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TECHNOLOGY OPTIONS FOR THE FUTURE SUGARCANE BIOREFINERIES

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INTRODUCTION

A biorefinery can be defined as an integrated complex that makes a variety of products (liquid fuels, chemicals, electricity or steam) from a variety of feedstocks (Ondrey, 2006); it may be more efficient regarding thermodynamics, economics and the environmental aspects. Ragauskas *et al.* (2006) present a comprehensive discussion on the concepts and possibilities involving biorefineries, focused on the optimized options for biomass utilization for the sustainable production of energy, fuels and materials in both short and long term. With such goal, considerable governmental and private investments have been made in the last year (Genencor, 2003; Oils and Fats International, 2005; Ondrey, 2006), rising the expectation for commercial competitive plants in a short time horizon.

Some analyses of hypothetical biorefineries have been presented, considering the employment of advanced technologies in their mature context. Lynd *et al.* (2005), based on ligno-cellulosic biomass, considered the future co-production of electricity, Fischer-Tropsch (FT) fuels and hydrogen, as well as scenarios for co-production of ethanol-electricity, ethanol-electricity-FT fuels, ethanol-hydrogen, and other combinations of products and protein. In this analysis, some scenarios presented energy efficiencies greater than 70%, and economical competitiveness with conventional process based on oil prices of recent years.

This is an area of great interest. The two key technologies are gasification (conversion to syngas) and the conversion of ligno-cellulose to sugars (Werpy *et al.*, 2005). When the latter becomes commercially competitive, all biochemical processes from sugar to plastics, organic acids, solvents, and others, would not be restricted to the conventional sugar industry, while the gasification technology involves the possibility producing power and also chemicals and fuels via synthesis.

These technologies are not commercial for biomass today, but current sugarcane based ethanol production (with sugar, ethanol and some other chemicals co-produced, as well as power and heat from the residual biomass), is an important precursor of future biorefineries using commercial technologies, though the use of the ligno-cellulosic material is still inefficient. In the near future, with the complete elimination of cane burning practices, huge amounts of cane trash will be available, and its use as energy source along with bagasse will be, possibly, an attractive business option for cane mills. This is already happening in some units of Brazil Center-South.

A recent analysis (Seabra, 2008) investigated the future technology options that might lead to a better use of sugarcane biomass and their possible implications in the mill's context. In addition to the possibilities involving the diversified use of cane's sugars, this study evaluated the use of bagasse and cane trash considering four technologies:

- power generation with conventional steam cycles (current options);
- ethanol production through biomass hydrolysis (options for short, middle and long term);

- power generation through biomass gasification integrated to combined cycles (BIG/GT-CC) (options for middle-long term);
- production of synthetic fuels through biomass gasification (options for middle-long term).

Here we present a comparative resume of the main results of this work, pointing out the effects on the mill's overall performance. In this comparison it is also discussed the value of the bagasse, the influence of feedstock characteristics and the environmental benefits (GHG emissions mitigation) associated to each technology route. In all cases involving advanced-non commercial technologies, it was considered the use of cane trash (40% recovery from the field, i.e. 56 kg_{dry}/t cane) as supplementary fuel to bagasse, recovered at 30 R$/$t_{dry}$.

The results presented here must be seen as caution, bearing in mind the different time horizons expected for each alternative to be commercially available, as illustrated in Figure 1. In this analysis we considered that one configuration would be commercially "mature" only after it has been tested in laboratory, pilot and demonstration plant stages, involving the successful operation for more than one year of at least two different plants.

TECHNOLOGY OPTIONS

Sucrose use

The main products of cane industry in Brazil are sugar, which is destined to the food market, and hydrous and anhydrous ethanol, which are mainly used as fuel. Nowadays about 60% of cane's sugars are used for ethanol production (MAPA, 2009). Despite possible variations, sugar and ethanol are, and will probably continue to be, the main products of cane industry in Brazil, though there are innumerous attractive alternatives for the cane's sugars utilization. Amino acids, yeasts and acidulants are only few examples of products with higher added value that could be produced from sucrose and could yield higher revenues to the cane mills. Actually, many of these products are currently commercial in Brazil.

