active in agroindustrial production technology and sugarcane bioethanol use include the following entities: *Instituto Agronômico de Campinas* (IAC – Agronomic Institute of Campinas), *Instituto de Pesquisas Tecnológicas* (IPT – Institute of Tecnological Research), *Instituto de Tecnologia de Alimentos* (ITAL – Food Technology Institute), *Companhia de Tecnologia de Saneamento Ambiental* (Cetesb – Environmental Waste Management Technology Company), and *Instituto Biológico* (Biological Institute). The list is completed by three State universities: Universidade de São Paulo (USP – Sao Pablo State University), home of the *Escola de Agronomia Luiz de Queiroz* (ESALQ – School of Agronomy Luis de Queiroz), traditionally active in sugarcane technology; *Universidade Estadual de Campinas* (Unicamp – Campinas State University) and *Universidade Estadual Paulista Júlio de Mesquita Filho* (Unesp – Paulista State University Julio de Mesquita Filho), which has several courses and research groups focusing on sugarcane bioenergy.

The oldest of these institutions is the *Instituto Agronômico de Campinas*, with experimental research stations throughout the State. The Institute began working with sugarcane as early as 1892. Since 1994, and in association with private enterprises (with which it shares an annual budget of R$ 2 million), the IAC has run ProCana an active program for the genetic improvement of sugarcane varieties that periodically launches new varieties and introduces new sugarcane management methods [Landell (2003)]. Procana has successfully introduced innovative and efficient practices in the management of its activities; so much so that the economic impact of its activities has been estimated at 13 times the amount of investments [Hasegawa and Furtado (2006)].

The *Centro de Tecnologia Canavieira* (CTC – Sugarcane Technology Center) stands out in the private sector. It was originally created in 1970 as the *Centro de Tecnologia Copersuca* (Copersuca Center of Technology), associated to Copersuca, a cooperative of sugar and bioethanol producers. In 2005 it was separated from that cooperative and reorganized as a nonprofit corporation. CTC currently has the membership of 161 plants, which account for 60% of the sugarcane produced in Brazil. It has an annual budget of R$ 45 million and a body of 107 researchers [Furtado et al. (2008)]. Although it is currently more visible because of agricultural research — with more than 60 sugarcane varieties launched and cultivated on 43% of the national area used for sugarcane cultivation — CTC acts throughout the entire sugarcane production chain, working in areas such as rural administration, variety improvement, phytosanitation, cultivation and harvest systems, extraction and fermentation systems, and energy systems for sugar and bioethanol plants. CTC has been the main innovation center for São Paulo plants and an important technical supporter of agricultural and industrial issues. In the sphere of sugarcane biotechnology, CTC has been conducting research since 1990. A pioneer in Brazil in the creation of sugarcane transgenic varieties, in 1997 it lead the constitution of the *Consórcio Internacional de Biotecnologia de Cana-de-açúcar* (ICSB – International Consortium of Sugarcane Biotechnology), a body that today brings together 17 institutions from 12 sugarcane producing countries. Recently, in Pernambuco and Alagoas, CTC installed research units dedicated to the development of varieties specific for those regions [CTC (2008)]. To sum up, CTC has surely been a leader in the introduction of innovations in the sugar-alcohol agroindustry and responsible for the notable gains in bioethanol production efficiency witnessed in recent decades.

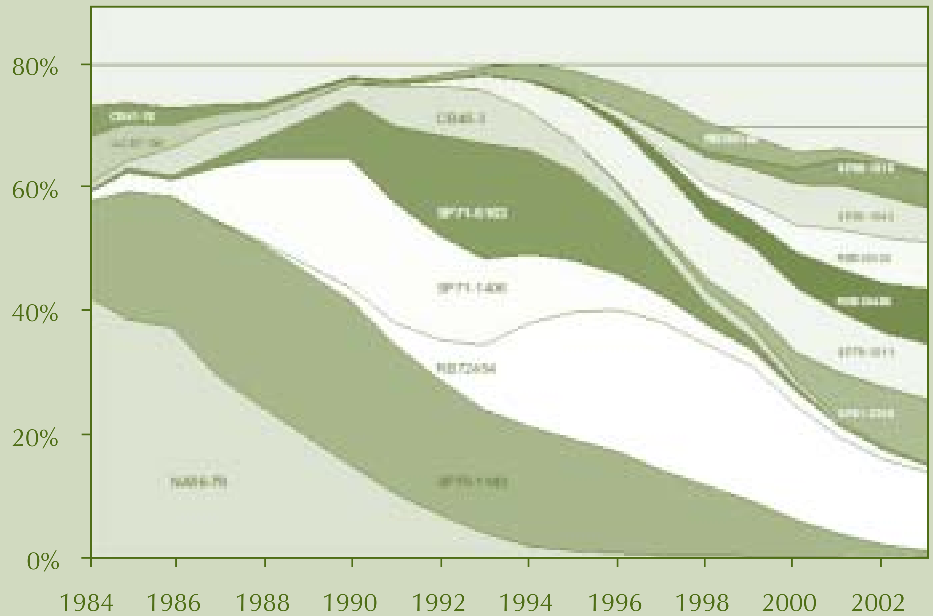
Among State institutions, the *Fundação de Amparo à Pesquisa do Estado de São Paulo* (Fapesp - Research Support Foundation of the State of São Paulo) has performed a very important role in supporting research and development activities within the sugarcane agroindustry, with significant resources invested in more than one hundred research studies in basic and applied areas, involving the academic community and private companies [Fapesp (2007)]. Examples of recent Fapesp initiatives with private companies (who provide half of the resources available for scientific community research) are the agreements signed with *Dedini Indústrias de Base* and *Braskem*. The first includes R$ 100 million for research projects on technologies for the elaboration of bioethanol. The second provides R$ 50 million for synthesis-process research using renewable raw materials derived from sugars, bioethanol and other biofuel chain products, with an emphasis on «green polymers». Fapesp also finances the *Programa Diretrizes de Políticas Públicas para a Agroindústria Canavieira do Estado de São Paulo* (Public Policy Guidelines Program for São Paulo State Agroindustry), which defines subsidies to support government initiatives in this field [Agência Fapesp (2008)].

Linked to the Federal Government and located in a traditional sugarcane producing region, *Universidade Federal de São Carlos* (UFSCar, São Carlos Federal University) also has performed an important role in the technological development of the bioethanol agroindustry, especially with regards to agriculture. In 1990, the *Centro de Ciências Agrárias* (Agricultural Science Center) of this university incorporated the *Programa Nacional de Melhoramento da Cana-de-Açúcar* (Planalsucar - National Program for the Improvement of Sugarcane), linked to the old *Instituto do Açúcar e do Álcool*. The program had as many as 30 experimental research stations around the country, making significant contributions to improve sugarcane yields in Northeastern states, especially in Alagoas [Furtado et al. (2008)]. Based on the human resources and infrastructure of Planalsucar, and to provide continuity to research on the improvement of sugarcane genetics, in 1991 was created the *Rede Interuniversitária para o Desenvolvimento do Setor Sucroalcooleiro* (Ridesa - Inter-University Network for the Development of the Sugar-Alcohol Sector), currently involving close to 140 researchers at nine federal universities (São Carlos, Paraná, Viçosa, Rural do Rio de Janeiro, Sergipe, Alagoas, Rural de Pernambuco, Rural de Goiás and Rural de Mato Grosso) located nearby the old Planalsucar experimental research stations. The program already has successfully launched 65 cultivars (canas RB) that account for 57% of the area cultivated with sugarcane in Brazil [Ridesa (2008). In addition to support granted by the Ministry of Science and Technology, which gave R$ 1.8 million in 2006, Ridasa has partnerships with 130 private companies that provide resources and benefit from the results of its research activities [Inovação Unicamp (2007)].

Genetic improvements and availability of cultivars

The phytosanitary health of sugarcane plantations relies on the periodic renewal and diversification of varieties in order to maintain high productivity and resistance to diseases and pests, which can be very harmful under monoculture conditions, as well as to control maturation characteristics (early or late), promote adaptation to mechanical harvesting and enhance resistance to certain weather condition, among others. In this regard, it is exemplary how agricultural technology has made possible to broaden the sugarcane germplasm base and the diversification of varieties utilized by this agroindustry in Brazil, by means of four sugarcane improvement programs, two of which are private. It is noteworthy that under Law 9.456/1997 — the Cultivar Law — businesses and research groups can charge producers for the use of sugarcane cultivated from the developed varieties. Each year, close to six new varieties are released to the market and the total number of varieties is currently close to 500. Among them, the most popular variety occupies 12.6% of the planted area, as can be seen in Graph 25.

Figure 25 – **Percent occupation of the main sugarcane varieties in Brazil from 1984 to 2003**



Source: Burnquist and Landell (2005).

In a sugarcane genetic improvement program, the starting point is the germplasm bank, where thousands of genotypes are stored, including cultivars used domestically, other species related to the Saccharum genus, and cultivars imported from the world's different sugarcane regions. After being obtained through crossbreedings pre-established by the researchers, the seeds are sent to laboratories at experimental stations, where the seedlings are raised and transplanted to the field to undergo successive selection phases over the course of three or four years. From the millions of original seedlings, just a few hundred clones are selected to go through long-term cultivation tests. Normally, the launching of new varieties takes close to 13 years of experimental clone testing, watching for reactions to pests and diseases and yield differences under different cultivation environments [Ridesa (2008)].

Based on the sequencing of sugarcane's 50 thousand genes carried out between 1988 and 2001 by the Fapesp-sponsored Projeto Genoma Cana-de-Açúcar (Sugarcane Genome Project), several Brazilian groups have been working on advanced biotechnological methods to identify quickly those clones with greatest resistance to disease, shortest maturation, highest sucrose content, highest total biomass, etc. In addition to the technical challenges, however, these studies depend on lengthy approval processes from the Ministry of Science and Technology's *Comissão Técnica Nacional de Biossegurança* (National Technical Commission for Biosecurity) [Burnquist and Landell (2005)].

Among federal institutions located in São Paulo, mention should also be made of three units of the *Empresa Brasileira de Pesquisa Agropecuária* (Embrapa - Brazilian Agricultural Research Corporation), which in some way are connected to the sugarcane agroindustry: Embrapa Environmental Research, in Jaguariúna, focusing on themes associated with the rehabilitation of damaged areas, sustainable use of water and biological control of pests and diseases; Embrapa Satellite Monitoring and Embrapa Agricultural IT, both located in Campinas, working with remote sensing, and geo-processing and computing. With the creation of Embrapa Agroenergy in Brasilia, in 2006, the institution is bound to be more involved in issues related to the use of sugarcane in the production of bioethanol and bioelectricity.

Last but not least, in the private sector it is noteworthy to mention CanaVialis and Allelyx, two companies working on research and development in this field. Both are located in Campinas and are supported by Votorantim Ventures, an investment fund. According to these firms they invest R$ 70 million annually in research, with special focus on improving transgenic varieties, in which genes from different varieties are inserted into the sugarcane genome to obtain more productive varieties resistant to disease and drought. CanaVialis has three experimental stations, certified by the *Comissão Técnica Nacional de Biossegurança* (CTNBio - National Technical Commission for Biosecurity), for developing its activities and servicing agreements signed with 34 plants. Together, the two companies have a team of more than 150 researchers and are dedicated to other applications of sugarcane agroindustrial biotechnology, such as molecular markers, advanced variety management systems, and assessments of genetic vulnerability [Furtado et al. (2008) and CanaVialis (2008)].

This broad technological base has strongly impacted the development of processes, equipment and systems, growing autonomously and sustaining lines of study and research based on the tangible and immediate realities of the neighbouring agroindustry. It is, therefore, difficult to say which has been the primary factor that triggered this dynamics of innovation. In essence, a parallel and simultaneous process of value generation and reinvestment has occurred: more applied knowledge, better technologies, greater efficiency, larger profits, improved perspectives and increased entrepreneurial and institutional motivation. Table 26 confirms this vision; it synthesizes the results obtained and the prospects for new advances in agricultural (annual yield per hectare for sugarcane) and agroindustrial (bioethanol yield per ton of sugarcane) productivity. Table 27 highlights which processes have the best perspectives for improving industrial agroproductivity.

As shown in Tables 26 and 27, in the coming years the expected increase in agroindustrial productivity (without considering the introduction of other production routes such as cellulosic bioethanol) should enable a reduction in the planted area of 3.4% per unit of bioethanol produced. Such significant improvement is a direct result of agroindustrial technological research and development. If cellulosic residual-based bioethanol is also included, productivity could reach 10,400 litres of bioethanol per hectare [CGEE (2005)], corresponding to a 33% reduction in the planted area per unit of bioethanol produced.

Table 26 – Impact of the introduction of new technologies on bioethanol production

Period		Productivity		
		Agricultural. yield (t/ha)	Industrial yield (litres/t)	Agroindustrial yield (litres/ha)
1977–1978	Initial phase of National Alcohol Program Low efficiency in agroindustrial processes and agricultural yields	65	70	4,550
1987–1988	Consolidation of National Alcohol Program Agricultural and industrial yields increase significantly	75	76	5,700
Current situation	Bioethanol production processes operating with the best technology available	85	80	6,800
2005–2010	First stage of optimization of processes	81	86.2	6,900
2010–2015	Second stage of optimization of processes	83	87.7	7,020
2015–2020	Third stage of optimization of processes	84	8.5	7,160

Source: CGEE (2006).

Table 27 **– Expectations for efficiency gains in bioethanol production processes (%)**

Scenario (as in Table 26)	Losses during sugarcane washing	Extraction efficiency	Losses treating sugarcane juice	Fermentation yield	Losses during dist. and stillage
Current situation	0.50	96.0	0.75	90.3	0.50
First optimization stage	0.40	96.5	0.75	91.0	0.50
Second optimization stage	0.30	97.0	0.50	91.5	0.25
Third optimization stage	0.25	98.0	0.35	92.0	0.20

Source: CGEE (2006).

In the industrial and administrative areas the results of improving processes can be replicated without difficulty; however, that is not the case in sugarcane production where differences in soil and climate variables that are region-specific have a decisive influence in production. The need to reduce costs then calls for decentralized development of improvement programs, increased cooperation between companies and expanded sharing of information between institutions. A detailed study on the evolution of the sugarcane industry in Paraná between 1990 and 2005 demonstrates that *leaning by interaction* has been the predominant learning paradigm in this industry [Rissardi Jr. and Shikida (2007)]. The study stresses the importance of direct interaction between institutes and technology suppliers and user companies for innovations to spread throughout sugar and bioethanol plants and highlights the importance of the existence of regional or decentralized technology centers for the process to unfold.

Collaboration among research centers is also important at the international level. In particular, reinforcing links that already exist between organizations in countries with potential for the efficient production of bioethanol is an important condition to strengthen the basis for an adequate development of their bioenergy agroindustries. In Latin America the following institutions have important capacities for the promotion of diversity and productivity in sugarcane agriculture: *Centro Guatemalteco de Investigación y Capacitación de la Caña de Azúcar* (Cengicaña – Guatemalan Sugarcane Research and Training Center); *Centro de Investigación de la Caña de Azúcar de Colombia* (Cenicaña – Sugarcane Research Center of Colombia); *Dirección de Investigación y Extensión de la Caña de Azúcar* (Dieca – Sugarcane Research and Extension Directorate), in Costa Rica; and the West Indies Central Sugar Cane Breeding Station, in Barbados. The last station has a famous germplasm bank that serves the entire Caribbean.

The establishment of priorities is essential to rationalize bioethanol research and development activities. In Brazil the following issues have been identified as the most relevant for the Center-South region [Macedo and Horta Nogueira (2007) and (2007b)]:

a. Processes for recovery and use of excess plant fibre and bagasse;

b. development of transgenic varieties of sugarcane;

c. selection of cultivars (conventional improvement for new cultivation areas and adoption of the concept of energy sugarcane to maximize the global results that are possible by processing both sugar and fibre for energy production);

d. Development of equipment and processes for juice extraction and bioethanol treatment, fermentation and separation;

e. precision farming systems, in which interventions in cultivation are aided by geoprocessing techniques and global positioning systems (GPS);

f. biological pest and disease control;

g. sugarcane cultivation practices compatible with mechanical harvesting;

h. new sucrochemical and alcochemical products and processes;

i. bioethanol end uses (improvements in biofuel engine technologies and bioethanol-operated fuel cells).

The Brazilian experience in financing research and development activities for the ethanol agroindustry — especially that of the State of São Paulo — stresses that besides providing adequate resources it is necessary to take the following initiatives: structure a plan of action with clear objectives and competencies, establishing coordinated management of activities and including mechanisms for monitoring and communicating results; strengthen training programs, especially at postgraduate level; encourage programs for semi-commercial pilot and demonstration units for new technologies; and, finally, take advantage of existing structures to consolidate currently active centers (eventually, incorporating new laboratories and equipment), as well as promoting and articulating available skills.

The constitution of a CT-ethanol has been suggested as one possible way to provide sustainable financing of research and development in the area of agroindustrial energy, especially basic and applied research on the entire biofuel production chain. Such instrument would allow to replicate the good results obtained with the so-called *Fundos Setoriais* (Sector Funds), in which a portion of the resources in a given energy sector (petroleum, electric power) is used for the generation and aggregation of knowledge in the same sector. It is estimated that an excise tax of 0.5% on net income from bioethanol sales will allow to raise R$ 185 million that could be used to enhance technological dynamism in the sector [Cortez (2007)].

During the course of writing this book, the Minister of Science and Technology announced the Creation of the Center for Bioethanol Science and Technology. The center will function within the *Pólo Tecnológico de Campinas* (Campinas Technology Center) and will be dedicated to a wide spectrum of technologies of interest for the efficient conversion of biomass into energy. Currently in its structuring stage, the center will include laboratories for basic research and a pilot plant and it is expected that it will have a strong focus on basic studies of the photosynthesis phenomenon, biomass production systems and advanced processes for biofuel production, such as hydrolysis.


5
Silmara

Chapter 7

Sustainability of sugarcane bioethanol: the Brazilian experience

*In a general sense (*ie*, beyond energy issues), important features of energy systems are not only their condition of renewability, but also their sustainability. As defined by the Brundtland Commission in the 1980s, it is expected that energy systems be capable of «meeting the needs of the present without compromising the ability of future generations to meet their own needs», while serving social and ecological equilibrium as well as the needs of the poor [United Nations (1987)]. In sum, measuring the sustainability of an energy system is not a simple task and depends not only on the energy vector itself, but also, fundamentally, on the context where it is produced and used. In this regard, it is usually easier to demonstrate the non-sustainability of an energy system (non-renewable, polluting etc.) than to guarantee the sustainability of systems based on renewable energy, especially bioenergy.*

Even though the debate regarding the sustainability of bioenergy is still ongoing, and it is often polarized between utilitarian and preservationist visions, human societies have used the energy flows associated with biomass production for millennia in all types of ecosystems. As such, bioenergy should be considered as an energy alternative, one to be better understood and utilized in those contexts where it is most appropriate. In that regard, this chapter presents bioethanol and sugarcane production from the perspective of sustainability, where sustainability is defined as the possibility that bioenergy systems maintain their production over the long term – without overt depletion of the resources that originally gave rise to them, such as biodiversity, soil fertility, and water resources –. Such focus is based on one of the classical definitions of sustainability: «the amount of production that can be sustained indefinitely without degrading capital stocks, including natural capital stocks» [Goodland (1992)].

After the United Nations Conference for the Environment and Development, the Earth Summit, held in Rio de Janeiro in 1992, sustainability came to be understood by its three pillars – environmental, social and economic – thereby making the concept widely used and a permanent presence in debates on the growth of nations. In the present chapter, sustainability will be approached from the both local and global perspectives. Aspects of the economic and social viability of bioethanol will also be analyzed with respect to the Brazilian model, a model which could be adopted by other countries with sufficient availability of arable land and similar soil and climate conditions. And as themes touching on the issue of sustainability, the use of soil and agroecological zoning for sugarcane cultivation in Brazil and advances and perspectives related to certification of biofuels will also be discussed.

7.1 Environment and sugarcane energy

The first point to mention regarding the environmental implications of bioethanol production is the importance of legislation to guide producers toward best practices and prohibit actions which harm the environment. To this end, for the implementation and operation of sugar and bioethanol plants in Brazil, in accordance with CONAMA Resolution 237/1997, there are three phases of environmental licensing that must be complied with, characterized by obtaining the following licenses:

a. *Licença Prévia (LP)* Preauthorization - approves the site and plan and establishes basic requirements and conditions to be met in subsequent phases.

b. *Licença de Instalação* (LI) Facility License – authorizes the facility and includes environmental control measures.

c. *Licença de Operação* (LO) Operating License – authorizes operations after complying with requirements established in the previous licenses and subject to periodic renewal.

Basic documents for the licensing process are the Environmental Impact Study and the Environmental Impact Report (EIA/Rima). A public hearing to present the project and the definition of Environmental Compensation (such as the planting of native species or the formation of a permanent natural reserve) are obligatory. The requirements for carrying out the studies and requirements to be complied with are established by the legislation, in accordance with the processing capacity of the agroindustrial units. In the case of small projects or process changes that are not potential causes of environmental impacts (eg, enlargement of cogeneration systems), a *Relatório Ambiental Preliminar* (RAP) (Preliminary Environmental Report) may be required. This is a simple procedure.

This section includes some comments regarding the most relevant isssues associated with environmental impacts of sugarcane and bioethanol production in Brazil. They include emissions with global impacts (greenhouse effect gases), local impacts (especially associated with pre-harvest burning), water use and the disposal of effluents (including stillage), use of agricultural pesticides and fertilizers, erosion and protection of soil fertility and biodiversity.

Emissions of gases with global impacts

Because of high photosynthesis yields in sugarcane production and biofuel conversion process efficiency, the utilization of sugarcane-based bioethanol significantly reduces greenhouse gas emissions compared with the use of fossil fuels (gasoline) in cars with similar characteristics.

This contribution to the mitigation of climate change is, possibly, one of the most important features of sugarcane bioethanol. The subject was presented in detail in Section 3.5 (Productivity, emissions and energy balances). There, not only was it shown just how positive the impact of ethanol is, but also, how relatively ineffective other inputs are in this regard considering the technologies currently used.

Table 28 shows a summary of the balance of carbon dioxide emissions from sugarcane planting through bioethanol end-use, for typical agricultural and agroindustrial conditions. Neither other gases nor second-order effects are taken into account, but all production and use operations for conditions observed in Brazil's Center-South region are included. The values in this table were calculated taking into account the composition of various sugarcane products and typical agroindustry mass balances. The values also assume that 12.5 tons of sugarcane yield one thousand liters of bioethanol. With future advances, these results should be improved.

***Table 28* – Summary balance of carbon dioxide emissions in the bioethanol and sugarcane agroindustry for the Brazilian Center-South region (kg/thou liters bioethanol)**

Stage	Photosynthesis CO_2 absorption	Release of CO_2	
		Fossil	Photosynthesis
Planting		173	
Growth	7,464		
Harvest and transport		88	2,852
Ethanol manufacture		48	3,092
Ethanol use			1,520
Total	7,464	309	7,464

Source: Elaborated by Luiz Augusto Horta Nogueira.

As can be seen, carbon released into the atmosphere corresponds to the sum of carbon of photosynthetic origin, absorbed during the growth of sugarcane and then released in four stages – the burning of straw, fermentation (conversion of sugars to bioethanol), the burning of bagasse in boilers and the burning of bioethanol by engines – and carbon of fossil original, corresponding to a net addition to the atmosphere and resulting from agricultural and industrial operations and the production of inputs and equipment. As such, only carbon of fossil origin should be considered, since photosynthetic carbon released corresponds to that absorbed by sugarcane. Comparing the net contribution of fossil emissions (of the order of 309 kg of CO_2 per thousand liters of bioethanol produced) with estimated gasoline emissions (of 3,009 kg of CO_2 including an increment of 14% of emissions during production), and assuming identical performance in terms of final use, there is a resultant reduction of approximately 90% in carbon emissions. These results do not significantly change when second order effects (associated with other gases besides carbon dioxide) are taken into consideration, as shown in Section 3.5, as previously mentioned. Similar results supporting the advantages offered by sugarcane bioethanol in terms of reductions in greenhouse gas emissions and the consequent mitigation of climate change have been presented in several studies [Concawe (2007), Esmap (2005) and IPCC (2008)].

According to the Brazilian Communication to the United Nations Framework Convention on Climate Change (1994 figures), the utilization of sugarcane energy has reduced carbon emissions by 13% in the energy sector. Considering Brazilian agroindustry production volumes (2003), the substitution of ethanol for gasoline and the generation of energy using bagasse reduced equivalent CO_2 emissions by 27.5 million and 5.7 million tons, respectively [Goldemberg et al. (2008)]. Calculations for similar situations indicate that for each 100 million tons of sugarcane used for energy, the emission of 12.6 million tons of equivalent CO_2 could be avoided (taking into account ethanol, bagasse and surplus electric power provided to the grid) [Unica (2007)].

Emissions of gases with local impacts

In bioethanol production, the local-impact emissions that are of the most concern come from pre-harvest burning and boiler chimneys. Straw burning increases production, but it is considered to be an environmental problem that affects mostly local cities in sugarcane regions. Brazilian public agencies are, therefore, strongly inclined to restrict this practice (which implies, indirectly, cutting by hand, a process which is harder when the sugarcane is unburned).

The best example of this stance can be seen in São Paulo, where State Law 11.241, 2002 established a deadline for unburned sugarcane harvesting to be implemented in all areas to be mechanized by 2021, while permitting the remaining areas and areas smaller than 150 hectares to continue burning until 2031. Due to pressures from environmental organizations and the Public Attorney, an agreement between the state government of São Paulo and sugarcane agribusiness has moved these deadlines up to 2014 and 2017, respectively, with additional burning restrictions in areas undergoing expansion. In the same vein, the authorization for 56 new São Paulo ethanol plants starting in 2008 was made contingent on the adoption of mechanized-raw sugarcane harvesting. The results of this process can be seen by remote satellite monitoring and show that unburned sugarcane harvesting accounts for 47% of the area planted in São Paulo for the 2007/2008 harvest. This has enabled the avoidance of 3,900 tons of particulate matter from being released into the atmosphere [Cetesb (2008)]. In other states, such as Goiás e Mato Grosso, similar initiatives to establish schedules for the elimination of burning can be seen, although thus far, results have not been measured. Besides environmental issues, it is also possible to utilize the energy from straw burning for power generation and this is one of the positive factors for raw sugarcane harvesting.

With the introduction of modern boilers in the plants (ie, less excess air and higher flame temperatures), chimney gas nitrogen oxide levels have reached levels similar to those observed in other thermal energy systems. Levels are now controlled by environmental agencies in accordance with specific legislation that entails limits and penalties regarding emissions (CONAMA Resolution 382, 2006). In this regard, boiler emissions can, and effectively are, abandoning conventional systems for cleaning chimney gases. Results have been positive, so this does not seem to be a relevant problem for the bioethanol agroindustry.

Water use and the disposal of effluents

From the hydro resources point of view, the particularly favorable conditions of countries in humid tropical climates such as Brazil, with plenty of well distributed rain, enables much of sugarcane culture to be carried out without irrigation. In the case of Brazil, it is estimated that irrigated agricultural areas amount to 3.3 million hectares, or around 4% of the area cultivated. Annual average runoff in Brazil is 5.74 thousand km^3, compared with an estimated water consumption of 55 km^3, ie, less than 1% of the needs and enabling an annual supply of 34 thousand m^3 water per inhabitant [Souza (2005a)]. However, in Brazilian regions with an annual availability below 1.5 thousand m^3 water per inhabitant the situation is critical. Implementation of water granting and charging systems is currently underway, which allow water to be charged according to the principle of «polluter/payer» (drafted by the Basin Committees, pursuant to Law 9.433/1997, The Water Law). This should encourage a more responsible use of water and a reduction of pollution in bodies of water.

Depending on the climate, sugarcane cultivation requires 1500 mm to 2500 mm of adequately distributed water during the growing cycle (a hot dry period for growth and a dry period for maturation and sugar accumulation). Irrigation is practically not used in the Brazilian Center-South region, being adopted only in the most critical periods in the Center-West region and, somewhat more frequently, in the Northeast region. In the latter case, irrigation is used as «salvation irrigation» at sugarcane planting, to ensure sprouting under dry conditions, and as «supplementary irrigation» under other rainfall conditions in periods of most critical growth development [Souza (2005a)]. To the extent that areas with less water availability become occupied by sugarcane, it is believed that irrigation could be an appropriate option (to be implemented in accordance with prevailing laws) in order to maintain agricultural output. Currently, in the opinion of Embrapa, sugarcane plantations have not impacted water quality [Rosseto (2004)].

Within the sphere of the industrial process, in addition to the volume of water used for processing sugarcane, a significant volume of water enters the plant with the sugarcane itself since water constitutes 70% of the cane weight. So, although the volume for processing is estimated at 21 m^3 per ton of cane processed, water consumption and waste is much lower. In relation to water consumption, 87% occurs in four processes: Cane washing, multi-jet/barometric condensers, cooling of fermentation vats and alcohol condensers. With the rationalization of water consumption (recycling and turning off of circuits, as well as certain process changes, such as dry washing, and reduced cane washing enabled by mechanical cutting), net water use has been significantly decreased. Studies performed in 1997 and 2005 point to an average reduction in water use of from 5 m^3 to 1.83 m^3 per ton of cane processed, with expectations of reducing this to 1 m^3 per ton of cane processed in the medium-term [Elia Neto (2005)].

The principal effluents from bioethanol production and treatment systems are presented in Table 29. A survey of 34 plants showed that the treatment used reduces organic load by 98.4%, with a residual of 0.199 kg BOD/t cane [Elia Neto (2005)]. Fertirrigation, in which stillage is applied to sugarcane, is the main form of final disposal of the organic load, one which has both environmental and economic advantages. Given its importance, the issue of stillage is worth analyzing more deeply.

Table 29 **– Liquid effluents from the bioethanol industry**

Effluent	Characteristics	Treatment
Water from sugarcane washing	Average polluting potential and high solids content	Decantation and stabilization pools in the case of disposal into bodies of water. When reused, treatment consists of decantation and pH correction.
Water from multi-jets and barometric condensers	Low pollution potential and high temperature (~ 50° C)	Spray tanks with cooling towers, with recirculation or release
Water for cooling vets and alcohol condensers	High temperature (~ 50° C)	Cooling towers or spray tanks for reuse or release
Stillage and residual water	High volume and organic load	Applied during cane farming along with residual water

Source: Elia Neto (2005).

The stillage, produced at a rate of 10.85 liters per liter of bioethanol, constitutes the most important effluent from sugarcane agroindustry. It contains high levels of potassium (close to 2 kg per m^3) and organic matter, but is relatively poor in other nutrients. At the beginning of Proálcool, stillage was released directly into rivers causing severe environmental problems. This was attenuated by the use of infiltration basins and finally resolved 1978 with fertirrigation systems.

The area of sugarcane plantation covered by fertirrigation depends on the topography and distribution of the lands around mills – some mills apply stillage to 70% of the area under cultivation; for others, it is considerably less. Currently, the intention is to increase the area covered by stillage to increase yields and reduce the use of chemical fertilizers (which can be then used at lower doses thereby lowering the risks of salinization and contamination of the water table) [Souza (2005b)]. Among mills in the state of São Paulo, stillage is predominantly spread using pumping and spraying systems, although conventional tanker trucks are also used for distribution.

Long-term studies on the effects of stillage on sugarcane plantations (taking into account nutrient leaching and groundwater contamination) confirm the physical, chemical and biological benefits to the soil. These include increased pH, increasing ionic exchange capacity and availability of certain nutrients, improved soil structure, increased water retention and development of soil microorganisms. Used at appropriate rates (lower than 300 m^3 per hectare, and taking into account the characteristics of the soil and the location of springs), stillage acts to revitalize soil fertility, even below the surface, as well as providing water and nutrients [Souza (2005b)]. Stillage is currently considered to be an organic fertilizer, being approved for the production of «organic» sugar, in which chemicals such as herbicides, insecticides or synthetic fertilizers cannot be used.

Some traditional sugar-producing regions of the State of São Paulo are located in environmentally vulnerable areas, such as catchment areas for important São Paulo aquifers. In these cases, the intensive and frequent use of stillage could cause long-term groundwater pollution. In such areas, the applicable environmental regulations for stillage use have been evolving. In 2005, the Secretary of the Environment of the State of São Paulo published a technical regulation regarding criteria and procedures for the application, transportation and disposal of stillage on agricultural land [SMA (2005)]. The regulation mainly stipulates measures for the protection of surface and ground water, requiring leak proofing of storage tanks and residue distribution channels, locations subject to application and a maximum rate of 185 kg K_2O per hectare, calculated based on stillage potassium ion levels being limited to 5% of the soil ion exchange capacity [Bertoncini (2008)]. Such legislation is compulsory in the State of São Paulo and, patterned on other environment-related regulation, tends to be adopted in the rest of the country.

Regardless of the results obtained by fertirrigation, the interest in exploiting the residual energy content in stillage remains, through biodigestion and biogas production. Another line of research is to concentrate the stillage, for example, by recirculating during fermentation combined with pre-concentration of the liquor, or by using reverse osmosis, in order to reduce volumes to facilitate transport over longer distances [CGEE (2005)]. Neither of the alternatives has reached economically viable levels, as already observed in Chapter 4. But, with the evolution of processes, they may come to be adopted in the medium-term, especially in those contexts in which topography and distances make fertirrigation more difficult.

As an important indicator of the evolution of the sugarcane agroindustry in the treatment and reduction of effluent releases into water bodies, Cetesb undertook a study of 16 hydrographic basins in the State of São Paulo where bioethanol production exists. It was estimated that there was a potential discharge of 9,340 thousand tons per day of Biochemical Oxygen Demand (BOD) associated with sugar and bioethanol plants and an effective release of 100 thousand tons, equivalent to a 99% decrease in pollution potential, based on organic load [Moreira (2007)]. Naturally, these significant results were stimulated by law-enforcement inspections, but they demonstrate the availability and use of technologies capable of significantly mitigating impacts of effluents on watercourses.

Despite the results obtained, permanent efforts for maintaining or reducing the environmental impacts of these effluents are justified by virtue of the sheer size of the sugarcane planted area and the amount of bioethanol produced. In this direction, interesting measures are being adopted for the protection of watersheds, particularly with respect to the progressive abandonment of sugarcane cultivation in *Áreas de Preservação Permanente* (APP) (Permanent Preservation Areas), which enables them to recuperate spontaneously or with the help of reforestation (especially in the case of riparian forests) with positive impacts on biodiversity [Ricci Jr. (2005a)].

Use of agrochemicals

Chemical products such as insecticides, fungicides, herbicides and flower-promoting or retarding products are regularly used in sugarcane production at levels which are considered low in comparison with averages used in other important commercial crops.

***Table 30* – Use of agricultural pesticides in the main crops in Brazil (In kg active ingredient per hectare)**

Product	Year	Culture				
		Coffee	Sugarcane	Orange	Corn	Soy
Fungicide	1999	1.38	0.00	8.94	0.00	0.00
	2003	0.66	0.00	3.56	0.01	0.16
Insecticide	1999	0.91	0.06	1.06	0.12	0.39
	2003	0.26	0.12	0.72	0.18	0.46
Miticide	1999	0.00	0.05	16.00	0.00	0.01
	2003	0.07	0.00	10.78	0.00	0.01
Other agrochemicals	1999	0.06	0.03	0.28	0.05	0.52
	2003	0.14	0.04	1.97	0.09	0.51

Source: Arrigoni and Almeida (2005) and Ricci Jr. (2005b).

As presented in Table 30, agrochemical application rates for some of the main Brazilian crops, according to the *Sindicato Nacional da Indústria de Produtos para Defesa Agrícola* - SINDAG (National Union of Agrochemical Producers), varies according to the crop. In the case of sugarcane, fungicide consumption is practically zero and insecticides are used in proportionately small quantities.

The reduced use of these pesticides is the result of pest combat procedures such as the choice of more resistant varieties in genetic improvement programs and above all by the adoption (with excellent results) of biological methods of control of the main sugarcane pests, which include the sugarcane borer (*Diatraea saccharalis*), a species of moth combated using a wasp (*Cotesia* *flavipes*), and the sugarcane spittle bug (*Mahanarva fimbriolata*), controlled by applying fungus (*Metarhizium anisopliae*) [Arrigoni and Almeida apud Macedo (2005)].

Sugarcane borer larva (*Diatraea saccharalis*) and the parasitic wasp (*Cotesia flavipes*).

Biological control employs parasites or predators to control agricultural pests with a high degree of accuracy and low impacts. This method has economic advantages in relation to the use of conventional insecticides since chemical products are not indiscriminately applied and pests are kept at tolerable levels. Restrictions on sugarcane burning will probably increase the need to use such controls on the spittlebug.

To combat weeds, sugarcane needs more herbicides than coffee or corn, but less than citrus, being equivalent to soybean in terms of requirements. Meanwhile, with the progressive adoption of raw (unburned) sugarcane harvesting, the straw that remains on the soil surface suppresses the germination and emergence of invasive plants, enabling significantly less herbicides to be applied [Urquiaga et al. (1991)]. With respect to the use of agrochemicals, it is important to mention that Law 7.802/89 establishes the *receituário agronômico* (agrochemical register), which defines responsibilities, application methods, and container disposal procedures.

