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 19th 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 20th 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:

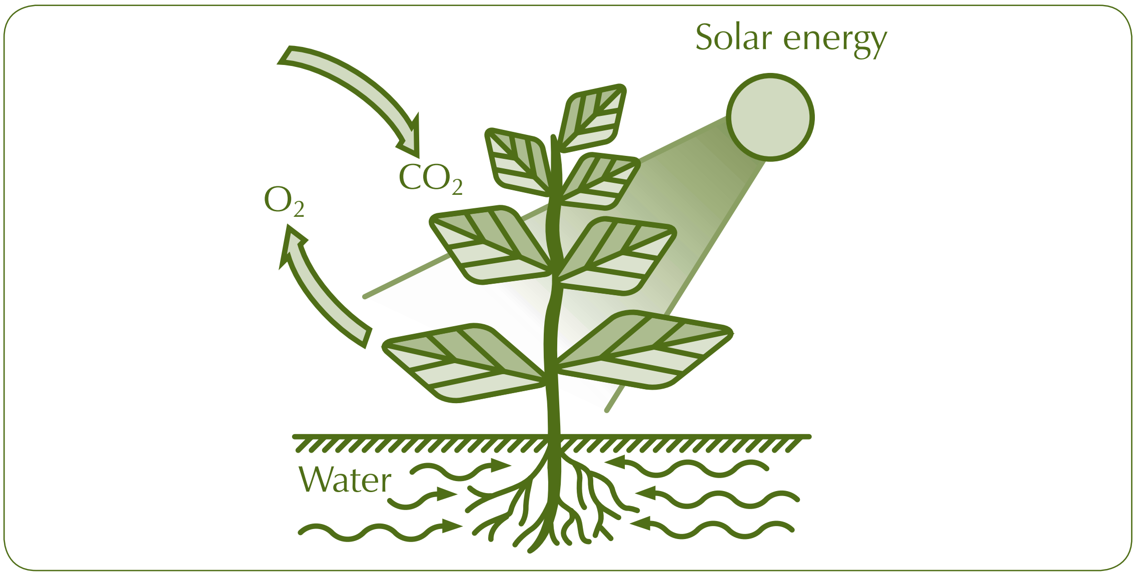
$$6\,H_2O + 6\,CO_2 \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6\,O_2 \qquad (1)$$

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.

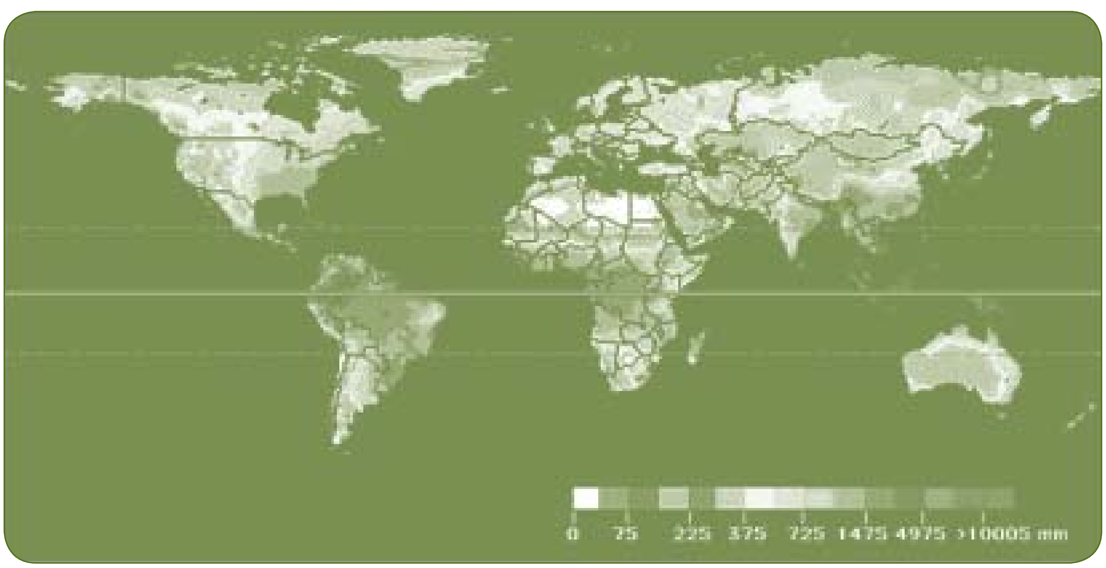
With regard to solar radiation, it is interesting to understand which portion is used by plants and how much of it is available on earth. Photosynthesis occurs through the absorption by chlorophyll of specific bands frequencies of the sunlight spectrum, especially the wavelengths between 400 and 700 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.