Macedo and Macedo (2005) evaluated the production of dozens of sucrose-derived products that could be produced from sugarcane in a competitive way, thanks to low sugar cost and high availability of energy through the bagasse. Considering market aspects and the interest to evaluate the impacts of such products in the mills' energy balance, four of these products were selected by Seabra (2008)

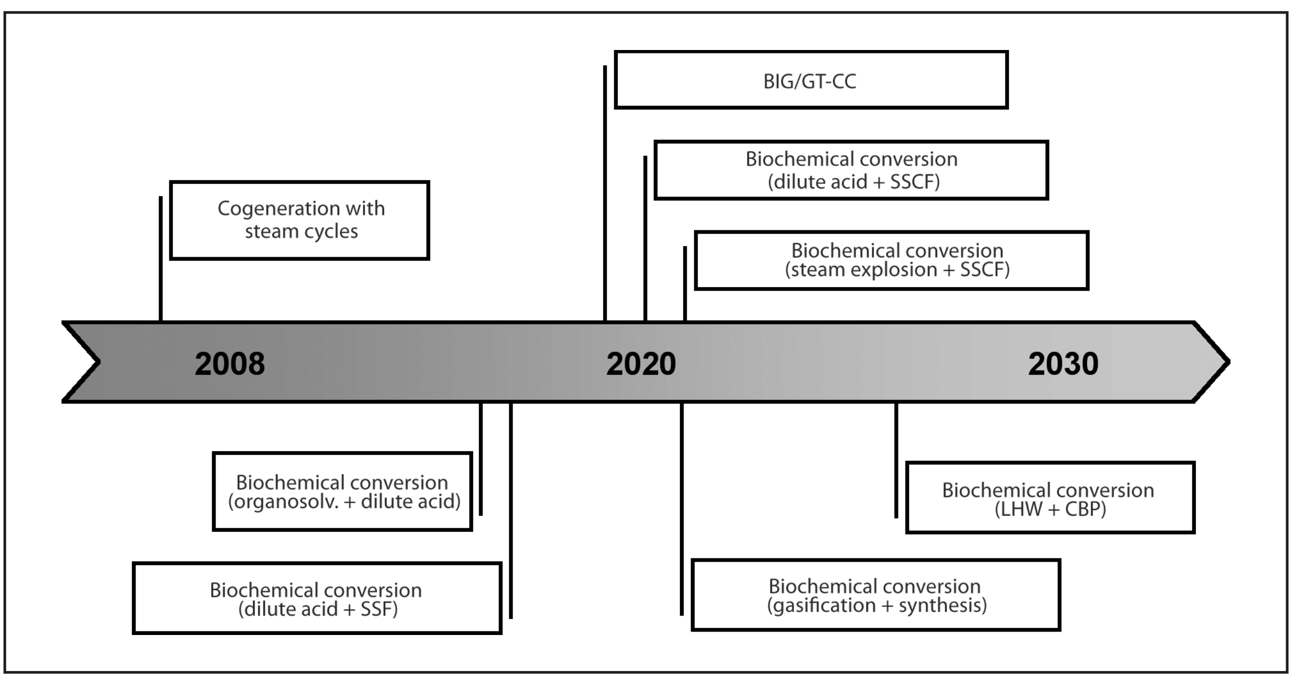

FIGURE 1 Expected evolution of the availability of commercially mature technologies for sugarcane residual biomass use.

for further analysis for the overall performance of an industrial complex producing sugar, ethanol, electricity and a third sucrose-derived product. Considering the assumptions made in the study, except for MSG, the adjacent production of all other products (lysine, yeast and citric acid) lead to more attractive alternatives than the usual option for only sugar and ethanol.

