



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 derivatives

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.

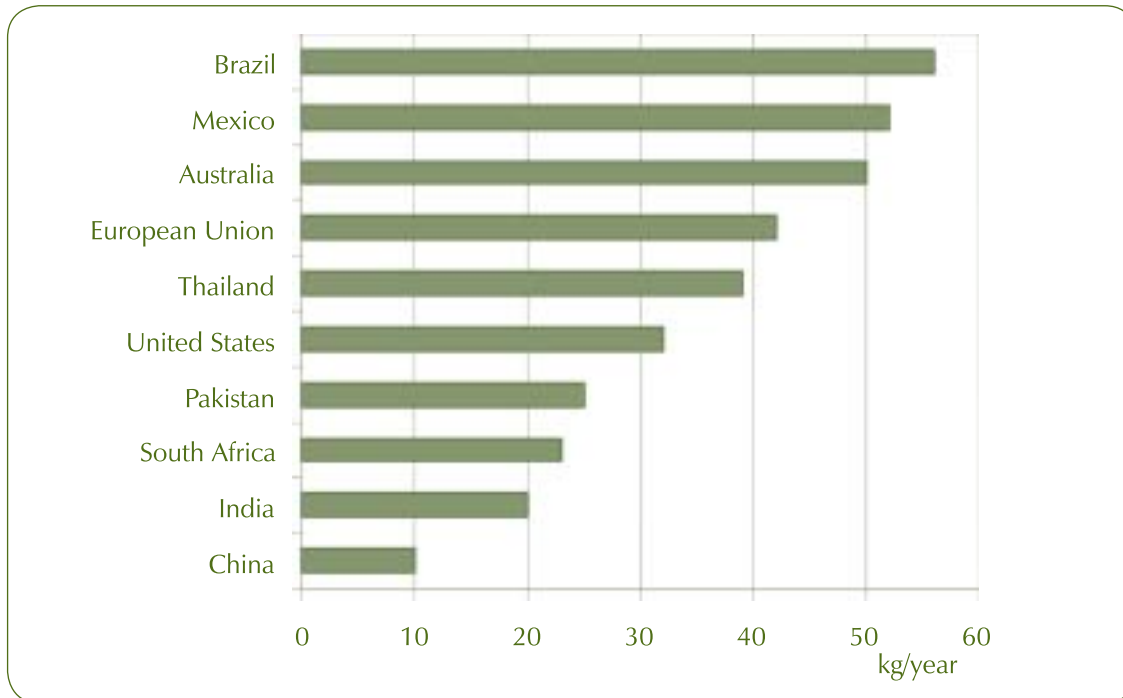
Organic sugar possibilities

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. Moreover, 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 become 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.

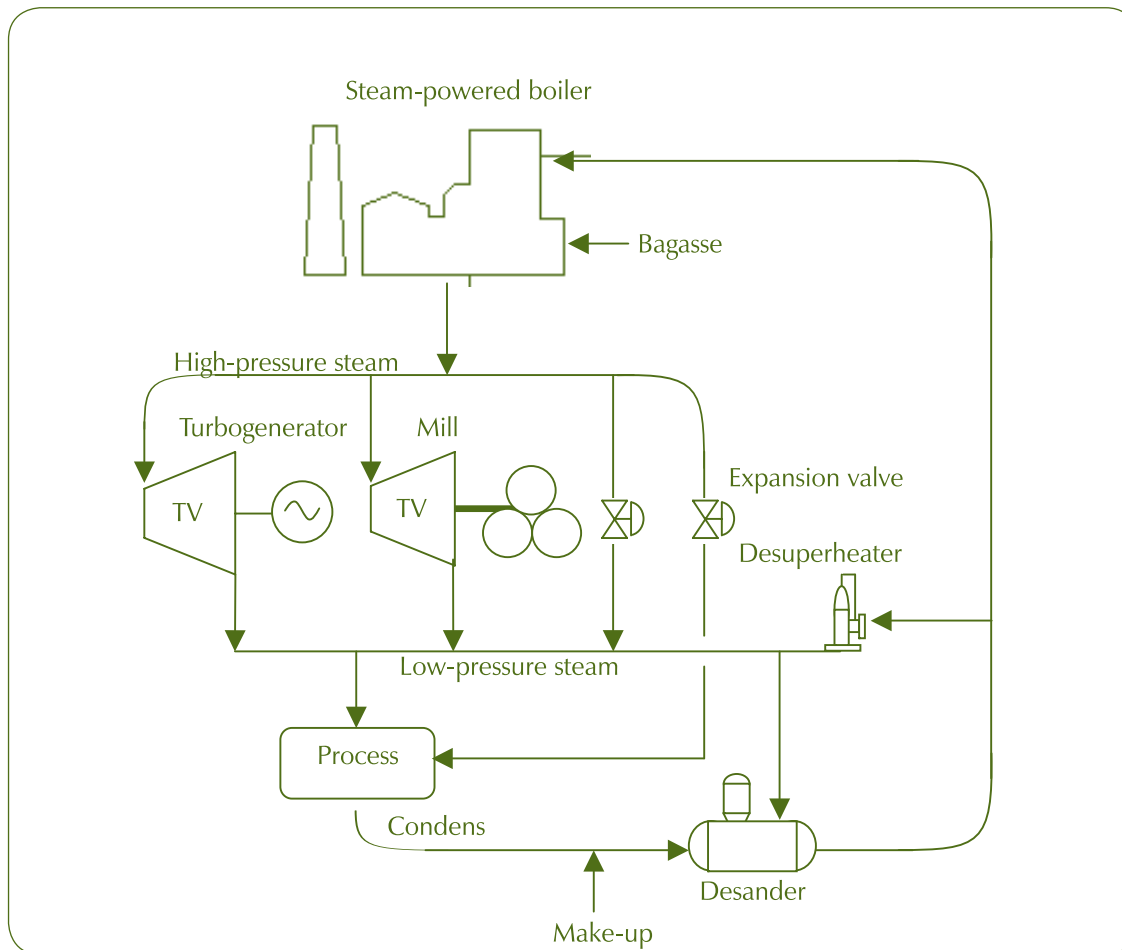
In the industrial processing of cane, three kinds of energy are required: thermal energy for heating and concentration processes; mechanical energy for milling and other mechanically driven systems, including pumps and large fans; and electric power for powering pumping, control systems and lighting, 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, attitudes 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)].