Fertilizer use

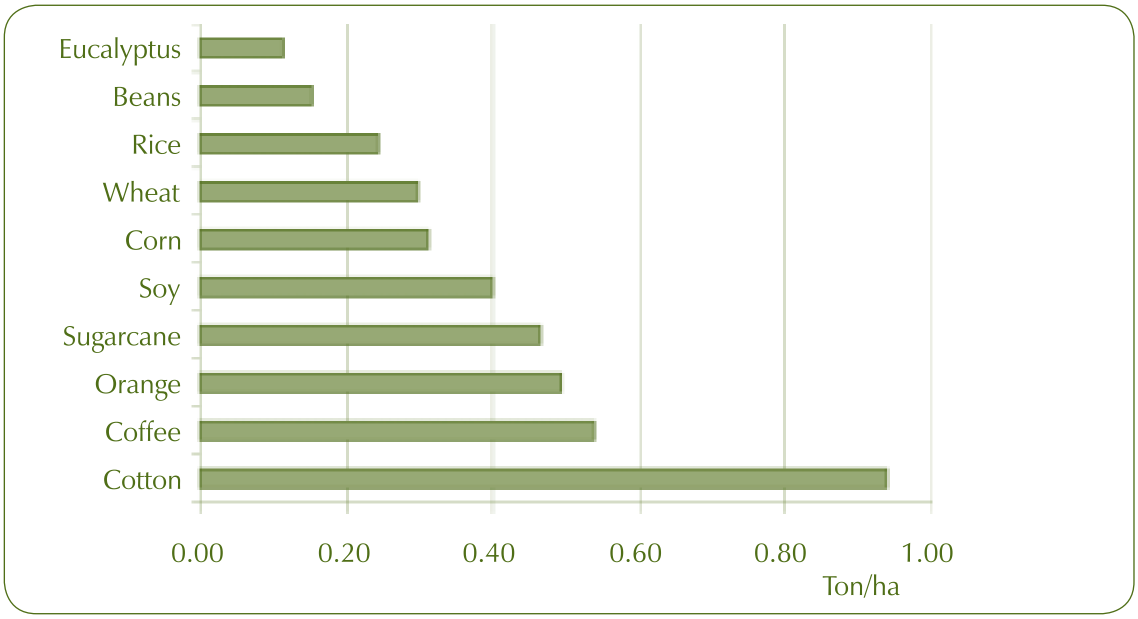
Sugarcane culture in Brazil consumes a relatively low quantity of conventional fertilizers, given he importance of recycling of nutrients. In effect, fertirrigation with stillage substantially reduces potassium requirements, and in conjunction with industrial process wastewater and boiler ashes, supplies a significant proportion of the nutrients for sugarcane, with both economic and environmental benefits. Considering a typical full cycle of sugarcane planting (plant-crop and four ratoon-crops), under average Brazilian conditions, the application of stillage and filter cake, although it does not have much impact on nitrogen supply, does reduce phosphorous demand (P_2O_5) from 220 kg/ha to 50 kg/ha and potassium demand (K_2O) from 170 kg/ha to 80 kg/ha, while maintaining similar yields [CGEE (2005)]. Note that for bioethanol production, only sugars and fiber (comprised of carbon, hydrogen and oxygen) are of importance. In as much as possible, all other nutrients removed from the cane should be returned to the soil.

Additionally (and of particular interest), it has been observed a much higher availability of nitrogen in sugar plantations than that provided by fertilizers, signaling the existence of biological nitrogen fixation by bacteria colonies of the genus *Azospirillum*, a diazotrophic bacterium – capable of converting atmospheric nitrogen in forms that can be assimilated by other organisms – living freely in the rhizome area or associated with gramineae like sugarcane. The pioneer studies in this area were conducted in recent decades by Johanna Döbereiner, a Brazilian researcher from Embrapa; those studies could well open up perspectives for significantly increased yields in the sugarcane agroindustry [CNPAB (2008)].

Considering plantations with cultivated areas above one millions hectares, sugarcane is in fourth place with respect to the consumption of chemical fertilizers in Brazil (as seen in Graph 24), based on data provided by the *Associação Nacional de Difusão de Adubos* - Anda (National Fertilizer Dissemination Association) and IBGE surveys. This level of consumption of fertilizers by sugarcane is considered relatively low, compared with other countries. Given the values suggested by CTC for fertilizing ratoon cane and plant cane in the Center-South Region, with the application of, respectively, 290 kg and 260 kg of average formula N-P_2O_5-K_2O, fertilizer levels for sugarcane in Australia are 30% and 54% higher than for Brazil [Donzelli (2005a)].

Fertilizer, when used as a complement to recycled by-products, is important to ensure that yields are maintained under current conditions; without it, productivity would fall substantially. However, fertilizer use represents a significant portion of agricultural costs, which justifies the increasing adoption of new technologies to diminish the demand for fertilizer and lime, rationalizing their use. With respect to this point, new methods of fertilizer distribution can be cited in which losses due to volatilization are reduced, organic material is increased (as with raw cane harvesting), and precision agriculture methods are applied. By using yield maps with physical and chemical soil attributes (granulometry, macronutrient and micronutrient levels, acidity, density and penetration resistance), significant fertilizer savings can be obtained by substituting the uniform application of fertilizers with variable-rate applications, based on detailed soil information. By using precision agriculture techniques the *Usina Jales Machado*, in Goianésia (GO), achieved a reduction of 34.5% in the application of lime and 38.6% in the application of phosphorus. This was equivalent to an economy of 36% in costs for these products, per fertilized hectare, maintaining the same productivity [Soares (2006)]. Experimental studies in the Araras region of São Paulo indicated that reductions of 50% in the consumption of phosphate and potassium fertilizer can be expected with the adoption of variable application rates [Cerri (2005)]. At present, it is estimated that around 10% of sugarcane plantations in Brazil already use some form of precision agricultural technique for the application of phosphorus and lime at variable rates (Molin, 2008).

Graph 24 – **Consumption of fertilizers by the main crops in Brazil**



Source: Donzelli (2005a).

In short, the use of fertilizers, highly important to yields for Brazilian sugar plantations, has been practiced at lower levels due to recycling of industrial process nutrients; application of conventional fertilizers has tended to decrease with the progressive introduction of new fertilizer technologies.

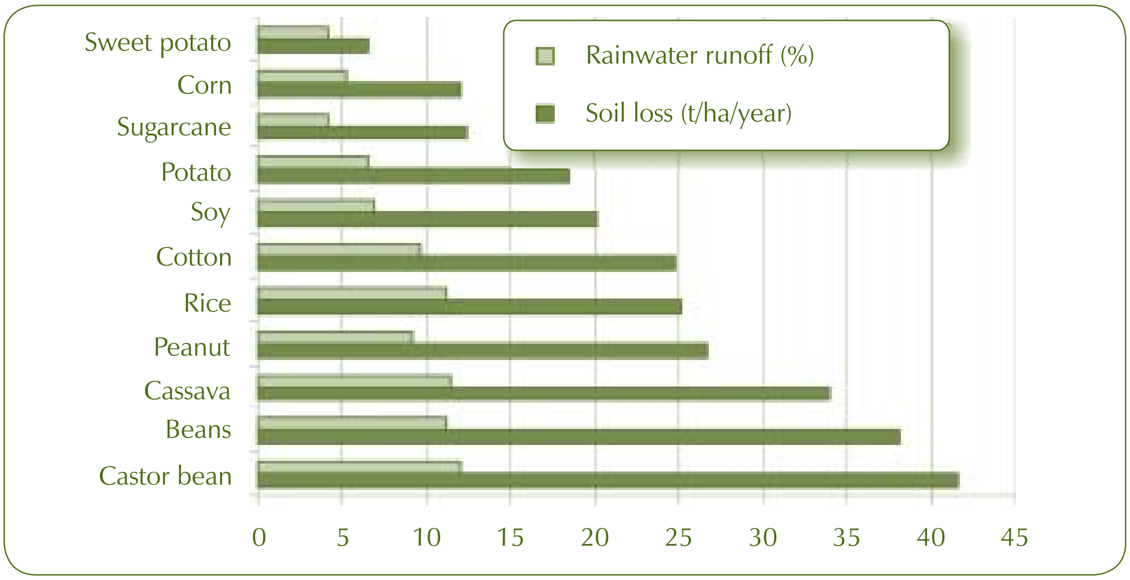
Erosion and soil protection

Frequently caused by inadequate agricultural practices, soil erosion is the largest cause of degradation of agricultural lands and it is often associated with the irreversible loss of arable land. Because of this, the productive use of land should take into account the type of soil (texture, diagnostic horizon types, and water infiltration rates), slope, precipitation regime, crop to be planted and establish plots, roads and cultivation lines, in order to protect the fertile topsoil. Since sugarcane production has been practiced for centuries in Brazil (in many cases, in the same area), there is already enough information regarding its impact on soil conservation [Donzelli (2005b)].

As a semi-perennial crop (a feature that reduces the number of agricultural operations that expose the soil to bad weather and subsequent loss of topsoil) sugarcane is recognized as being a soil-conserving crop, a fact supported by Graph 25 (topsoil loss and rainwater runoff for different crops in Brazil). For example, soil loss with sugarcane is only 62% of that for soybean. From the point of view of rainwater retention capacity – an important aspect for farming and for soybean. protection – sugarcane is demonstrably one of the most efficient crops, as Graph 25 confirms.

The increasing use of raw cane harvesting, reviewed in previous paragraphs (in which straw protects the soil against the direct impacts of raindrops and soil requires less preparation and tilling), should, in coming years, improve even more conservation levels of soil planted with sugarcane, resulting in a reduction of approximately 50% in the levels of soil loss and rainwater runoff currently observed [(Donzelli (2005b)].

***Graph 25* – Soil loss and rainwater runoff for some Brazilian crops**



Source: Donzelli (2005b).

Biodiversity

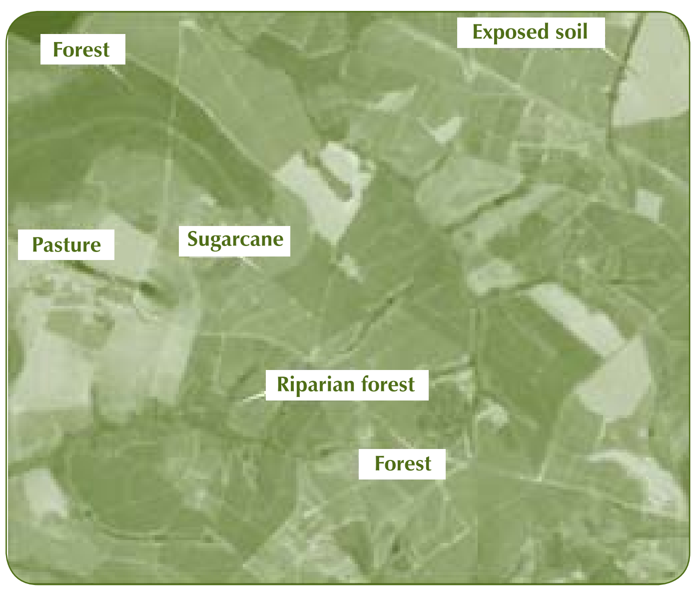
The efficient production of bioethanol in Brazil implies the planting of sugarcane, a monoculture whose environmental impact depends on the original characteristics of the land and on mitigation measures. Thus, with regard to endangering pre-existing biodiversity, the effects of sugarcane planting in areas previously occupied by other crops or where there has been extensive cattle farming are certainly distinct to planting in virgin areas, especially forests. In the first case, there is a change in land use; in the second case, significant negative impacts are possible.

Brazilian law (in particular, the *Código Florestal Brasileiro* (Brazilian Forest Code), Law 4.771, of 1965, and Law 7.803, of 1989) determines that farms have to preserve a *Reserva Legal*

- RL (Legal Reserve): This is an area located within a property or rural possession (except for permanent preserves), dedicated to the sustainable use of natural resources, conservation and rehabilitation of ecological processes, conservation of biodiversity and the shelter and protection of native fauna and flora. The Legal Reserve must be a minimum of 20% of the total area, depending on the region (in the Amazon, 80%); additionally the original vegetation must be maintained in *Áreas de Preservação Permanente* – APP (Permanent Preservation Areas) eg, hilltops, slopes and banks of water bodies.

Unfortunately, the expansion of farmland over the last decades has, in general, ignored these rules. Currently, due to increased environmental awareness, reinforcement of the responsible institutions and availability of satellite monitoring systems (see Figure 26), such legal provisions have been enforced by government agencies at several levels and have been effectively incorporated into the farming practices of several plants, both operating and under construction. For example, in many plants in the State of São Paulo, during the last decade, there has been a reduction of sugarcane planting in gallery (riparian) forest areas, as well as forest regrowth in water springs: even with the significant expansion of farming, a marginal increase of the state's forest coverage, estimated in 3.5 million hectares, has been discerned [Instituto Florestal (2004)]. In new units, especially in the Brazilian *cerrado*, concern with acting in an environmentally correct way is evident at many companies. Motivated by the legal risks of noncompliance and by the positive image associated with being environmentally friendly, they seek, from the outset, to comply with the legislation applicable to Permanent Preservation Areas and Legal Reserves.

Figure 26 **– Example of satellite image from monitoring of vegetation coverage**



Source: CTC (2008).

Although sugarcane is less aggressive than other crops and its cultivation makes extensive use of byproduct recycling and biological pest control, it is essential that the bioethanol agroindustry strictly complies with environmental legislation and be duly penalized for any infractions, given the size of the area planted with sugarcane. The current experience in many Brazilian plants (with good results vis-à-vis agroindustry/the environment) combined with the current availability of low-environmental-impact farm and industrial technologies confirm the possibility of producing sugarcane bioethanol in a rational way: conservationist environmental practices make economic sense [Smeets et al. (2006)].

Nevertheless, it is very important to note that effective application of the law and a more favorable attitude towards nature, in all the aspects mentioned above (eg, biodiversity, water and soil resources) derives, above all, from the clear and active presence of the State, implementing and enforcing compliance with environmental laws. Higher environmental awareness in public and private entities helps to bring pressure in favor of a responsible development of bioenergy in Brazil, as it is one of the few alternatives capable of promoting alternatives capable of promoting change (for the better) in the worrisome status quo of global energy [FBDS (2005)].

Other environmental aspects

Recently, two new environmental issues related to sugarcane bioethanol production have arisen: the emission of greenhouse gases associated with land use changes (with loss of original vegetation, when sugarcane farming is implemented) and the indirect process of deforestation caused by the occupation of rangeland by sugarcane, which causes the transfer of livestock to the agricultural frontiers where new cattle raising areas may be created. These are certainly complex subjects, still under discussion, but some important and relevant information can be put forth.

The impact of land use change on greenhouse gas emissions has been considered in several studies. Depending on the previous vegetation in the area used for biofuel production, the disturbance provoked by the land use change could release a quantity of carbon – previously sequestered in the vegetation and soil – into the atmosphere, possibly in levels high enough to outweigh the environmental benefit. However, there is still much uncertainty as to the magnitude of this effect, because in-balance soil carbon levels depend, among other factors, on crop, soil type, farming practices and local climate. Carbon release and accumulation rates, after the cyclic planting of biofuel crops, also depend on many factors. Though preliminary, assessments of this type of impact suggest sugarcane bioethanol produced in the Brazilian *cerrado* has the lowest impact among the biofuels studied [Fargione (2008)]. This is an area that deserves attention and more research is still necessary to estimate, in a consistent way, the real share of these emissions in the biofuel lifecycle.

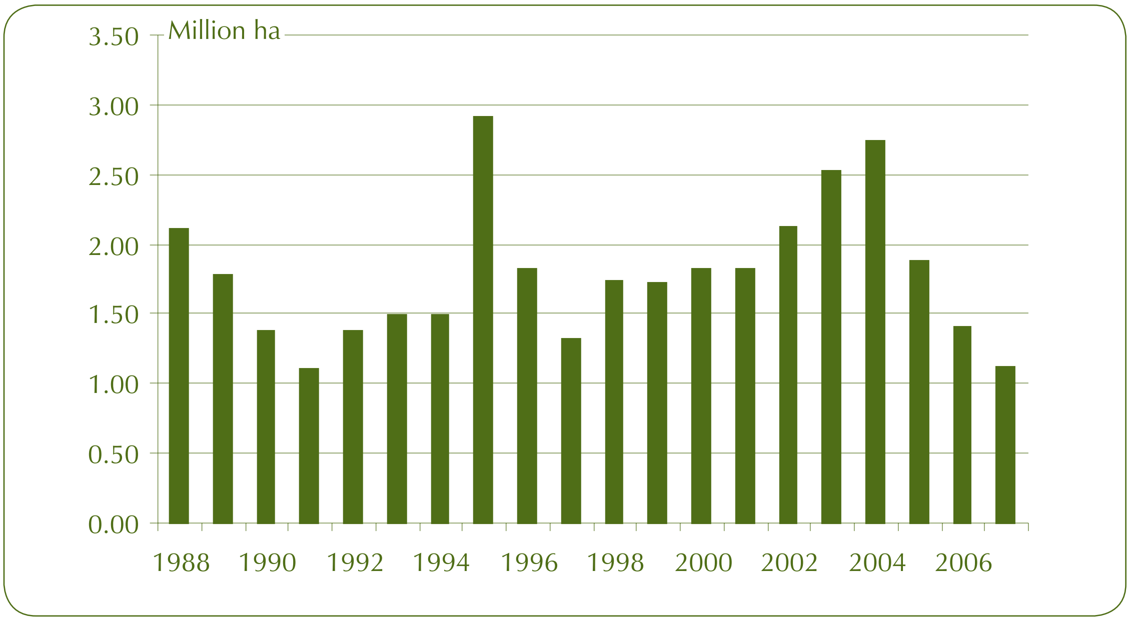
Moreover, in the case of bioethanol in Brazil it is very unlikely that forest cover losses can be attributed to bioethanol production because the expansion of sugarcane farming has occurred basically in areas previously occupied by low productivity pastureland or annual crops (such as soybean, mostly destined for export). In both these cases, the root system and the above-soil biomass are generally of lesser magnitude than in the case of sugarcane. Another aspect to be kept in mind is the increased practice of raw sugarcane harvesting, in which more of the straw (and, therefore, carbon) is incorporated into the soil [Macedo (2008)].

Indirect deforestation caused by the expansion of sugarcane production is an argument difficult to sustain in regard to criticism of bioethanol, since there is not much data on a causal relationship; however, it is an issue that deserves attention. Rainforests all across the planet suffer from enormous pressures regarding the use – rational or not – of their timber resources and the possibility of providing new land for agriculture. In Brazil, deforestation is an old problem and reducing it remains a significant challenge. This is despite growing governmental efforts to organize protection of the Amazon Forest, including the definition of protected areas, increased inspections, coordination of a variety of agencies and deployment of modern technology (such as remote sensing).

The loss of forest cover in the Amazon Forest in Brazil reached an annual average of 1.8 million hectares between 2000 and 2006 but has diminished lately, as shown in Graph 26, based on results of satellite image monitoring. However, only during the course of the next few years it will be possible to confirm whether deforestation rates have really been contained [Inpe (2008)]. It is estimated that around 17% of the original coverage of the Amazon Forest has been cut down, mainly for wood, charcoal for the steel industry and farmland occupied by extensive livestock systems and soybean plantations [ISA (2008)].

Nineteen billion hectares of the Brazilian Amazon Forest have been cleared during the last decade (1998–2007). This is 10 times greater than the expansion of the area planted with sugarcane to produce bioethanol in the same period. Bioethanol production does not imply deforestation; moreover, deforestation in the Amazon Forest region is a complex problem that imposes the need for land-use planning to regulate the expansion of agriculture, as well as reinforcement of inspections and law enforcement. Brazil, like several other countries located in the humid tropical region of the planet, has sufficient land for a significant expansion of agricultural production and can produce food and bioenergy in a sustainable way without giving up its forest assets (as will be covered in more detail in the next section).

Graph 26 – **Annual deforestation of the Brazilian Amazon**



Source: INPE (2008).

7.2 Land use

A recurring theme in the discussion of perspectives for bioethanol is the issue of farm land use in relation to its availability and eventual impacts on the availability of food. This section analyzes such aspects from the viewpoint of sugarcane bioethanol production in Brazil, followed by an assessment of the evolution of farmland use during the last decades. Perspectives on agricultural zoning are also discussed, concluding with a vision of the estimated potential for the expansion of sugarcane production in Brazil.

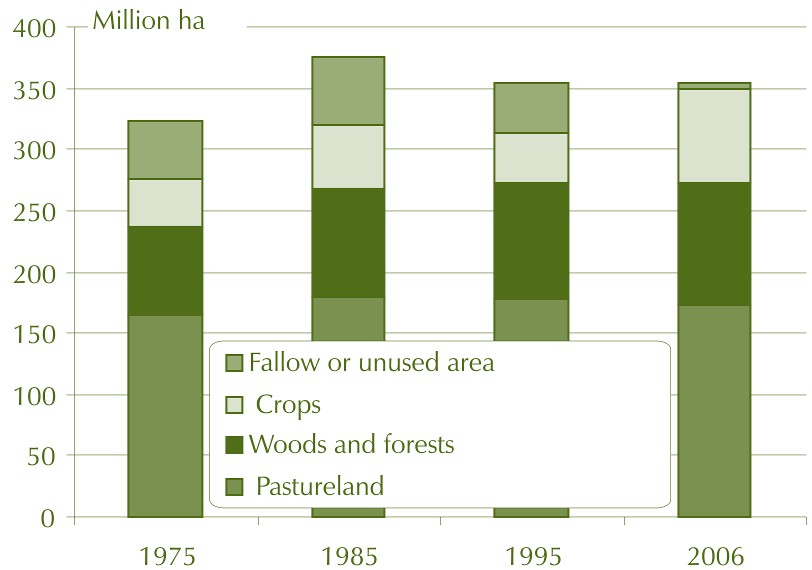
In the following chapter the relevant causal links between bioenergy production and food safety will be analyzed. The scope will be a global one, taking into account not only Brazil and also including the production of other biofuels.

Development of agricultural land use in Brazil

Brazil has a total surface area of 851.4 million hectares, mostly covered by tropical forests. Based on 2006 Agricultural Census results, the area of Brazilian rural properties (which excludes protected areas, water bodies and areas unfit for agriculture and includes legal reserves of native formations) amounts to 354.8 million hectares (42% of the total area of the country), dedicated to natural and planted pasturelands, forestry, native forests and annual and perennial crops. The evolution of the different types of land use in the last 30 years can be seen in Graph 27, which shows the relatively small variation in the total area of rural properties and the significant expansion of crop land in the last decade.

Between 1995 and 2006, Brazilian crop land expanded by 83.5% to occupy 76.7 million hectares, around 9% of the national territory. Such growth essentially took place in unused or fallow areas and, to a smaller degree, in pastureland, which shrank by 5.4 million hectares, to represent approximately 20% of the Brazilian territory. This growth of crop land in pasturelands has been happening systematically since the 1970s and has made the ratio of pasture land to cropland shrink from 4:5 in 1970, to 2:2, in 2006.

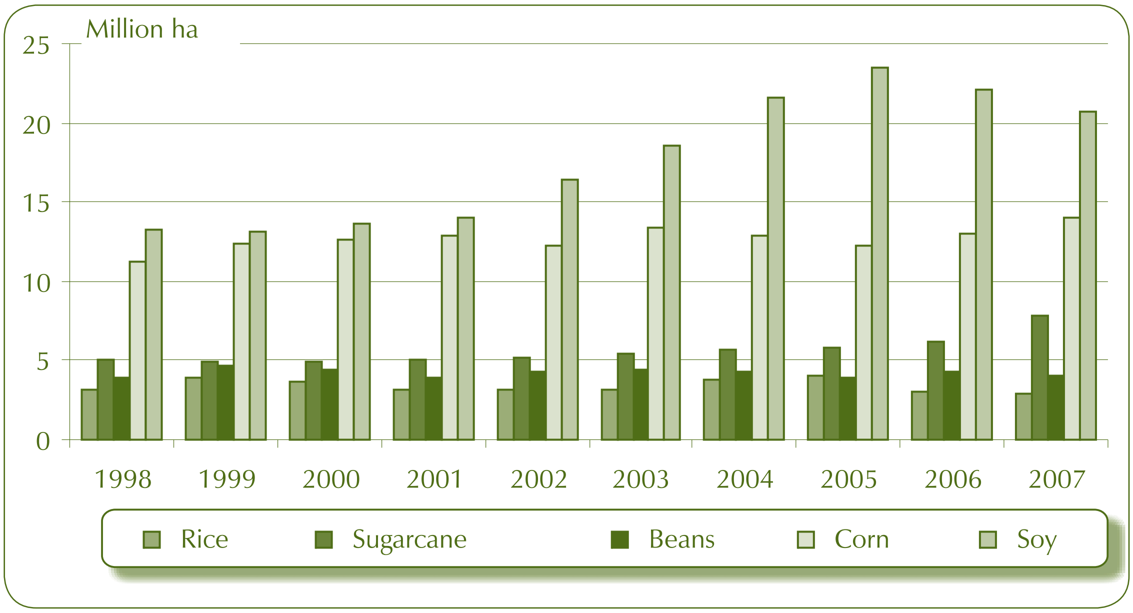
Graph 27 **– Rural Brazilian property land-use**



Source: IBGE (2007).

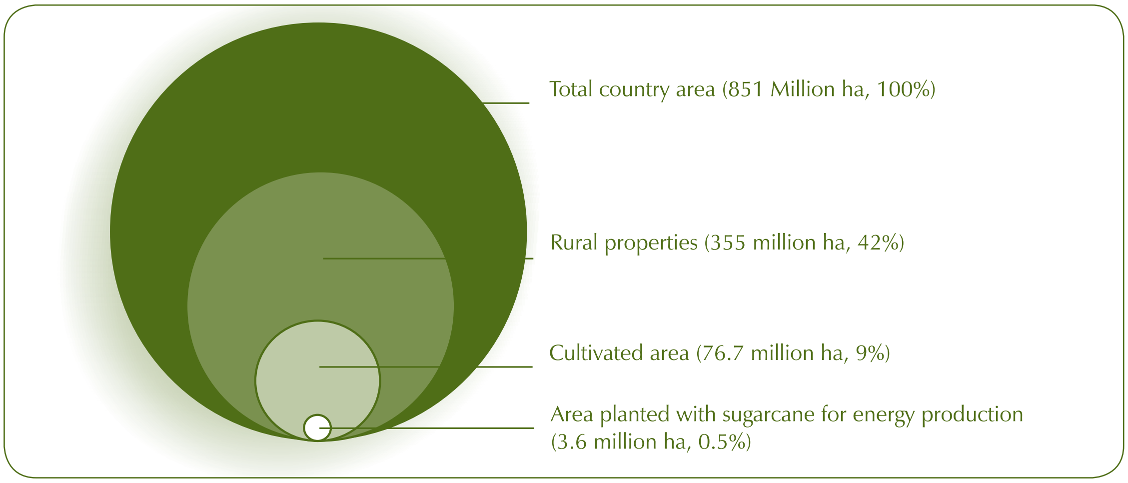
In 2007, sugarcane production in Brazil occupied 7.8 million hectares, around one third of that occupied by soybean and half of that planted with corn, as shown in Graph 28. Approximately half the sugarcane production goes to bioethanol production. Hence, sugarcane plantations for fuel production in Brazil correspond to 5% of cultivated land, 1% of the area of agricultural property, 2.3% of pastureland and 0.5% of the area of Brazil. Both the sheer size of the country and the efficiency of sugarcane in solar energy capture contribute to the size of these numbers: any other bioethanol input, with current technologies, would require a greater extension of land. Graph 29 presents the relative importance of the area dedicated to sugarcane production for energy purposes, compared to Brazil's total and cultivated areas.

Graph 28 – **Evolution of the area used by the principal crops in Brazil**



Fonte: IBGE (2007).

Graph 29 – **Land-use in Brazil**



Source: IBGE (2007).

The significant increase in the area planted with sugarcane in Brazil's Central West region between 1998 and 2007, confirms the tendency of this agroindustry to expand in regions close to traditionally producing areas and which have adequate topography, soil and climate conditions. Although weak infrastructure (especially transportation) needs to be addressed, this region effectively constitutes a new and important center for Brazilian sugarcane agroindustry. In this region, sugarcane expansion has mostly taken over pasturelands, as well as over some soybean fields (which were Cerrado a few decades earlier).

Agroecological zoning

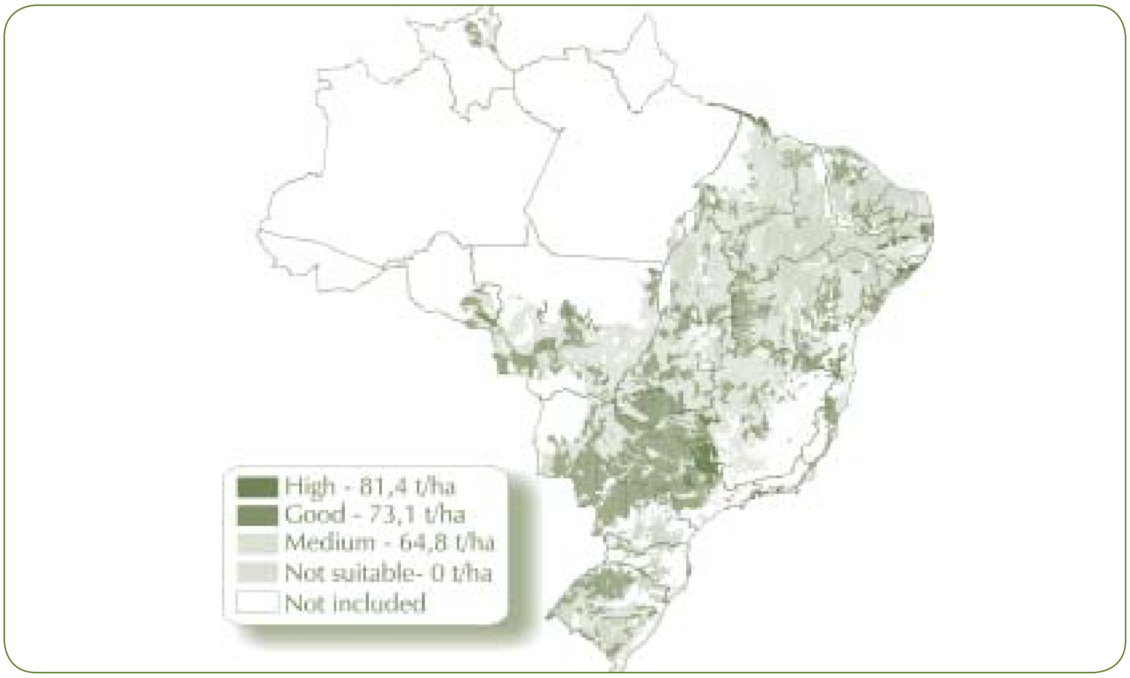
In an effort for planning the expansion of sugarcane agroindustry in Brazil, under the auspices of the Ministry of Agriculture and Supply (MAPA), the Sugarcane Agroecological Zoning (ZAE-Cana) was organized, the first results of which should be available this year. This is a comprehensive study, led by *Embrapa Solos* (EMBRAPA Soils), involving dozens of institutions and researchers. The purpose is to define which areas and regions are appropriate/inappropriate for large-scale sugarcane farming. The zoning is to be used to orient financing policies, infrastructure investments and tax regime improvements, and may also be useful for socio-environmental certification to be implemented in the future [Strapasson (2008)].

Agroecological zoning is focusing on agricultural and cattle raising areas where sugarcane is not yet grown, but has potential. It combines information on soil, climate, environmental reserves, geomorphological and topographical maps. It also identifies current land use, examines federal and state environmental legislation, and presents information on sugarcane cultivation, such as ideal growth temperatures, compatible soil types, water requirements, etc. Thus, areas of greatest potential for planting sugarcane are defined and classified, as well as those areas where it is not recommended or not possible. As a requirement for this work, a minimum productivity threshold was established, based on the national average of 70 tons of sugarcane per hectare.

Potential for the expansion of sugarcane production in Brazil

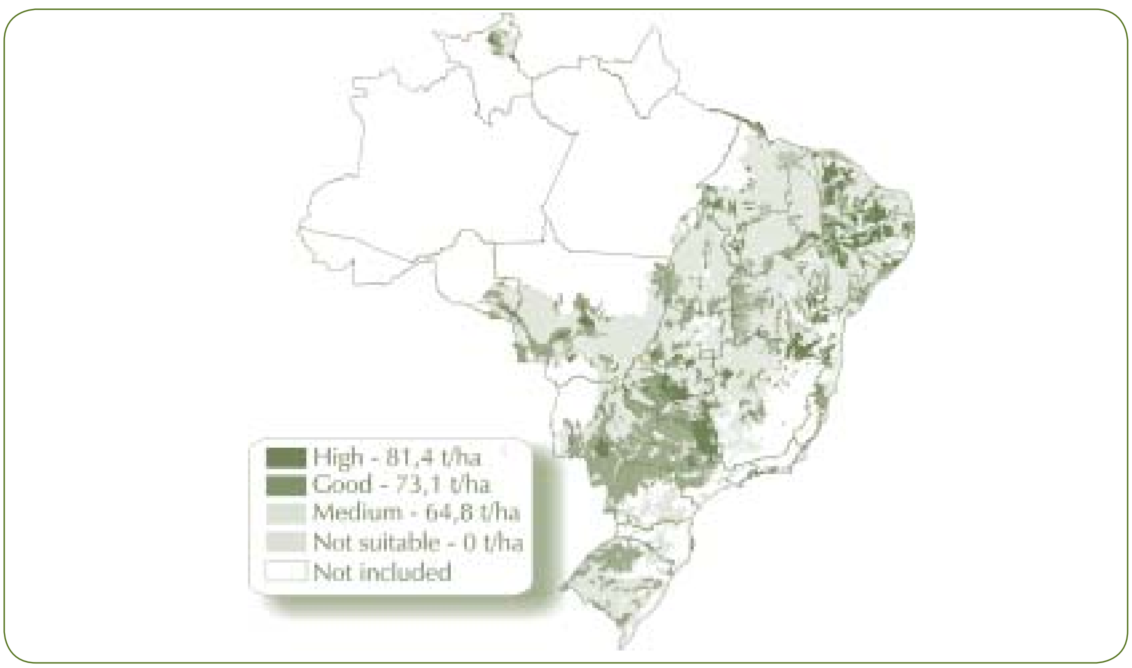
The study developed by *Centro de Gestão de Estudos Estratégicos* - CGEE (Center for Strategic Studies and Management) in conjunction with the *Núcleo Interdisciplinar de Planejamento Energético* - NIPE (Interdisciplinary Center of Energy Planning) of the State University of Campinas is less detailed than the agroecological zoning under development by MAPA; however, it has a similar goal of prospectively examining the possibilities and impacts of large-scale bioethanol production, under the assumption of partial substitution of gasoline on a global scale. The study is a survey of areas with sugarcane production potential based on soil and climate maps. It also considers water availability and gradient (slopes of less than 12° to facilitate mechanical harvesting), and excludes protected or preservation areas (eg, the Pantanal (Brazilian Wetlands) and the Amazon Forest) and forest and Indigenous reserves [CGEE (2005)]. The results of this study are shown in Figures 27 and 28, with areas classified in accordance with their suitability for sugarcane production, both with and without «salvation irrigation». Salvation irrigation is so called because it is only used on growing sugarcane, where an increase in production is of secondary importance; less than 200 mm of water is applied during more critical periods of water shortfall (equivalent to total annual irrigation of less than 2,000 m^3/ha/year).

Figure 27 – **Potential unirrigated sugarcane cultivation**



Source: CGEE (2005).

Figure 28 – **Potential sugarcane cultivation with "salvation irrigation"**



Source: CGEE (2005).

The map of unirrigated sugarcane production potential (Figure 27), shows that most of the areas with high and medium potential, equivalent to 121.8 million hectares (33.7% of the total), are located in Brazil's Central-South region. These areas are flat or mildly hilly and do not have significant soil or climate limitations. On the other hand, when salvation irrigation is contemplated (see Figure 28), high and medium potential areas increase in size to 135.9 million hectares (37.6% of the total), including in this case areas of the Brazil's semi-arid Northeast region [CGEE (2005)].

A summary of these results is presented on Table 31. It should be noted that, in the classification of expected yields, the value of 65 t/ha defined for low potential is equal to the world average sugarcane yield; therefore, an additional 167.5 million hectares (46.4%) of the total can also be included, for purposes of expansion of this crop.

***Table 31* – Potential sugar cane yields in Brazil**

Potential	Expected yield (t/ha)	Area with potential use			
		Unirrigated		Irrigated	
		Million ha	%	Million ha	%
High	> 80	7.90	2.2	37.92	10.5
Medium	>73	113.90	31.5	98.02	27.1
Low	> 65	149.22	41.3	167.65	46.4
Not suitable	< 65	90.60	25.1	58.00	16.0
Total	–	361.62	100.0	361.59	100.0

Source: CGEE (2005).

The bioethanol agroindustry has significant prospects for growth. Guided by environmental protection regulations and encouraged by high potential yields, it does not face significant restrictions in terms of land availability in Brazil. The following estimates reinforce this view.

As an exercise in calculating the existing potential, let us consider the global numbers for the 2007/2008 crop: in Brazil, around 22 billion liters of bioethanol were produced on 3.6 million hectares. In order to substitute (based on this empirical data, under current conditions) 10% of the gasoline consumed worldwide (1.3 billion cubic meters) with anhydrous alcohol, 136.5 billion liters of bioethanol would be necessary. Again, under Brazilian conditions, this would require 23 million hectares, equivalent to the area currently occupied by soybean in Brazil. Under similar conditions of productivity and energy efficiency, this production could be distributed over the humid tropical regions of the planet, in Latin American and the Caribbean, Africa and Asia, where sugarcane is traditionally grown, as discussed in Chapter 3 and shown in Figure 29. Biofuel production based on other crops or by any other technological routes currently available would require much larger cultivation areas.

Figure 29 – **Areas cultivated with sugarcane**

Source: Adapted from Tetti (2005).

Looking forward to 2025, the CGEE study predicts an effective availability of 80 million hectares for the expansion of sugarcane production in Brazil, based on cluster development scenarios (ie, grouped ethanol production units), the existence of sufficient logistics and area requirements for other permanent or temporary crops. In terms of demand, this same study estimated 205 billion liters of bioethanol would be necessary to substitute 10% of the projected global gasoline consumption for 2025. Assuming two levels of bioethanol/gasoline fuel blend (5% and 10%) and two (current and improved) technological scenarios, the required area was calculated to supply the Brazilian and global sugar and bioethanol market (also taking into account that 20% of the area is kept as environmental reserve). Results are summarized in Table 32 [CGEE (2005)].

Sugarcane agroindustry productivity increases, which should continue, and the introduction of innovative fuel production technologies can significantly reduce area requirements for fuel crops. In Table 32, the last line indicates the areas required (assuming technological progress) to supply domestic and foreign sugar demand (4 million hectares), as well as to produce sufficient bioethanol to supply the domestic market (6 million hectares) and include a 10% bioethanol content in global gasoline consumption (30 million hectares), with a total requirement of 40 million hectares (including 8 million hectares to be reserved for environmental protection). This area represents half of the available areas in Brazil for bioenergy production. This suggests that the availability of suitable land does not seem to be the limiting factor for rational promotion of bioethanol for domestic consumption and exports in the production regions [CGEE (2005)].

***Table 32* – Area requirements for bioethanol production for the 2025 global market**

Scenario	Global ethanol consumption	Technology	Area cultivated in sugarcane (million ha)				Use of available land
			Sugar production: domestic market and exports	Bioethanol production		Total required area	
				Domestic market	Exports		
E5	102.5	Current	4.5	8.5	19.0	32	40
		Improved	4.0	6.0	15.0	25	31
E10	205.0	Current	4.5	8.5	38.0	51	64
		Improved	4.0	6.0	30.0	40	50

Source: CGEE (2005).