Actually, the diversification of mills' products is the current trend of the cane sector in Brazil, and some groups (e.g., Grupo Zillo, São Martinho, Santo Antônio) have installed plants adjacent to the mills to produce alternative products from sugar. Besides food products, the production of biodegradable plastics from cane's sugars has been tested in a facility adjacent to a mill. For years the PHB Industrial S.A. has operated a pilot plant (60 t/y of polyhydroxybutyrate), adjacent to the Usina da Pedra, which supplies all the sugar, steam and electricity required by the plant. In this case, the biodegradable plastic presents the additional advantage of being produced from renewable sources.

Power generation

The cane processing into sugar and ethanol is an energy intensive process, especially regarding the thermal energy fraction. However, the interest in increasing the biomass surplus in the mills is growing (either for power or other purposes), leading to technology options that enable lower process energy demand. Furthermore, mills are investing in high pressure cogeneration systems (65-90 bar) with condensing-extraction turbines and utilization of totally electrified drivers. And for the short term it is expected that part of the cane trash will be recovered from the field, which would enable the power generation throughout the year. Considering these commercial steam cycles cogeneration systems, the mills' electricity surplus could leap from the current 0-10 kWh/t cane level (pure cogeneration at 22 bar/300 °C) to more than 140 kWh/t cane (CEST, 90 bar/520 °C, using bagasse and trash), and with competitive costs for the current electricity market.

For the future, gasification technology integrated to combined cycles (BIG/GT-CC) is expected to increase considerably the electricity generation efficiency. Despite the demonstration efforts, it is expect that such technology might be commercially available only in the middle to long term. Among the alternatives that have been tested, the near atmospheric gasification with indirect heat and pressurized gasification with oxygen injection attracts special attention. In the case of cane mills with reduced steam consumption (340 kg/t cane) and using cane trash (40% recovery) as supplementary fuel to bagasse, these configurations would lead to electricity surpluses of 194 and 203 kWh/t cane, for near atmospheric and pressurized systems, respectively. In general, the former is indicated to lower scales, while the pressurized gasification is more appropriate for larger scale units. Even though the sizes involved in the mills context justify the adoption of pressurized systems, the electricity costs would not be competitive with current prices in Brazil, despite the low biomass cost. Table 1 summarizes the main results presented by Seabra (2008).

TABLE 1 Electricity generation and costs[a].

Configuration	Electricity surplus (kWh/t cane)	Cost (R$/MWh)
Steam cycles[b]	—	—
65 bar/480 ºC	133	97
90 bar/520 ºC	145	99
BIG/GT-CC[c]	—	—
BIG-ATM(CO)	184	142
BIG-ATM(AG)	194	149
BIG-PR(CO)	192	144
BIG-PR(AG)	203	149

[a] Costs were estimated considering retrofit projects in existing mills (originally operating with 22 bar/300 ºC cogeneration cycle; only backpressure turbines; mill's energy demand – steam: 500 kg/t; electricity: 12 kWh/t cane; mechanical power: 16 kWh/t cane). In all cases it was considered: reduction of steam consumption to 340 kg/t cane; electric drivers; use of trash (40% collection from the field) in addition to bagasse; electricity generation during 11 months per year. See details in Seabra (2008).

[b] Current commercial options.

[c] It was considered atmospheric (BIG-ATM) and pressurized (BIG-PR) gasification systems, as presented in Jin *et al*. (2006) and Consonni and Larson (1996a and b). For both cases two configurations were evaluated: one conservative (CO, in which process steam demand is supplied by 90 bar/520 ºC boilers) and another aggressive (AG, aimed at the maximum electricity generation, in which part of the process steam demand being supplied by the HRSG of the gas turbine cycle).

Fuels production

Except for sugarcane, the commercially available technologies for ethanol production today (from starch and sugars) present narrow energy and environmental benefits. Despite its advantages, sugarcane is not a feasible crop for all regions of the world, what has encouraged many countries of the North Hemisphere to pursue technology routes to produce an efficient biofuel, for both environmental and economic reasons. Nowadays the predominant idea is that, for the near term (5 to 10 years), ethanol production from the hydrolysis of ligno-cellulosic materials is the best option.