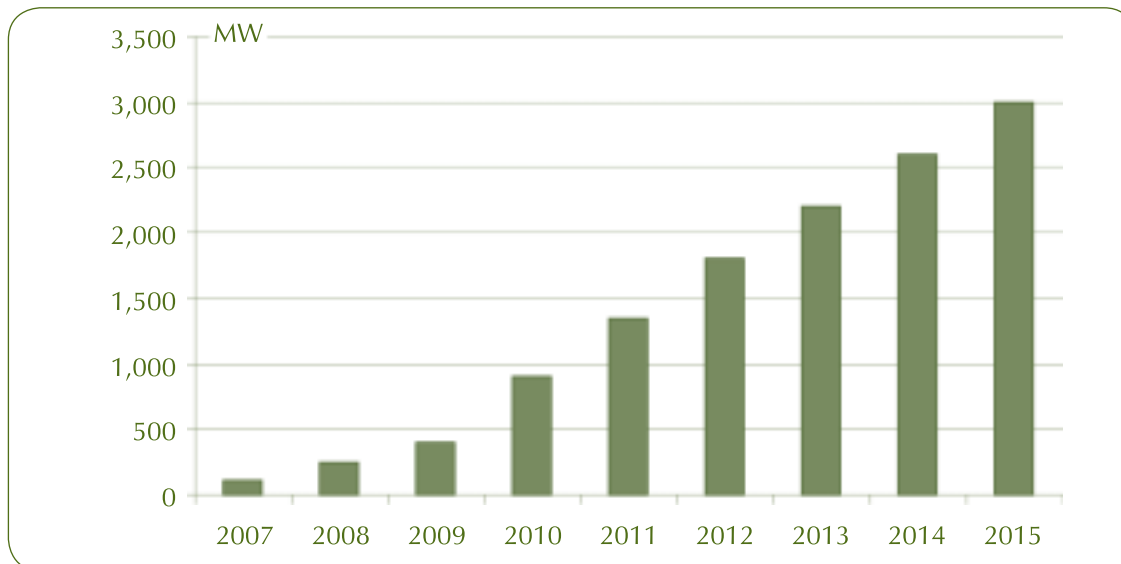
The operation of a sugar and bioethanol plant under typical conditions in Central-South Brazil, milling 2 million tons of sugarcane annually using conventional cogeneration systems at 65 bar and 480°C (896°F), would translate into an installed production capacity of 31 MW. If the cogeneration systems 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, considering 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).