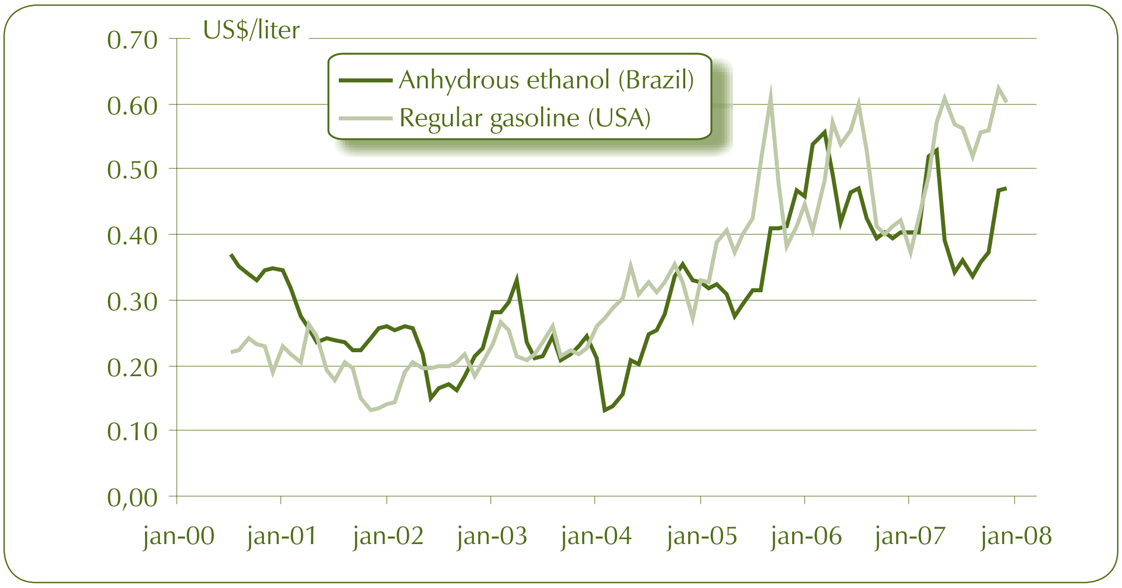
7.3 Economic viability of sugarcane bioethanol

Clearly, for the sustainability of bioethanol production it is fundamental that production costs – comprising all agroindustrial activity and investments for growing sugarcane and industrial plant implementation – are covered by the returns. In previous chapters, some economic aspects have been discussed, such as price formation mechanisms, bioethanol competitiveness compared to sugar production, the economic importance of the sugar-alcohol industry and the learning curve reflecting the sustained reduction of costs over the last decades. In this section the bioethanol economics analysis is taken up once again, presenting aspects of competitiveness vis-à-vis oil, the cost structure of bioethanol in Brazil and the projections of prices for this biofuel in the next years. It is important to acknowledge that in recent years there has been significant volatility in prices and exchange rates making the task of analyzing costs and prices more difficult. However, for purposes of general conclusions, the results presented below are sufficient.

The low cost of sugarcane bioethanol production in Brazil is a well-known fact. Several sources estimate that costs are between US$ 0.25/liter and US$ 0.30/liter (including all inputs and factors), which corresponds to an oil price of between US$ 36/barrel and US$ 43/barrel. This estimate assumes gasoline prices are 10% higher than crude oil prices in terms of volume and that substitution with anhydrous bioethanol is done on a one-to-one volume basis (a consistent assumption, especially when bioethanol blends such as E10 are assumed). Under such conditions, substitution of gasoline with bioethanol is patently viable, but a more complete confirmation of the advantage of this biofuel can be seen by comparing plant prices prior to taxation.

Graph 30 shows how prices paid to sugarcane bioethanol and gasoline producers have evolved (excluding freight and taxation), referring, respectively, to the price of anhydrous bioethanol in the State of São Paulo (data from *Centro de Estudos Avançados em Economia Aplicada* – CEPEA (Center for Advanced Studies in Applied Economics), part of the *Escola Superior de Agricultura Luiz de Queiroz*, (Luiz Queiroz School of Agriculture at São Paulo University), and US Gulf Coast Conventional Gasoline Regular Spot Price FOB data from US Energy Information Administration (EIA, 2008). CEPEA regularly monitors anhydrous and hydrated bioethanol prices in four Brazilian states (São Paulo, Alagoas, Pernambuco and Mato Grosso), constituting one of the most reliable information sources in this market.

***Graph 30* – Evolution of prices paid to producer, not including taxes: US gasoline and Brazil sugarcane bioethanol**

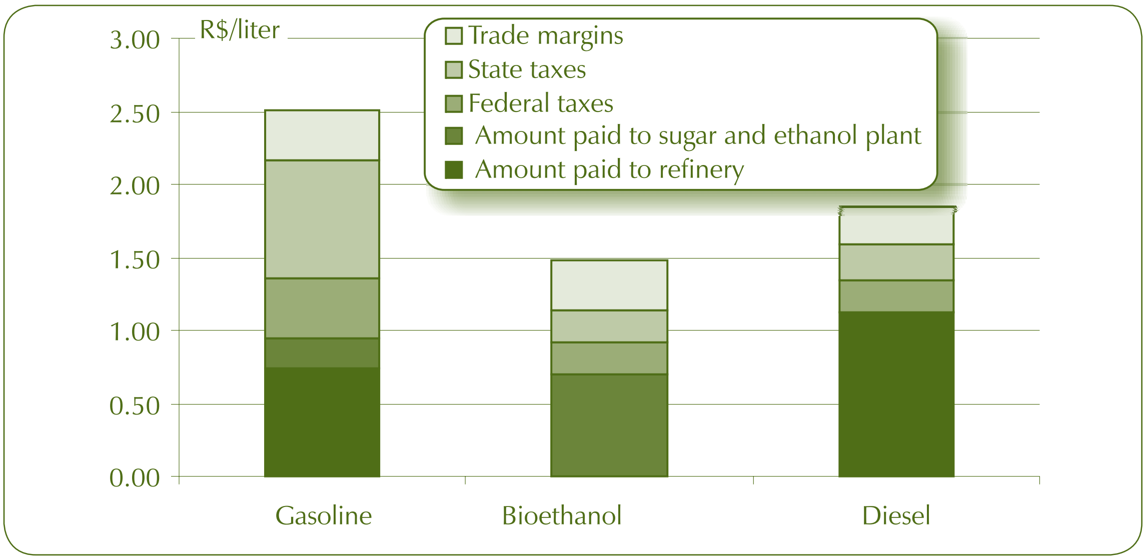


Source: Data from CEPEA (2008) and EIA (2008).

Although the adoption of the US dollar enables USA and Brazil prices to be compared, this should be done with caution taking into account the significant depreciation of the US dollar starting in 2005. The US dollar lost close to 30% of its value in two years leading to overestimate the value of Brazilian bioethanol. Regardless, these graphs show that in recent years, sugarcane bioethanol has brought consistently better prices than gasoline at the producer level, without including taxes or subsidies. In sum, under these conditions, the addition of anhydrous bioethanol leads to lower average market fuel prices.

In Brazil, federal and state taxes differentiate between different types of vehicle fuels, depending on the economic implications and typical applications of each; diesel oil and biofuels receive preferential treatment. Hence, higher taxes are levied on gasoline in comparison with hydrated bioethanol, natural gas, or diesel oil. Although there is a reasonable amount of variation in state tax rates (ICMS - Service and Goods Tax), the taxes, freight and sales margins that are levied on manufacturer prices for gasoline, hydrated bioethanol and diesel increase prices by 239%, 112% and 63%, respectively. These reference values reflect the situation in Rio de Janeiro, March 2008 and can be seen in Graph 31. Note that in the graph, the amount paid to the gasoline producer refers to a volume of 0.75 liter, since the product as delivered to the consumer contains 25% anhydrous ethanol.

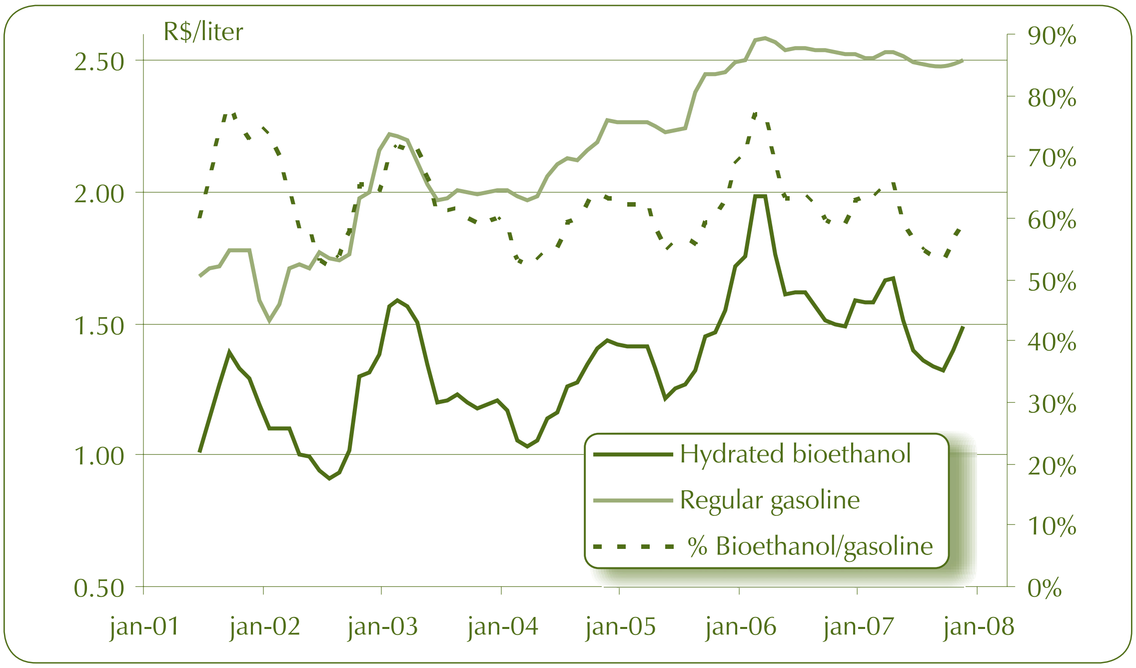
***Graph 31* – Price structure of regular gasoline, hydrated bioethanol and diesel oil (Rio de Janeiro, March 2008)**



Source: Values based figures from on ANP (2007), CEPEA (2008) and Petrobras (2008).

Another way to assess the relative attractiveness of bioethanol vis-à-vis conventional fuels is to compare the average consumer sale prices of hydrated bioethanol and regular gasoline. In this case, surveys of fuel prices can be used. These are made available on regular basis by the *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* – ANP (The National Agency for Petroleum, Natural Gas and Biofuels), using a broad sample covering the whole of Brazil [ANP (2007)]. Examining the series of prices, it can be seen that hydrated bioethanol is competitively priced with gasoline, in terms of cost per kilometer traveled. This is due to the lower manufacturer price, as well as the more favorable tariff structure (as noted in the previous paragraph). In the case of flexible fuel vehicles, where the user selects the fuel at the time the tank is filled, bioethanol is usually chosen when priced at up to 70% of the price of gasoline. In this respect, it can be seen that in the majority of recent years, choosing bioethanol over gasoline has made sense, except for some short periods lasting a few weeks as shown in Graph 32. The graph also shows a regular pattern of price variation, rising at the end of the harvest and falling at the beginning, around the middle of the first semester.

Graph 32 **– Evolution of average consumer prices for hydrated bioethanol and regular gasoline in Brazil and the relationship between them**



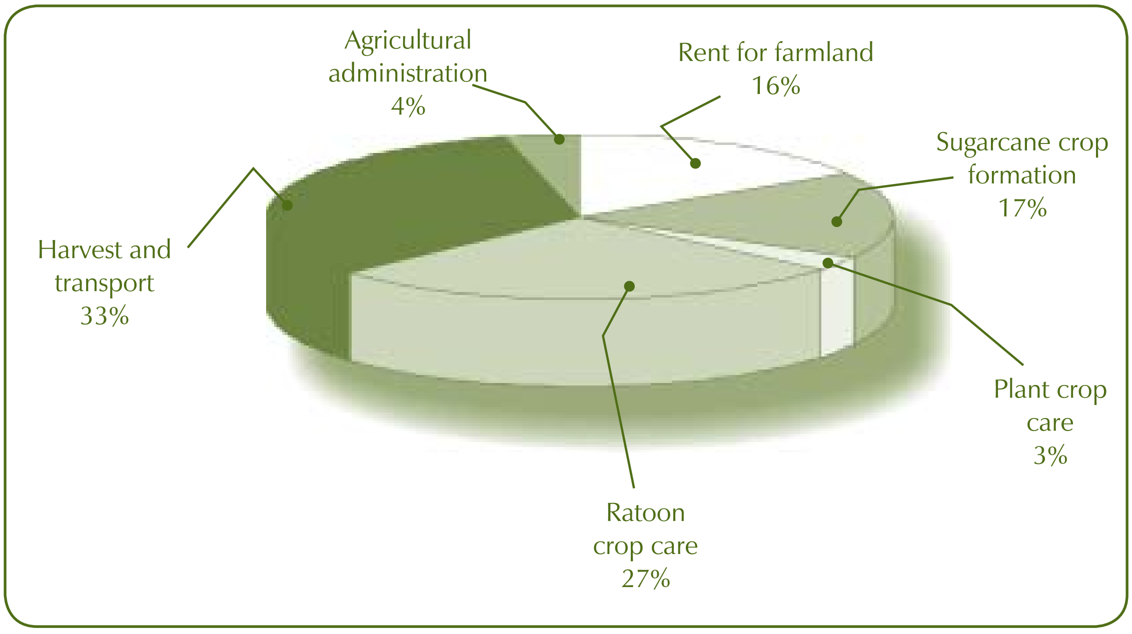
Source: Based on ANP (2007).

The previous data refer to prices as actually practiced in fuel markets, thus clearly demonstrating the competitiveness of bioethanol for consumers. It is equally interesting, however, to assess the production costs of this biofuel to see if producers are being adequately compensated. For many years, the Brazilian Federal Government audited sugar-and alcohol costs and set prices throughout the chain, from production to sale. However, as of the 1998 harvest, government controls of this agroindustry were eased, a process which finished in 2002, as described in Chapter 6. Currently, economic agents set prices independently, based on marketing strategies, and taking into account stocks and future prospects for the sugar and fuel markets. In this competitive environment estimating costs is often complex. Besides the variety of scenarios, with different yields and different technologies being used, bioethanol's main cost component is raw material: this may be produced by the processing company itself, on rented land, or grown by independent producers. The difficulty of knowing production costs is not just confined to the bioethanol market: detailed production costs for oil and natural gas are also seldom available.

In a study carried out by NIPE/Unicamp, an average sugarcane cost of R$ 33.16 per ton (ex-works) was estimated for the Central-South region in 2005. The breakdown is shown in Graph 33 [CGEE (2005)]. In this same study, a per-ton cost of R$ 24.59 in Goiás is estimated for sugarcane, mostly due to lower land costs.

The *Associação Rural dos Fornecedores e Plantadores de Cana da Média Sorocabana* – ASSOCANA (Média Sorocabana Rural Association of Sugarcane Producers and Suppliers) has made a more recent assessment of sugarcane production costs, assuming a cycle of five cuts in six years and including plantation implementation activities, soil preparation, planting, harvest and transport, and taking into account all production factors (ie, inputs, equipment, land, labor) [ASSOCANA (2008)]. For April 2008, this study estimated an average cost of R$ 2,513.50 per hectare, for each cut, resulting in an average sugarcane cost of R$ 35.00 per-ton. Assuming a raw material cost of between R$ 26.00 and R$ 35.00, an exchange rate of R$ 2.00 = US$ 1.00 and an industrial yield of 85 liters of bioethanol per processed sugarcane ton, the raw material share of the cost of bioethanol equals US$ 0.153 to US$ 0.206 per liter. These values seem to represent the current average costs of the Brazilian Central-South region and are substantially higher than the US$ 0.12 per liter often cited as the raw material share of the cost of bioethanol at the end of the 1990s. Note that this price has been greatly affected in recent years by increased costs, including equipment, fertilizers and agrochemicals. From the perspective of the alternative applications for this raw material, the per-ton cost of sugarcane will naturally depends on the price of sugar, which rose to US$ 0.27 per liter of bioethanol equivalent in the middle of last year.

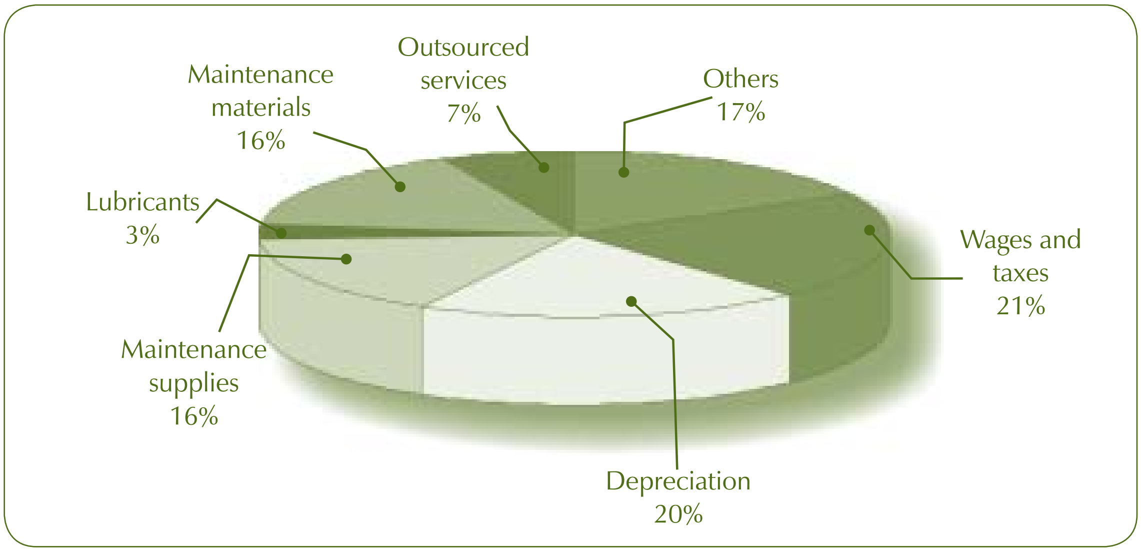
Graph 33 **– Structure of sugarcane production costs in Brazil's Center-South in 2005**



Source: CGEE (2005).

Costs related to the plant investment, to the operation and maintenance of the sugarcane processing unit and the production of bioethanol have also increased considerably in recent years, in particular because of increases in the prices of equipment and materials. The study developed by NIPE/Unicamp estimated that a plant with an annual processing capacity of two million tons of sugarcane could cost around US$ 97 million (corresponding to capital costs of US$ 0.13 per liter estimated at an internal rate of return of 12%, a ratio debt/capital of 50%, with an 8% interest rate and production of 40 kWh of surplus electrical power per ton of processed sugarcane marketed at US$ 57 per MWh. For this unit, operation and maintenance costs (including depreciation) were estimated at US$ 0.07 per liter of bioethanol produced, with the breakdown shown in Graph 34 [CGEE (2005) and Almeida et al. (2007)].

***Graph 34* – Breakdown of operation and maintenance costs for an independent sugarcane bioethanol production distillery in the Central-South in 2005**



Source: CGEE (2005).

Therefore, considering all the factors – inputs, operation, maintenance and investments – the cost of sugarcane bioethanol is somewhere between US$ 0.353 and US$ 0.406 per liter, amounts which correspond to oil at US$ 50 to US$ 57 per equivalent barrel.

It is likely that bioethanol costs are lower for plants being established in new production frontiers, bearing in mind the location of these plants, which have greater sugarcane crop density (lower transport costs) and the fact that they are dedicated to biofuel production, which reduces input costs and investments. On the other hand, the older and fully amortized plants of bioethanol should have lower financial costs, the same way that higher levels of electrical power production based on bagasse tend to improve the indicators of this agroindustry. Another important exception refers to the impact of the adopted exchange rate, because the sharp appreciation of Brazilian currency in recent years has considerably increased the value of sugar-alcohol agroindustrial products in terms of foreign exchange.

Considering the possibilities of continuity in the incremental process of agricultural and industrial productivity previously presented, it is reasonable to expect that the costs of sugarcane bioethanol production will remain stable or somewhat lower in relative terms, while the expected scenarios of fossil fuels maintain high price levels with no prospects of a decline to the price levels of a few decades ago [IEA (2007)]. Therefore, from an economic point of view, the production of sugarcane bioethanol appears to be sustainable, with essentially viable prices and costs, without the need for subsidies to compete with conventional fuels.

7.4 Job and income generation in the bioethanol agroindustry

The important relationship between the production of sugarcane bioethanol and the demand for labor is a central bioenergy topic in Brazil and certainly a determinant for its social viability. The sugarcane agroindustry is a major job generator: based on the *Relação Anual de Informações Sociais* - RAIS (Social Information Annual Report), from the Ministry of Labor and Employment and the *Pesquisa Nacional por Amostragem de Domicílios* - PNAD (National Household Survey), carried out periodically by IBGE, it is estimated that in 2005 there were 982 thousand workers directly and formally engaged in sugar-alcohol production [Moraes (2005)]. According to a 1997 study based on the Input-Output Matrix of the Brazilian economy, there are 1.43 indirect jobs and 2.75 induced jobs for each direct employee in this sector [Guilhoto (2001)].This allows an estimate for 2005 of a total of 4.1 million working people dependent on the sugarcane agroindustry, if these relationships have been maintained. These jobs are widely distributed throughout a large part of the Brazilian territory and include a range of competencies and training; however, most of them are low qualification jobs.

With the evolution of the technologies employed, less growth can be observed in labor demand, along with higher required qualifications and an increase in quality of the work performed. This dynamic has been the driving force for many studies in the realm of rural economics and sociology, which provide a comprehensive view of the processes in progress and their implications. In the next paragraphs, issues related to the generation of jobs and income within the scope of bioethanol production will be covered. First, information about the levels of employment and their recent evolution will be reviewed and then their perspectives discussed, especially those associated with the expansion of mechanization in sugarcane harvesting.

From the total number of direct and formal jobs in the sugar-alcohol agroindustry (which has expanded significantly in recent years, as Table 33 shows) 63% are in the Center-South, where more than 85% of Brazilian sugarcane is produced. This is evidence of higher labor productivity in this region. On the other hand, the number of workers per production unit in the Northeast is three to four times greater than the numbers observed in the Center-South region [Macedo (2005a)]. Indeed, relating all the sugarcane production data [Mapa (2007)] to the number of employees in the sector [Moraes (2007)] reveals the productivity per worker indicated in Graph 35. According to this graph, the significant gain in productivity in agro-industry in the Center-South region is evident, with levels of over 500 tons of sugarcane per worker; however, no change in the numbers for the Northeast is observed.

Table 33 **– Direct formal jobs per activity and region in the sugar-alcohol sector**

Activity	Region	Year			
		2000	2002	2004	2005
Sugarcane production	North Northeast	81,191	86,329	104,820	100,494
	Central-South	275,795	281,291	283,820	314,174
	Brazil	356,986	367,620	388,121	414,668
Sugar production	North Northeast	143,303	174,934	211,864	232,120
	Central-South	74,421	126,939	193,626	207,453
	Brazil	217,724	301,873	405,490	439,573
Bioethanol production	North Northeast	25,730	28,244	26,342	31,829
	Central-South	42,408	66,856	80,815	96,534
	Brazil	68,138	95,100	107,157	128,363
All	Brazil	642,848	764,593	900,768	982,604

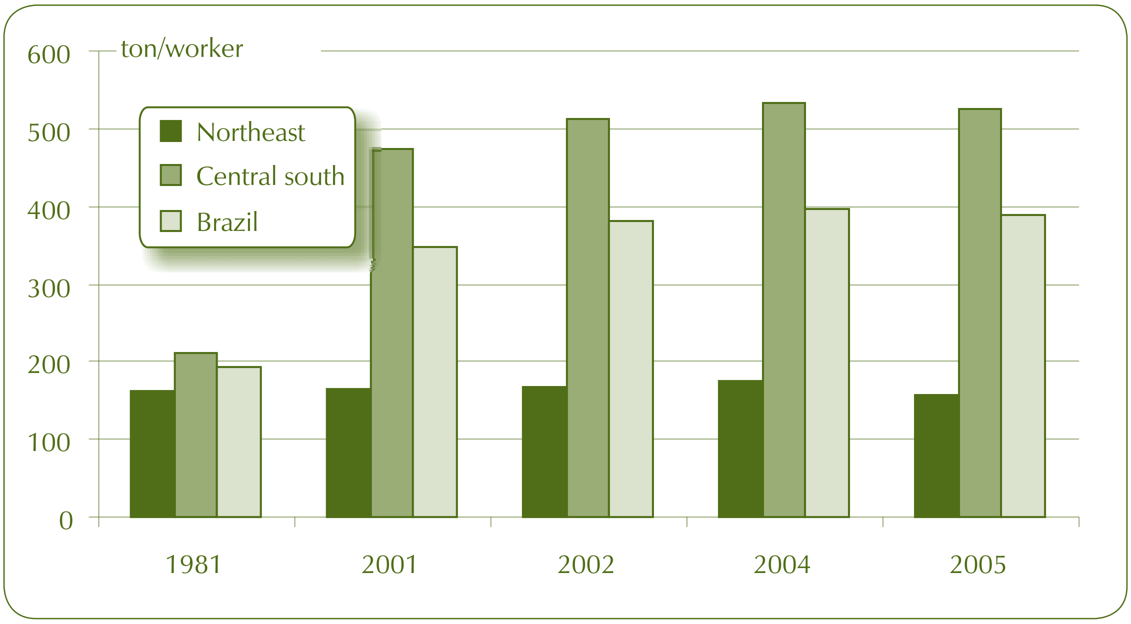
Source: Moraes (2005).

Sugarcane planting, pest control and harvesting in particular represent the greatest demand for temporary personnel in a sugar and bioethanol plant, corresponding to approximately 70% of hired labor, with different levels of employment for harvest and non-harvest periods. For a modern agroindustrial unit, which processes two million tons of sugarcane annually, nearly 2,500 workers are needed, a number that can vary considerably depending on the technological and mechanization levels of the plant [Macedo (2005a)]. In the study carried out by NIPE/Unicamp on groups of 15 bioethanol production plants with a milling capacity of two million tons of sugarcane each, a total generation of 22 thousand jobs was estimated. [CGEE (2005)].

The relationship between levels of employment at harvest and non-harvest time is called the seasonal factor and makes it possible to determine how variable personnel demand is throughout the year. The seasonality of jobs in the sugarcane agroindustry has been decreasing as a consequence of extending harvests and higher levels of mechanization. The numbers in São Paulo dropped from 2.2 in 1980 to 1.8 at the end of the 1980s, and fell to 1.3 in the mid 1990s [Macedo (2005a)]. For reference, the seasonal factor of rice is 7, beans between

3 and 4.5, oranges 7.8, soybean between 3.5 and 12 and cotton is as high as 40, evidence that employment associated with these crops over time is much more seasonal than that of sugarcane [Leite (1990)].

***Graph 35* – Average productivity of sugarcane agroindustry workers in Brazil**



Source: Moraes (2005).

In addition to the number of jobs offered, the quality of these jobs is equally important. In this regard, it is interesting to review the work of Balsadi (2007) on the evolution of job quality in Brazilian agriculture between 2001 and 2004 for main crops and different types of job relationships. Based on detailed PNAD data, the educational level of employees, degree of job formality, income received for the main job and benefits received by employees were adopted as variables to define quantitative indices and establish an objective evaluation of job quality. The conclusions of the study indicate significant improvements in various socio-economic indicators for sugarcane farming workers in Brazil in recent years:

– an increase in job formality, with a high percentage of workers with labor ID cards (allowing access to retirement benefits and other rights, such as paid overtime and medical care), which makes sugarcane production one of the activities with the highest level of job formality in the rural environment;

– real gains in salary between 1992 and 2005, 34.5% for permanent employees with urban residence, 17.6% for permanent rural employees and 47.6% for temporary rural employees;

– increase and diversification of benefits received by workers, such as transportation and meal vouchers in all categories as well as housing benefits for rural residents and health benefits for permanent employees with urban residence.

Other positive facts pointed out in the study are the significant reduction in child labor (only 0.9% in 2004, compared with Pernambuco, 1993, when 25% of sugarcane cutters were between the ages of 7 and 17) and the increase in employees' schooling. Other researchers have revealed similar conclusions, strengthening the role of worker organizations, collective labor agreements and labor legislation as important components in achieving these improvements, especially in the Center-South region where the average schooling level of workers in sugarcane production and the bioethanol industry, in 2005, was over five and nine years, respectively. For the same conditions, in 2005 the average salaries were US$ 280.00 and US$ 509.00, respectively, for sugarcane and bioethanol production [Moraes (2007)].

In spite of the improvements achieved, there are still adverse situations, especially for temporary employees hired for manual sugarcane harvesting, where working conditions are much more arduous than in industry and payment is based on the amount of sugarcane cut. This system has been questioned because it causes extreme wear and tear on the sugarcane cutters [Alves (2006)]. Nonetheless, this is a controversial issue. There is no consensus about putting an end to piecework among the unions and there is a portion of workers in favor of keeping it. As a representative of the plants, Unica has been opposed to ending this method of compensation, although it stresses that it is seeking, along with the plants, to guarantee full compliance with current norms and is aiming for fair payment to the cutters as set forth in collective labor agreements [Moraes (2007)].

In this context of greater valorization of workers, the sugarcane agroindustry is undergoing an important transition. This transition is a consequence of the gains in agroindustrial productivity associated with mechanical, physicochemical and biological innovations, which make it possible to expand production by maintaining the demand for inputs and resources. Among these innovations, the growing mechanization of harvesting stands out, arising from the need to progressively eliminate straw burning during the coming years and reduce harvesting costs, among other issues. It is estimated that for the 2006/2007 crop, mechanized harvesting covered 40% of sugarcane crops in the Center-South, in a growing trend where more than 400 harvesting machines are sold every year, each of them doing the work of 80 to 100 sugarcane cutters [CGEE (2007)]. Sooner or later, this sugarcane production model will be replicated in other Brazilian regions, with obvious impact on employment levels. In the period from 2000-2005 the number of jobs grew 18%, vs. an increase of 28.8% in sugarcane production. It is estimated that by 2020 the manual cutting of sugarcane in São Paulo will be practically non-existent. It is also anticipated that between 2006 and 2020, the number of employees in the sugarcane agroindustry in that state will be reduced from 260 thousand to 146 thousand workers, even with an increase of 20 thousand employees in manufacturing [Moraes (2007)].

To face these new times, two lines of action directly related to the workers can be undertaken: first, offering and supporting alternative economic activities for potentially unemployed workers in their places of origin; and second, strengthening the preparation of human workers for the agroindustry. These are not trivial tasks: they must be treated as a priority. The raising of training requirements of personnel by the Brazilian plants in all their areas and on the various levels of responsibility has already motivated a great effort to meet this growing demand for specialized labor, especially through high school and college level courses focusing specifically on sugarcane and bioethanol production. A third possibility would be to adopt intermediary technologies such as the *Unidade Móvel de Auxílio à Colheita* - UNIMAC (Harvest Assistance Mobile Unit), which substitutes labor only partially, offering more security and comfort to workers in cutting raw sugarcane and in straw retrieval [Alves F. (2007)].

It is worth noting here that even with significant reductions in the demand for labor, sugarcane bioethanol production will continue to be labor intensive. Under current conditions, the production of bioethanol per unit of energy produced, compared with mineral carbon, hydroelectricity and oil, requires, respectively, 38, 50 and 152 times more human labor [Goldemberg (2002)]. As an interesting variation on the same theme, Leal (2005) shows that while each vehicle fueled with petroleum products requires one person-year of work to meet its consumption, the introduction of 24% bioethanol as a gasoline additive increases the demand for personnel to six person-year. If pure hydrated bioethanol is used, this same vehicle will need 22 workers to produce its biofuel.

The creation of job opportunities and the possibility of their distribution among workers with value added in the production chain are two of the most important characteristics of bioenergy, and in particular of sugarcane bioethanol, constituting a significant difference between this energy technology and similar technologies. Even with the adoption of technologies with high productivity and less impact on the demand for labor, bioethanol production continues to be a major generator of jobs of increasingly better quality and with a corresponding rise in qualification requirements and average remuneration. Additionally, it is important to recognize the important role of the agroindustrial activity as a generator of income and a stimulus to local and regional economic activities, with significant indirect benefits. In no way should exhausting and low-productivity activities be considered as inherent to bioenergy. The progressive reduction of manual sugarcane harvesting should be viewed as a desirable advance leading to greater sustainability in this agroindustry.

Sugarcane ethanol and the issue of land property

One issue correlated with the role of bioethanol in generating jobs and income in the rural milieu is the concentration of property associated with the expansion of production. Generally speaking, this topic has possibly become a part of one of the major challenges to the harmonious development of the Brazilian economy: making social demands compatible through access to land with the implementation of an efficient and competitive productive base in the rural milieu. In the case of the sugar-alcohol industry this question is all the more significant, because of the extent of occupied areas and because of the level of existing vertical integration, in spite of the existence of thousands of sugarcane suppliers and tenants. Indeed, sugarcane and bioethanol production show significant economies of scale, which increase with the progressive adoption of technologies of greater productivity and the corresponding dilution of fixed costs per greater product volume. Under these conditions, in the larger capacity units, a sharp cost reduction can be observed, justifying the gradual concentration of properties within the scope of agrarian legislation.

This trend is aggravated because of the low attractiveness of a large number of farming activities and the economic deprivation of some regions where sugarcane cultivation becomes one of the few viable alternatives, compared with traditional crops. As with other issues mentioned previously, it is incumbent on the state to stimulate not only bioenergy production, but also the production of other agricultural goods in order to preserve economic efficiency and small rural entrepreneurs. There does not seem to be an inescapable conflict here, especially considering the wide availability of lands and the perspectives of the agricultural markets, including innovative cultivation and breeding alternatives that allow more value added per product unit than bioenergy production.

Nevertheless, in order to preserve small scale agriculture and its agricultural production model it has been suggested that biofuel production be stimulated in a decentralized manner with scales that allow for the entry of the small-scale farmer as biofuel producers, associated with the implementation of agroecological practices and the eventual reduction of displacement between production areas and consumer centers. The viability of these possibilities has not yet been demonstrated, since they assume productive models that are quite different from those currently practiced. Given the reduced experience with micro and mini bioethanol distilleries (which produce one thousand and five thousand liters per day, respectively), their promotion requires an innovative vision of sugarcane-based bioethanol production technologies. To this end, an important point is the need to link bioethanol production with other agricultural and livestock raising activities that allow to compensate for the low productivity inherent to these units, characterized by simplified extraction, fermentation and distillation systems that produce 40 liters of bioethanol per ton of processed sugarcane, around half the amount observed in larger plants [Horta Nogueira (2006b)]. One possibility to be explored to improve this scenario would be to associate bioethanol production with cattle raising, which could make use of the bagasse from the harvest as forage. In any case, as efficient systems go, sugarcane bioethanol production has been proven more adequate, thus far, on an industrial scale. Possibly, production cooperatives associated with conventional plants are a more stable alternative than the small production units.

Also, concerning economic concentration and its implications, it should be noted that the bioethanol industry, as practiced in Brazil, could be considered relatively concentrative compared with some other agricultural activities. However, when compared with energy related activities (as it is classified), it is characterized as a highly decentralized industry with thousands of suppliers and the most important industrial groups not managing to control 10% of total production capacity. Indeed, decentralization is an inherent characteristic of bioenergy, which needs large spaces to capture solar energy.

Induced effects in other sectors of the economy

The extensive connection of the bioethanol agroindustry with other economic sectors and the upstream and downstream linkages of sugarcane production and processing, allow a distribution of the benefits generated in this sector in a very interesting way. A survey for this end, using an extended model of input-output matrices, shows how the entire national economy tends to expand with the growth of bioethanol production [CGEE (2005)]. Besides the sugarcane and ethanol production sectors and computing indirect and induced effects, the sectors more impacted are other farming activities, the chemical sector (including fertilizer), and the petroleum refining, commerce, logistics and real estate rental sectors.

Table 34 **– Direct, indirect and induced impacts of processing one million tons of sugarcane for alcohol production**

Sector	Production value (R$ million)	Value added (R$ million)	Employment
Sugarcane	44.5	20.8	1,467
Farming: other	14.3	8.1	697
Sugar	8.0	2.7	31
Alcohol	97.8	38.9	211
Electricity	6.8	7.3	37
Mineral extraction	0.3	0.2	4
Steelwork, mining and metallurgy	7.1	2.1	48
Machines, vehicles and parts	9.3	4.2	51
Oil and Gas	29.5	12.1	12
Chemical sector	13.9	4.7	41
Food	15.4	3.1	93
Civil construction	1.3	0.8	23
Transformation: other	16.8	5.7	287
Trade and Services	81.3	53.0	2,679
Families	–	7.3	–
Total	346.3	171.0	5,683

Source: Scaramucci and Cunha (2008).

Using an adjusted matrix for 2002 and assuming the results obtained are typical, it has been estimated in this study that, for each million cubic meters of bioethanol production capacity installed, R$ 119 million per year would be added because of investments. During the operation, nearly R$ 1.46 billion should also be generated annually, computing direct, indirect and induced effects [CGEE (2005)]. In an extension of this study, for conditions observed in the Brazilian Center-South, it was estimated that the processing of a million tons of sugarcane for the production of bioethanol corresponds to an increase of R$ 171 million in economic production and the generation of 5,683 jobs, considering analogically the direct, indirect and induced effects, separated as shown in Table 34.

7.5 Certification and sustainability in the bioethanol agroindustry

Certification systems have been proposed as one of the ways for ensuring observance of sustainability criteria in bioethanol and biodiesel production, mainly by industrialized countries, to ensure explicitly that biofuels are produced in a sustainable manner and consequently may be used to meet environmental goals.

The establishment of widely accepted sustainability criteria and standards must face the inherent complexity of bioenergy systems with their range of raw materials and production technologies and contexts as a basic difficulty. It should also be noted that the certification systems for biofuels, on a voluntary or mandatory basis, do not yet have an international legal framework for their support. Nevertheless these systems could be used within the scope of climate change mitigation commitments, biodiversity protection and trade agreements.

Certification is typically a requirement that consumers impose upon producers. Thus, the concept of certification demands an objective and careful treatment of the aspects of sustainability, and their implementation necessarily implies the existence of independent monitoring agents who ensure the required balance and impartiality. A risk that should not be ruled out is that poorly designed certification systems could serve as additional trade barriers and act as protectionist measures, restricting the development of truly sustainable alternatives in favor of inefficient bioenergies. Another concern, regarding producers, is the cost of certification systems, which could make small-scale production unviable.