The production of cellulosic ethanol through biochemical conversion is not a mature technology today, and different stages must yet be verified in the development of more efficient and less capital intensive processes. In the short term, processes based on organosolv treatment with acid hydrolysis and enzymatic processes with dilute acid pretreatment are expected to be commercially available. These options would enable, respectively, yields of 20 and 32 L of cellulosic ethanol per tonne of cane. For the medium term, the SSCF configuration combined with the dilute acid pretreatment or steam explosion may be available, which could present yields around 37 L of cellulosic ethanol per tonne of cane. Finally, in the long run, the consolidated bioprocessing is expected to be available, which could enable the production of almost 40 L of cellulosic ethanol per tonne of cane. Again, it is important to point out that these estimations consider the use of cane trash (40%) as supplementary fuel to bagasse. As for costs, significant evolution is also expected, but even for the short-term configurations, the values would be competitive with current cane ethanol costs, due to low biomass cost the credits derived from the electricity surplus.

Alternatively to the biochemical route, different biofuels can be produced via thermochemical conversion, through biomass gasification and conversion of syngas. As well as for the BIG/GT-CC technology, this option is also expected to be commercially available only in medium-long term, and demonstration efforts are still needed. Among the several alternatives, Seabra (2008) compared the production of Fischer-Tropsch gasoline and diesel, DME and ethanol. Based on pressurized gasification with oxygen injection, the yield for FT liquids production would be around 490 MJ/t cane, while for DME the yields would be 350 MJ/t cane and 750 MJ/t can, respectively for *once-through* and unconverted gas recycling configuration alternatives. For ethanol production, based on an atmospheric gasification with indirect heat, the yield would be 570 MJ/t cane. Except for DME, the costs of these biofuels, as well as for the biochemical conversion technology, would also be competitive with the current values due to the low biomass cost and the credits associated to electricity surplus. Table 2 presents a summary of the results.

TABLE 2 Estimated yields and costs of biofuels derived from cane residual biomass[a].

Configuration	Fuel yield (L/t cane)	Cost[b] (R$/m³)
Biochemical conversion (ethanol)		
Organosolv + dilute acid	20	680
Dilute acid + SSF	32	480
Dilute acid + SSCF	37	390
Steam explosion + SSCF	37	300
LHW + CBP	40	270
Themochemical conversion[c]		
FT liquids	5.9 (gasoline) 8.6 (diesel)	~1,075
DME-OT	12.3 kg/t cane	820 R$/t
DME-RC	26.5 kg/t cane	980 R$/t
Ethanol	25.6 (ethanol)	455
	4.4 (other alcohols)	

[a] In all cases it was considered conversion process integrated to mill with reduced steam consumption (340 kg/t cane), electric drivers, and that uses trash (40% collection from the field) in addition to bagasse. See details in Seabra (2008).
[b] Cost relative to the fuel derived from the ligno-cellulosic material. The study considered that the costs of cane juice derived products would not be affected, and all the revenue related to the sales of electricity surplus would be attributed as credit to the cellulosic fuel.
[c] The analyses were based on conversion processes presented in Larson *et al*. (2006) and Phillips *et al*. (2007).

Even for configurations aimed at the production of fuels, it is interesting for the mills to be able to produce some electricity surplus, because of the characteristics of the Brazilian power sector. Furthermore, electricity is an important co-product, which is largely responsible for the competitiveness of the biofuels/processes considered. As indicated in Figure 2, even for cases with high fuel yields, the electricity surplus is considerably high. In the "worst" case, the electricity surplus would be around 30 kWh/t cane, which is about three times greater than the current levels. This stresses the importance that the sugarcane mills may have in the Brazilian power sector in the future.