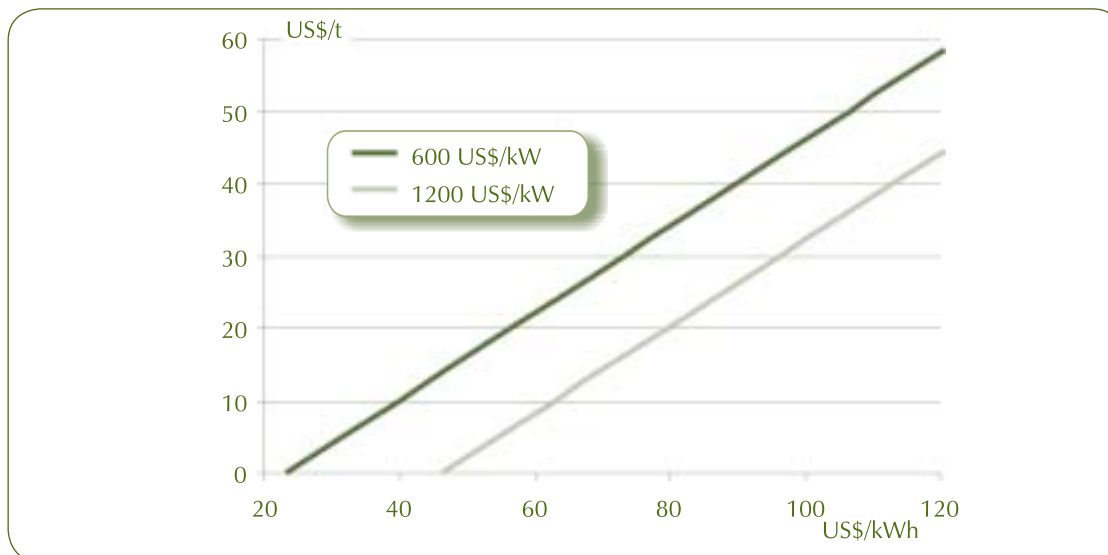
With the likely development of processes for the production of bioethanol from bagasse, there is interest in the analysis of the competitive prospects for this biomass, or in other words, figuring out the ways to maximize its economic prospects. In this context, a preliminary assessment comparing the 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.

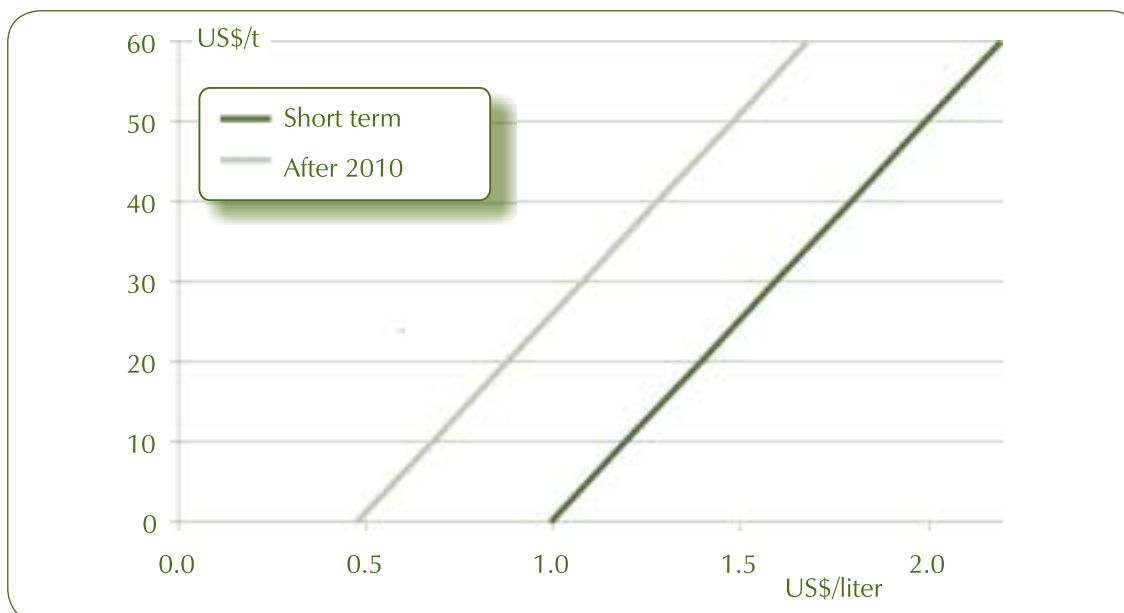
The evolution of electricity production at a Brazilian sugarcane mill



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 CO₂ 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 CO₂. 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 CO₂ 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 is 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
<i>Biotechnology: Materials produced based on the biological functions of living organisms</i>	Molasses	<ul style="list-style-type: none"> a) Citric acid b) Amino acids: lysine c) Agrochemicals: Growth regulator or phyto regulators (indolacetic acid, jasmonic acid), pesticide (biofungicide, biological controller, biological Insecticide, biological pesticide) d) Nitrogen fixer e) Silage inoculum
<i>Chemical: Products resulting from chemical reactions carried out with or without a catalyst</i>	Molasses, bagasse, and vinasse	<ul style="list-style-type: none"> 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
<i>Veterinary-drugs: Chemical, biological, biotechnological substances or manufacturing preparations, given directly or mixed to the food, to prevent and treat animal diseases</i>	Molasses and bagasse	<ul style="list-style-type: none"> a) Anti-diarrheic syrup b) Ferrous-dextran complex c) Probiotic
<i>Food</i>	Molasses, bagasse, and vinasse	<ul style="list-style-type: none"> a) Yeast, fructose and glyucose by-products b) Fructooligosaccharides c) Inverted syrups by enzymatic pathway d) Edible mushrooms of the species <i>Pleurotus ostreatus</i>.
<i>Biologics</i>	Bagasse	<ul style="list-style-type: none"> a) Fertilizing compound
<i>Structural: Materials whose properties make them useful in structures, machines or consumable products</i>	Bagasse	<ul style="list-style-type: none"> 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.