The main efforts currently in progress for evaluating and eventually certifying the sustainability of biofuels include the following initiatives (GBEP, 2007):

- In January 2007, the European Commission established as a goal (non-mandatory) the introduction of 10% biofuel (ethanol and biodiesel) in fuels used for transportation in each member country by 2020, with an assessment system of sustainability, currently in development, being adopted.

– Associated with the requirement of 5% renewable fuel in all automotive fuel sold in the United Kingdom in 2010, as defined in the Renewable Transport Fuel Obligation (RTFO), biofuel producers must report the balance of greenhouse effect gases and the environmental impact of their products (House of Commons, 2008).

– In Holland, the development of bioenergy sustainability criteria began in 2006, with activities in progress to both test these criteria in pilot projects and define monitoring and certification systems. An extensive exercise of possible indicators has presented a favorable assessment of the bioethanol produced in Brazil, especially in the state of São Paulo [Smeets et al. (2006)].

– In Germany, legislation to support biofuels has been recently revised, including compulsory requirements to meet sustainability criteria, based on raw materials used, natural habitat protection and the reduction of greenhouse gas emissions.

– Within the scope of the United Nations Environment Programme (UNEP), there is a definition of sustainability criteria for biofuels under discussion, with suggestions that concrete goals and instruments be adopted for their implementation. To this end, UNEP has been working in close collaboration with governmental institutions, private entities and representatives of civil society, including the Global Bioenergy Partnership and the Roundtable on Sustainable Biofuels [UNEP (2008)].

– The Food and Agriculture Organization of the United Nations (FAO) is developing the Bioenergy and Food Security project to establish an analytical framework to evaluate impacts on food supply that could be attributed to the expansion of bioenergy production, taking into consideration systems based on food-related raw materials and the so-called second generation bioenergy systems [BFS/FAO (2008)].

– FAO and the United Nations Industrial Development Organization (UNIDO) are preparing a project for the Global Environment Facility – GEF to orient countries with respect to environmental and socioeconomic conditions for the sustainable production, conversion and use of biofuels.

– The Roundtable on Sustainable Biofuels – RSB, led by the Energy Center of the Federal Polytechnic School of Lausanne, in Switzerland, is an international initiative involving farmers, companies, non-governmental organizations, specialists, and international and government agencies interested in guaranteeing the sustainability of biofuel production and conversion. To this end, it has been holding a series of meetings, teleconferences and debates, seeking to arrive at a consensus concerning the principles and criteria for the production of sustainable biofuels. The principles considered for evaluating sustainability in the production of biofuels are available for analysis [Frie et al. (2006) and EPFL (2008)].

- The international work group IEA Task 40, within the scope of the International Energy Agency Bioenergy Agreement, develops activities focused on the international trade of biomass and bioenergy, especially their implications and perspectives. The group focuses in the development of certification, standardization and terminology systems to promote the international trade of bioenergy products on a sustainable basis, providing analysis and important information about efforts underway in this field [IEA Bioenergy (2008)].

- The governments of Brazil, the United States and the European Union (the main worldwide producers of biofuels and members of the International Biofuels Forum – IBF) published the "White Book of Specifications of Internationally Compatible Biofuels" in February 2008, with an analysis of current specifications conducted by an international group of specialists for the purpose of facilitating trade expansion of products. Initial efforts are to develop procedures, systems and reference materials for bioethanol and biodiesel quality tests, and even to make it possible, through analytical methods, to determine if a fuel comes from renewable sources [NIST (2008)].

The private sector in the fuel area, especially in Europe, considers sustainability an important factor in the development of bioenergy, and some companies are developing their own procedures to assure the acquisition of sustainable products. However, most companies interested in buying and selling sustainable biofuels are seeking to be involved in these processes with a more plural participation and to be seen as more legitimate by consumers. For example, BP, DuPont, Petrobras and other major companies participate in the Roundtable on Sustainable Biofuels (RSB). In the arena of other agricultural-related products, analogous systems for certifying aspects of sustainability have also been implemented, such as for wood, soy and palm oil.

As a final initiative to mention, which is aimed at ensuring standards of sustainability in bioethanol production, the Agro-Environmental Protocol, signed in 2006 by the São Paulo State Government, has implemented the Green Bioethanol Program to encourage best practices in the sugar-alcohol sector through compliance certification and to determine a positive standard to be followed by producers. In a phase of large-scale operation and application throughout the state, the instrument covers some of the main points for reducing the impacts of cultivation, such as the anticipation of deadlines for eliminating the burning of sugarcane straw, protection of springs and forest vestiges, control of erosion and adequate management of agrochemical packaging [Lucon (2008)].

Systems of sustainability certification having the characteristics described in this section, if adequately designed and well implemented, may serve as effective instruments for biofuel production to develop in a framework of rationality, since it has already been demonstrated that sugarcane bioethanol is competitive.

Chapter 8

Perspectives for a global biofuels market

Several countries have been interested in the development of bioethanol use and production. Until now the main driver has been the need to cover domestic energy needs, especially for liquid transportation fuels. However, there is also growing interested in creating a global biofuels market, which helps to bring together producer and importing countries, with advantages for both of them. Nowadays, such market is still incipient, but it is expanding because of the increasing demand for a renewable and environmentally friendly fuel. Sugarcane-based bioethanol is a biofuel that presents interesting perspectives for the development of such market, given that it can readily meet straightforward sustainability and energy criteria and that production can be competitive vis-à-vis gasoline, the equivalent fossil fuel. This Chapter analyses factors that are relevant for sugarcane bioethanol to become a global international product, taking into consideration its current and future supply and demand, as well as the policies and trends related to its production and trading.

Although the focus of the book is on sugarcane bioethanol, the general context of biofuel is also analyzed in this chapter, including information on other bioethanols and biodiesel. The first section presents estimates about the potential of bioenergy production, followed by data on the current (Section 8.2) and projected (Section 8.3) demand and supply for bioethanol, and a review of policies and strategies that have been proposed to support bioethanol production and use (Section 8.4). The last sections discuss trade-offs between food and biofuels production (Section 8.5), as well as some critical factors for the creation of a global bioethanol market (Section 8.6), which are related to environmental challenges and strengthening of international agricultural trade.

Based on a study carried out by the Global Bioenergy Partnership (GBEP, 2007), which will be quoted later in the chapter, the following definitions will be used: bioenergy is energy derived from biomass; a biofuel is an energy carrier derived from biomass; and liquid biofuels are liquid fuels derived from biomass, and include bioethanol, biodiesel, biodimethylether, raw vegetable oil, synthetic diesel and pyrolysis oil (biooil).

8.1 Overall potential for biofuels production

Several studies have been carried out to shed light on the main issues governing the future of biofuels, and bioethanol in particular. How much and where can they be made available? This question is not simple, since the potential of biofuel supply is not an absolute and static number, like in the case of a mineral reserve. In fact, it is a very dynamic figure dependant on changing geographic, economic and political scenarios, as well as on technologies of production and conversion that in many cases are still being developed.

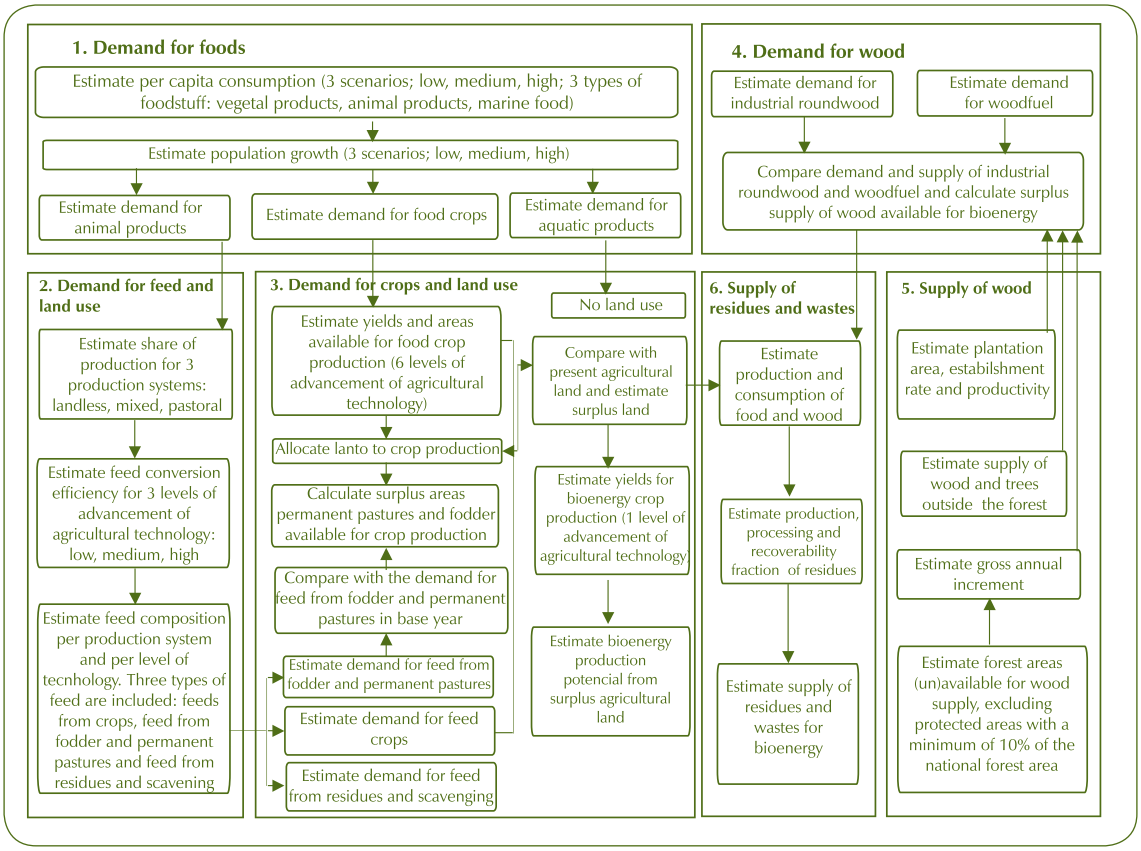
Additionally, the natural resources needed to grow energy crops, like soils and water, are necessarily limited and must be shared with the production of food and feed, industrial inputs (eg, textile fibbers, wood for cellulose and other purposes, hydro energy, etc.) and the protection of nature, among other uses. Such thematic complexity increases because of the relationship between biofuels and the food supply, which makes it relevant to know about the sustainable potential of production, conversion and use of biofuels vs. the concerns with food security.

In this context, establishing the limits and boundaries to biofuel production and, particularly, setting sustainability criteria become complex tasks. As we can see later in this Chapter, analytical and computational models have been developed to face such tasks. These models, which allow to model and simulate different types of impacts, are intended to evaluate policies and to support decision makers in the creation of bioenergy programmes. Figure 30 presents the wide range of issues to be considered in assessing bioenergy potential from energy crops, according to the model suggested by Smeets et al (2006), while also taking into account other agricultural and forestry demands.

Early studies of biomass availability [Berndes et al. (2003)] concluded that in 2050 the possible contribution of biomass to global energy supply could vary from 100 EJ/year to 400 EJ/year, which represents from 21% to 85% of the current total consumption of energy in the planet, estimated in 470 EJ. The interactions between the expanding bioenergy sector and other land uses, such as food and feed production, biodiversity protection, soil and nature preservation and carbon sequestration, were recently evaluated in some studies.

One of the most important works [Smeets et al. (2006)] uses a bottom-up approach to process information about land use, agricultural management systems, estimates of food demand and information concerning possible improvements in agricultural management (both for crops and production of meet and dairy products). Recent studies group the biomass used to produce energy in three categories: energy crops on current agricultural lands; biomass production on marginal lands; and residues from agriculture and forestry waste, manure and other organic wastes [Junginger et al. (2007)]. Based on the approach presented in Figure 30, it is estimated that these categories could supply 200 EJ, 100 EJ and 100 EJ, respectively, corresponding to the higher limit of 400EJ previously presented.

***Figure 30* – Overview of the key elements in the methodology to assess the bioenergy potential from dedicated bioenergy crops**

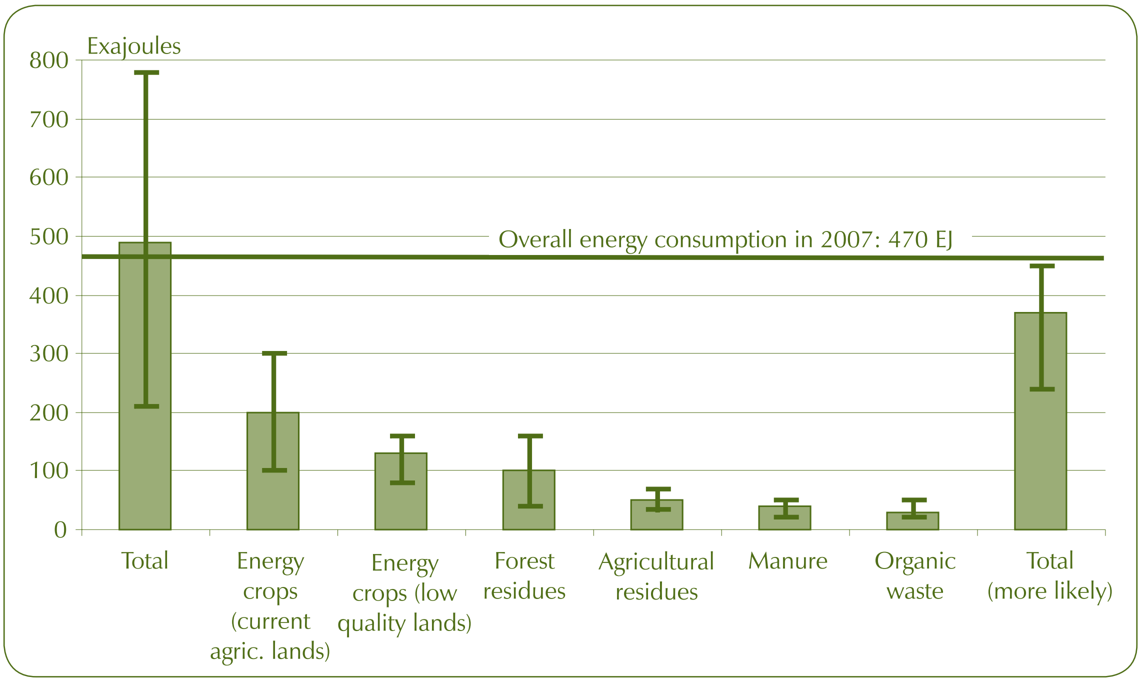


Source: Smeets et al. (2006)

It is difficult to arrive at a single figure representing the overall energy potential from biomass, as it is determined by several factors. Such difficulty is illustrated by Graph 36, which provides an idea of the ranges of biomass supply for energy purposes resulting from various approaches and methods. The estimates vary from 205 EJ to 790 EJ, that is, between 43.6% and 168.1% of the overall energy demand estimated for 2007, also shown in the figure. The main reason for such variations, between upper and lower limits, is the high uncertainty vis-à-vis land availability and productivity levels, the two most critical parameters considered in the estimation. In addition, there are significant variations among studies regarding expectations of future biomass supply from forest wood and from agricultural and forestry residues.

Table 35 presents an assessment of possible variations in the technical potential of biofuels, under four hypothetical agricultural production systems. The estimates consider energy crops and agricultural and forestry residuals, but exclude suet and other fat by-products with bioenergy potential. Food demand data was obtained from the national Food Balance Sheets (FBS) published by FAOSTAT, an FAO (Food and Agriculture Organization of the United Nations) global information system on food and agriculture [FAO in Bruinsma (2003)]. In addition, no food shortages are allowed to occur in all scenarios.

***Graph 36* – Bioenergy potential per biomass type**



Source: Juergens (2007).

Systems 1 to 3 assume medium global population growth between 1998 and 2050 (between 5.9 billion and 8.8 billion people), as well as medium food consumption per capita growth (between 2.8 Mcal to 3.2 Mcal person/day). In the production side they assumed that during the same period a high plantation scenario has been established (from 123 million to 284 million hectares) and that a high technological level for the production of bioenergy crops has been reached. System 4 presumes that advances in research and development permit a 25% increase in yields above system 3. The agricultural production system determines the amount of food crops and feed crops produced, and consequently also the volume of harvest residues generated. System 3 is based on a landless animal production system in which all feed comes from crops and residues. Systems 1 and 2 are based on a mixed production system, in which a significant part of the feed comes from grazing. The production of harvest residues from food and feed crop production is consequently the highest in system 3. Small differences in residue production between systems 1 and 2 are caused by differences in the allocation of crop production. The production system also determines the level of advancement of agricultural technology and therefore influences the crop harvest residue generation fraction.

***Table 35* – Total technical bioenergy production potential in 2050, by regions and production system**
(EJ per year)

Region	Agricultural production system			
	1	2	3	4
Latin America and Caribbean	89	162	234	281
North America	39	75	168	204
Sub-Saharan Africa	49	117	282	347
North Africa and Middle East	2	2	31	39
Western Europe	13	19	25	30
Eastern Europe	5	13	24	29
Commonwealth of Independent States (CIS) and Baltic States	83	111	223	269
India and South Asia	23	26	31	37
East Asia	22	28	158	194
Japan	2	2	2	2
Oceania	40	55	93	114
Total	367	610	1,273	1,548

Source: Smeets et al. (2006).

The study found that the largest potential for energy crop production is located in Sub-Saharan Africa and Latin America and the Caribbean, with 317 EJ and 281 EJ in scenario 4, respectively. Both regions have large areas that are agro-ecologically suitable for crop production and for sugar cane in particular, and that are not being used presently. East Asia also has a considerable potential for energy crop production, 147 EJ in scenario 4. The Commonwealth of Independent States and Baltic States, North America and Oceania present the most significant potentials among the development countries. Land stressed regions such as Japan, South Asia, North Africa and Middle East have zero or a very limited potential. Highly relevant to the Latin American case is the attention the model gives to the impact of animal production on biofuels development since these products are far more land intensive per kg of product than crop production [FAO in Bruinsma (2003)].

The results are quite optimistic regarding the impacts of bioenergy on food production. An important conclusion is that the technical potential to increase the efficiency of food production is sufficiently large to compensate for the increase in food consumption projected between 1998 and 2050. The total global bioenergy potential in 2050 is estimated to be 78% (367 EJ), 129% (610 EJ), 270% (1273 EJ) and 329% (1548) of the energy demand in 2005, for systems 1 to 4, respectively. The bulk of this potential comes from specialized energy crops grown on surplus agricultural land that would not longer be needed for food production. It is worth noting that variation in surplus agricultural land among the agricultural production systems is mainly dependent on the efficiency with which animal feeds are produced. Residues and wastes account for 76 EJ to 96 EJ per year of the technical potentials. The authors cite other estimates published in the scientific literature [Hoogwijk et al. (2003) and Wolf et al. (2003)], which seem to confirm the results they obtain.

Pre-requirements to achieving the above levels of the energy crops production are the introduction of advanced agricultural production systems, an increased use of inputs such as fertilizers and agrochemicals and, in particular, and optimization of crop production yields. It is noted that as a result of those improvements, between 15% and 72% of the agricultural area in use could be made available for energy crop production, in systems 1 and 4, respectively.

Table 36 presents similar data on the overall bioenergy production potential from various biomass feedstocks, indicating the general conditions to reach the production levels estimated. In some cases two potential ranges are provided for each biomass category: a) average potential under normal conditions with projected technological progress; and b) average potential in a world aiming for large-scale utilization of bioenergy. A lower limit equal to zero means that the available potential may be zero or negative, which will be the case if agriculture is not modernized so that more land is needed to feed the world [Faiij and Domac, 2006].

In the case of biomaterials the bioenergy potential could be even negative, since the biomass demand to produce bioplastics or construction materials can reduce the biomass availability for energy production. However, the more biomaterials are used the more by-products and organic waste will become available to be used in the energy production. The biomass use will result in a "double" benefit regarding greenhouse gases, avoiding the emission that would have occurred if the materials had been produced using fossil fuels and producing energy from the waste. The energy supply from biomaterials that become waste may vary between 20 EJ to 50 EJ, estimate that does not include the cascade effect (successive uses) and does not consider the time elapsing between production of the material and the release as organic waste [Faiij and Domac, 2006].

In relation to land use and its impact on the availability of lands for agriculture, a report of the International Energy Agency [IEA Bioenergy (2007)] points out that it is realistic to expect a considerable increase in the bioenergy contribution, from the current estimate of 40 - 55 EJ per year to an annual supply of 200 - 400 EJ by 2050. Based on generally accepted data, this report indicates that one third of this energy could be supplied by residues and wastes; one-fourth by the regeneration of degraded or marginal lands; and the remaining by current agricultural lands and pastures. Hence, almost one billion hectares in the world could be used in the production of energy-related biomass, including 400 million hectares of current agricultural lands and pastures, as well as a larger area of degraded and agricultural lands, which account for around 7% of the land surface and less than 20% of the land currently used in agricultural production.

Table 36 – **Potential of several feedstock and production systems for bioenergy**

Context of bioenergy production	Main hypothesis and observations	Potential of bioenergy supply until 2050 (EJ/year)	
		Normal scenario	Optimist scenario
I. Energy farming on current agricultural land	Potential land surplus: 0-4 Gha (more average: 1-2 Gha). A large surplus requires structural adaptation of the agricultural production systems. When this is not feasible, the bio-energy potential could be reduced to zero as well. On average higher yields are likely because of better soil quality: 8-12 dry t/ha/yr is assumed. (Heating value: 19 GJ/t dry matter)	0 to 700	100 to 300
II. Biomass production on marginal lands	On a global scale a maximum land surface of 1.7 Gha could be involved. Low productivity of 2-5 dry t/ha/yr (Heating value: 19 GJ/t dry matter). The supply could be low or zero due to poor economics or competition with food production.	0 to 150	60 to 150
III. Bio-materials	Range of the land area required to meet the additional global demand for bio-materials: 0.2-0.8 Gha (average productivity: 5 dry t/ha/yr - Heating value: 19 GJ/t dry matter). This demand should be come from category I and II in case the world's forests are unable to meet the additional demand. If they are however, the claim on (agricultural) land could be zero.	0 to 150	40 to 150
IV. Residues from agriculture	Estimates from various studies. Potential depends on yield/ product ratios and the total agricultural land area as well as type of production system: extensive systems require re-use of residues for maintaining soil fertility. Intensive systems allow for higher utilisation rates of residues.	15 to 70	
V. Forest residues	The (sustainable) energy potential of the world's forests is unclear. Part is natural forest (reserves). Range is based on literature data. Low value: figure for sustainable forest management. High value: technical potential.	0 to 150	30 to 150
VI. Manure	Use of dried manure. Low estimate based on global current use. High estimate: technical potential. Utilisation (collection) on longer term uncertain.	0 to 55	5 to 55
VII. Organic wastes	Estimate on basis of literature values. Strongly dependent on economic development, consumption and the use of biomaterials. Figures include the organic fraction of MSW and waste wood. Higher values possible by more intensive use of biomaterials.	5 to 50	
Total	Most pessimistic scenario: no land available for energy farming; only utilisation of residues. Most optimistic scenario: intensive agriculture concentrated on the better quality soils.	40 to 1,100	250 to 500

Source: Faaij and Domac (2006).

Other reports [Best et al. (2008)] point out that of the 13.2 billion hectares of the world's total land area, 1.5 billion are used to produce agricultural crops and 3.5 billion are used in livestock production. Crops currently used specifically for biofuels, as a result of farmer's choice, use only 0.025 billion hectares. In Brazil, for example, more than 40% of total gasoline demand is supplied by the ethanol produced from sugarcane grown in 1% of the 320 million hectares of agricultural and pasture land and none in the Amazon Rainforest.

It is worth noting that crops used in energy production, in addition to biofuels also provide by-products, such as animal fodder, fertilizers and bioelectricity, in significant volumes. The previous chapter includes information about the diversity of sugarcane co-products that can be produced along with bioethanol, under current and expected future conditions.

In conclusion, it is possible to assert that — although methodologies and tools to assess in detail the global potential of biofuels are still under development and that biomass data is not available in many countries — there is a large and untapped global potential for biofuels. Some relevant preliminary conclusions can be stated: a) the potential bioenergy supply depends on food production patters, particularly concerning land requirements for animal production; b) some regions present a clear comparative advantage; and c) the total potential available is of the same magnitude as the overall energy demand, under optimist assumptions. The following section shows how that potential is being explored in the case of biofuels.

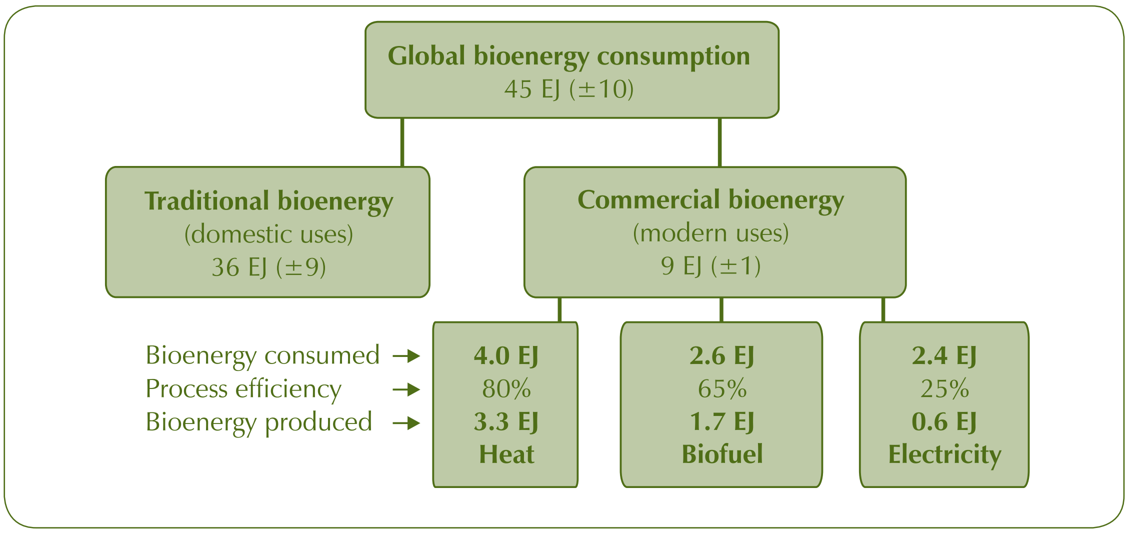
8.2 Biofuel supply and demand: current scenario

Biofuels can indeed play an important role in meeting the global energy demand. Most countries have some level of bioenergy resources potential, making biomass a more widespread energy supply option than any other source across the globe. In fact, biomass is the only renewable energy source that can be used to meet a wide range of energy applications, in the form of electric power, heat, gaseous and liquid fuels. This section presents data on the current contribution of bioenergy to the global energy matrix, considering the main markets and specific conditions of bioethanol supply.

Figure 31 exhibits the contribution of biomass to global primary and secondary energy supplies in 2007. Firewood and sugarcane bagasse must be highlighted as heat and electricity sources, while bioethanol and biodiesel are the main liquid biofuels. Also included are cogeneration systems, in which heat released in thermoelectric systems is used in some thermal process, with a sensible energy gain.

Liquid biofuels, mainly bioethanol produced from sugarcane and surpluses of corn and other cereals, and to a far lesser extent biodiesel from oilseed crops, represent a modest 1.7 EJ (about 1.5%) of transport fuel use worldwide. Global interest in transport biofuels is growing, particularly in Europe, Brazil, North America and Asia (notably Japan, China and India) [IEA (2005)]. Global ethanol production has more than doubled since 2000, while biodiesel production, starting from a much smaller base, has expanded threefold. In contrast, crude oil production has increased by only 7% since 2000 and, indeed, might be reaching its peak of production soon, according to several analysts. In fact, biofuels show a significant expansion when compared with the relative stagnation of oil production. In 2007, production of ethanol and biodiesel was 43% higher than in 2005. Ethanol production in 2007 represented about 4% of the 1.300 billion litres of gasoline consumed globally [REN21 (2008)].

Figure 31 **– Bioenergy contribution to the primary and secondary energy supply in 2007**



Source: Best et al. (2008).

It is interesting to note that in 2006 liquid biofuels accounted for just over 1% of global renewable energy and less than 1% of the global crude oil supply, estimated at 4,800 billion litres (approximately 83 million barrels per day). This scenario is changing very rapidly with most big energy-consuming countries adopting policies that will result in much higher biofuels use by the next decade [ESMAP (2005)]. Based on the origin of supply and raw materials used, today's liquid biofuels can be crudely classified into three main categories, namely, Brazilian ethanol from sugarcane, US bioethanol from corn and German biodiesel from rapeseed, followed by bioethanol form beet and wheat in Europe. Therefore, biofuel production is still concentrated in a few countries: in the last few years Brazil and the United States combined for about 90% of ethanol production, while Germany accounted for over 50% of global biodiesel production [Martinot (2008)].

A study carried out by Global Bioenergy Partnership [GBEP (2007)] shows the biofuels trends in the G8+5 countries, which include some of the most active countries in the bioenergy scene, either as producers, users, exporters or importers. Besides the G8 countries (Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States), the study included five emerging economies ("+5 countries"): South Africa, Brazil, China, India and Mexico. Out from the study, Table 37 shows the contribution of biofuels to Total Primary Energy Supply (TPES). TPES is equal to domestic energy production, plus imports, minus exports, minus international bunkers plus net stock change. China is the most important user of biomass as an energy source with 9,000 PJ per year, followed by India with 6,000 PJ, the United States with 2,300 PJ, Brazil with 2,000 PJ. Consumption trends show that the demand for biofuels is increasing at a quite high pace in Brazil, Germany, Italy and the United Kingdom while it remains stable in other countries like France, Japan, India and Mexico.

***Table 37* – Total primary energy supply from biofuels (In PJ)**

Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Canada	409	408	418	437	480	481	451	487	489	510	525
France	440	467	438	453	439	430	437	406	420	419	422
Germany	139	143	195	210	207	229	246	271	312	348	441
Italy	52	51	59	63	69	74	79	76	81	121	123
Japan	191	193	199	183	190	196	180	187	191	190	198
Russia	259	221	190	157	208	163	158	151	149	143	146
United Kingdom	52	54	57	55	56	61	64	70	82	96	115
United States	2,554	2,607	2,531	2,601	2,507	2,551	2,285	2,256	2,474	2,633	2,697
G8 Countries	**4,097**	**4,144**	**4,086**	**4,160**	**4,156**	**4,186**	**3,900**	**3,904**	**4,198**	**4,460**	**4,666**
Brazil	1,728	1,706	1,719	1,756	1,838	1,794	1,823	1,951	2,110	2,277	2,801
China	8,610	8,656	8,703	8,750	8,906	8,973	9,053	9,127	9,202	9,277	9,360
India	5,862	5,918	5,978	6,039	6,144	6,230	6,313	6,389	6,464	6,539	6,620
Mexico	328	329	338	343	337	333	337	333	336	337	348
South Africa	479	487	495	504	516	529	539	545	551	547	564
+5 Countries	**17,006**	**17,095**	**17,233**	**17,392**	**17,741**	**17,859**	**18,064**	**18,345**	**18,662**	**18,977**	**19,693**
G8+5 Countries	**21,103**	**21,239**	**21,319**	**21,552**	**21,897**	**22,045**	**21,964**	**22,249**	**22,860**	**23,437**	**24,359**

Source: GBEP (2007).

Table 38 presents the trends of the percentage of TPES covered by biofuels in the G8+5 countries over the last decade. These data is quite representative of other countries of Europe, Asia and Latin America. In most of African countries, as well as the poorest countries of other regions, data would be quite different since fuelwood and other traditional forms of biofuels would overwhelmingly cover demand data. Biofuels contribution to total energy demand reaches almost 30% in Brazil and India, but only 1% in the United Kingdom and Russia. In some developed countries, such as Canada, France, Germany and the United States such contribution varies from 3% to 4%, but reaches almost 20% in Sweden and Finland. The bioenergy share in India, China and Mexico is decreasing, probably because the increased use of kerosene and LPG (liquefied petroleum gas) by the household sector. On the contrary, the contribution of biofuels is increasing in the G8 countries, especially Germany, Italy and the United Kingdom, where it grew at an annual rate of 4% - 6% during the last few years.

Table 38 **– Relative participation of biofuels in total primary energy supply (In %)**

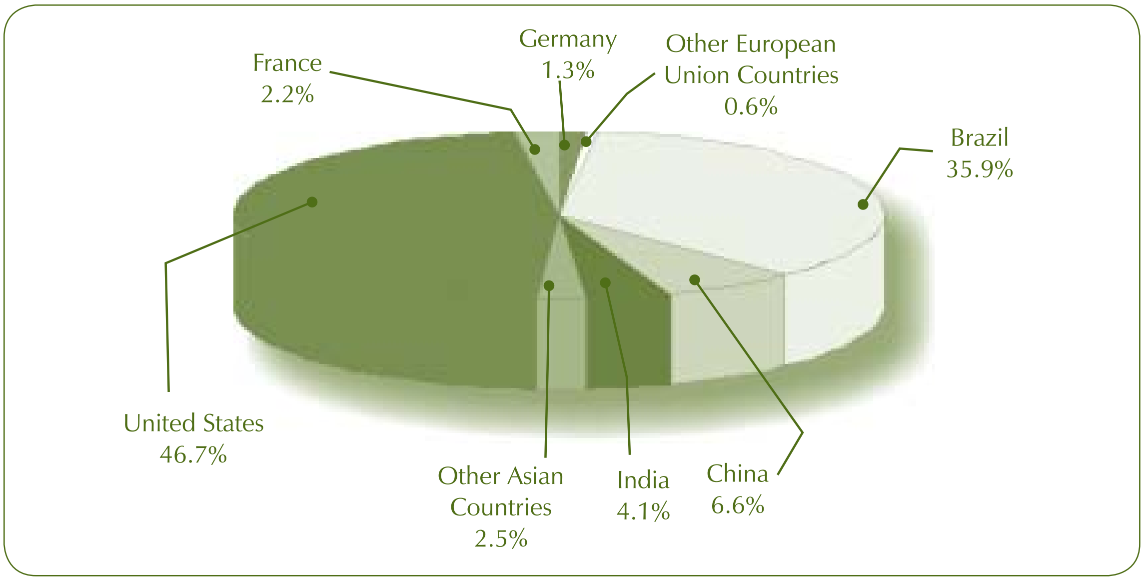
Country	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Canada	4.2	4.1	4.2	4.4	4.6	4.6	4.4	4.7	4.5	4.5	4.6
France	4.4	4.4	4.2	4.2	4.1	4.0	3.9	3.6	3.7	3.6	3.6
Germany	1.0	1.0	1.3	1.4	1.4	1.6	1.7	1.9	2.1	2.4	3.1
Italy	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.0	1.1	1.6	1.6
Japan	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9
Russia	1.0	0.8	0.8	0.6	0.8	0.6	0.6	0.6	0.6	0.5	0.5
United Kingdom	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.8	1.0	1.2
United States	2.9	2.9	2.8	2.8	2.7	2.6	2.4	2.4	2.6	2.7	2.8
G8 Countries	**2.2**	**2.2**	**2.2**	**2.2**	**2.2**	**2.1**	**2.0**	**2.0**	**2.1**	**2.2**	**2.3**
Brazil	26.6	25	23.9	23.7	24.1	23.1	23.3	24.3	26	26.5	29.8
China	19.6	19	19.1	19.2	19.4	19.4	19.6	18.2	16.2	14.0	13.0
India	36.1	35.3	34.3	33.9	32.5	32.4	32.3	31.9	31.5	30.0	29.4
Mexico	5.9	5.7	5.7	5.5	5.4	5.3	5.3	5.1	5.0	4.9	4.7
South Africa	10.9	11	11.1	11.1	11.3	11.4	11.8	12.4	11.1	10.2	10.7
+5 Countries	**22.2**	**21.6**	**21.4**	**21.3**	**21.3**	**21.2**	**21.4**	**20.6**	**19.2**	**17.4**	**16.9**

Source: GBEP (2007).

Data on bioethanol production shows important trends in terms of expansion and diversification. In 2006, total world bioethanol production was 51.3 billion litres and it reached 55.7 billion litres in 2007. In recent years the United States has been the leader in global production, with an output of 26 billion litres of corn-based ethanol in 2007, followed by Brazil, with approximately 20 billion litres of sugarcane-based bioethanol [REN21 (2008)]. The main bioethanol producers in Asia are China and India, which produced 3.7 billion and 2.3 billion litres in 2007, respectively. Production for all Asian countries reached 7.4 billion litres in

2007. In the European Union, bioethanol production rose to approximately 2.3 billion litres in 2007 from 1.6 billion litres in 2006. The largest producer in the European Union is France, which produced an estimated 1.2 billion litres in 2007, followed by Germany with 850 million litres [F. O. Licht (2007)]. Graph 37 synthesizes the distribution of bioethanol production among the main producers; developing countries account for half of observed production.

***Graph 37* – Distribution of ethanol production by region in 2007**



Source: Prepared based on REN21 (2008) e F. O. Licht (2007).

It is noticeable how rapidly the scenario has evolved, with elevated growth rates every year. Indeed, bioethanol production data presented in this section represent a small portion of the existing production potential that must be developed in the coming years, as analyzed in the next section.

8.3 Bioethanol supply and demand projections for 2010-2015

This section focuses on bioethanol supply and demand estimates for the 2010-2015 timeframe, the period in which the biofuels market is expected to start developing and consolidating. The section analyzes the situation of North America (except Mexico, which is analyzed as part of the Latin American region), the European Union, Latin America and the Caribbean, Asia and Oceania. In all cases the focus is on countries that have already implemented — or are expected to start to implement — policies to stimulate biofuels production and consumption. Most data used is from studies developed by the Global Biofuel Center, an institution that carries strategic studies of the biofuel market. Estimates for Brazil will be presented in Latin America's section, based on the foreseen evolution for its domestic fuels market and installed processing capacity in the sugarcane industry. Estimates for Africa — where some initiatives to foster biofuels are making a start — are presented aggregated. A general outlook is presented at the end.

North America, except Mexico

Both the United States and Canada are developing nationwide renewable fuel standards that would require biofuels in a certain percentage of the gasoline and diesel pools. In the United States the current federal public policy framework for biofuels is the Renewable Fuels Standard (RFS) programme. The Energy Policy Act of 2005 established the framework for the RFS programme that the US Environmental Protection Agency (EPA) then developed and issued a rulemaking upon it which began on September 1st, 2007. The programme required that a certain percentage of all gasoline sold or used by motorists be renewable fuel. The measure was accomplished without difficulty because the United States already consumed more renewable fuels than was required by the RFS [White House (2008)].