ECONOMIC ASPECTS

The improvement of cane energy use does not necessarily lead to higher profits, even though the better use of the ligno-cellulosic material represents an attractive business option for most of the configurations presented here. In extreme cases, the profit associated to the ligno-cellulosic products could represent the largest share of the total mill's profit, while some configurations would not be economically attractive at all. This result, however, is strongly dependent on the products price considered, so that small combined changes may lead to totally different conclusions. Regardless, it is clear that the ligno-cellulosic derived products will play an important role in context of the future sugarcane mills.

In this case, the definition of the value of the sugarcane residual biomass is therefore relevant. Today, bagasse is treated as an industrial residue of cane juice processing, and its costs is generally assumed as zero. However, as different alternatives (with different profitability) for its use rise, it is important to know the value of this biomass. Figures 3, 4 and 5 show the results of such analysis for the technologies considered here. The bagasse value was calculated as the gross profit of the mill (before income taxes) related to the ligno-cellulosic products divided by the total bagasse available at the mill.

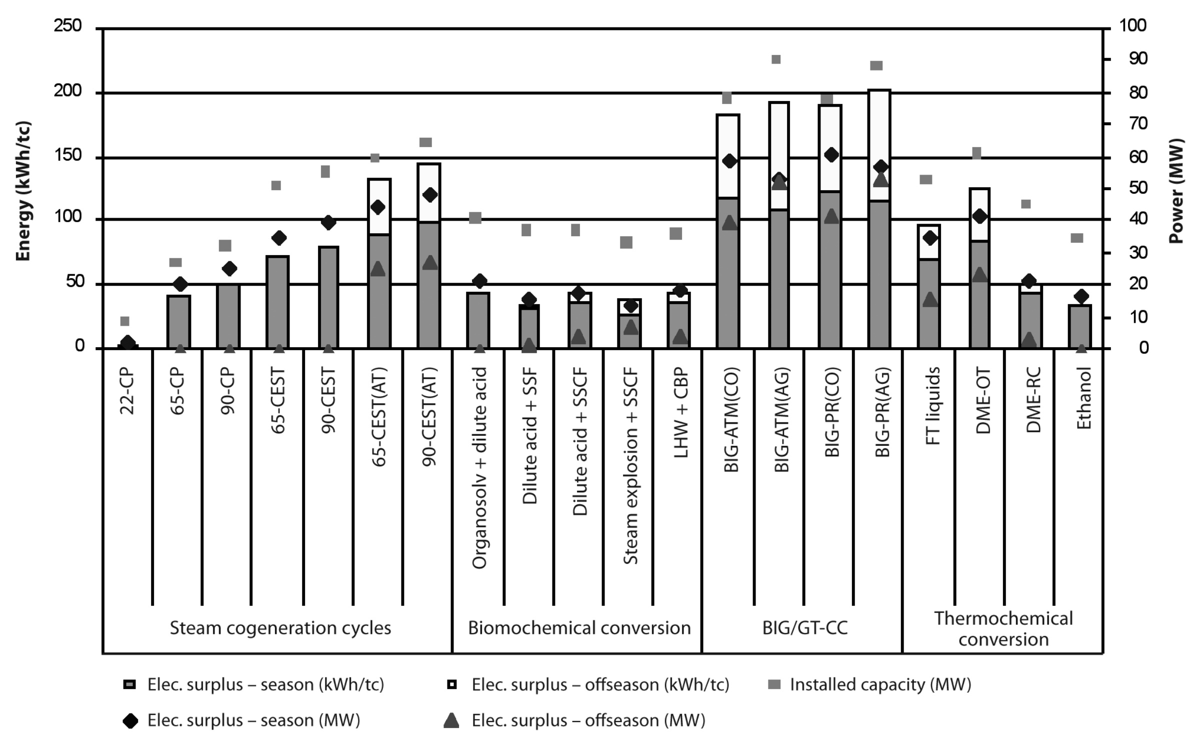

FIGURE 2 Mill electricity generation for different technology alternatives for biomass use (reference scale: 2 Mt cane/year mill)