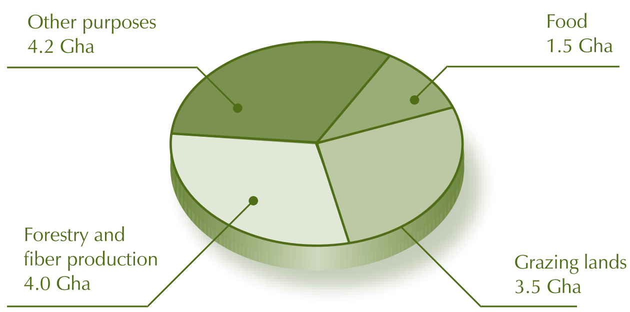
Figure 2 **– Average annual rainfall**



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)

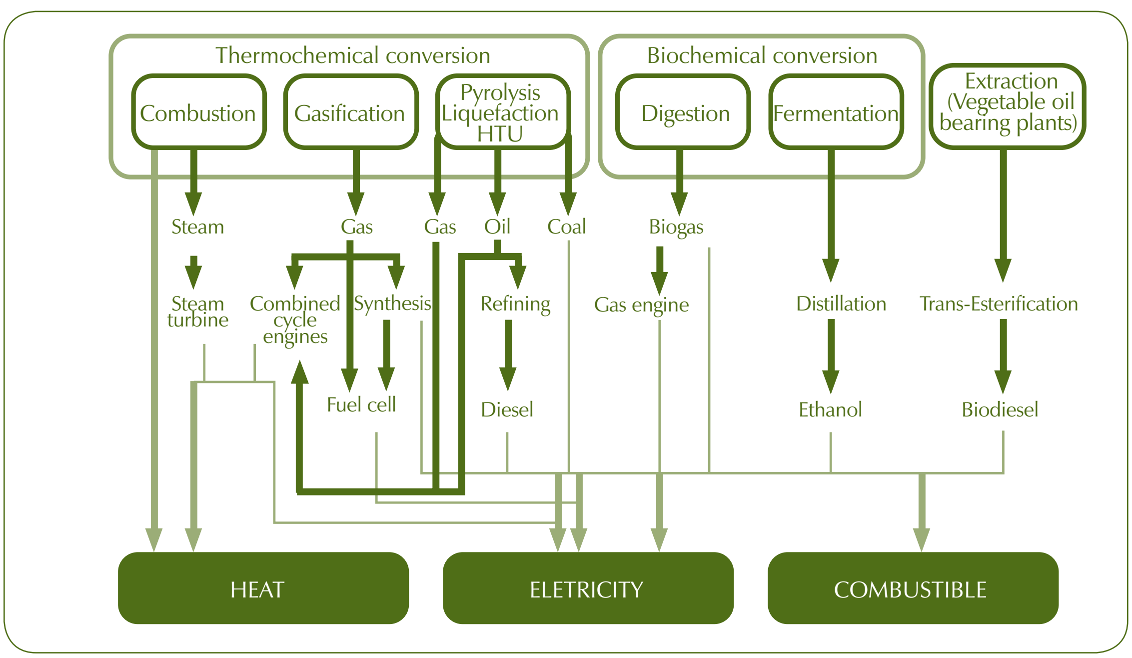
It is estimated that only about 0.1% of the solar radiation falling on Earth (ie, 180 out of 178,000 terawatts or billion kilowatts) is used in the photosynthetic processes, either natural or man-induced. The annual production of biomass on earth is approximately 114 billion tons, which on a dry basis 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.