Then, on December 2007 "The Energy Independence and Security Act" (EISA, HR6) was signed into law by the US President. The new law increases the RFS requirements between 2008 and 2022. Starting in 2008 the requirement is set at 34 billions litres gallons of renewable fuel, which progressively increases to 136 billion litres in 2022 [USDA (2008)]. This law defines new biofuels categories based on GHG-lifecycle impact:

> *Conventional Biofuel* is defined as cornstarch bioethanol. In addition, new conventional ethanol-producing facilities that begin construction after the enactment of this law must achieve a lifecycle GHG emission reduction of 20% compared to baseline emissions. The GHG emission reduction requirement may be lowered to as low as 10% if EPA determines that the requirement is not feasible.
>
> *Advanced Biofuels* are defined as renewable fuels other than cornstarch-based bioethanol, derived from renewable biomass and that achieve lifecycle GHG emission reductions of 50% below the baseline. This definition includes cellulosic biofuels (including ethanol from cellulose, hemicellulose, or lignine; sugar or starch other than corn; and animal, food, crop or yard waste material); biomass-based diesel, biogas (including landfill and sewage-based gas); butanol and other alcohols produced from biomass; and other fuels derived from cellulosic biomass.
>
> *Cellulosic Biofuels* are renewable fuels derived from any cellulose, hemicellulose, or lignin that is obtained from renewable biomass and achieves a lifecycle GHG emissions reduction of 60% below the baseline.

The new provision requiring renewable fuels to meet lifecycle GHG emission reduction thresholds is inclusive of emissions from all stages of fuel and feedstock production and distribution, counting direct and indirect emissions and including those emissions resulting from land use changes. According to Global Biofuel Center estimates, the new RFS targets set out in the EISA legislation are largely expected to be met, with bioethanol supply reaching around 70 million of cubic meters in 2015 [Global Biofuel Center (2008)].

Similarly, Canada will require a 5% volume of renewable content in gasoline starting in 2010 and the Federal Government is developing a regulation to implement its RFS. According to the proposed RFS regulation (ie, 5% blend) 2.2 billion litres of bioethanol will be demanded by 2010, with supply expected to be about 2.9 billion litres (not counting proposed ethanol facilities, some of which are expected to be constructed and begin operating by 2015). Moreover, a 10% blend (E10) by 2015 would require more than 4.7 billion litres and additional bioethanol production facilities would be needed to meet demand.

European Union

In the European Union (EU-27) a few countries became interested in biofuel during the 1990s; however, the EU as a whole became interested much later, in 2001. On the other hand, the industry really became involved with the induction of favourable policies or fiscal incentives in different Member States. Currently, the two countries where biofuels used in road transportation have achieved the greatest penetration in the motor fuel pool are Germany and Sweden. Countries with large areas of arable land and protective of their farming industries such as France have also implemented specific tools to promote the use of biofuels. It is important to note that in 2006 European bioethanol-related investments to comply with the goals established for 2010 exceed biodiesel-related investments for the first time.

Other members-states, such as Spain, have started production without having large domestic biofuels markets but aim to export their production. The Netherlands and the United Kingdom adopted more cautious approaches and see second-generation biofuels as a more sustainable alternative than existing first-generation biofuels. These two countries, however, have set up mandatory systems for biofuels use. The case of Czech Republic, which became a Member State in 2004, is also of interest because of the rapid biofuels developments that have been taking place there since 2006, when the crude oil price peaked.

The two main directives setting the use of biofuels in the UE are the Biofuels Directive, which sets biofuels use targets, and the Fuels Quality Directive, which sets fuels specifications. The targets established by the Biofuel Directive are indicative non-binding targets, set as energy percentages of fossil fuel use in the UE. For 2005 the target was 2% and for 2010 is 5.75% by energy content.

Recently, in January 2008, the European Commission published its proposed Renewable Energy Directive, which should take over the Biofuels Directive after 2010. The proposal includes a biofuels mandate of 10% by energy content by 2020. In fact, this target should be achieved through the use of sustainable fuels defined against parameters set out in the proposed directive and with the use of second-generation biofuels, which will count double against the 2020 target. The proposal is being discussed in the European Parliament and Council of Ministers and a decision is expected by June 2009.

According to the European Bioethanol Producers Association (eBIO), ethanol production in 2007 increased at a modest pace of 13.5% compared to 70% in 2006 and 2005. The association reports that ethanol imports were a record high in 2007 at one billion litres. Table 39 shows the evolution of EU ethanol capacity, production and consumption from 2005 to 2007 and the growing volume of imported ethanol.

Table 39 **– Bioethanol capacity, production and consumption in the European Union (In million litres/year)**

Year	2005	2006	2007
Installed Capacity	–	2,876	3,344
Production	913	1,593	1,770
Consumption	1,150	1,700	2,700
Import	237	107	930

Source: Global Biofuel Center (2008).

Based on the assumptions seen in the moderate scenario of the Refuel Research project — sponsored by the European Union in a joint effort with several institutions to promote biofuel use — bioethanol should achieve a target of 5% by energy content in 2010, 7.5% in 2015 and 10% in 2020 [Refuel (2008)]. In comparison, the increase in production calculated as a fraction of existing and announced ethanol plants shows whether there would be a market for imported ethanol should all the existing plants work at 70% of capacity in 2010 and 80% capacity in 2015 and 2020 [Global Biofuel Center (2008)].

Based on the 10% ethanol target in 2020, 17.7 billion litres of ethanol will be required. Local production capacity may reach 12.16 billion litres in 2015 and could then remain constant as no new first generation projects are initiated but rather cellulosic ethanol starts entering the market [Global Biofuel Center (2008)]. In short, as a result of mandated targets in the EU and several countries implementing individual targets for ethanol and biodiesel, the growth of demand should be significant and above internal production capacity. Imports will continue to make up the difference between domestic supply and demand in the EU.

Latin America and Caribbean, including Brazil

Biofuels production and use has a great potential in the Latin America and Caribbean (LAC) region. Most countries have a heavy dependence on imports of petroleum products, coupled with growing demand for transport fuels and abundant feedstock potential to produce ethanol and biodiesel. These countries share the desire for the energy security and economic and social development that they see has occurred in Brazil in relation to biofuels production. In fact, many countries see the development of a biofuels programme as a way to achieve both goals. For example, several countries in the LAC region are currently working to introduce bioethanol blending targets, usually between 5% to 10% on gasoline volume and 2% to 5% on biodiesel volume. Among the several initiatives in place Colombia and Costa Rica can be highlighted because of their advances [Horta Nogueira (2007)].

The implementation of ethanol production and use started in Colombia in 2001 with the enactment of Law 693. The main purposes of the law are: reduction of hydrocarbons and carbon monoxide emissions; creation and maintenance of agricultural employments; development of the agroindustrial sector; and contribution to energy self-sufficiency as a strategic objective. The first article of the law establishes that gasoline used in urban centers of more than 500 thousand inhabitants must contain fuel alcohol starting in September 2006. The law defines as oxygenated a gasoline with a 10% biofuels content [UPME (2006)]. The introduction of the programme was preceded by a careful process of planning and informing consumers, which continues in place.

The first Colombian sugarcane bioethanol plant started operation in 2005, with a production of 300 thousand litres/day. In 2006 other five sugarcane bioethanol plants began operation in the Cauca River Valley with a combined production capacity of 357 million litres/year. Sugarcane production in the Cauca Valley is well established and production can be carried out during the entire year, which allows the operation of an elevated number of distilleries. The Colombian government expects that in 2010 the country reaches an annual production of 1.7 million litres of bioethanol; such volume would be needed for a blend of 10% of bioethanol in gasoline and generate an exportable surplus equivalent to 50% of total production [Horta Nogueira (2007)].

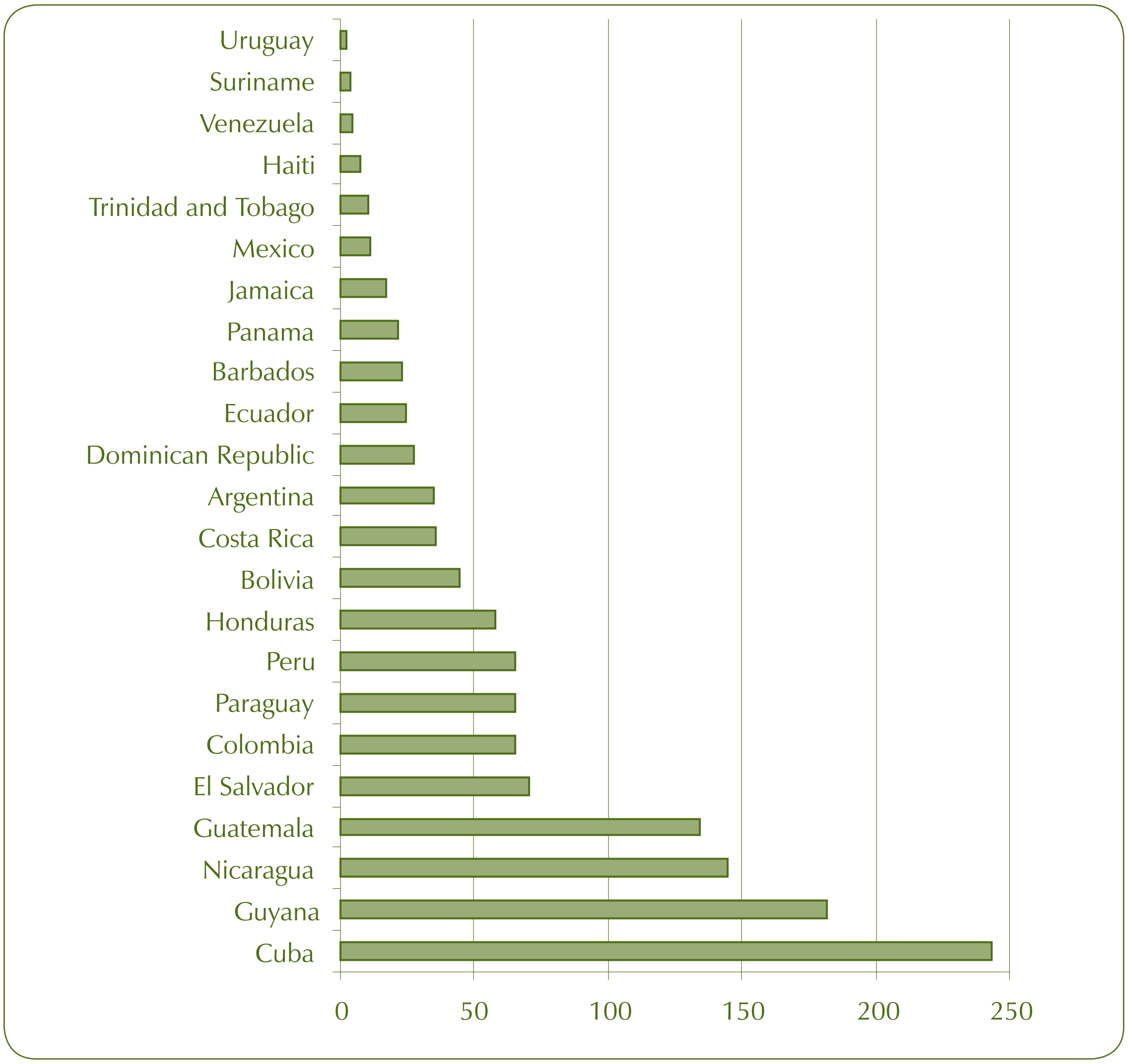
In Costa Rica the first experiences with bioethanol fuel were developed in the early 1980s, but they were interrupted in 1985, because low fossil fuel prices made ethanol production economically unfeasible. However, in 2003 the Costa Rican government created a new bioethanol programme in the context of an scenario favourable to biofuels, because of high petroleum prices. The programme was launched in May 2003 by Executive Decree No. 31.087-MAG-MINAE, which created a Technical Commission to «formulate, identify and elaborate strategies for the development of nationally distilled anhydrous ethanol and local feedstocks to produce substitutes for MTBE in gasoline". The main objectives of that Decree were agroindustrial development (economic reactivation, added value production) environmental improvement (eg, MTBE replacement), and energy diversification and reduction of fossil fuels import dependence. The programme, which initially established a 7.5% blend of ethanol in gasoline, has been carried-out in phases to allow consumer to assimilate operating procedures and provide for gradual infrastructure expansion. In the initial phase several successful vehicle tests were conducted using the same blend, followed by sales of the bioethanol-gasoline blend in limited markets. Adding 10% of bioethanol to the entire gasoline used in the country would yield an estimated bioethanol demand of 110 million litres in 2010. Recope, the Costa Rican state oil company, has played an important role for the appropriate introduction of bioethanol in the country [Horta Nogueira (2007)].

A recent study [Cepal (2007)] tried to determine the potential of Latin American countries to produce sugarcane bioethanol for a 10% blend with gasoline, considering two main restrictions: availability of suitable lands and dimension of the local sugarcane industry. Two scenarios were analyzed: a) bioethanol production from the conversion of molasses, assuming a production of 78 litres of bioethanol per ton of produced sugar; and b) exclusive production of bioethanol, considering a sugarcane yield of 75 ton/ha and an industrial production of 80 litres of bioethanol per ton of sugarcane, that is, 6 thousand litres of bioethanol per sugarcane hectare. The first scenario determines the percentage of bioethanol demand that could be fulfilled out of molasses, a by-product of sugar processing. The second scenario estimates the sugarcane area required both as a percentage of total agricultural land and current sugarcane area, based on Faostat data (2008a). Gasoline demand data and therefore bioethanol demand, correspond to 2004 [Olade (2006)]. The results of the study are presented in Graphs 38 and 39, which include countries with more than one thousand hectares of planted sugarcane. Brazil is excluded because it already has a large bioethanol programme and bioethanol is widely used and produced. Brazilian data is presented later in the chapter.

Graphs 38 and 39 show that sugarcane bioethanol production can allow meeting national blending needs without significant impacts, especially in terms of land use conversion. On average, the LAC region can reach a 35% blend through the use of existing molasses, with most countries being able to achieve the 10% blend (Graph 38). On the other hand, the 10% blend can be reached with a 22% increase of the current sugarcane cultivated area, which is equivalent to an increase of about 0.4% of the current agricultural area. In the second case there is remarkable country variation.

Cuba, Guatemala, Guyana and Nicaragua present an elevated bioethanol production potential from molasses conversion, well above the 10% blending target. On the other hand, Haiti, Surinam, Uruguay and Venezuela can not reach the 10% target. When land availability is considered most countries in the region can meet the 10% blending target: with the exception of Barbados, Jamaica, Trinidad and Tobago, Surinam and Venezuela, the rest of countries can produce ethanol for a 10% blend with an increase of less than 1% over the current agricultural land.

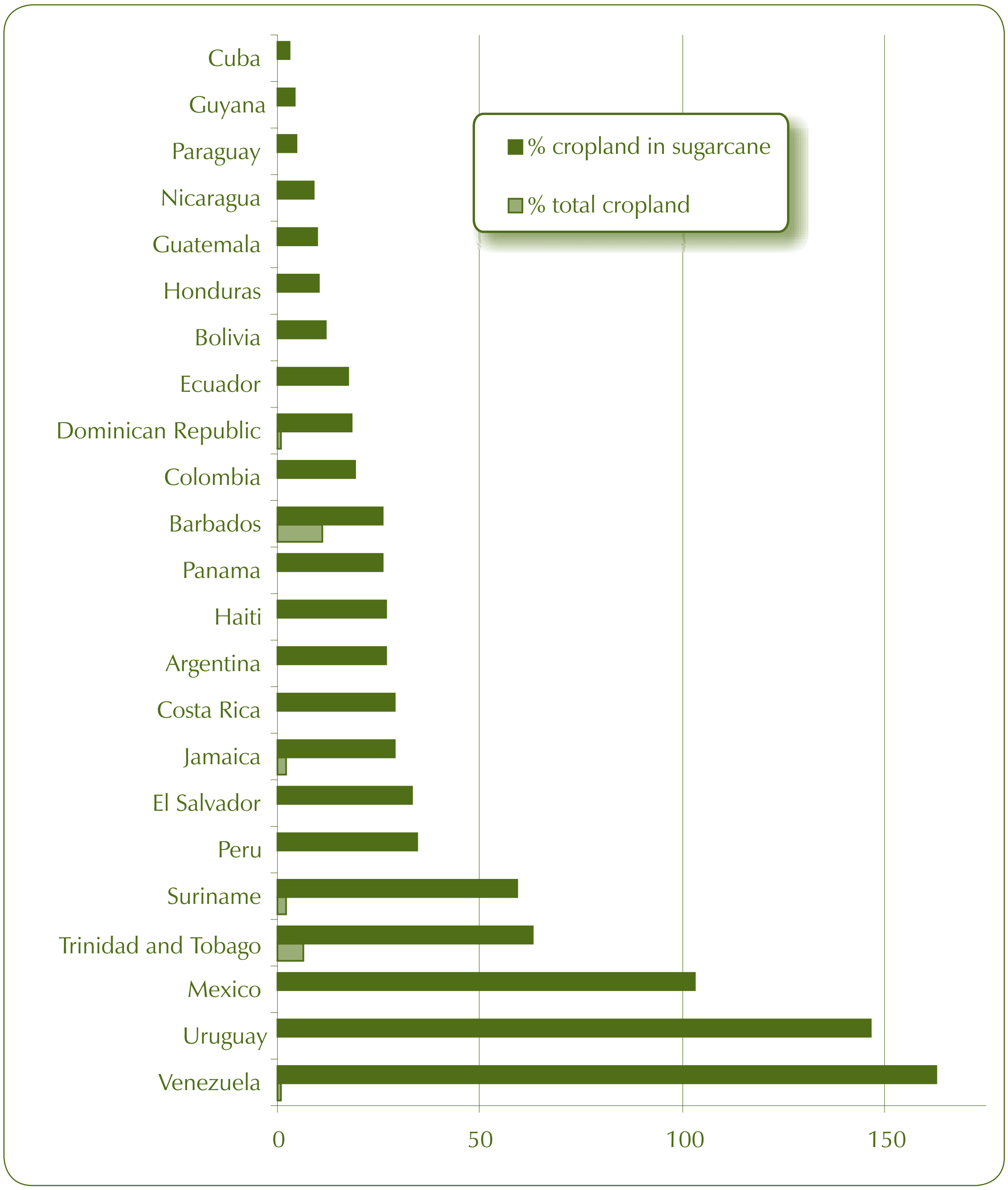
Graph 38 **– Bioethanol-gasoline blend that can be produced from the conversion of molasses available out of sugar production**
(percentage of gasoline use)



Source: Cepal (2007).

Another important driving force for bioethanol production in LAC countries is the revision of the sugarcane regime by the European Union within the Common Agricultural Policy, which will reduce price support by 36% in four years. Some countries, especially in the Caribbean, such as Barbados, Belize, Jamaica and Guyana, are considering to convert the sugar they produce into ethanol as a way to respond to both the new sugarcane regime and the increase in the fossil fuels bill. Jamaica is the most developed country, since it intends to implement the 10% mandatory bioethanol blend.

Graph 39 – **Agricultural land requirements to produce bioethanol for a 10% gasoline blend (percentage of total agricultural land and planted sugarcane)**



Source: Cepal (2007).

In addition to supplying their internal fuel markets, which in general are limited, LAC countries are also interested in the possibility of exporting bioethanol, especially to the United States. This interest is supported by some agreements signed between the United States and countries in the region, such as the US-Dominican Republic–Central American Free Trade Agreement (DR-Cafta), ratified by the US Congress in 2005, as well as the Caribbean Basin Initiative (CBI), established by the US Congress in 1983.

The CBI exempts beneficiary country products from import duties under certain conditions. Beneficiary countries are Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, British Virgin Islands, Costa Rica, Dominica, Dominican Republic, El Salvador, Granada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Montserrat, Netherlands Antilles, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and Grenadines, and Trinidad and Tobago. Under the CBI hydrated ethanol is usually shipped from Brazil to beneficiary countries where it is dehydrated and exported to the United States. The main ethanol exporters under the CBI are Jamaica, Costa Rica, El Salvador and, recently, Trinidad and Tobago. According to rules bioethanol may be exported in the following cases: a) up to 7% of the US market without origin restrictions; that it, ethanol processed (but not necessarily produced) in beneficiary countries; b) a supplementary quote of 132 million litres of bioethanol containing at least 35% of the local product; and c) no volume restrictions to biofuel with more than 50% of local content. The US market imported 4.6 billion litres of bioethanol in 2006 and 2007. In fact, most imports (about 75%) were carried under the CBI, with only a minor part imported directly from Brazil, Canada and other countries [Global Biofuel Center (2008)].

A bioethanol supply and demand estimate was obtained for the LAC region, excluding Brazil. The estimates include countries that are implementing or expected to implement biofuel programmes by 2010, namely, Argentina, Colombia, Costa Rica, Dominican Republic, Ecuador, Jamaica, Mexico, Paraguay, Peru, Trinidad and Tobago, Uruguay and Venezuela. The supply estimate considers production facilities currently in operation along with those under construction and expected to be in operation by 2010. It is also assumed that by 2015 most of the currently proposed facilities will be constructed. Bioethanol production potential estimates are based on current nominal capacity data, while demand is estimated considering expected gasoline demand and implementation of blending targets [Global Biofuel Center (2008)].

The analysis showed that several countries should increase their production capacity to be able to meet the proposed blending targets. Several countries will remain or even can become bioethanol exporters; such is the case of Costa Rica, Jamaica, Paraguay, Peru, Trinidad and Tobago and even Uruguay. Exports from these countries, except Peru, will enter the US under some of the agreements mentioned above. In the case of Peru ethanol can be exported to the US market under the auspices of the US – Peru Free Trade Agreement. [Global Biofuel Center (2008)].

The perspectives of the Brazilian bioethanol market are obviously different because of the maturity of its biofuel programmes and the large expansion observed in bioethanol consumption and production capacity (see previous chapter). The estimation of future scenarios is not an easy task because of the intense dynamics observed in the bioethanol agroindustry, in which new projects are frequently implemented to meet the growing internal demand. However, some conservative production and consumption estimates are obtained for the period of interest. The bioethanol production estimate is based on the expected production for 2008 (around 26.1 billion litres) and considers an annual growth rate of 8%, which is consistent with the evolution observed in recent harvests and the number of projects currently under implementation and expected to become operative (35 new plants in the 2008/2009 sugarcane crop season and 43 units in the next season) [Nastari (2008)]. That yields a bioethanol production estimate of 30.5 billion litres in 2010. During the years that follow the foreign market should become more important allowing bioethanol production capacity to reach about 47 billion litres by 2015, which is equivalent to a 9% annual growth rate [Milanez et al. (2008)].

Regarding bioethanol demand, it is important to point out that previous estimates for the Brazilian market underestimated real consumption, because the market expansion caused by the introduction of flex-fuel vehicles. This new technology is a source of uncertainty for demand estimates because drivers can choose using pure bioethanol, gasoline mixed with bioethanol in different proportions, or the gasoline-bioethanol available in the market. In addition, the government can change the bioethanol blend between 20% and 25%. Finally, the margin of error of consumption estimates increases because of the uncertain petroleum price scenario.

Based on the evolution of the small-size vehicle fleet and fuel consumption patterns, internal bioethanol demand for Brazil is estimated to be in the range of 28 - 34.3 billion litres by 2015. The estimate considers that 50% and 70% of consumption by flex-fuel vehicles, respectively, is met by hydrated bioethanol [Milanez et al. (2008)]. The study presents several estimates of the Brazilian bioethanol market which show reasonable dispersion. Also following a conservative approach, it was assumed that bioethanol production will be used to meet the needs of the domestic market; exports are estimated at 5 billion litres by 2010 (which is equivalent to exports in 2008) and 10 billion litres in 2015, when the international bioethanol market should be better structured. It is important to stress that the domestic bioethanol demand estimates correspond to vehicular uses and industrial applications, segments that have shown significant expansion in Brazil during the course of the last few years.

Africa

The relatively small size of the African fuels market and the limited information base about biofuels national projects do not mean this region is of less interest as part of prospective bioethanol assessments. Actually, there is significant bioenergy potential, especially in the southern regions, which can be used to support other social and economic development goals.

In fact, since the 1980s there have been interest in promoting bioethanol use in Africa. Two pioneer initiatives were the Ethanol Company of Malawi (ETHCO), which has operated since 1982 producing ethanol from sugarcane molasses for fuels purposes; and a bioethanol-fuel programme implemented in 1980 in Zimbabwe, which was cancelled in the early 1990s because of a serious drought, but that can be re-implemented [Gnansounou et al. (2007)]. In Nigeria testing of bioethanol-gasoline blends have been performed since 2006 and South-African businessmen have shown interest in implementing bioethanol production facilities in light of the possibility that gasoline-biofuel blends are introduced [Alexander (2005)]. In Ghana, a production facility with an installed capacity of 150 million litres/year of sugarcane bioethanol is being implemented, following a model that can be replicated in Tanzania and Mozambique [F.O.Licht (2008b)]. Nowadays, at least 11 African countries are creating rules for bioethanol production and trading, including South Africa, Angola, Mozambique and Benin. Most countries are considering to adopt 10% (E10) bioethanol blends [Exame (2007)].

African sugarcane-bioethanol production reached 439 million litres in 2006, with 89% of production coming from South Africa. A conservative preliminary aggregate estimate is for 1 billion and 1.5 billion litres by 2010 and 2015, respectively, based on information about potential internal gasoline consumption and considering export-related production perspectives. Production and demand are expected to be similar by 2010, while exports of 500 million litres are anticipated by 2015.

Certainly, in the medium term Africa will become an important player within the bioenergy scenario. In light of that development, the Brazilian Government has stimulated sugarcane planting and the implementation of distilleries in several countries, such as Botswana, Congo, Gabon and Tanzania, as part of a recent joint effort between the Ministries of Foreign Affairs and Agriculture. Considering land availability and weather conditions the southern African countries with the most important potential to develop bioenergy production programmes are South Africa, Zambia, Angola, Mozambique, Zimbabwe, Malawi and Madagascar. Basically, such programmes can be developed through the diversification of the sugarcane agro-industry already in place in the countries [Gnansounou et al. (2007)].

Asia and Oceania

Asia and Oceania have been active in implementing biofuel programmes and promoting the use of agricultural raw materials to produce biofuel, not only to meet the expanding domestic demand, but also for eventual foreign markets. However, some Asian countries were not able to reach ambitious biofuel goals in the proposed time or were cautious in introducing biofuel into their markets, because of concerns about prices, long-term supply, logistic and infrastructure, as well as vehicle-fuel compatibility issues.

Biofuels are stimulated for a variety of reasons. Developed countries such as Australia, Japan, New Zealand and South Korea are aiming to achieve Kyoto Protocol targets to reduce CO_2 emissions by 2012, regardless of whether they are mandatory or voluntary. Programs to promote biofuels have been introduced in these countries mainly by setting production or sale targets. However, Japan, South Korea and Taiwan do not have sufficient land to grow biofuel-crops because of high population density. As a result, biofuels are only produced on a small-scale from recycled oils and waste material. Long-term feedstock supply is a primary issue in these countries. Japan has taken a systematic and progressive approach to its biofuel programme, which can serve as an example to follow for other countries in the region. The country has set a target to add bioethanol to gasoline in a volume equal to 0.6% on the vehicular fossil energy consumption by 2010, the equivalent of 500 million biofuel litres. It is still a modest programme but it indicates a favourable intention. The programme started in 2007 with the introduction of 7% ETBE blend in gasoline traded in the Tokyo area. Furthermore, it is expected that bioethanol penetration in the energy transport demand reaches 30% by 2030.

The Japanese government, supported by the local automotive industry, has carried out tests of 3% bioethanol blends in the cities of Osaka and Miyakojima, located in the Okinawa Island, where sugarcane is cropped [Global Biofuel Center (2008). Recently, Petrobras (the Brazilian Petroleum Company) and Mitsui (a Japanese international business organizer and a provider of integrated trade facilitating services worldwide) created a company in Brazil to support bioenergy projects to produce ethanol for the Japanese market.

On the other hand, Asian developing countries like China, India, Indonesia, Philippines and Thailand are mainly looking to reduce their dependence on conventional fuels by using surplus agricultural feedstocks to produce biofuels and at the same time, reduce ambient emissions and provide stability to farmers. Indonesia and the Philippines are further looking at biofuels as an alternative to increase economic activity and reduce their foreign debt. Programmes to promote biofuels have been implemented in these countries either by setting production targets or requiring biofuels blends at certain percentages.

In the case of China, it has an informed 10% bioethanol blending target for gasoline sold in five provinces, corresponding to an annual demand of 1.6 billion litres, which will gradually increase with the inclusion of other provinces into the programme. India and Thailand, on the other hand, intended to implement a 10% blend, equal to an initial estimated consumption of 400 million and 300 million litres/year, respectively, but faced logistic barriers in implementing the programmes. They are now also more cautious with their biodiesel programmes [Global Biofuel Center (2008)].

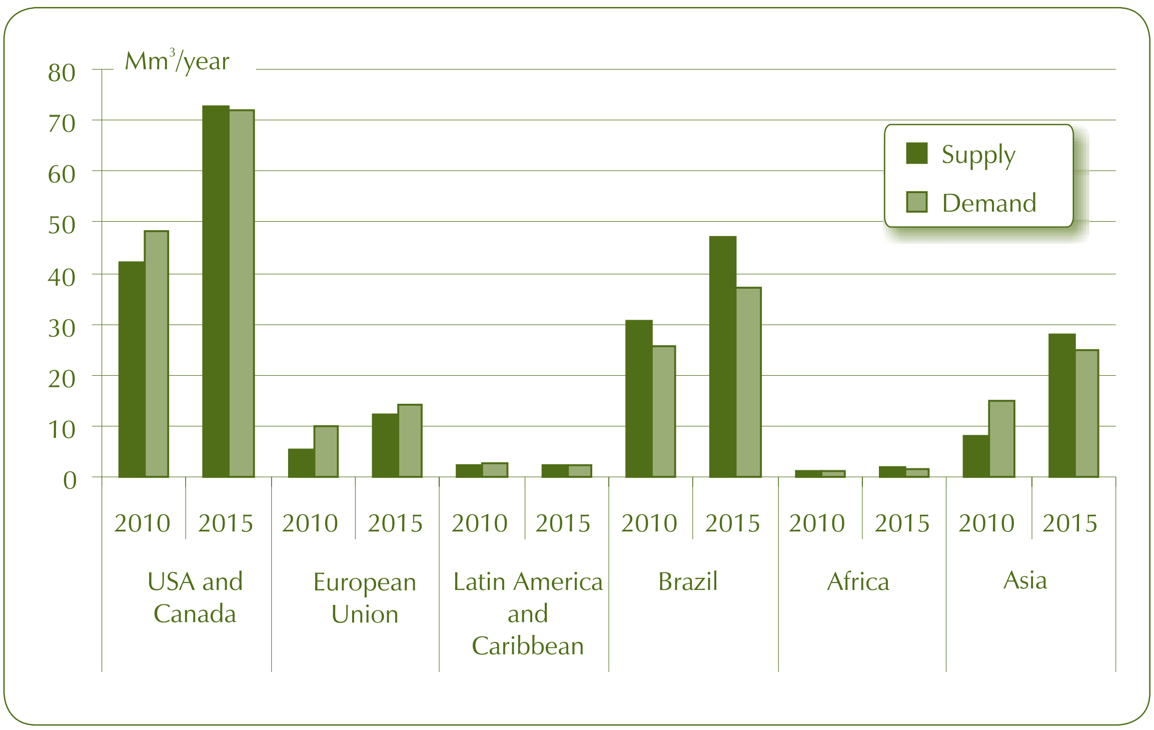
As petroleum products in this region are generally heavily subsidized, countries are looking towards biofuels to replace conventional fuels. As a result, most of countries are moving toward 5% to 10% ethanol blends, including Australia, China, India, Indonesia, Japan, New Zealand, Philippines and Thailand. Significant bioethanol production currently exists in Australia, China and India, but they will need to add more to meet their targets.

A regional supply and demand estimate was calculated [Global Biofuel Center (2008)] considering Australia, China, India, Indonesia, Japan, New Zealand, Philippines and Thailand. The analysis assumes that all countries will meet the ethanol targets set for 2010 and 2015. The calculations point out that the region will be supply constrained by 2010; however, the situation is expected to improve by 2015. Australia, India and China need to bring new ethanol production facilities on line to meet their targets. They will lag behind by 2010, having to rely on imports to comply with targets, but will largely catch-up with local production by 2015. Japan will need to rely almost exclusively on imports. Japan, China, and potentially Australia and New Zealand will be major ethanol importers in the region. However, India, Indonesia and Thailand will be able to export by 2015 [Global Biofuel Center (2008)].

General outlook for bioethanol supply and demand in 2010 and 2015

Graph 40 shows a summary of bioethanol market perspectives in different regions for 2010 and 2015. There are significant regional differences regarding conditions and capacities to participate in a future international biofuels market. Globally, by 2010 bioethanol demand is estimated at 101 billion litres and bioethanol supply at 88 billion litres. The imbalance should have been closed by 2015, with supply close to 162 billion litres and demand around 150 billion litres.

Graph 40 **– Biofuels supply and demand estimates for 2010 and 2015**



Source: Modified based on Global Biofuel Center (2008).

A significant demand increase is expected in the coming years in the US, as new legislation to be implemented requires more than 57 billion litres of bioethanol in the gasoline supply by 2015. In the US meeting the proposed blending targets will possibly require import, unless new conversion routes become feasible soon. However, taken together the US and Canada could be self-sufficient by 2015.

In Europe, ethanol demand should increase significantly if the target blends of 5% in 2010 and 7.5% by 2015 are implemented. In fact, meeting those targets might require importing biofuels. In Brazil, local production should allow to met the expanding internal demand without difficulty and to generate a sizeable exportable surplus. That is, Brazil has a significant potential to participate in the international bioethanol market if it eventually takes-off. A moderate growth is expected in other regions included in the study. Other LAC countries will need to add capacity to meet expected national targets and be able to export to the US; that is particularly the case of countries that can access such market under preferential conditions.

Countries in Asia and Oceania will possibly face constraints to meet demand by 2010, but improvements should allow supply to increase significantly, above demand, by 2015. As indicated previously, Japan, China, and potentially Australia and New Zealand will be the major ethanol importers in the region. On the other hand, India, Indonesia and Thailand will be in a position to export, but certainly without the capacity of Brazil [Global Biofuel Center (2008)]. In Africa, despite significant uncertainties a moderate domestic market growth can be expected, as well as the possibility of exporting to the European market, especially if it expands rapidly.

It must be stressed that theses estimates were developed around the end of 2007 and beginning of 2008, a period of major uncertainty and volatility with regard to petroleum prices. If fossil-fuel prices stabilize at higher than recent historical level it would be difficult to foresee how the bioethanol demand will behave, as bioethanol is currently one of the few available alternatives to substitute gasoline demand.

Finally, it must be mentioned that estimating and keeping track of global bioethanol flows are not easy tasks, because of restrictions in access to information. However, international cooperation can contribute to broaden the base of information and data on bioethanol markets and to bring more transparency to that information, which can benefit all countries

The next section reviews policies that have been proposed to promote biofuels in some of the most important producer and consumer countries.

8.4 Policies to support and promote biofuels

Policies and legal frameworks for biofuels, which have been defined and implemented in several countries with different degrees of clearness and objectivity, are relevant elements that explain and justify the evolution of the global bioethanol demand presented in the previous sections. Table 40 shows the main purposes and motivations behind biofuels public-policy programmes and projects, based on official documents from several countries and European Union [GBEP (2007).

***Table 40* – Main objectives of bioenergy development**

Country	Objectives						
	Mitigating Climate Changes	Enhancing the Environment	Improving energy Security	Promoting rural development	Promoting agriculture	Fostering technological Development	Profiting from comparative advantages
+5 Countries							
South Africa	X		X	X			
Brasil	X	X	X	X	X	X	X
China	X	X	X	X	X		
India			X	X		X	X
Mexico	X	X	X	X		X	
G8 Countries							
Germany	X	X		X	X	X	X
Canada	X	X	X			X	
United States	X	X	X	X	X	X	
France	X		X	X	X		
Italy	X	X	X		X		
Japan	X	X			X	X	
United Kingdom	X	X	X	X			X
Russia	X	X	X	X	X	X	
European Union	X		X	X	X	X	

Source: GBEP (2007).

According to the survey, improving energy security and mitigating climate changes are among the most important bioenergy drivers in most countries. Environmental concerns are usually considered in developed countries, while rural development issues are key factors in developing countries, usually linked to the rural poverty reduction agenda. Increased biofuels use is also seen as an opportunity to increase access to modern energy, including electrification in rural areas. Rural development-related objectives in developed countries focus on agriculture's multi-functionality in terms of environmental and cultural good and services.

In developing countries, agricultural objectives envisage new opportunities not just for high-end commercialised energy crop production, but also for poorer small scale suppliers. All countries stress at least three main and concurrent purposes in their policies, which can make bioenergy development more complex vis-à-vis the need to reach multiple purposes not always mutually compatible. Furthermore, it is important to recall that the stress on agricultural conservation and development in some OCDE countries has led to unsustainable biofuels programmes [UN-Energy (2007)]. Summarizing, biofuel promotion policies tend to focus on multiple and challenging objectives that eventually go beyond the possibilities for a transition of the energy base, which is complex in itself.

In many countries bioenergy development and use are guided mainly through policies in the energy sector, as presented in Table 41 [GBEP (2007)]. Voluntary measures for biofuels refer to the authorization of blending with conventional fuels and its progressive introduction into the market. Direct incentives include those financed by government agencies, such as the reduction of taxes, allowances, and support and guarantee loans. The table presents separate bioenergy policies according to different final uses, such as heating, electricity production, transport, and ethanol and biodiesel production. European Union policies are valid for Member States and can be complemented by national measures, as illustrated in the cases of Germany, France and Italy.

As illustrated by Table 41, most energy policy measures for bioenergy promotion relate to uses in electricity generation, heating and transportation, with specific trade and fiscal measures to encourage ethanol and biodiesel production. Yet, policy measures in the transport sector have an immediate effect in terms of fostering biofuels. It is also evident that an important number of measures are under development or awaiting approval. In short, the instruments to promote bioethanol are well known and are being progressively implemented.

Reviews such as the one conducted by the Worldwatch Institute [REN21 (2008)] confirm that there is important on-going progress in developing normative frameworks to broaden bioethanol use. During the last three years normative instructions were promulgated in at least 17 countries, in most cases mandating 10% to 15% ethanol blends or 2% to 5% biodiesel blends. Subnational normative bioethanol instructions enacted by local governments were found in 13 Indian states; 9 Chinese provinces; 9 US states; 3 Canadian provinces; and 2 Australian states. Such decisions confirm the relevance of local conditions, possibilities and interests.