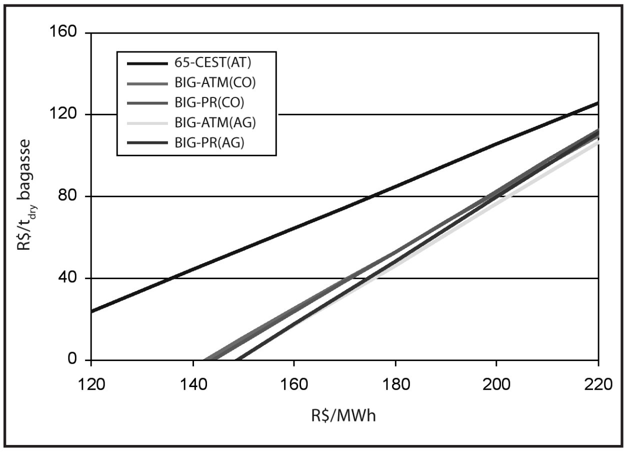

FIGURE 3 Bagasse value for electricity generation.

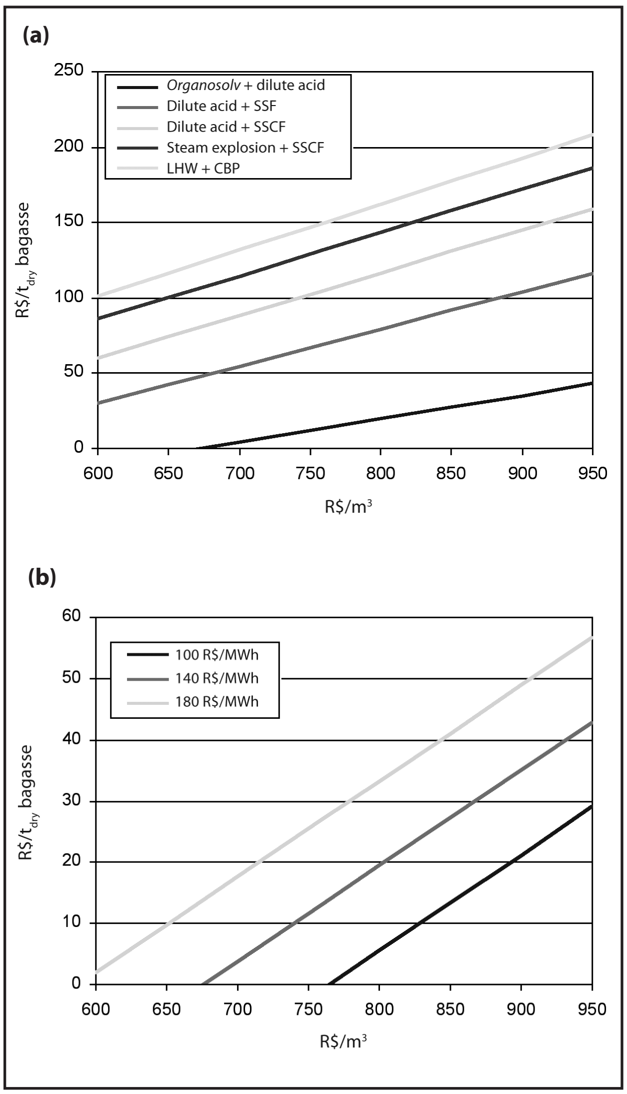

FIGURE 4 (a) Bagasse value for ethanol production via biochemical conversion, and (b) influence of electricity price for the short-term configuration (Organosolv + dilute acid).