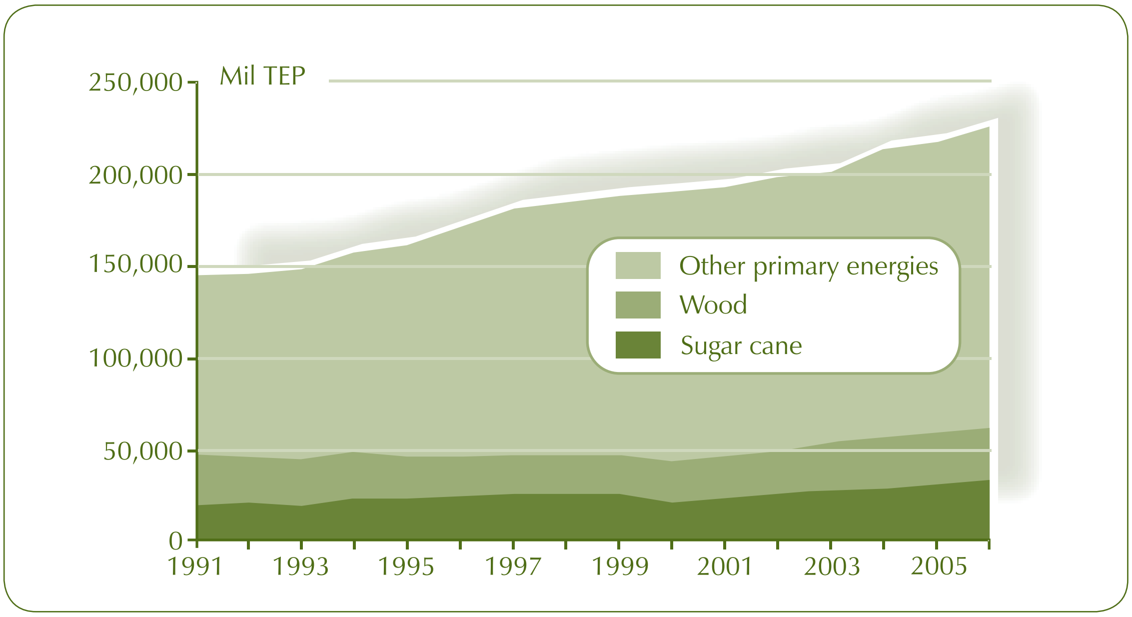
We have an interesting record of an economically important agroindustrial process sustained by biomass energy from Brazilian colonial times. According to Antonil (1982), during the 17th century the sugar mills of the *Recôncavo Baiano* had "*furnaces, burning day and night for seven months that require 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.

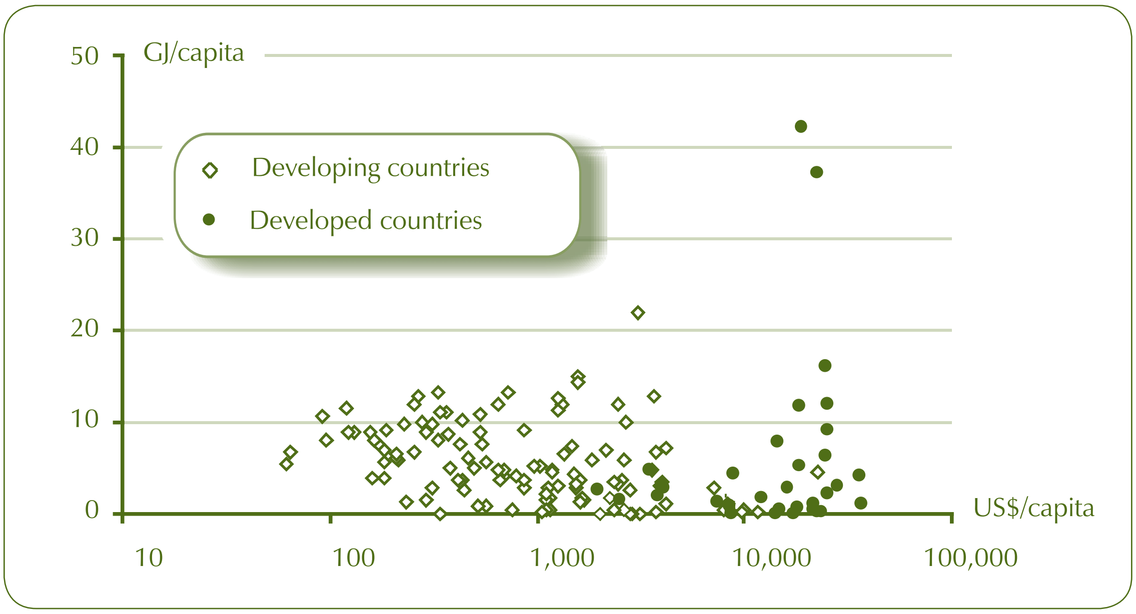
The second is the innovative paradigm of cutting-edge bioenergy systems. Production mostly occurs on a commercial basis, using environmental and economically efficient technologies to meet energy needs of the modern industry and transport sectors and to generate electricity. Some examples include the 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).