Table 41 – **Main bioenergy policy instruments in selected countries**

Country	Energy Policy							
	Mandatory targets	Voluntary targets	Direct Incentives	Grants	Feed-in tariffs	Compulsory Grid Connection	Sustainability Criteria	Tariffs
+5 Countries								
Brazil	T	E	T					Et
China		E,T	T	E,T	E, H	E,H		n/a
India	T, (E*)		E	E,H,T	E			n/a
Mexico	(E*)	(T)	(E)			(E)		Et
South Africa		E, (T)	(E),T					n/a
G8 Countries								
Canada	E**	E**,T	T	E,H,T				Et
France		E*,H*,T	E,H,T		E			Et ; B
Germany	E*,T		H	H	E	E	(E,H,T)	Et ; B
Italy	E*	E*,T	T	E, H	E	E		Et ; B
Japan		E,H,T				E		Et ; B
Russia		(E,H,T)	(T)					n/a
United Kingdom	E*,T*	E*,T	E,H,T	E,H	E		T	Et ; B
United States	T	E**	E,T	E,T				Et
European Union	E*, T	E*,H*, T	T	E,H,T		E	(T)	Et ; B

Conventions

Bioenergy technology
E: electricity
H: heating
T: transport use
Et: ethanol production
B: biodiesel production

*: target applies to all renewable energy sources
**: target is set at a sub-national level
(..) : policy instrument still under development or awaiting approval
n/a : non-available or non-informed

Source: GBEP (2007).

8.5 Food – bioenergy linkages

Understanding food-bioenergy interactions is key to future production, conversion, marketing and use of biofuels. The fast and strong increase in food prices observed during 2007 and early 2008 confirmed the importance of adequately assessing the implications of increasing biofuels production on food availability and prices of food-related agricultural commodities.

This section analyses food – bioenergy interactions relevant to both bioenergy-support policies and food security concerns. The section starts with a review of the food security concept and an evaluation of its requirements vis-à-vis the expansion of bioenergy production and dynamics relevant for an adequate balance between food demand and supply. The analysis continues with a review of analytical models that have been proposed to deal with the complexity involved in analyzing the consequences of bioenergy expansion on food security. The section closed with an analysis of agricultural commodity prices that distinguishes whether the different commodities are directly, indirectly or not related with bioenergy production.

Food security and bioenergy production

FAO defines food security as « a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life « [Faurès (2008)]. The definition considers four dimensions: food availability, food access, food use and food stability. These dimensions are appraised next with regard to bioenergy production expansion.

Food availability refers to having sufficient quantities of food of appropriate quality, supplied through domestic production or imports (including food aid). Regarding the impact of biofuels expansion of food availability it is important to point that the use of agricultural lands for bioenergy feedstock production is quite low relative to total agricultural land area. Currently only 1% of the world's agricultural land is used for biofuels production; the figure could increase up to 3% or 4% in 2030 [BFS/FAO (2008)].

Furthermore, it is difficult to assert that there are effective land restrictions to produce both food and biofuels, considering that the world's total agricultural areas (roughly 1.5 billion hectares) currently represent about 12% of world's surface. Additionally, an important portion of current agricultural land is used to produce animal feed (eg. grains for animal feeding), which is an inefficient way to meet the food needs of the world's population. That is the case, for example, with the production of corn in the US and soybeans in Brazil, which are widely used as feeds in animal production systems (ie, to produce protein and edible fats for human consumption) with a 15% ratio between caloric consumption and production.

A similar low efficiency ratio is found in the production of animal protein in livestock pasture systems. Pasture areas for livestock production occupy an estimated 3.5 billion hectares globally, which basically include native pastures of limited productivity. Indeed, 35 million hectares would be released if pasture productivity increased by 1%, through adequate livestock handling and the introduction of better fodders. Such land-saved area is larger than the estimated 23 million hectares required to produce sugarcane bioethanol for the equivalent of 10% of the global gasoline market (ie, for a global 10% bioethanol blend).

In fact, it is not the availability of agricultural land what structurally affects food security and constrains biofuels production. Likewise, the recent increase in food prices is not caused by insufficient food production. Globally, food production has systematically increased allowing a 24% increase in the per capita food supply over the last 40 years, along with an increase from 2,360 to 2,803 calories per capita per day, while global population increased from three to six billion people [FAO in Ricupero (2008)].

It must be recognized, however, that in recent years there have been important imbalances between supply and demand, especially in grains, which has been simplistically attributed to expanding biofuels production. In fact, the recent increases in food inflation and agricultural commodity prices are part of a more complex process affected by many structural and transitory factors [Rodríguez (2008a), FAO (2008), Trostle (2008) e Best et al. (2008)]. On the demand side it is noticeable how cereal and animal protein consumption per capita have grown in important markets, especially in Asia (India and China). On the supply side production has been constrained by structural (eg, a reduction in the rate of growth of cereal yields) and transitory phenomena (eg, adverse weather conditions), as well as by increases in production costs caused by direct and indirect effects of high petroleum prices, especially on fertilizers and transportation costs. Those supply-demand dynamics have led to a reduction in cereal stocks that started around 2000. The situation has been compounded by additional aggravating factors that have contributed mainly to the price volatility observed during the last two years and intensified over the last few months. Such factors include the devaluation of the US dollar; the low interest rates policy followed by the US Federal Reserve (to face the financial distress caused by the so called subprime mortgage crisis), which has motivated investors to seek for investment alternatives in commodity markets; and related to both, the eventual increase in speculative movements in international agricultural commodity markets [Frankel (2008a and 2008b) e Calvo (2008)]. The explanation for the acceleration in the growth of commodity prices as the result of the low interest rate policy followed by the US Federal Reserve rests on an analytical framework developed by Frankel (2006).

Some numbers illustrate the scenario just described. China, one of the current main food importers, with approximately 20% of the world's population and less than 10% of world's agricultural land, was able for decades to reasonably provide itself with cereals produced out of its own agricultural resources. However, food imports have significantly increased since 2004 along with increases in purchasing power and diet diversification, especially an increase animal protein demand. China's meat consumption per capita increased from 20 kg/year in 1985 to 50 kg in 2000 and it is expected to reach 85 kg in 2030 [SOW-VU (2007)], a level representative of a medium-to-high development country. This increase in animal protein demand has significantly increased grain demand, since as much as 5 - 8 kg of feed-grain are required to produce one kilogram of pork or beef.

In 2007 Brazil exported 11 million tons of soybean to China. Considering the soybean average productivity of 2.5 tons per hectare, it means that Brazil devoted 4.4 million hectares to meet soybeans demand in the Chinese market [Abiove (2008)], an area larger than the area currently cropped with sugarcane to produce bioethanol.

As indicator of inflation in international food-related agricultural commodities markets, between 2000 and 2007 nominal cereal prices increased 225%, below the increase of about 330% in oil prices. The increase of food prices intensified in recent years, especially in the case of some important cereals: from January 2007 until March 2008 the nominal prices of corn, wheat and rice increased by 40%, 130% and 82%, respectively [Faostat (2008b)]. The evolution of agricultural commodity prices is analyzed at the end of the chapter. The increase in food-related agricultural commodity prices has stronger impacts in poor energy and food importing countries and describes a scenario that can be a reflection of deeper long-lasting structural changes in the world [World Bank (2008)].

The contribution of sugarcane bioethanol to higher volatility and increase in agricultural commodity prices is marginal, given how sugarcane production is structured, especially in Brazil. As indicated previously, the area required to replace 10% of global gasoline consumption is approximately of 23 million hectares, which is equivalent to 1.5% of the world's cultivated land area, or 0.2% of the world's arable land. The argument is also supported by the limited impact of bioethanol production on sugar prices, which have remained stable over the last few years vis-à-vis the evolution of other agricultural products, as it will presented latter in this chapter.

The same is not true of other biofuels produced out of food-related agricultural commodities. A study carried out by the International Monetary Fund (IMF) on the growing demand of agricultural products indicates that corn, soybean and rapeseed markets will be strongly influenced by bioenergy production. An good example is US corn-based bioethanol production, responsible for 60% of the increase in the global corn demand, with direct effects on corn prices. The US, the largest corn producer and exporter, is expected to devote approximately 30% of its annual corn production to bioethanol, until 2011. Similarly, the increase in European biodiesel production can affect vegetable oils markets [IMF (2007)].

Therefore, it is important to recognize that domestic low-productivity biofuels production in the US and EU present limitations, because they involve the use of production niches, especially agricultural surpluses, which allow to meet only a small fraction of their internal liquid fuels consumption. Such reality creates an opportunity for a more sustainable and economically rational biofuels production in humid tropical countries of Latin America and the Caribbean, Africa and Asia. That could progressively enable high energy-consuming countries to reach fossil fuel replacement rates from 20% to 30% without affecting the production of other agricultural products and a considerable boost to development in producing regions.

Therefore, biofuels clearly have different impacts depending on the origin of the raw materials used. Sugarcane bioethanol produced in countries that have adequate conditions in terms agricultural productivity and climate has little impacts on other agricultural sectors. On the other hand, biofuels largely produced in the US and the EU have direct an increasing effects on food availability and prices. Impacts on the demand of agricultural products are aggravated by protectionist practices widely adopted in developed countries, which have severe implications in at least two domains. First, price support policies to farmers work as an effective trade barrier that limits the entry of agricultural products from developing countries, discouraging export-led production. And second (and worse), surplus-subsidized production unbalances global agricultural markets, depressing international prices and dislocating agricultural production in low income countries.

An eloquent example is subsidized corn production in the US. Subsidized corn surpluses exported from the US at prices below production cost have promoted a gradual reduction in corn production in traditional LAC corn producer countries such as Mexico, Colombia and Guatemala. Adequate coordination of national agricultural policies and harmonization with the objectives of energy policies will take some time, but the role of coherent public policies will continue to be fundamental to the sustainable development of biofuels [Rodriguez (2007)].

Subsidies can certainly be legitimate public policy instruments to support agricultural production. However, a large portion of the US$ 280 billion allocated annually by OCDE countries to support their farmers [OCDE (2007b)] (a 30% equivalent of the gross revenue generated by rural activities) has contributed to reduce food production in developing countries. The revision of subsidies is one of the most complex issues in the international trade agenda, and it needs to be readily addressed to bring more rationality to global agricultural production. The same argument can be extended to biofuels subsidies that obstruct international trade and encourage inefficient biofuel production systems that end up wasting food commodities with insignificant energy and environmental gains. In short, food availability may be adversely affected if biofuels are produced with low energy productivity and making an unsustainable use of natural resources. Certainly, that is not the case of sugarcane bioethanol.

The other dimensions of food security are not expected to be significantly affected by the production of biofuels. Food access relates to individuals having adequate resources (entitlements) for acquiring appropriate foods for a nutritious diet. It depends on purchasing power of the population as well as the availability of adequate transport, storage and distribution infrastructure. Food access can be favoured in contexts where bioenergy production stimulates the development of rural production system and increases household disposable income. On the other hand, food access can be negatively affected if biofuels development leads to significant food prices increases that reduce purchasing power among the population. This effect would be higher in poor countries or regions where a significant portion of disposable income is spent on food.

Food utilization relates to how food is used through adequate diet, clean water, sanitation and health care to reach a state of nutritional well-being where all physiological needs are met. Food utilization brings out the importance of non-food inputs in food security; therefore, it is not expected to be meaningfully impacted by biofuels development.

Finally, stability refers to the possibility that a population, household or individual has access to adequate food at all times. They should not risk losing access to food as a consequence of sudden shocks (eg, an economic or climatic crisis) or cyclical events (eg, seasonal food insecurity). The concept of stability can refer to both food availability and food access. Biofuels development can therefore affect the stability dimension of food security through the effects it can have on food availability, if fuel uses of agricultural commodities prevail over food uses or production of other food-related agricultural goods is displaced to produce biofuel feedstocks. Biofuel development can also affect food stability through the effect on food access, negatively if it leads to significant food price increases that reduce purchasing power, or positively if it increases purchasing power among farmers and the general population in biofuels producing regions.

Sugarcane production for biofuel conversion in Brazil is a good concrete example of how biofuels can enhance the stability dimension of food security. Sugarcane can be used in both sugar and ethanol production. The final use depends on relative prices and arbitrage among uses is facilitated because the industry has developed the technological capacity to jointly produce both final products, in different mixes within certain ranges (recall from Chapter 6 that several plants can jointly produce sugar and ethanol). Therefore, there is always the possibility of using a portion of sugarcane to produce sugar if the price is sufficiently attractive, even if the original intended used was in bioethanol. This arbitrage — at the plant level and driven by relative prices — then provides a mechanism to stabilize sugarcane farmers' income. The positive stability effects tend to be more effective when bioenergy and food markets are integrated and not affected by trade restrictions.

Concluding, the earth's base of natural resources allows sustainable bioenergy production in reasonable volumes. Impacts can be reduced if rational technological routes are adopted, such as sugarcane bioethanol. Broadly speaking, the use of more efficient technologies that reduce losses and rationalize farming production systems is more important than the large availability of natural resources vis-à-vis the mitigation of the food-feed-fuel trade offs.

Productivity increase can therefore provide an immediate alternative to the increasing demand for agricultural energy-related feedstocks derived from the bioenergy expansion. A good example of the positive impacts of technological improvement also comes from Brazil, where productivity increases and densification is the livestock sector led to increases in meat and milk production without increasing pasture land area. Data for the last 20 years indicates that cattle and the milk production increased by 32% and 67%, respectively, while the pasture area decreased by almost 4% [IBGE (2008)]. Moreover, average bovine density in the Brazilian livestock sector is approximately one head per hectare, while in the State of São Paulo it is 1.4 heads per hectare (ie, 40% higher). If the entire Brazilian livestock sector had a productivity level similar to São Paulo an area between 50 to 70 million hectares would be released for other agriculture uses [Jank (2007)]. Such area would be two to three times the surface required to produce enough bioethanol to substitute 10% of global gasoline consumption.

Models to assess the impact of bioenergy production on the food security and food prices

One way to evaluate the feasibility of expanding bioenergy production, broadly speaking, is the use of analytical models that take into account the multiple production and socioeconomic dimensions involved. In these models production and demand functions are represented by mathematical equations that replicate historical data and information. The models are used to simulate the effects of biofuel production in contexts and scenarios defined *a priori*, in order to support policy decision-making and implementation in the agricultural and bioenergy fields.

One of the most relevant initiatives is FAO's Bioenergy and Food Security Project (BEFS) launched in 2007 [FAO (2008)]. The project has been developing an analytical structure to assess the bioenergy and food security linkages and will be applied in specific countries. It is expected that the project will contribute with a strong and scientifically-based tool to the ongoing international debate on the possible benefits and problems of expanding bioenergy use.

The main objective of the analytical framework is to analyze the impact of different bioenergy production and utilization schemes on food security, which are specific for each country. The focus of the bioenergy and food security nexus analysis is on income and price changes that depend mainly on variation in land use patterns, on bioenergy and food production levels and on food and energy market prices. After a specific country scenario in selected, five steps are needed to carry-out the required analysis:

i) definition of bioenergy "technical biomass potential" using the model proposed by Smeets et al. (2006)] (see Graph 30);

ii) estimation of cost supply curves for food and biomass production;

iii) estimation of the "economic biomass potential";

iv) estimation of macroeconomic impacts of additional biomass on income, employment and prices; and

v). evaluation of the impact of income, price and employment changes on food security.

The evaluation looks at population groups that can be affected differently by bioenergy development. The selection of population groups is specific to countries and bioenergy scenarios. The project is currently active in Peru, Tanzania and Thailand and should be expanding to other countries.

Similar models have been developed by the International Food Policy Research Institute (IFPRI) and the United States Department of Agriculture (USDA).

IFPRI developed the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), which has been used to project global food supply, food demand and food security to the year 2020 and beyond. The model contain three categories of commodity demand: food, animal feed and other uses, including biofuels. The bioenergy-commodities considered are corn, sugarcane, sugar beet, wheat and cassava for bioethanol and soybean and other oilseed crops for biodiesel. Drawing on biofuels demand projections for the relevant countries and regions, IMPACT models three scenarios with regard to productivity and technology.

One of the main conclusion reached in the study is that there will be significant increases in world feedstock crops prices, especially for cassava under the scenario of aggressive biofuels growth without productivity change. That conclusion confirms the importance of efficiency in bioenergy development [IFPRI (2006)].

The Economic Research Service (ERS) of the USDA carried out a study to evaluate the impact of biofuels production on agricultural and food prices. In this study the impact of climatic effects and energy price increases on food prices is more important vis-à-vis the increase in biofuels production. In fact, it was estimated that only 3% of the increase in food prices can be attributed to corn-based bioethanol production; moreover, it points out that high oil prices have played a more important role. Data on the evolution of nominal prices from 1992 to 2008 indicates that oil prices increased by 547%, commodities prices (basically metals) by 286% and food by 98%. The study estimates that in the coming years the market can reach an equilibrium at a more adequate price level [ERS (2008)].

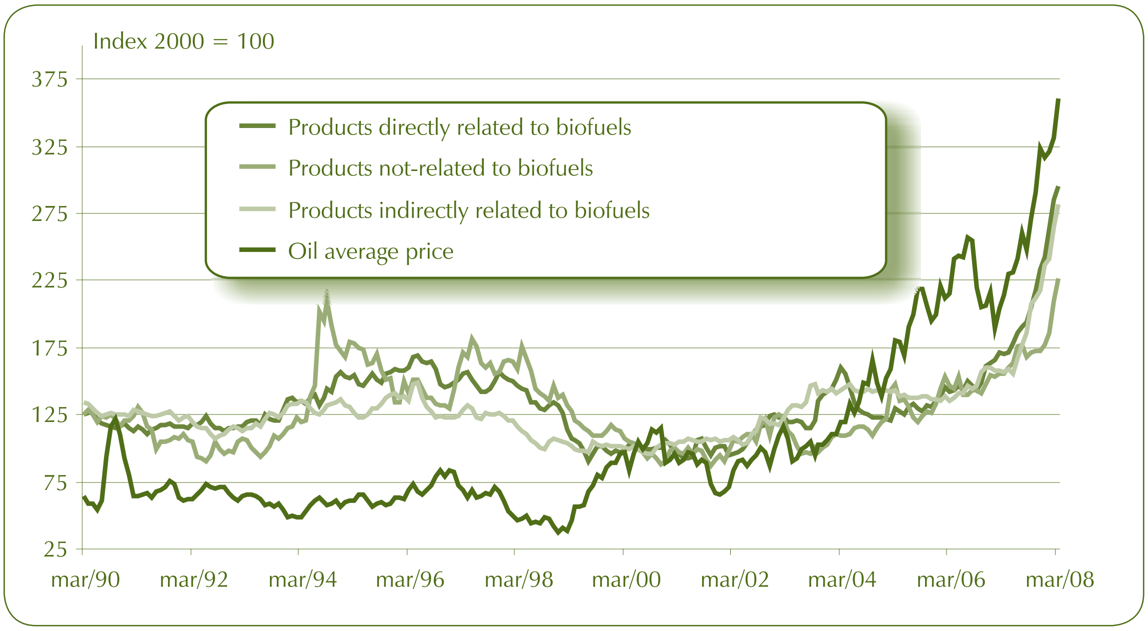
The significant difference in results between the IFPRI and USDA studies illustrates the limitations of modeling complex dynamic systems that are subject to stochastic behaviour. The usual approach is to broaden the complexity of the matrixes used, increasing the number of variables; however, such approach is restricted because the lack of detailed data for an adequate model calibration and implementation. Therefore, approaches are usually static with limited possibilities for application to more varied contexts. Nevertheless, such models are useful devices that compensate low predictive capacity with their use as tools for scenario exploration, in many cases following an approach more qualitative than quantitative. It must be recognized, however, that in the future more elaborated models could be developed, including adaptive logics and capable of simulating dynamic interactions between socioeconomic and bioenergy systems.

Evolution of international food and bioenergy commodities

This section presents an analysis of the evolution of nominal agricultural commodity prices between 1990 and 2008, using World Bank Data. The objective is to strengthen the discussion on the linkages between biofuel production and food prices and to characterize eventual relationships among the prices of different agricultural commodities. Agricultural commodities are classified in three groups, depending on whether they have a direct (sugar, corn, soybean oil and palm oil), indirect (meat and wheat) or no relationship (Arabica and Robusta coffee, tea and bananas) with biofuels production. The analysis does not intend to assess cause-effect relationships. The only objective is to illustrate that there is an increasing price interconnection between international oil and agricultural markets, which may be explained by several factors, including bioenergy expansion. However, determining the relative impact of different explanatory factors goes beyond the scope of this book. The analysis includes a series of figures that go from a general to more specific cases.

Graph 41 shows the evolution of a crude oil price index and three simple unweighed agricultural commodity price indexes. Since around the beginning of 2002 commodity prices have followed the general trend of crude oil prices. The relationship is more clear after March 2007, as both biofuel and biofuel-related commodities have increased at a rate similar to that of crude oil and significantly faster than non- biofuel related commodities.

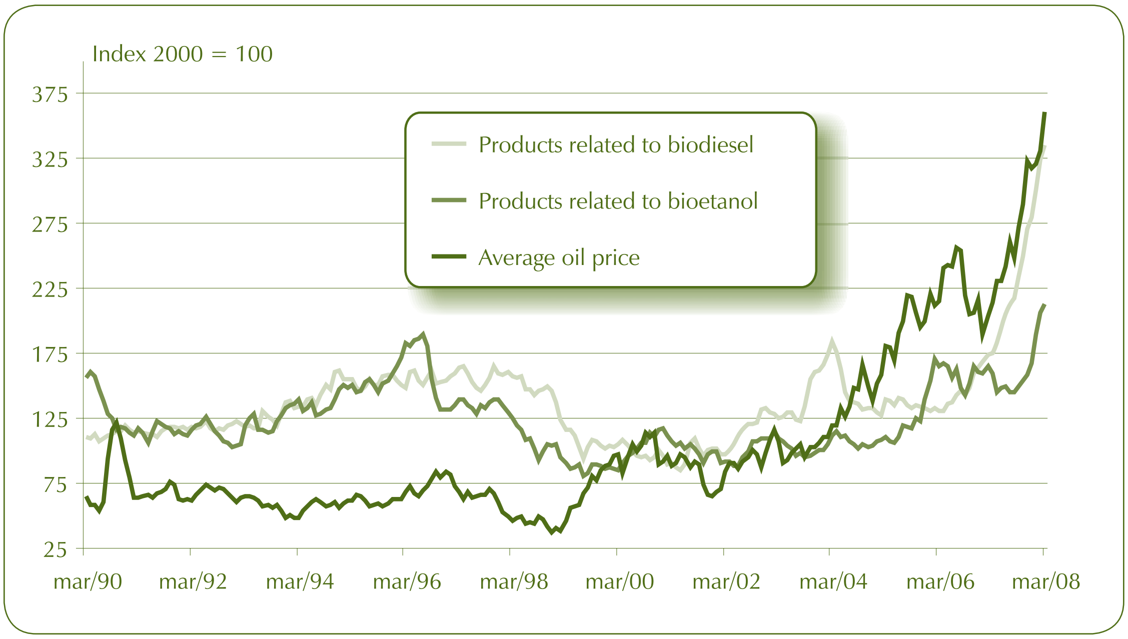
Graph 41 **– Price indexes for crude oil and agricultural commodities (January 1990 – March 2008; Average 2000 = 100)**



Source: Rodríguez (2008b).

Graph 42 distinguishes between biodiesel (vegetable, soybean and palm oils) and bioethanol (sugar and corn) commodities. Both sets of commodity prices show a general upward trend since the beginning of 2002; however, during the last two years biodiesel commodities have risen at a significantly faster rate than bioethanol commodities, very closely to the growing rate of crude oil prices.

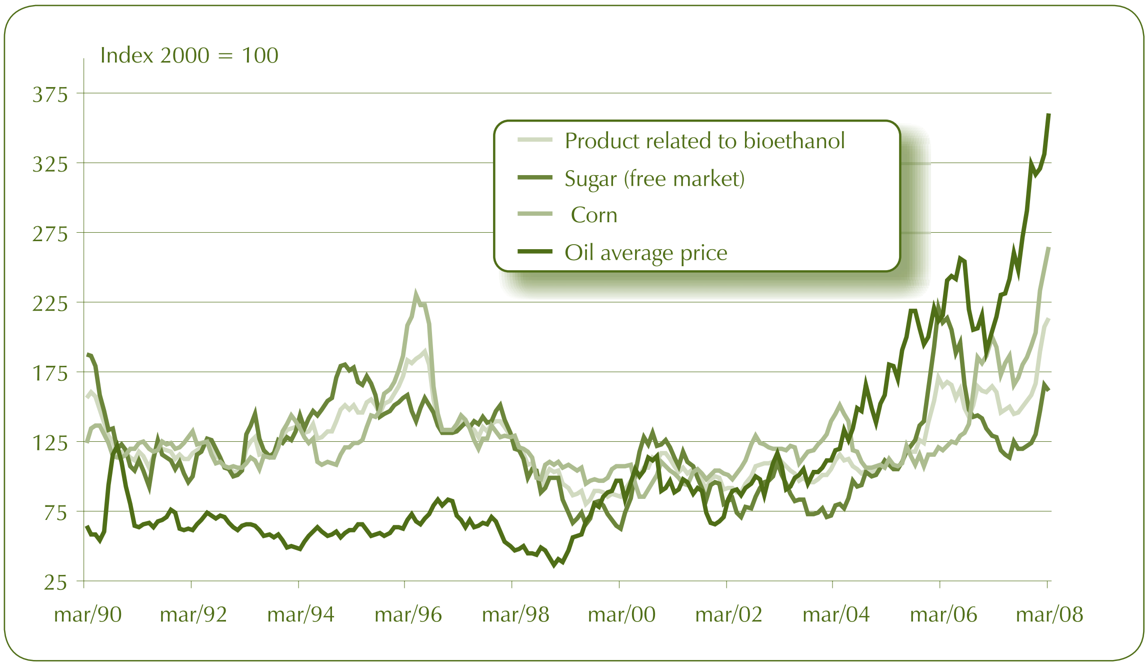
***Graph 42* –Price indexes for crude oil and agricultural commodities used in the production of bioethanol and biodiesel**
(January 1990 – March 2008; Average 2000 = 100)



Source: Rodríguez (2008b).

Graph 43 identifies each component of the bioethanol-commodity price index. The prices of corn and sugar — the two bioethanol commodities included in the analysis — evolved in opposite directions since 2002 and up to the middle of 2007. Since then both prices have increased steadily, following the growth in crude oil prices. The price of crude oil peaked in July 2006, dropped until January 2007 and increased at a sustained rate ever since. Both the prices of sugar and corn dropped after that peak; however, the reduction was more significant and lasted longer for sugar than for corn. The prices of both commodities started to increase again, following the escalation in crude oil prices that started in February 2007. However, the increase was significantly higher for corn, which reached its highest nominal average monthly price in March 2008, 14.4% higher than the previous historical peak in May 1996. On the other hand, the average price of sugar in March 2008 was 27% below the level reached in the historical peak of February 2006. In other words, the price of sugar, which is directly related to sugarcane, increased less than the price of corn.

***Graph 43* – Price indexes for crude oil and agricultural commodities used in bioethanol production**
(January 1990 – March 2008; Average 2000 = 100)



Source: Rodríguez (2008b).

Table 42 summarizes the relationship between the evolution of crude oil prices and agricultural commodity prices. It is clear that the strength of the relationships increase with time. Relationships are evaluated using simple correlation coefficients, which are statistical measures that indicates how strongly related are two variables: a positive value indicates that the variables evolve in the same direction; a zero value indicates no relationship and a negative value indicates that the variables evolve in opposite directions. As the values approach 1 or -1 the strength of the relationships increases. Table 42 shows that for bioethanol commodities there are important differences between sugar and corn prices. In the case of corn the strength of the relationship clearly increases with time; while in sugar it decreases after 2005.

In biodiesel commodities there is a change in the direction of the relationships, from negative and weak during the 1990s toward strong and positive after 2000, a tendency that further strengthened after 2005.

As Graphs 41, 42 and 43 and Table 42 show, there is a clear relationship between the evolution of petroleum and agricultural bioenergy-related commodities. The relationship, however, is lower in the case of sugar, which competes with bioethanol production from sugarcane. The international debate on this field will be enriched as more research is developed and better data becomes available. More research and better data can provide for a better understanding of the multiple factors that affect international food prices, reducing current speculation on the subject.

Table 42 **– Simple correlation coefficient between crude oil prices and biofuels-commodity prices, in different periods from January 1990 to March 2008**

Product	Period			
	1990 to 2008	1990 to 1999	2000 to 2008	2005 to 2008
Corn	0.43	0.04	0.76	0.74
Sugar	0.21	0.03	0.68	0.22
Soybean oil	0.61	-0.41	0.82	0.89
Palm oil	0.42	-0.44	0.81	0.86

Source: Rodríguez (2008b), using World Bank Data.

8.6 Key factors to induce a global bioethanol market

Adopting bioethanol as a component of the global energy matrix requires addressing a variety of issues. Previous sections in this chapter indicate there are solid production potential, expanding demands and strengthening markets for biofuels, with limited impacts on the availability and prices of food. In particular, the role of public policies is highlighted as strategic to foster advantages, mitigate risks and protect societal interests. Considering that context, this section provided some complementary comments on issues that are relevant for the emergence of an international biofuels market, emphasizing the role of sugarcane bioethanol in the global environmental agenda and the context of international negotiations on agricultural trade and environmental issues.

Global environmental challenges and bioethanol

Biofuels, including bioethanol, are explicitly discussed in global environmental negotiations, especially in the Convention on Biological Diversity (CBD) and in the United Nations Framework Convention on Climate Change (UNFCCC).

Biofuels production was the subject of a specific recommendation by the 12th Session of the Subsidiary Body on Scientific, Technical and Technological Advice (SBSTA) of the CBD [CBD (2008)]. The recommendation applies to both the positive and adverse effect of liquid biofuels production and use on «biodiversity and human well-being». The recommendation indicates that beneficial effects arise when biofuels production and use are associated with, among other: a reduction of fossil fuels consumption; a decrease in land use for agricultural purposes associated with the increase in energy output per area; a reduction in water used for irrigation and increased water use efficiency in crops; a reduction in the conversion of agricultural lands to other uses; and an increase of the income-base and economic opportunities in rural areas.

The recommendation also indicates that adverse effects arise when biofuels production and use are connected with: loss, fragmentation and degradation of valuable habitats such as natural and semi-natural forests, grasslands, wetlands and peatlands and carbon sinks, their biodiversity components and the loss of essential ecosystem services and leading to increase in greenhouse gas emission from these changes; competition for land managed for the production of alternative crops, including land managed by indigenous and local communities and small-holder farmers, and competition for the commodity prices potentially leading to food insecurity; increased water consumption, increased application of fertilizers and pesticides, increased water pollution and eutrophication, soil degradation and erosion; uncontrolled cultivation, introduction and spread of genetically modified organisms; uncontrolled introduction and spread of invasive alien species; and emissions from burning biomass and potential adverse effects on human health.

Thus, CBD/SBSTA recommendations converge with many of the sustainability points raised in other chapters (eg, Chapter 7), such as those related to the energy and carbon balances (local and global), natural resources and biological diversity, agricultural yields, land use and social criteria.

Biofuels also have been discussed in the context of UNFCCC fora because of the impact of climate change on agriculture and forest yields and the role of biofuels on GHG emissions, carbon balances, afforestation/reforestation, land use change, and other climate change mitigation and adaptation activities [UNFCCC (2008)]. The Kyoto Protocol identifies three mechanisms that allow industrialized countries to earn and trade emission credits through projects implemented in other developed countries or in developing countries, which they can use towards meeting their commitments. One of those, the Clean Development Mechanism (CDM), promotes projects that in addition to furthering sustainable development goals, involve activities that would not otherwise have occurred and result in real and measurable emission reductions.

The two most common type of CDM projects tend to be land use and energy related, which demonstrate there is potential for bioethanol production and use related projects. Despite such potential has not been sufficiently explored, there are examples of ongoing and planned CDM bioenergy projects, related to electric co-generation with sugarcane bagasse, with information available on methodologies to calculate emission reductions [CDM (2008)].

Certainly, an expanded bioethanol market, if promoted with sustainability criteria, should contribute to the objectives of the CBD and UNFCCC.

International bioethanol trade

As noted in this chapter, there are many challenges associated with the creation of an international bioethanol market. For example, Legal Tariff settings and production quality standards can affect the opportunities of developing countries in the international bioethanol market. Potential trade opportunities are reduced by measures that focus exclusively on enhancing production in industrialized countries, or by protectionist measures designed to limit market access. There are concerns that tariff escalation on biofuels in industrialized country markets force developing countries to export energy raw materials, such as unprocessed molasses and crude vegetable oils, leaving the more profitable value-added industrial phase of biofuel production to the importer countries. Two example of such protectionist policies are the current ad valorem duty of 6.5% on imports of biodiesel to the European Union and the duty of 0.54 US$/gallon (0.142 US$/litre) on most imported ethanol to the United States.

To address these concerns, a number of EU and US preferential trade promotion initiatives and agreements have been developed in recent years, offering new opportunities for developing countries to benefit from the increased global demand for biofuels. Preferential trade with the EU for developing countries falls under the EU's Generalised System of Preferences (GSP). Within that system there are provisions that affect the bioethanol sector provisions in the Everything But Arms (EBA) initiative and the Cotonou Agreement (that replaced the Lomé Convention). Under the current GSP, in effect until December 31st, 2008, duty-free access to the EU is provided to denatured or un-denatured alcohol. The GSP also has an incentive programme for ethanol producers and exporters who adhere to sustainable development and good governance [European Commission (2005)]. The EBA initiative provides least developed countries with duty free and quota-free access to ethanol exports, while the Cotonou Agreement provides duty free access to certain imports from Africa, Caribbean and Pacific low-income countries. Similarly, the Euro-Mediterranean Agreement has provisions for preferential trade in biofuel for certain countries in the Middle East and North Africa.

In the US ethanol may be imported duty free from certain Central American and Caribbean countries under the Caribbean Basin Initiative (CBI), although there are specific quantitative and qualitative restrictions depending on the country of origin of the feedstock, as previously observed. Provisions for duty-free ethanol imports are also included in the Free Trade Agreement between the US, Central America and the Dominican Republic.

It is important to note that despite these agreements do not change the general context of restrictions to biofuels trade, they represent important exceptions that must be valued.

Key issues for promoting bioethanol international trade include: the classification for tariff purposes of biofuel products as agricultural, industrial or environmental goods; the role of subsidies in increasing production; and the coherence between various domestic measures and World Trade Organization (WTO) standards. Since the biofuels industry did not exist when the current WTO rules were written, biofuels are not subject to the Harmonized Standard (HS) classification system, a situation that creates uncertainty because the HS affects how products are characterized under specific WTO agreements. For example, bioethanol is considered an agricultural product and is therefore subject to Annex 1 of the WTO Agreement on Agriculture (AoA). Biodiesel, on the other hand, is considered an industrial product and it is therefore not subject to AoA rules.

Some WTO members have suggested that renewable energy products, including bioethanol, should be classified as "environmental goods" and therefore subject to negotiations under the "Environmental Products and Services" cluster [Steenblik (2005)]. In this context, the Doha Development Agenda has launched negotiations on "the reduction or, as appropriate, elimination of tariff and non-tariff barriers to environmental goods and services". However, disagreement remains among countries on the identification of environmental goods, on the scope and approach to take for liberalizing trade in such products, and on mechanisms for regularly updating the list of products.

Biofuels will remain an important factor in Doha negotiations with some analysts even proposing that because of their impact on agricultural markets, they have the potential to rescue the failed round of agricultural trade negotiations held at the WTO [Turner (2006)]. Others are more pessimistic and consider that the new trade opportunities opening up in industrialized developed countries with the strong interest in biofuels are not likely to be protected by the rules-based system of the WTO. Instead, they foresee that taking advantage of such opportunities will be subject to less reliable unilateral decisions by countries to allow more imports to meet a given domestic demand [IIED (2007)]. Thus, a tariff could remain in place but not be applied or a lower tariff would be applied to a given volume of imports before the maximum tax went into effect. It is then possible that if imports are politically sensitive, because local producers or processors were threatened, or because the environmental standards in place in the production of imported biofuels were deemed inadequate by consumers, then the border could immediately close again without recourse for the exporting country of firm.

The conditions surrounding the Doha negotiations reproduce well the difficulties for global negotiations in the construction of healthy biofuels market. It is in the context of such difficulties that producing countries will have to make decisions and define strategies for bioethanol promotion, aiming to meet their development goals as well as energy, agriculture and trade demands. The strategies must be validated in light of their economic, social and environmental merits, national energy and carbon balances and opportunities for international trade, aiming toward participation in an eventual future international biofuels market, or prioritizing bioethanol production to meet national energy demand and promote rural development goals, for example.

Decisions of that nature will depend basically on how countries approach bioethanol development. A short-term view from producer and consumer countries could lead to a focus on exports and enhancing energy security. On the other hand, a long-term view would probably stress equity in the distribution of the economic and global environmental benefits from biofuels production. However, it is worth noting that national markets can pave the way for international biofuels trade through the establishment of infrastructure, logistics and managerial skills required in well developed biofuels production systems.

It is also important to indicate that developing proposals for biofuels programmes, especially bioethanol, in countries where biofuels do not exist, require detailed assessments and studies (eg, land use, biomass potential, demand) that allow to establish coherent goals. Certainly, bioenergy is not a panacea as it is not going to solve by itself global energy demands. Its advantages should be measured in specific contexts, as it has been repeatedly stressed in this book. Probably, the most important recommendation at this point is to valorize knowledge aggregation and to carry-out careful assessments of energy, environmental, economic and social implications.

Concluding, it is possible to foresee that a global bioethanol market could be a reality in a few years. Trade volumes and country participation will depend on several elements yet being defined, such as country's political decisions regarding their internal markets, discussions about sustainability criteria, international trade negotiations, as well as civil society responses in developing and developed countries. Indeed a complex and dynamic equation. Undoubtedly, bioethanol presents an global potential and therefore it demand global cooperation.

Chapter 9

An outlook for bioethanol fuel

Modern society is facing the worsening of environmental degradation while, at the same time, realizing that its reserves of natural resources, be they energy, water or metals are limited. In this context, energy plays a central role, compelling us to urgently rethink the foundations of an energy-supply model that is showing signs of depletion and seeks new resources which will allow continued socioeconomic development. Like a beacon amidst shortage, the sun, the underlying source of so many forms of energy and one of the few resources still underused by mankind, shines once again. Indeed, only a tiny fraction of the solar radiation reaching the Earth is currently captured through technological processes. There is although a huge potential for its use, but this requires the development of efficient and competitive technologies. Within this context, bioenergy has proven to be one of the best alternatives to capture and store solar energy, wherever idle land and favorable climate (sunlight, water and temperature) are matched by sufficent knowledge and an entrepreneurial spirit to apply it. In this light, it is worth recalling Henry Ford's visionary reflection published in 1934:

> I foresee the time when industry shall no longer denude the forests which require generations to mature, nor use up the mines which were ages in the making, but shall draw its raw material largely from the annual products of the fields. I am convinced that we shall be able to get out of the yearly crops most of the basic materials which we now get from forest and mine [Modern Mechanix (1934)].

Solar energy in the form of bioethanol, efficiently and sustainably produced, stands out among all available renewable energies to supply vehicle fuels. It is also able to meet pressing demands to reduce emissions of greenhouse gases, enhance air quality in large cities, and compete with conventional energies in terms of price. Additionally, it may provide a new dynamism for agroindutry in tropical countries with available land and a willingness to diversify away from concentrated and environmentally problematic energy sources, providing energy security and bringing new economic development.

The preceding chapters sought to demonstrate -- using the detail and reasoning that a document of this scope permits -- how the production of bioethanol from sugarcane, associated with the production of electric power, food and biomaterials, presents attractive returns and constitutes the best alternative to use labor, land, water and sunlight in the production of biofuels. This study also sought to demonstrate that this energy source still offers a great potential for improvement, developing its by-products and optimizig the agroindustrial processes. In the forthcoming years, production could exceed ten thousand liters of ethanol per hectare, with low exogenous energy requirements and emissions of greenhouse gases one-tenth of the amount generated using petroleum products with the same energy output.

The Brazilian experience in this field was accumulated over many decades, with its share of trial and error. Presently, it has hundreds of plants and millions of vehicles running normally, using fuel that a couple of months before was only water, carbon dioxide in the atmosphere and sunlight in sugarcane leaves. Therefore, Brazil can and must be a benchmark for other countries with similar conditions. Many countries could undertake efficient bioenergy programs, applying the Brazilian example to their characteristics, potential, and markets, but they apparently are reluctant, having doubts about the appeal of the solutions.

Similarly, many countries have tried to reduce their energy dependence, minimize their carbon emissions and enhance the air quality of their cities. However, they do not consider the use of bioethanol from sugarcane as an option, erecting barriers that protect alternatives that are not very efficient nor sustainable. Certainly, there is a lack of information and limited knowledge on the potential of bioethanol from sugarcane, even among energy and environmental decision makers. One of the main purposes of this book was to provide more comprehensive and objective information about this biofuel.

The most important points regarding bioethanol from sugarcane are emphasized below, well-documented and solidly based on decades of experience in Brazil with this type of biofuel. Together, these points demonstrate that bioethanol is a strategic and sustainable energy alternative, which can be replicated and adapted in countries with available land and suitable edaphoclimatic conditions:

1. Bioethanol can be used in vehicle engines, either pure or mixed with gasoline, delivering good performance and using the existing distribution and storage system for gasoline. In concentrations of up to 10%, the bioethanol effects on car fuel consumption are imperceptible and can be used in engines without requiring any modifications.

2. Bioethanol from sugarcane is produced with high efficiency in terms of the capture and conversion of solar energy (with an energy production/energy consumption ratio above 8). The productivity and yields achieved with current technology exceed all other biofuels, reaching 8000 l/ha plus generating significant energy surpluses, in the form of solid biofuels (bagasse and straw) and, principally, bioelectricity.

3. Bioethanol from sugarcane, produced under Brazilian conditions, is competitive with gasoline derived from petroleum priced at or above US$ 45 per barrel, with production costs largely determined by the cost of raw materials. The technology adopted for its production is open and available and can be gradually introduced in the sugarcane agroindustry currently focused on sugar manufacturing.

4. The local environmental impact on water resources, soil and biodiversity deriving from the production of bioethanol from sugarcane, resulting, among others, from the use of agrochemicals, have been effectively reduced to tolerable levels, lower than for most agricultural crops.

5 The use of bioethanol produced from sugarcane reduces the emissions of greenhouse gases by almost 90%, contributing to minimize climate change. Currently, for every million cubic meters of sugarcane bioethanol mixed with gasoline, there is an emission reduction of around 1.9 million tons of CO_2 into the atmosphere.

6 The prospects for further technological advancements in the production of bioethanol from sugarcane are substantial. These include increases in yields and energy performance (including in the agricultural phase), diversification of feedstocks, and special focus on hydrolysis and gasification, to increase the production of bioethanol and bioelectricity. The proper development of bio-energy programs depends fully on their continuous interaction with sources of innovation.

7 Even though the increasing mechanization of the sugarcane harvest has reduced the need for manual labor, employment in the bioethanol agroindustrial sector is growing and is still high per unit of energy produced compared to other energy sources.

8 The production of bioethanol from sugarcane, as developed in Brazil, does hardly affect food production. Cropland planted with sugarcane is limited compared to areas planted with food crops or areas available for expanding agricultural activities.

9 The sugarcane bioethanol agroindustry is linked to many other economic sectors and spurs the development of different areas, such as services, agricultural and industrial equipment and logistics. Fostering scientific and technological development is a key element in this production chain, critical to ensure the use of environmentally friendly and highly efficient raw materials.

10 Considering the availability of unused lands or lands used for low-productivity cattle-raising activities, the production of bioethanol from sugarcane is very likely to increase, not only in Brazil, but also in other tropical-humid countries.

Given that the virtues of bioethanol produced from sugarcane are not widely known or appreciated, it is advisable that private and public decision-makers and opinion-leaders receive accurate information so that they can take informed decisions on this energy source. Bioethanol could play an important role in the energy matrix of many countries. Nevertheless, because of the innovation involved and diversity of competing bioenergy development paths, it is understandable that there are concerns, prejudices and lack of information.

The starting point to a deeper understanding of the potential and limitations of biofuels is to recognize the importance of the production context. Many misconceptions found in studies involving the prospects of bioethanol arise from the oversimplified view that there is a raw material and a product; however, as discussed in Chapter 3, bioethanol production from sugarcane cannot be compared to the production of ethanol from other crops, especially in relation to the most important criteria of sustainability.

An example of this limited understanding is the use of the term "second generation biofuels" to refer to biofuels produced by emerging technologies, especially based on lignocellulosic residues requiring enzymatic hydrolysis or gasification followed by Fischer-Tropsch processes, as discussed in Chapter 5. Several studies and reports suggest that these biofuels will be the redeemers of bioenergy viability (that could then be considered a modern and sustainable source of energy), as long as they are economically competitive, present a good ratio between the energy produced and the energy consumed in production, cause minimal environmental impact, have potential to mitigate climate change, do not adversely affect food production, fully utilizing the raw material. But presently, all these conditions have already been met by sugarcane bioethanol. There is therefore no need to await technologies still in the stage of development and whose costs -- projected to be competitive within 20 years -- are of the same order as present costs incurred by the sugarcane agroindustry in tropical countries [IEA (2005)]. New technologies for bioethanol are certainly worth developing; however, sugarcane-based bioethanol is an alternative that is readily available and meets desirable economic, energy and environmental criteria.

Fortunately, the understanding of the potential of bioethanol from sugarcane is increasing and, in some important forums, it is now distinguished from other biofuels as the most rational and viable option. Specifically, documents from International Organizations are increasingly clear in recognizing that fostering bioethanol production through inefficient means and the adoption of barriers to sugarcane ethanol imports by developed countries have actually increased the distortions in the markets for energy and agricultural goods.

A study by the Organization for Economic Co-operation and Development (OECD) on the impact of biofuels on agricultural markets, for example, states that:

reducing such barriers (including the creation of international standards for biofuels) would not only allow the developing countries to better sell their products, but also help importing countries to fulfill the environmental goals set out in the national biofuel policies, provided that biofuels are produced in the exporting countries in an environmentally friendly manner [OECD (2007a)].

Other examples are the annual report of the International Monetary Fund, which shows how import barriers on efficient biofuels are harmful to all countries [IMF (2007)], as well as the bulletin of the World Bank's Energy Sector Management Assistance Program (ESMAP), which recommends the liberalization of international biofuel trade as a way to expand its energy and environmental efficiency [ESMAP (2007)].

By the same token, the United Nations Development Program (UNDP) clearly states in its Human Development Report 2007/2008 that:

International trade could play a much larger role in expanding markets for alternative fuels. Brazil is more efficient than either the European Union or the United States producing ethanol. Moreover, sugar-based ethanol is more efficient at cutting carbon emissions. The problem is that imports of Brazilian ethanol are restricted by high import tariffs. Removing these tariffs would generate gains not just for Brazil, but for also for climate change mitigation [UNDP (2007)].

The World Bank, in a document on solutions to the food supply crisis, signed by its President, expresses a similar opinion:

We need action in the US and Europe to ease subsidies, mandates and tariffs on biofuels from corn and oilseeds. The US's use of corn for ethanol has consumed more than 75 per cent of the increase in global corn production over the past three years. Policymakers should consider "safety valves" that ease these policies when prices are high. The choice does not have to be food or fuel. Cutting tariffs on ethanol imported into the US and European Union markets would encourage the output of more efficient sugarcane biofuels that do not compete directly with food production and expand opportunities for poorer countries, including in Africa [World Bank (2008)].

Developing global markets for bioethanol and expanding its benefits requires that this correct understanding of reality be transformed into effective measures.

Several measures need to be taken in order to create the markets discussed above and promote the development of biofuel production on a sustainable basis. These include the coordination and integration of national policies, and the preparation of feasibility studies which assess the opportunities for biofuel production, clearly identifying the challenges, adverse effects and advantages of each case. They also include, bolstering the knowledge of decision-makers, and promoting the articulation of trade policies and the struggle against climate change, according to the vision of a group of biofuel experts [Best et al. (2008)].

It is important to note that the modern sugarcane agroindustry still has important possibilities to diversify its products and increase energy resources, using technologies that are currently being developed or that are already being tested at the pilot level. Thus, they are increasingly moving towards becoming biorefineries, or production complexes capable of providing various types of bioenergy and biomaterials, including food and biodegradable plastics. Likewise, current agronomic studies aiming to preserve and diversify the germplasm base of sugarcane will expand from basic studies on the photosynthetic process, which still are on the frontier of knowledge, but show promising prospects to improve the energy and productive performance of this plant, that already is one of the most efficient converters of solar energy. The sugarcane agroindustry, indeed, is just starting to demonstrate its potential.

Certainly, there is much more to do and many challenges to overcome for the expansion of bioenergy systems, but the benefits will be equally large, since sustainable energy development is critical to consolidate a new relationship between nature and society. Based on this point of view the production and use of bioethanol from sugarcane offers a real potential to start building a new energy reality that is sustainable and which will make this agroindustry the lever for desirable social and economic transformations. The Brazilian model, improved over decades and with new possibilities of expanding with productivity and efficiency, is at the disposal of those countries that, due to their fuel needs, desire to competitively reduce their emissions of greenhouse gases and diversify their sources of energy, or which, given their climate, soil and people may successfully replicate the efficient production of biofuels for the use and benefit of all.

Appendix

Appendix 1 – **Production of sugar cane and anhydrous and hydrated alcohol in Brazil**

Year	Sugarcane production [tons, in millions][(1)]	Ethyl alcohol production [10^3 m^3][(2)]	Hydrated alcohol production [10^3 m^3][(2)]	Anhydrous alcohol production [10^3 m^3][(2)]
1975	88.92	580	360	220
1976	102.77	642	370	272
1977	120.01	1,388	300	1,088
1978	129.06	2,248	399	1,849
1979	139.27	2,854	527	2,327
1980	146.23	3,676	1,501	2,175
1981	153.78	4,207	2,859	1,348
1982	186.38	5,618	2,091	3,527
1983	216.45	7,951	5,395	2,556
1984	241.39	9,201	7,059	2,142
1985	246.54	11,563	8,419	3,144
1986	238.49	9,983	7,863	2,120
1987	268.58	12,340	10,185	2,155
1988	258.45	11,523	9,837	1,686
1989	252.29	11,809	10,315	1,494
1990	262.60	11,518	10,669	849
1991	260.84	12,862	10,818	2,044
1992	271.43	11,766	9,540	2,226
1993	244.30	11,395	8,869	2,526
1994	292.07	12,513	9,715	2,798
1995	303.56	12,745	9,742	3,003
1996	325.93	14,134	9,701	4,433
1997	337.20	15,494	9,823	5,671
1998	338.97	14,121	8,438	5,683
1999	331.71	12,981	6,807	6,174
2000	325.33	10,700	5,056	5,644
2001	344.28	11,466	4,985	6,481
2002	363.72	12,588	5,548	7,040
2003	389.85	14,470	5,638	8,832
2004	416.26	14,648	6,789	7,859
2005	419.56	16,040	7,832	8,208
2006	457.98	17,764	9,851	7,913

Fonte: [(1)] IBGE; [(2)] BEN 2007.

Appendix 2A – Area planted with sugarcane in Brazil

Year	Brasil		
	Production (1000 t)	Area harvested (1000 ha)	Average yield (t/ha)
1990	262,674	4,273	61,5
1991	260,888	4,211	62,0
1992	271,475	4,203	64,6
1993	244,531	3,864	63,3
1994	292,102	4,345	67,2
1995	303,699	4,559	66,6
1996	317,106	4,750	66,8
1997	331,613	4,814	68,9
1998	345,255	4,986	69,2
1999	333,848	4,899	68,1
2000	326,121	4,805	67,9
2001	344,293	4,958	69,4
2002	364,389	5,100	71,4
2003	396,012	5,371	73,7
2004	415,206	5,632	73,7
2005[1]	455,272	6,172	73,8

Appendix 2B – Area planted with sugarcane in principal producing states

Ano	Leading Producing States									
	São Paulo		Paraná		Alagoas		Minas Gerais		Pernambuco	
	Production	Área harvested	Produção	Área colhida	Produção	Área colhida	Produção	Área colhida	Produção	Área colhida
1990	137,835	1,812	11,736	159	26,151	559	17,533	298	22,818	467
1991	136,200	1,852	12,219	172	22,214	484	17,583	276	23,505	467
1992	145,500	1,890	13,571	186	22,669	448	17,354	272	25,199	488
1993	148,647	1,896	13,694	190	12,922	323	15,743	261	14,347	363
1994	174,100	2,173	15,946	216	21,740	439	16,212	262	19,259	400
1995	174,960	2,259	20,430	256	21,573	450	16,726	268	20,665	418
1996	192,320	2,493	23,468	285	20,754	432	13,331	247	18,784	401
1997	194,025	2,446	24,564	300	24,850	450	16,262	279	20,765	421
1998	199,783	2,565	26,642	310	28,524	461	16,918	279	19,622	402
1999	197,144	2,555	27,106	338	26,860	451	17,557	280	12,253	323
2000	189,040	2,485	23,192	327	27,798	448	18,706	291	15,167	304
2001	198,932	2,567	27,424	338	28,693	456	18,975	294	15,977	339
2002	212,707	2,661	28,083	359	25,171	438	18,231	278	17,626	348
2003	227,981	2,818	31,926	374	27,221	416	20,787	303	18,522	359
2004	239,528	2,952	32,643	400	26,284	423	24,332	335	19,015	364
2005[1]	266,071	3,285	34,882	437	23,991	397	31,587	424	18,832	370

Source: Production, area and average yield: IBGE – Agricultural Production by City (PAM – 1990 - 2004) and Systematic Reporting of Agricultural Production (LSPA –July 2006). Prepared by: Secretariat for Agricultural Policy – Ministry of Agriculture, Livestock and Supply (Mapa). Annual Report, 2005.

Note: [1] Estimate.

Appendix 3 – **Price paid for ethanol to the producer in São Paulo**

Year (semester)	Anhydrous alcohol (R$/liter)	Hydrated alcohol (R$/liter)
2000 (2)	0.668678	0.749999
2001 (1)	0.629092	0.716373
2001 (2)	0.623336	0.706785
2002 (1)	0.584636	0.503122
2002 (2)	0.6228	0.543285
2003 (1)	0.913213	0.783303
2003 (2)	0.653644	0.559895
2004 (1)	0.521573	0.454482
2004 (2)	0.832212	0.713184
2005 (1)	0.803179	0.70349
2005 (2)	0.883684	0.774705
2006 (1)	1.070215	0.998262
2006 (2)	0.908019	0.795583
2007 (1)	0.850049	0.763721
2007 (2)	0.719413	0.634066

Source: Center for Advanced Studies in Applied Economics (Cepea). <http://www.cepea.esalq.usp.br/alcool/>. Note: In June 2003, Cepea/Esalq Alcohol Indicators began to use CDI (Interbank Certificate of Deposit) to discount payments over time and no longer used the NPR. Since the week of May 6-10, 2002, weekly indicators for anhydrous alcohol and hydrates alcohol fuels began to be calculated without any tax or tariff (ICM, PIS/Cofins or Cide).

References

Abiove. “Estatísticas do Complexo da Soja”. Associação Brasileira das Indústrias de Óleo Vegetal, accessed in March 2008. www.abiove.com.br.

Abrantes, R. et al. “Caracterização das emissões de aldeídos de veículos do ciclo diesel”. *Revista de Saúde Pública*, São Paulo, v. 39 (3), 2002.

Aden, A. et al. *Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover.* Golden, Colorado: National Renewable Energy Laboratory, 2002 (Technical Report NREL TP-510-32438).

Aeroálcool. “Vantagens do uso do álcool em motores aeronáuticos”, accessed in April 2008. http://www.aeroalcool.com.br/vantagens.htm.

Agência Fapesp. “Notícias sobre etanol”. Fundação de Amparo à Pesquisa do Estado de São Paulo (Fapesp), accessed in April 2008. http://www.agencia.fapesp.br/.

Akiyama, M. et al. “Environmental life cycle comparison of polyhydroxyalkanoates produced from renewable carbon resources by bacterial fermentation”. *Polymer Degradation and Stability*, v. 80, 2003.

Alexander, M, “Ethanol Africa: clean maize fuel”. *Sustainable Development*, 2005, accessed in June 2008. http://www.southafrica.info/about/sustainable/ethanol-120905.htm.

Almeida, E. F. et al. *The performance of Brazilian biofuels: an economic, environmental and social analysis*. Rio de Janeiro: Instituto de Economia, Universidade Federal do Rio de Janeiro, 2007.

Alves, F. “Por que morrem os cortadores de cana?”. *Saúde e Sociedade*, São Paulo, v. 15 (3), 2006.

Amyris. “Amyris and Crystalsev join to launch innovative renewable diesel from sugarcane by 2010”. *Amyris Press Release*, April 2008.

Andersson, P. & Victorin, K. *Inhalation of ethanol: literature survey and risk assessment*. Stockholm: Institutet for Miljomedicin (Institute of Environmental Medicine), Karolinska Institute, 1996 (IMM Rapport 3/96).

Aneel – Agência Nacional de Energia Elétrica. “Banco de Informações de Geração”, accessed in March 2008. http://www.aneel.gov.br.

Anfavea – Associação Nacional dos Fabricantes de Veículos Automotores. “Anuário Estatístico da Indústria Automobilística Brasileira”. São Paulo: Anfavea, 2008.

ANP – Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. "Preços dos combustíveis", accessed in December 2007. http://www.anp.gov.br/index.asp.

______. "Qualidade dos combustíveis", accessed in February 2008. http://www.anp.gov.br/index.asp.

Antonil, A. J. *Cultura e opulência do Brasil*. Belo Horizonte: Itatiaia, 1982.

Apace Research. *Intensive field trial of ethanol/petrol blends in vehicles.* Apace Research Ltd, EDRC Project 211, Australia,1998.

API – American Petroleum Institute. *Alcohols and ethers, a technical assessment of their application as fuel and fuel components*. Washington: American Petroleum Institute, 1998 (API Publication 4.261).

______. *Shipping ethanol through pipelines.* American Petroleum Institute, accessed in November 2007. http://www.api.org/aboutoilgas/sectors/pipeline/.

Apla – Asociación Petroquímica y Química Latinoamericana. "Álcool é solução para indústria química". Asociación Petroquímica y Química Latinoamericana, acessed on June 2006. http://www.apla.com.ar/petroquimica2/mostrar.php?&id=3679.

Arrigoni, E. D. B. & Almeida, L. C. "Defensivos (pesticidas e outros)". Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005.

Assocana – Associação Rural dos Fornecedores e Plantadores de Cana da Média Sorocabana. *Custo médio operacional da lavoura da cana-de-açúcar*. Assis: Assocana, 2008.

Autoalliance. *Worldwide Fuel Chart*. 4th ed. Ecea, Alliance, EMA, Jama, September 2006.

Babu, S. P. *Observations on the current status of biomass gasification.* International Energy Agency (IEA) Task 33: Thermal gasification of Biomass, 2005.

Babu, S. P. & Hofbauer, H. "Status and prospects of biomass gasification". *Science in Thermal and Chemical Biomass Conversion Conference (STCBC)*, August 2004.

Balaji, R. *Oil cos in a bind gasohol supply.* Calcutta: Business Line (The Hindu Group), 2002.

Balsadi, O. V. "Mercado de trabalho assalariado na cultura da cana-de-açúcar no Brasil no período 1992-2004". *Informações Econômicas*, São Paulo, v. 37, n. 2, February 2007.

Baumol, W. J. "Contestable markets: an uprising in the theory of industry structure". *American Economic Review*, v. 72, 1982.

Berndes, G. et al. "The contribution of biomass in the future global energy supply: a review of 17 studies". *Biomass and Bioenergy*, v. 25 (1), 2003.

Bertelli, L. G. "A verdadeira história do Proálcool – Programa Nacional do Álcool". *O Estado de S. Paulo*, October 30, 2007.

Bertoncini, E. I. "Geração de resíduos da indústria da cana-de-açúcar". *Workshop: Aspectos Ambientais da Cadeia do Etanol de Cana-de-Açúcar*. Projeto Diretrizes de Políticas Públicas para a Agroindústria Canavieira do Estado de São Paulo, São Paulo, 2008.

Best. *Bioethanol for Sustainable Transport*, accessed in March 2008. http://www.best-europe.org/.

Best, G. et al. "A sustainable biofuels consensus". Bellagio: Rockefeller Foundation, Bellagio Center, April 2008.

BFS/FAO. "Second FAO Technical Consultation on Bioenergy and Food Security". Summary Proceedings, Roma, February 2008.

Bias – Baylor Institute for Air Science. *Development of renewable aviation fuels*. Baylor Institute for Air Science, Baylor University, accessed in September 2006. http://www.baylor.edu/bias.

Biocycle, accessed in March 2008. http:// www.biocycle.com.br.

Blanco-Canqui, H. & Lal, R. "Soil and crop response to harvesting corn residues for biofuel production". *Geoderma*, v. 141, 2007.

BNDES. "BNDES aprova financiamento de R$ 1,5 milhão para apoio a pesquisa de inovação em etanol", accessed in December 2007. http://www.bndes.gov.br/noticias/2007/not194_07.asp.

Branco, G. M. "Motores diesel: ecológicos ou poluidores?". *ECOinforme*, September 2004.

Brasil. "Decreto 19.717, Obrigatoriedade da adição de álcool à gasolina de procedência estrangeira". Rio de Janeiro, February 20, 1931.

Brusstar, M. & Bakenhus, M. "Economical, high efficiency engines technologies for alcohol fuels". US Environmental Protection Agency, 2005.

Burnquist, W. L. & Landell, M. "O melhoramento genético convencional e a disponibilidade de variedades". Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005.

Calvo, Guillermo. *Exploding commodity prices, lax monetary policy, and sovereign wealth fund*. VOX, 20 de junho de 2008. http://www.voxeu.org

CanaVialis. "Melhoramento genético", accessed in March 2008. http://www.canavialis.com.br/.

Carbogás. "Produção de CO_2 de grau alimentar", accessed in March 2008. http://www.carbogas.ind.br.

Carvalho, E. *Perspectivas da agroenergia*. São Paulo: Unica, 2007.

Carvalho, P. A. *Informações pessoais*. Rio de Janeiro: Superintendência de Qualidade de Produtos, Agência Nacional do Petróleo, 2003.

Castro, M. H. M & Schwartzman, S. *Tecnologia para a indústria: a história do Instituto Nacional de Tecnologia* [1981], accessed in April 2008. http://www.schwartzman.org.br/simon/.

Cavalcanti, E. *Importância da qualidade do álcool etílico combustível*. Presented in "I Seminário sobre Tecnologia para Pequena Produção de Álcool", Confederação Nacional da Agricultura, Brasília, 2007.

Cavalcanti, F. C. B. *Transformando competências em casos de sucesso: a Oxiteno e o desenvolvimento de tecnologia nacional em catalisadores*. Annals of "XII Congresso Brasileiro de Catálise", Sociedade Brasileira de Catálise, 2005.

CBD – Convention on Biological Diversity. *Recommendations. Convention on Biological Diversity*, accessed in April 2008. http://www.cbd.int/recommendations/?rec=XII/7.

CDM – Clean Development Mechanism. *United Nations Framework Convention on Climate Change*, accessed in April 2008. http://cdm.unfccc.int/index.html.

Cepal – Comissão Econômica para América Latina e o Caribe. *Fuentes Renovables de energia en América Latina y el Caribe: dos años después de la Conferencia de Bonn*. Santiago de Chile: Proyecto Cepal/GTZ, Economic Commission for Latin America and the Caribbean, 2007.

Cepea – Centro de Estudos Avançados em Economia Aplicada. *Preços de etanol anidro e hidratado*. Centro de Estudos Avançados em Economia Aplicada. April 2008. http://cepea.usp.br.

Cerri, D. G. P. *Agricultura de precisão em cana-de-açúcar: instrumentação de uma colhedora, mapeamento da produtividade e de atributos do solo*. Campinas: Universidade Estadual de Campinas, Faculdade de Engenharia Agrícola, 2005 (PhD Thesis).

Cetesb – Companhia de Tecnologia de Saneamento Ambiental. *Redução da queima da palha da cana-de-açúcar no Estado de São Paulo*. São Paulo: Companhia de Tecnologia de Saneamento Ambiental, March 2008.

CGEE – Centro de Gestão de Estudos Estratégicos. *Estudo sobre as possibilidades e impactos da produção de grandes quantidades de etanol visando à substituição parcial de gasolina no mundo – Fase 1*. Campinas: Nipe/Unicamp and Centro de Gestão de Estudos Estratégicos, 2005.

______. *Estudo prospectivo de solo, clima e impacto ambiental para o cultivo da cana-de-açúcar e análise técnica/econômica para o uso do etanol como combustível – Etanol Fase 3*. Campinas: Nipe/Unicamp and Centro de Gestão de Estudos Estratégicos, 2007a.

______. *Estudo sobre as possibilidades e impactos da produção de grandes quantidades de etanol visando à substituição parcial de gasolina no mundo – Fase 2*. Campinas: Nipe/Unicamp and Centro de Gestão de Estudos Estratégicos, 2007b.

______. *Informações aos autores*. Campinas: Centro de Gestão de Estudos Estratégicos, 2008.

ChevronTexaco Corp. *Motor Gasolines/Oxygenated Gasoline*, July 2006. http://www.chevron.com/prodserv/fuels/bulletin/motorgas/ch4.shtml.

CMAI – Chemical Market Associated Inc. *Petrochemical demand growth tracks economic growth*. Chemical Market Associated Inc., 2005.

CNPAB. *Fixação biológica de nitrogênio em plantas não leguminosas*. Embrapa Agrobiologia, April 2008. http://www.cnpab.embrapa.br/pesquisas/fbnnl.html.

Coelho, S. T. et al. *A expansão da cultura canavieira no Estado de São Paulo*. Presented in the "VI Congresso Brasileiro de Planejamento Energético" (6th Brazilian Congress of Energy Planning), Salvador, May 2008.

Concawe. "Well-to-wheels analysis of future automotive fuels and powertrains in the European context". Concawe, Eucar, European Commission, Version 2007c, March 2007. Access in May 2008. http://ies.jrc.ec.europa.eu/WTW.

Consonni, S. & Larson, E. D. "Biomass-gasifier/aeroderivative gas turbine combined cycles: Part A – Technologies and performance modeling". *ASME Journal of Engineering for Gas Turbines and Power*, v. 118, 1996a.

______. "Biomass-gasifier/aeroderivative gas turbine combined cycles: Part B – Performance calculations and economic assessment". *ASME Journal of Engineering for Gas Turbines and Power*, v. 118, 1996b.

Cortez, L. A. B. *A expansão da produção de álcool como programa de desenvolvimento nacional*. Presented in the scope of “Projeto Etanol”, Brasília, CGEE/Nipe, 2007.

Cresesb/UFPE/Chesf. *Atlas solarimétrico do Brasil.* Centro de Referência para Energia Solar e Eólica Sérgio de Salvo Brito (Cresesb), Universidade Federal de Pernambuco (UFPE) and Companhia Hidroelétrica do São Francisco (Chesf). Recife: UFPE, 2000.

CTC – Centro de Tecnologia Copersucar. *Diagrama de fases água/gasolina/etanol.* Piracicaba: Centro de Tecnologia Copersucar (currently Centro de Tecnologia Canavieira), 1998.

______. *Síntese do controle mútuo agroindustrial.* Piracicaba: Centro de Tecnologia Canavieira, 2005.

______. *Projetos e Pesquisas*. Centro de Tecnologia Canavieira. Access in April 2008 http://www.ctc.com.br/.

Cunha, F. *A logística atual de transporte das distribuidoras e a infra-estrutura para a exportação de álcool*. Petrobras Distribuidora, August 2003 (presentation in Power Point).

Dai, D. et al. “Energy efficiency and potentials of cassava fuel ethanol in Guangxi region of China”. *Energy Conversion and Management*, v. 47, 2006.

Dedini. *DHR Dedini Hidrólise Rápida*. Dedini Indústrias de Base. March 2008. http://www.dedini.com.br/pt/pdf/dhr.pdf.

Demeyer, A. et al. *La conversion bioenergetique du rayonnement solaire et les biotechnologies*. Paris: Technique et Documentation, 1985.

Dias Leite, A. *A Energia do Brasil*. Rio de Janeiro: Elsevier, 2007.

Dipardo, J. *Outlook for biomass ethanol production and demand*. Washington: Energy Information Administration, Department of Energy, 2000.

DOE – Department of Energy. *Breaking the biological barriers to cellulosic ethanol: a joint research agenda*, Report DOE/SC-0095, Office of Science and Office of Energy Efficiency and Renewable Energy, Department of Energy. Access in June 2006. http://www.doegenomestolife.org/biofuels/.

DOE/USDA. *Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply*. Washington: Department of Energy, US Department of Agriculture, 2005.

Donzelli, J. L. “Uso de fertilizantes na produção de cana-de-açúcar no Brasil“. In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil* e *a sua sustentabilidade*. São Paulo: Unica, 2005a.

______. "Erosão na cultura da cana-de-açúcar: situação e perspectivas". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005b.

Dröscher, M. *Kunststoffe: Werkstoffmärkte und Prognosen*. Kongress Zukunft der Werkstoff, Oberhausen, Frauenhofer Institut, Sep. 2006.

DuPont. *BioButanol*. Access in May 2008. http://www2.dupont.com/Biofuels/en_US/index.html.

EBAMM. *ERG Biofuels Analysis Meta-Model*. Release 1.0, Energy and Resources Group, University of California, Berkeley, 2005.

Ecoinvest. *Informações aos autores*. Empresa de investimentos e desenvolvimento de projetos MDL, Apr. 2008.

EIA – Energy Information Administration. *Petroleum Statistics*. Energy Information Administration, Department of Energy. Access in March 2008. http://www.eia.doe.gov/oil_gas/petroleum/info_glance/petroleum.html.

El Sayed, M. A. et al. *Production of ethanol from sugar beet (Appendix Q)*. Carbon and Energy Balance for a Range of Biofuels Options, DTI Project B/B6/00784, London, 2005.

Elia Neto, A. "Captação e uso de água no processamento da cana-de-açúcar". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005.

______. *Meio ambiente e setor sucroalcooleiro*. "Canasul 2007, I Congresso da Cadeia Produtiva da Cana-de-Açúcar em Mato Grosso do Sul" (1st Congress of the Sugarcane Production Chain in Mato Grosso do Sul), Campo Grande, 2007.

EPFL – École Polytechnique Fédérale de Lausanne. *The roundtable on sustainable biofuels: ensuring biofuels deliver on their promise of sustainability*. Energy Center, École Polytechnique Fédérale de Lausanne, 2008. Access in April 2008. http://cgse.epfl.ch/page65660.html.

ERS – Economic Research Service. *Global agricultural supply and demand: factors contributing to the recent increase in food commodity prices*. Washington: Economic Research Service, Department of Agriculture, 2008 (Report WRS-0801).

ESMAP – Energy Sector Management Assistance Programme. *Potential for biofuels for transport in developing countries.* Washington: Energy Sector Management Assistance Programme, United Nations Development Program/World Bank, 2005.

______. *Considering trade policies for liquid biofuels*. Washington: Energy Sector Management Assistance Programme, United Nations Development Program/World Bank, 2007.

Ethanolbus. *Ethanol buses in Sweden*. Access in March 2008. http://www.ethanolbus.com/.

European Commission. *Council Regulation (EC) nº 980/2005*. Bruxelas: European Commission, Jun. 2005.

Exame. "A nova fronteira do etanol". *Portal Exame*, 20.9.2007. Access in June 2008. http://portalexame.abril.com.br/revista/exame/edicoes/0902/economia/m0138746.html.

F. O. Licht. *World Ethanol Markets: Outlook to 2015*. Kent: F. O. Licht, 2006.

______. *World Sugar Yearbook 2007*. Kent: F. O. Licht, 2007.

______. "Cogeneration may be the next big story for the Brazilian sugar industry". *World Ethanol & Biofuels Report*, v. 6 (13), Mar. 2008 (2008a).

______. "Ghana: Sekab to source ethanol from Northern Sugar in 2010-20". *World Ethanol & Biofuels Report*, v. 6 (17), May 2008 (2008b).

Faaij, A. P. C. et al. *Long term perspectives of Biomass Integrated Gasification/Combined Cycle Technology: costs and electrical efficiency*. Utrecht: Novem/Department of Science, Technology and Society, Utrecht University, 1998.

Faaij, André & Domac, Julije. "Emerging international bio-energy markets and opportunities for socio-economic development. *Energy for Sustainable Development*, v. X, n. 1. p. 7-19, 2006.

FAO – Food and Agriculture Organization of the United Nations. *Climdata Rainfall Database*. Roma: United Nations Food and Agriculture Organization, Sustainable Development Department, Agrometeorology Group, 1997.

______. *Wood Energy Information System (WEIS)*. Preliminary report. Roma: Food and Agriculture Organization of the United Nations, Forestry Department, 2001.

______. "World agriculture: towards 2015/2030". In: Bruinsma, J. (ed.). *An FAO perspective*. London: Food and Agriculture Organization of the United Nations, Earthscan Publications, 2003.

______. *Global Forest Resources Assessment 2005*. Roma: Food and Agriculture Organization of the United Nations, 2006.

______. “Sugar: global market analysis”. *Food Outlook*. Roma: Food and Agriculture Organization of the United Nations, 2007a.

______. *What is food security*. Roma: Food and Agriculture Organization of the United Nations, 2007b.

______. *Soaring food prices: facts, perspectives, impacts and actions required*. Document HLC/08/INF/1, abr. 2008, presented at the “High-Level Conference on World Food Security: The Challenge of Climate Change and Bioenergy”, Rome, 3- 5 June.

FAOSTAT. *Sugar cane production*. Access in March 2008 (2008a). http://faostat.fao.org.

______. *Food commodities prices*. Access in April 2008 (2008b). http://faostat.fao.org

______. *Bioenergy and Food Security Project (BEFS)*. Access in May 2008 (2008c). http://www.fao.org/nr/ben/befs/.

FAPESP. *Brazil world leader in sugarcane and ethanol knowledge and technology (Fapesp´s contribution)*. São Paulo: The State of São Paulo Research Foundation, 2007.

FARGIONE, J. et al. “Land clearing and the biofuel carbon debt”. *Science*, v. 319 (5.867), 2008.

FARRELL, A. E. et al. “Ethanol can contribute to energy and environmental goals”. *Science*, v. 311 (27), 2006.

FAURÈS, J. M. *Competition for natural resources: the case of water*. “II FAO Consultation on Bioenergy and Food Security”, FAO, Roma, 2008.

FBDS – FUNDAÇÃO BRASILEIRA PARA O DESENVOLVIMENTO SUSTENTÁVEL. *Liquid biofuels for transportation in Brazil*. Projeto GTZ/FBDS. Rio de Janeiro: Fundação Brasileira para o Desenvolvimento Sustentável, 2005.

FERNANDES, A. C. *Cálculos na agroindústria da cana-de-açúcar.* 2nd ed. Piracicaba: Sociedade dos Técnicos Açucareiros e Alcooleiros do Brasil, 2003.

FRANKEL, Jeffrey. *The effect of monetary policy on real commodity prices.* Cambridge, MA: National Bureau of Economic Research, 2006 (Working Paper, 12.713).

______. *An explanation for soaring commodity prices.* VOX, March, 25 (2008a). http://www.voxeu.org

______. *Monetary policy and commodity prices.* VOX, May, 29 (2008b). http://www.voxeu.org

Frie, C. et al. *White paper: sustainable biofuels program: the need for biofuel certification/labelling*. Lausanne: École Polytechnique Fédérale de Lausanne, 2006.

Furey, R. L. *Volatility characteristics of gasoline-alcohol and gasoline-ether fuel blends*. Society of Automotive Engineers, 1985 (SAE Paper 852116).

Furtado, A. T. et al. *O sistema de inovação da agroindústria canavieira brasileira*. Presented at the "VI Congresso Brasileiro de Planejamento Energético" (6th Brazilian Congress of Energy Planning), Salvador, May 2008.

Galbe, M. & Zacchi, G. "A review of the production of ethanol from softwood". *Applied Microbiology and Biotechnology*, v. 59, 2002.

Gazeta Mercantil. "Etanol vai ter padrão mundial em 2008", *Gazeta Mercantil*, São Paulo, 7.2.2008.

Gnansounou, E. et al. *The Context of the Southern Africa Development Community (SADC)*. Sustainable Liquid Biofuels for Transport, Energy Center, École Polytechnique Fédérale de Lausanne, nov. 2007. Access in June 2008. http://lasen.epfl.ch/webdav/site/lasen/shared/Sustainable_Liquid_Biofuels_for_Transport-SADC.pdf.

Gava, G. J. C. et al. "Urea and sugarcane straw nitrogen balance in a soil-sugarcane crop system". *Pesquisa Agropecuária Brasileira*, Brasília, v. 40 (7), 2005.

GBEP. *A review of the current state of bioenergy development in G8 + 5 countries*. Access in April 2008. http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2007.

Genencor International Inc. "Genencor celebrates major progress in the conversion of biomass to ethanol". *Focus on Catalysts*, Dec. 2004.

Global Biofuels Center. "Informações aos autores" por Klein, T. [diretora executiva], 2008. http://www.ifqcbiofuels.org/.

Goldemberg, J. "Brazilian Energy Initiative". Presented at the "World Summit on Sustainable Development", Johannesburgo, Set. 2002.

Goldemberg, J. & Macedo, I. C. "The Brazilian Alcohol Program – An overview". *Energy for Sustainable Development*, v. 1 (1), 1994.

Goldemberg, J. et al. "The sustainability of ethanol production from sugarcane". *Energy Policy*, v. 36 (4), 2008.

Goldemberg, J. et al. "Ethanol learning curve: the Brazilian experience". *Biomass and Bioenergy*, v. 26 (3), 2004.

Goldemberg, J. et al. “The Brazilian Fuel-Alcohol Program”. In: Johansson, T. B. et al. (eds.). *Renewable energy: sources for fuels and electricity*. Washington: Island Press, 1993.

Gomes, M. G. F. M. “Experiência da Petrobras no transporte de etanol carburante”. *Revista Opiniões*, special issue on logistics in the sugarcane sector, Apr.-Jun. 2008.

Goodland, R. et al. (eds.). *Population, technology, and lifestyle: the transition to sustainability*. Nova York: Island Press, 1992.

GPC – Global Petroleum Club. *Oil from algae*. Global Petroleum Club. Access in February 2008. http://www.globalpetroleumclub.com.

Grabowski, P. *Biomass termochemical conversion: OBP efforts*. Washington: Office of Biomass Program, 2004.

Graf, A. & Koehler, T. *Oregon cellulose-ethanol study: An evaluation of the potential for ethanol production in Oregon using cellulose-based feedstocks*. Salem: Oregon Office of Energy, Jun. 2000.

Gray, K. A. et al. “Bioethanol”. *Current Opinion in Chemical Biology*, v. 10, 2006.

Guilhoto, J. J. M. “Geração de emprego nos setores produtores de cana-de-açúcar, açúcar e álcool no Brasil e suas macro-regiões”. *Cenários para o setor de Açúcar* e *Álcool* Report. São Paulo: MB Associados e Fipe, 2001.

Guimarães, M. et al. *Energia da biomassa – Alavanca de uma nova política industrial*. Brasília: Secretaria de Tecnologia Industrial, Ministério da Indústria e Comércio, 1986.

Hall, D. O. et al. “Visão geral de energia e biomassa”. In: Rosillo-Calle, F. et al. (orgs.). *Uso da biomassa para produção de energia na indústria brasileira*. Campinas: Unicamp, 2005.

Hall, D. O. & Rao, K. *Photosynthesis*. 6th ed. Cambridge: Cambridge University Press, 1999.

Hamelinck, C. N. *Outlook for advanced biofuels*. Utrecht: Universiteit Utrecht, 2004 (PhD Thesis).

Hamelinck, C. N. et al. *Production of FT transportation fuels from biomass: process analysis and optimisation, and development potential*. Utrecht: Copernicus Institute, Utrecht University, 2003 (Report NWS-E-2003-08).

Hamelinck, C. N. et al. *Future prospects for the production of methanol and hydrogen from biomass*. Utrecht: Science, Technology and Society/Utrecht University, 2001.

Hamelinck, C. N. et al. “Ethanol from lignocellulosic biomass: techno-economic performance in short, middle and long-term”. *Biomass and Bioenergy*, v. 28 (4), 2005.

Hasegawa, M. & Furtado, A. T. “Avaliação dos impactos de programas de P&D”. (Um estudo do ProCana). *Inovação Uniemp*, Campinas, v. 2 (3), 2006.

Hassuani, S. J. et al. “Biomass power generation: sugar cane bagasse and trash”. Piracicaba: PNUD-CTC, Caminhos para Sustentabilidade Series, 2005.

Heck, J. *Cogeração de eletricidade a partir do bagaço de cana*. Cia. Açucareira Vale do Rosário, 2006.

Hoogwijk, M. et al. “Exploration of the ranges of the global potential of biomass for energy”. *Biomass and Bioenergy*, v. 25 (2), 2003.

Horta Nogueira, L. A. *Perspectivas de un programa de biocombustibles en América Central*. Mexico City: Proyecto Cepal/GTZ Uso Sustentable de Hidrocarburos, Economic Commission for Latin America and the Caribbean, 2004.

______. *Costos y precios para etanol en Centro América*. Mexico City: Proyecto Cepal/Gobierno de Italia, Economic Commission for Latin America and the Caribbean, 2006a.

______. *Ethanol as fuel in Brazil (small distilleries and use of ethanol as cooking fuel)*. Belo Horizonte: Projeto Gaia, Winrock Fundation and Banco do Povo, 2006b.

______. *Biocombustíveis na América Latina: situação atual* e *perspectivas*. São Paulo: Cadernos do Memorial da América Latina, 2007.

______. *Sustainable woodfuel production in Brazil*. Roma: Food and Agriculture Organization of the United Nations, 2008.

Howeler, R. *Cassava in Asia: present situation and its future potential in agro-industry*. Bangkok: CIAT Cassava Office for Asia, Departament of Agriculture, 2003.

Ibama – Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis. *Proconve – Programa de Controle das Emissões Veiculares*. Brasília: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2006. Access in November 2006. http://www.ibama.gov.br/proconve.

IBGE – Instituto Brasileiro de Geografia e Estatística. “Pesquisa Nacional por Amostragem de Domicílios 2004”, *microdados Brasil*. Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística, 2005 (CD-ROM, 2005).

______. *Censo Agropecuário 2006* (Preliminary data). Access in April 2008. http://www1.ibge.gov.br/home/presidencia/noticias/.

Icrisat – International Crops Research Institute for the Semi-Arid Tropics. *Icrisat develops sweet sorghum for ethanol production*. International Crops Research Institute for the Semi-Arid Tropics, 2004. Access in May 2006. http://www.icrisat.org/media/2004/media13.htm.

Idea – Instituto de Desenvolvimento Agroindustrial. *Digital Usinas – Cadastro Nacional de Unidades Sucroalcooleiras*. Ribeirão Preto: Instituto de Desenvolvimento Agroindustrial, 2007.

______. "X Seminário de Mecanização e Produção de Cana-de-Açúcar". Instituto de Desenvolvimento Agroindustrial, Ribeirão Preto, 2008.

IEA – International Energy Agency. *Biofuels for transport: an international perspective*. Paris: International Energy Agency, 2004.

______. *World Energy Outlook*. Paris: International Energy Agency, 2007.

______. *Sustainable international bioenergy trade*. International Energy Agency. Access in March 2008. www.fairtrade.org.

IEA Bioenergy. *Potential contribution of bioenergy to the world's future energy demand*. Paris: International Energy Agency, 2007 (IEA Bioenergy Task 40).

IEL/Sebrae. *O novo ciclo da cana: estudo sobre a competitividade do sistema agroindustrial da cana-de-açúcar e prospecção de novos empreendimentos*. Brasília: Instituto Euvaldo Lodi/Serviço Brasileiro de Apoio às Micro e Pequenas Empresas, 2005.

IFPRI – International Food Policy Research Institute. *A 2020 vision for food, agriculture, and the environment, International Food Policy Research Institute*. Washington: International Food Policy Research Institute, 2006.

IIED. *The multilateral trade and investment context for biofuels: Issues and challenges*. Sophia Murphy Institute for Agriculture and Trade Policy, Dec. 2007. Access in May 2008. http://www.iatp.org/

Illovo. *International Sugar Statistics*. Illovo Sugar, 2008. Access in March 2008. http://www.illovosugar.com/worldofsugar

IMF – International Monetary Fund. "Making the most of biofuels". *World Economic Outlook*. Washington: International Monetary Fund, 2007.

India Infoline. *Sugar*. Access in March 2008. http://www.indiainfoline.com/sect/suin/ch07.html

Inovação Unicamp. "Oxiteno apresenta projeto ao BNDES para construir biorrefinaria; quer obter etanol a baixo custo para fabricar produtos químicos" [2006]. Access in March 2008. http://www.inovacao.unicamp.br/report/news oxiteno060807.shtml

______. "Diretor-executivo da Ridesa conta a história e o que faz a maior rede de pesquisa universitária em melhoramento genético da cana-de-açúcar" [2007]. Access in December 2007. http://www.inovacao.unicamp.br/etanol/report/entre-marcosridesa070522.php

______. "Empresas asiáticas investem US$ 170 mi na produção de lisina: componente de ração animal multiplica por sete valor do açúcar" [2008]. Access in March 2008. http://www.inovacao.unicamp.br/report/news-lisina.shtml.

Inpe – Instituto Nacional de Pesquisas Espaciais. *Projeto PRODES – Monitoramento da Floresta Amazônica Brasileira por Satélite*. Annual Estimates from 1988 to 2007, Instituto Nacional de Pesquisas Espaciais, 2008. Access in April 2008. http://www.obt.inpe.br/prodes/

Instituto Florestal. *Situação atual dos remanescentes da cobertura vegetal natural do Estado de São Paulo*. São Paulo: Secretaria de Meio Ambiente do Estado de São Paulo, 2004.

Iowa Corn. "How our corn crop was used in 2005-06". Access in March 2008. http://www.iowacorn.org.

IPCC – Intergovernmental Panel on Climate Change. *Climate Change 2007 – Synthesis Report*. Geneva: Intergovernmental Panel on Climate Change, WMO, Unep, 2008.

ISA – Instituto Socioambiental. *Desmatamento na Amazônia e agronegócio.* Instituto Socioambiental, 2008. Access in May 2008. http://www.socioambiental.org/nsa/detalhe?id=2357.

Janick, J. *Sugarcane*. Tropical Horticulture, Purdue University. Access in December 2007. http://www.hort.purdue.edu/newcrop/tropical/lecture_21/sugarcane_R.html

Jank, M. *Outlook for Brazilian ethanol technologies*. São Paulo: Unica, 2007.

Janssens, M. J. J. et al. *The role of photosynthesis and bio-productivity on bioenergy yields.* Bonn: University of Bonn, Institute of Crop Science and Resource Conservation, 2007.

Jin, H. et al. "Performance and cost analysis of future, commercially-mature gasification-based electric power generation from switchgrass". Draft Manuscript to *Biomass and Bioenergy*, nov. 2006.

Jornal do Commercio. "Coperbo: uma idéia feliz e adequada ao seu tempo". Access in December 1999. http://www2.uol.com.br/JC/_1999/80anos/80d_29.htm.

JornalCana. "Alltech reúne 400 produtores do Brasil e do mundo e anuncia início de atividades de fábrica de U$ 25 milhões no Paraná". *JornalCana*, 8.9.2005.

Joseph Jr., H. *Ethanol fuel: vehicular application technology*. São Paulo: Anfavea, Energy and Environment Division, 2005.

______. *Flex fuel technology in Brazil*. São Paulo: Anfavea, Energy and Environment Division, 2007.

Juergens, I. "Can biofuels make a significant contribution to sustainable energy supply?". *Biofuels – Global Issues*, The Foundation for Science and Technology, May 2007.

Junginger, M. et al. "A growing role: opportunities, challenges and pitfalls of the biofuels trade". *Renewable Energy World*, 2007.

Karlsson, M. *Integrated forest biorefinery*. Latin America European Union Biofuels Research Workshop, Campinas , 2007.

Keese, W. J. *Transition from methyl tertiary-butyl ether to ethanol in California*. Washington: (Chairman of California Energy Commission), Congress of the United States, House of Representatives, Committee on Government Reform, Subcommittee on Energy Policy, Natural Resources and Regulatory Affairs, Jul. 2003.

Koisumi, T. *Biofuel policies in Asia*. "FAO Expert Meetings 5 and 6", Roma, Feb. 2008.

Lamonica, H. M. *Potencial de geração de excedentes de energia elétrica a partir da biodigestão da vinhaça*. Presented at the "VI Congresso Internacional sobre Geração Distribuída de Energia no Meio Rural – Agrener 2006" (6th International Congress on Distributed Power Generation in Rural Areas) , Nipe, Unicamp, 2006.

Landell, M. "ProCana – O Programa Cana-de-Açúcar do Instituto Agronômico". *O Agronômico*, Campinas, v. 55 (1), 2003.

Larson, E. D. et al. "Large-scale gasification-based co-production of fuels and electricity from switchgrass". Draft Manuscript to *Biomass and Bioenergy*, Mar. 2006.

Larson, E. D. et al. *Gasification based liquid fuels and electricity from biomass with carbon capture and storage*. Presented at the "IV Annual Conference on Carbon Capture and Sequestration", Alexandria, 2005.

Larson, E. D. et al. "A review of biomass integrated-gasifier/gas turbine combined cycle technology and its application in sugarcane industries, with an analysis for Cuba". *Energy for Sustainable Development*, v. V (1), 2001.

LEAL, M. R. L. V. *Importância do álcool combustível na matriz energética brasileira*. Presented at the "Álcool de Bagaço de Cana-de-Açúcar" *workshop*, Instituto de Pesquisas Tecnológicas, São Paulo, Feb. 2005.

______. "The potential of sugarcane as an energy source". *Proceedings of the International Society of Sugar Cane Technologists*, v. 26, 2007.

______. "Informações aos autores", 2008.

LEITE, R. C. C. *Proálcool, a única alternativa para o futuro*. Campinas: Unicamp, 1990.

LORA, E. S. "Thermodynamics limits for the production of ethanol and electricity from sugarcane". *Zuckerindustrie*, v. 131 (11), 2006.

LOWCVP. "Well-to-wheel evaluation for production of ethanol from wheat". A Report by the LowCVP Fuels Working Group, WTW Sub-Group, Low Carbon Vehicle Partnership, London, 2004.

LUCON, O. *Aspectos ambientais na cadeia de biocombustíveis*. Presented at the "Aspectos Ambientais da Cadeia do Etanol de Cana-de-Açúcar" *workshop*, Projeto Diretrizes de Políticas Públicas para a Agroindústria Canavieira do Estado de São Paulo (Guidelines of Public Policies for the Sugarcane Agribusiness in the State of São Paulo Project), São Paulo, 2008.

LUENGO, J. M. et al. "Bioplastics from microorganisms". *Current Opinion in Microbiology*, v. 6, 2003.

LYND, L. R. *Tomorrow's biomass refineries*. Presented at the "XXVII Symposium on Biotechnology for Fuels and Chemicals", Golden, Colorado, 2005.

LYND, L. R. et al. "Likely features and costs of mature biomass ethanol technology". *Applied Biochemistry and Biotechnology*, v. 57/58, 1996.

MACEDO, I. C. "The sugar cane agro-industry and its contribution to reducing CO_2 emissions in Brazil". *Biomass and Bioenergy*, v. 3 (2), 1992.

______. "Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996)". *Biomass and Bioenergy*, v. 14 (1), 1998.

______. (coord.). *Sugar cane's energy – Twelve studies on Brazilian sugar cane agribusiness and its sustainability.* São Paulo: Unica, 2005.

______. *Biomass as a source of energy*. Report prepared for the InterAcademy Council Study on "Transitions to Sustainable Energy Systems", Sep. 2005.

______. “Cana-de-açúcar e energia renováveis no Brasil: a perspectiva tecnológica”. *Revista Opiniões*, special issue on renewable energies, Apr.-Jun. 2007.

______. “Informações aos autores”, 2008.

Macedo, I. C. & Horta Nogueira, L. A. “Balanço de energia na produção de açúcar e álcool nas usinas cooperadas”. *Boletim Técnico Copersucar*, v. 31/85, 1985.

______. “Biocombustíveis”. *Cadernos NAE 2*, Brasília, Centro de Gestão de Estudos Estratégicos e Núcleo de Assuntos Estratégicos (CGEE/NAE), 2005.

______. *Tecnologia e ciência para o desenvolvimento sustentável da bioenergia em São Paulo: cana-de-açúcar e outros vetores bioenergéticos*. Document prepared for the “Comissão Especial de Bioenergia do Estado de São Paulo” (Special Bioenergy Commission of the State of São Paulo), São Paulo, Aug. 2007.

Macedo, I. C. et al. *Balanço das emissões de gases do efeito estufa na produção e no uso do etanol no Brasil*. São Paulo: Secretaria do Meio Ambiente, Governo de São Paulo, Apr. 2004.

Macedo, I. C. et al. *Geração de energia elétrica e de gás de síntese a partir de gaseificação de biomassa*. Funcamp/Unicamp-Nipe/LH2 and Petrobras/Cenpes-Finep, Nov. 2006.

Macedo, I. C. et al. “Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020”. *Biomass and Bioenergy,* v. 32 (4), 2008.

Mandioca Brasileira. “Sistema de Informações Agroindustriais da Mandioca Brasileira”. Access in March 2008. http://www.mandioca.agr.br

Mapa – Ministério da Agricultura, Pecuária e Abastecimento. *Balanço nacional de cana-de-açúcar e agroenergia*. Brasília: Ministério da Agricultura, Pecuária e Abastecimento, Secretaria de Produção e Agroenergia, 2007.

______. *Cronologia da mistura carburante (álcool anidro – gasolina)*. Brasília: Ministério da Agricultura, Pecuária e Abastecimento, Secretaria de Produção e Agroenergia, 2008.

Martinot, E. *Renewables 2007 Global Status Report*. REN21 Network, 2007. Access in April 2008. http://www.martinot.info/RE2007_Global_Status_Report.pdf.

MCT – Ministério de Ciência e Tecnologia. *Mudanças climáticas*. Ministério de Ciência e Tecnologia, 2008. Access in March 2008. http://www.mct.gov.br/index.php/content/view/3881.html

Mears, M. *Ethanol Transportation & Distribution*. Magellan Midstream Holdings, Presentation in Power Point for Governors Ethanol Coalition, 2007.

Meirelles, A. J. A. *Expansão da produção de bioetanol e melhoria tecnológica da destilação alcoólica*. Campinas: Unicamp, 2006.

Milanez, A. Y. et al. *Perspectivas para o etanol brasileiro.* Rio de Janeiro: Departamento de Biocombustíveis/BNDES, 2008.

MME – Ministério de Minas e Energia. *Balanço Energético Nacional 2008/ano base 2007*. Rio de Janeiro: Ministério Minas e Energia, Empresa de Pesquisa Energética, 2008.

Modern Mechanix, "Henry Ford discusses America's Industrial Future", Dec. 1934.

Molin, J. P. "Agricultura de precisão em cana-de-açúcar é mais do que uma realidade". *Revista Coplana*, Guariba, Jan. 2008.

Moraes, M. A. F. D. "Número e qualidade dos empregos na agroindústria da cana-de-açúcar". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005.

______. "O mercado de trabalho da agroindústria canavieira: desafios e oportunidades". *Economia Aplicada*, Ribeirão Preto, v.11 (4), 2007.

Moreira, J. R. "Water use and impacts due ethanol production in Brazil". Linkages between Energy and Water Management for Agriculture in Developing Countries International Conference, Hyderabad, International Water Management Institute and Food and Agriculture Organization of the United Nations, Jan. 2007.

Moreira, J. R. & Goldemberg, J. "Política energética no Brasil". *Estudos Avançados*, São Paulo, v. 19 (55), 2005.

Nastari, P. "Estrangeiros dobram participação em açúcar e álcool no Brasil". Interview to Reuters agency, 25.9.2007.

______. *O mercado de etanol*. Presented at the "I Simpósio Internacional de Combustíveis, Biocombustíveis e Emissões" (1st International Symposium of Fuels, Biofuels and Emissions), Datagro, Associação Brasileira de Engenharia Automotiva, São Paulo, May 2008.

Native. *Projeto Cana Verde*. Access in May 2008. http://www.nativealimentos.com.br/cana_verde

NCGA – National Corn Growers Association. *Fossil energy use in the manufacture of corn ethanol*. National Corn Growers Association, 2008. Access in March 2008. http://www.ncga.com.

Neiva Embraer. *Aeronave Ipanema – Vantagens do motor a álcool*. Access in March 2008. http://www.aeroneiva.com.br/site/content/produtos/produtos_ipanema_vant_alc.asp.

Nguyen, T. L. T. et al. "Energy balance and GHG-abatement cost of cassava utilization for fuel ethanol in Thailand". *Energy Policy*, v. 35 (9), 2007.

NIST – National Institute of Standards and Technology. *White paper on internationally compatible biofuels standards*. National Institute of Standards and Technology, 2008. Access in March 2008. http://www.nist.gov/public_affairs/biofuels_report.pdf.

Nonato, R. V. *Plástico biodegradável a partir de açúcar*. Presented at the "V Workshop Internacional Brasil-Japão em Biocombustível, Meio Ambiente e Novos Produtos da Biomassa" (5th International Brazil-Japan Workshop on Biofuel, Environment and New Biomass Products), Campinas, 2007.

Nonato, R. V. et al. "Integrated production of biodegradable plastic, sugar and ethanol". *Applied Microbiology and Biotechnology*, v. 57, 2001.

Novozymes. *Fuel ethanol production: technological and environmental improvements*. Novozymes & BBI International, 2002.

NYBOT – New York Board of Trade. *Sugar prices – Contract No. 11*. New York Board of Trade, 2008. Access in January 2008. http://www.nybot.com/.

OCDE – Organização para a Cooperação e Desenvolvimento Econômico. *Agricultural market impacts of future growth in the production of biofuels*. Paris: Organização para a Cooperação e Desenvolvimento Econômico, 2007a.

______. *Economic survey of the European Union 2007: reforming agricultural and trade support*. Paris: Organização para a Cooperação e Desenvolvimento Econômico, 2007b.

Olade – Organización Latinoamericana de Energía. *Sistema de Informaciones Económicas y Energéticas (SIEE)*. Quito: Organización Latinoamericana de Energía, 2006.

Ondrey, G. "The path to biorefineries". *Chemical Engineering*, v. 113 (4), 2006.

Orbital Engine Company. *A literature review based assessment on the impacts of a 10% and 20% ethanol gasoline fuel blend on non-automotive engines*. Orbital Engine Company, report for Environment Australia, 2002.

Ortolan, M. C. A. *Relacionamento entre indústrias e fornecedores: mercado atual e futuro*. Presented at the "I Congresso de Tecnologia na Cadeia Produtiva em Mato Grosso do

Sul” (1st Technology Congress in the Production Chain in Mato Grosso do Sul), Canasul 2007, Campo Grande, 2007.

Owen, K. & Coley, T. *Automotive fuels reference book*. 2nd ed. New York: Society of Automotive Engineers, 1995.

Pádua Rodrigues, A. *Informações pessoais*. Unica, Nov. 2006.

Pesquisa Fapesp. “Riqueza nas sobras das usinas”. *Revista Pesquisa Fapesp*, v. 76, Jun. 2002.

Petrobras. *Produtos e Serviços – composição de preços, cadeia de comercialização e composição dos preços da gasolina e do óleo diesel no Rio de Janeiro*. Access in April 2008. http://www2.petrobras.com/produtos _serviços/

Philippidis, G. P. & Smith, T. K. “Limiting factors in the simultaneous saccharification and fermentation process for conversion of cellulosic biomass to fuel ethanol”. *Applied Biochemistry and Biotechnology*, v. 51/52, 1995.

Phillips, S. et al. *Thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass*. Golden, Colorado: National Renewable Energy Laboratory, 2007 (Technical Report TP-510-41168).

Pimentel, D. & Patzek, T. W. “Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower”. *Natural Resources Research*, v. 14 (1), 2005.

Pires, A. “Bicombustíveis serão 32% dos carros no Brasil em três anos”. Centro Brasileiro de Infra-Estrutura, interview published in several newspapers, Rio de Janeiro, 26.4.2007.

Pizaia, W. *Steam economy improvement*. Report RLT-025 for MCT/PNUD. Projeto BRA/96/G31, Geração de Energia Elétrica por Biomassa, Bagaço de Cana-de-Açúcar e Resíduos (BRA/96/G31 Project, Electric Energy Generation by Biomass, Sugarcane Waste and Waste), Brasília , 1998.

Pordesimo, L. O. et al. “Distribution of aboveground biomass in corn stover”. *Biomass and Bioenergy*, v. 26 (4), 2004.

ProCana. *Conheça o setor: dados da safra 2006/07*. Access in March 2008. http://www.jornalcana.com.br/Conteudo/.

Ragauskas, A. J. et al. “The path forward for biofuels and biomaterials”. *Science*, v. 311, Jan. 2006.

Rauch, R. *Biomass gasification to produce synthesis gas for fuel cells, liquid fuels and chemicals*. Technology Brief, IEA Bioenergy Agreement – Task 33: Thermal Gasification of Biomass, 2002.

Refuel. *Eyes on the track, mind on the horizon (from inconvenient rapeseed to clean wood: a European road map for biofuels)*. Access in May 2008. http://www.refuel.eu/refuel-project/.

REN21. *Renewables 2007 Global Status Report*. Washington: Worldwatch Institute, 2008.

RFA – Renewable Fuels Association. *Annual Industry Outlook 2008*. Renewable Fuels Association, 2008. Access in February 2008. http://www.ethanolrfa.org.

Ricci Jr., A. "Proteção de nascentes e cursos de água". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005a.

______. "Defensivos: herbicidas". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005b.

Ricupero, R. "Mais comida – e muitos mais comensais". *O Estado de S. Paulo*, Caderno Aliás, May 4th 2008.

Ridesa. Rede Interuniversitária para o Desenvolvimento do Setor Sucroalcooleiro. Access in February 2008. http://www.ridesa.org.br/

RIRDC – Rural Industries Research and Development Corporation. *Sugar beet preliminary feasibility of ethanol production from sugar beet in NE Tasmania*. Canberra: Department of Primary Industries, Water and Environment, Rural Industries Research and Development Corporation, Australian Government, 2007.

Rissardi Jr., D. J. & Shikida, P. F. A. "A agroindústria canavieira do Paraná pós-desregulamentação: uma abordagem neoschumpeteriana". *Revista de Economia e Sociologia Rural*, Brasília, v. 45 (2), 2007.

Rodríguez, A. G. "Seguridad alimentaria y biocombustibles". In: *Biocombustibles como energía alternativa: una mirada hacia la región*. Quito: Centro Ecuatoriano de Derecho Ambiental, 2007.

______. *Análisis de los mercados de materias primas agrícolas y de los precios de los alimentos*. Santiago de Chile: Unidad de Desarrollo Agrícola/Cepal, Aug. 2008a (Documento de Trabajo).

______. "Information on biofuel commodity prices (based on World Bank data)". In: Cepal. *Agricultural Development Unit.* Santiago: Economic Commission for Latin America and the Caribbean, 2008b (Internal document).

Rossell, C. E. V. & Olivério, J. L. *Produção de álcool a partir do bagaço: o processo DHR – Dedini Hidrólise Rápida*. Dedini S/A Indústrias de Base, Piracicaba, Mar. 2004.

Rossetto, R. "A cultura da cana, da degradação à conservação". *Visão Agrícola*, Esalq-USP, ano 1, 2004.

Sachs, I. *Brasil: desafios da energia para o desenvolvimento sustentável*. Lecture given at the Memorial da América Latina (Memorial of Latin América), São Paulo, Mar. 2007.

Salih, F. M. & Andrews, G. E. *The influence of gasoline/ethanol blends on emissions and fuel economy*. Society of Automotive Engineers Fuel and Lubricants Meeting, San Francisco, 1992 (SAE Paper 922378).

Scandiffio, M. I. G. *Análise prospectiva do álcool combustível no Brasil – Cenários 2004–2024*. Campinas: Universidade Estadual de Campinas, Faculdade de Engenharia Mecânica, 2005 (PhD Thesis).

Scania. "New highly efficient diesel-ethanol engine – ready to cut fossil CO_2 emissions by 90%". *Scania Press Info*, P07503EN, May 2007.

Scaramucci, J. A. & Cunha, M. P. "Aspectos sócio-econômicos do uso energético da biomassa de cana-de-açúcar". In: Cortez, L. A. B. & Lora, E. E. S. *Tecnologias de conversão energética da biomassa*. 3rd ed. Campinas: Unicamp (on print).

Schuchardt, U. et al. "A indústria petroquímica no próximo século: como substituir o petróleo como matéria prima?". *Química Nova*, v. 24, n. 2, 2001, pp. 247-251.

Scientific American Brasil. "Mistura em pleno vôo: depois de inovar com o avião a álcool, país desenvolve motor aeronáutico flex fuel". *Scientific American Brasil*, n. 44, Jan. 2006.

Seabra, J. E. A. *Análise de opções tecnológicas para uso integral da biomassa no setor de cana-de-açúcar e suas implicações*. Campinas: Universidade Estadual de Campinas, Faculdade de Engenharia Mecânica, 2008 (PhD Thesis).

Seabra, J. E. A. & Macedo, I. C. *Demanda de energia para a produção de PHB a partir do açúcar da cana*. Report prepared for PHB Industrial S.A., Campinas, 2006.

Serôa da Motta, R. & Ferreira, L. R. "The Brazilian National Alcohol Programme: an economic reappraisal and adjustments". *Energy Economics*, Jul. 1988.

Silvestrin, C. R. *Dependência Elétrica de São Paulo: Desafios & Oportunidades*. São Paulo: Cogen-SP, Secretarias de Desenvolvimento e de Saneamento e Energia do Estado de São Paulo, March 2007.

SMA – Secretaria de Meio Ambiente do Estado de São Paulo. "Vinhaça: critérios e procedimentos para aplicação no solo agrícola". *Norma Técnica Cetesb P4.231*, Secretaria de Meio Ambiente do Estado de São Paulo, 2005.

Smeets, E. et al "A bottom-up assessment and review of global bio-energy potentials to 2050". *Progress in Energy and Combustion Science*, doi:10.1016/j.pecs.2006.08.001, 2006.

Smeets, E. et al. *Sustainability of Brazilian bio-ethanol*. Utrecht/Campinas: Copernicus Institute/Utrecht University, Universidade Estadual de Campinas, 2006 (Report NWS-E-2006-110).

Smil, V. *General energetics: energy in the biosphere and civilization*. New York: Wiley, 1991.

Soares, M. L. Q. *Direitos humanos, globalização e soberania*. Belo Horizonte: Inédita, 1997.

Soares, R. A. B. *Uso da agricultura de precisão na Usina Jalles Machado*. Presented at the "Congresso Brasileiro de Agricultura de Precisão – Conbap 2006" (Brazilian Congress of Precision Agriculture), Piracicaba , 2006.

Sopral – Sociedade de Produtores de Açúcar e de Álcool. *Avaliação de caminhões e tratores a álcool*. Coleção Sopral 3. São Paulo: Sociedade de Produtores de Açúcar e de Álcool, 1983.

SOW-VU. *China's rapidly growing meat demand: a domestic or an international challenge?* Amsterdam: Center for World Food Studies, 2007.

Souza, S. A. V. "Disponibilidade e uso de água no Brasil: irrigação". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil* e *a sua sustentabilidade*. São Paulo: Unica, 2005a.

______. "Vinhaça: o avanço das tecnologias de uso". In: Macedo, I. C. (org.). *A energia da cana-de-açúcar: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade*. São Paulo: Unica, 2005b.

Steenblik, R. *Liberalising trade in "environmental goods": some practical considerations.* Paris: OCDE, 2005 (OECD Trade and Environment Working Paper No. 2005-05).

Strapasson, A. "Governo prepara estudo para mapear áreas adequadas para plantio de cana-de-açúcar em grande escala" [Information provided in note]. *Inovação Unicamp*, March 10th 2008.

Sun, Y. & Cheng, J. "Hydrolysis of lignocellulosic materials for ethanol production: a review". *Bioresource Technology*, v. 83, 2002.

Szmrecsányi, T. *O planejamento da agroindústria canavieira no Brasil (1930-1975).* São Paulo: Hucitec, 1979.

Szwarc, A. *Informações aos autores*. Unica, April 2008.

Teixeira, C. G. et. al. "Utilização do sorgo sacarino como matéria-prima complementar à cana-de-açúcar para obtenção de etanol em micro-destilaria". *Ciência e Tecnologia de Alimentos*, Campinas, v.17 (3), 1997.

Tereos. *Bio-ethanol*. Access in May 2006. http://www.tereos.com.

The House of Commons. "Are biofuel sustainable?". *First Report of Session 2007–08*, Environmental Audit Committee, Londres, 2008.

Toyota. *Support for diversification of alternative fuels*. Toyota Technology, 2007. Access in November 2007. http://www.toyota.co.jp/en/tech/environment/powertrain/.

Trindade, S. *Fuel ethanol issues in thailand: ethanol production, stillage disposal and market penetration*. *Report to UN/DTCD* (draft), Nova York, 1985.

TSB – Transportation Systems Branch. *Use of higher than 10 volume percent ethanol/gasoline blends in gasoline powered vehicles*. Ottawa: Transportation Systems Branch, Air Pollution Prevention Directorate, Environment Canada, 1998.

Turkenburg, W. C. et al. "Renewable energy technologies". In: Goldemberg, J. (ed.). *World energy assessment of the United Nations*. Chapter 7. New York: UNDP, Undesa/WEC. UNDP, 2000.

Turner, T. "Biofuels, agriculture and the developing world". In: *Linking trade, climate change and energy*. Geneva: ICTSD, 2006. Access in April 2008. http://www.trade-environment.org/output/ictsd/resource/Energy_issuebriefs.pdf.

Ulate, W. *Perspectivas de uso actual y futuro de etanol carburante en Costa Rica*. San José: Refineria Costarricense de Petróleo, 2006.

UNDP – United Nations Development Program. *Human development report 2007/2008 – Fighting climate change: human solidarity in a divided world*. New York: United Nations Development Program, 2007.

UN-Energy. *Sustainable bioenergy: a framework for decision makers*. New York: United Nations, 2007. Access in May 2008. http://esa.un.org/un-energy/pdf/susdev.Biofuels.FAO.pdf.

UNEP – UNITED NATIONS ENVIRONMENTAL PROGRAM. *Working papers 2007*. United Nations Environmental Program, 2008. Access in March 2008. www.unep.org.

UNFCCC – UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE. *Kyoto Protocol*. United Nations Framework Convention on Climate Change, 2008. Access in April 2008. http://unfccc.int/kyoto_protocol/items/2830.php.

UNICA – UNIÃO DA INDÚSTRIA DE CANA-DE-AÇÚCAR. *Produção e uso do etanol combustível no Brasil: respostas às questões mais freqüentes*. São Paulo: União da Indústria de Cana-de-Açúcar, 2007.

______. *Estatísticas*. União da Indústria de Cana-de-Açúcar, 2008. Access in January 2008. http://www.portalunica.com.br.

UNITED NATIONS. *Our common future*. New York: World Commission on Environment and Development, 1987.

UPME – UNIDAD DE PLANEACIÓN MINERO ENERGÉTICA. *Los biocombustibles en Colombia*. Bogotá: Ministerio de Energía y Minas, Unidad de Planeación Minero Energética, 2006.

URQUIAGA, S. et al. *A importância de não queimar a palha na cultura da cana-de-açúcar*. Seropédica: Embrapa, Centro Nacional de Pesquisa de Biologia do Solo, 1991.

USDA – UNITED STATE DEPARTMENT OF AGRICULTURE. *Data and Statistics*. United State Department of Agriculture, 2008. Access in February 2008. http://www.usda.gov.

VAN DER LAAN, G. P. *Kinetics, selectivity and scale up of the Fischer-Tropsch Synthesis*. Groningen: University of Groningen, 1999 (PhD Thesis).

VARGAS, M. *História da técnica e da tecnologia no Brasil*. São Paulo: Unesp, 1994.

VENTURI, P. & VENTURI, G. "Analysis of energy comparison for crops in European agricultural systems". *Biomass and Bioenergy*, v. 25 (3), 2003.

VIEIRA, M. C. A. et al. *Setor sucroalcooleiro brasileiro: evolução e perspectivas*. Rio de Janeiro: Deagro/BNDES, 2006.

WALTER, A. C. S. & ENSINAS, A. *Produção de eletricidade a partir da biomassa da cana-de-açúcar*. Presented at "Abimaq" workshop, Ribeirão Preto, 2006.

WALTER, A. C. S. & HORTA NOGUEIRA, L. A. "Produção de eletricidade a partir da biomassa". In: CORTEZ, L. A. B. & LORA, E. E. S. *Tecnologias de conversão energética da biomassa*. 2nd ed. Manaus: Universidade do Amazonas, 2007.

Waste online. *Plastics recycling information sheet*. Access in February 2008. http://www.wasteonline.org.uk.

Werpy, T. A. et al. ”Top value added chemicals from biomass”. Presented at the “XXVII Symposium on Biotechnology for Fuels”, Golden, Colorado, 2005.

Whims, J. *Pipelines considerations for ethanol*. Sparks Companies, Inc., Agricultural Marketing Resource Center, Kansas State University, 2002.

White House. “New Energy Act 2007”. Access in April 2008. http://www.whitehouse.gov/news/releases/2007/12/20071219-1.html.

Williams, R. H. et al. *Low-carbon liquid fuel and electricity from coal and crop residues with CO_2 capture and storage*. Presented at the “GCEP International Workshop” (Stanford University, Tsinghua University and Zheijiang University), Beijing, 2005.

Wolf, J. et al. “Exploratory study on the land area required for global food supply and the potential global production of bioenergy”. *Agricultural Systems*, v. 76 (3) 2003.

Wooley, R. et al. *Lignocellulosic biomass to ethanol – Process prehydrolysis and enzymatic hydrolysis – Current and futuristic scenarios*. Golden, Colorado: National Renewable Energy Laboratory, 1999 (Report TP-580-26157).

World Bank. *Rising food prices: Policy options and World Bank response*. Washington: World Bank, 2007a.

______. *World Development Report 2008*. Washington: World Bank, 2007b.

______. *A 10-point plan for the food crisis*. Washington: World Bank, 2008.

Wyman, C. E. *Handbook on bioethanol: production and utilization*. Applied Energy Technology Series. Washington: Taylor & Francis, 1996.

______. “What is (and is not) vital to advancing cellulosic ethanol”. *Trends in Biotechnology*, doi:10.1016/j.tibtech.2007.02.009, 2007.

Yacobucci, B. D. “Ethanol imports and the Caribbean Basin Initiative”. *CRS Report for Congress*, 2006.

Yacobucci, B. D. & Womach, J. “Fuel ethanol: background and public policy issues”. *CRS Report for Congress*, n. RL30369, Summary, 21 fev. 2002.

Zacchi, G. *The state of the art and future trends of ligno-cellulose biomass conversion to ethanol*. Presented at Unicamp, Campinas, Feb. 2007.

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