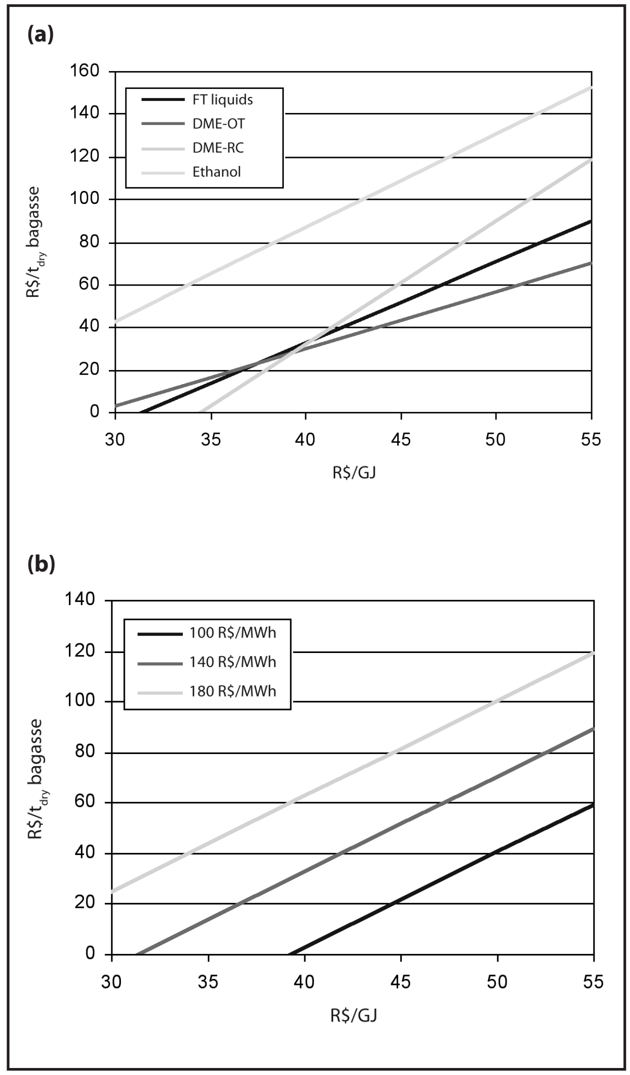

FIGURE 5 (a) Bagasse value for fuels production via thermochemical conversion, and (b) influence of electricity price for FT liquids production.

These results must be compared with caution, since they involve technology options that would be available in different time horizons. For the short term, the options for biomass use lie on ethanol production via biochemical conversion and electricity cogeneration with steam cycles. Such alternatives would lead, respectively, to bagasse values of 15 and 45 R$/$t_{dry}$, considering the current electricity and ethanol prices. But for the enzymatic route, the bagasse value would reach 70 R$/$t_{dry}$, if the yields expected for this configuration were actually achieved. In the long run, when all alternatives would be commercially available, the ethanol production via biochemical conversion would present the higher bagasse value, estimated as 150 R$/$t_{dry}$.

For electricity generation, despite the greater efficiencies, the high costs associated to the BIG/GT-CC technology impose an important barrier for the adoption of this option in the mills context. The biomass gasification for fuels synthesis, however, represents an interesting option for the medium-long term, especially considering the expectation for higher oil prices in the future. Furthermore, it is expected that the technological hurdles associated to this route could be overcome more easily than those related to the biochemical route, once previous gasification demonstration efforts have been conducted, and the remaining challenges of the thermochemical conversion are mostly associated to process engineering. For the biochemical route, on the other hand, current conversion yields and residence times are far from the projected values for the future, and many science level issues must be addressed yet.

For both cases, it is important to remark the sensitivity of their competitiveness to electricity sales, as illustrated in Figures 4b and 5b. The influence of cane trash costs in this analysis must be stressed as well. Those bagasse values can only be achieved if cane trash is recovered from the field at low costs and with appropriate characteristics to be used as fuel or raw material in the mill. This is still a technological challenge today, but it is expected that for the short term the most suitable route for trash recovery and processing will be fully developed. Despite the uncertainties regarding trash costs, for the range of values expected (normally less than 80 R$/$t_{dry}$), the final products costs would not be very sensitive to the trash cost, as it represents only about 30% (in this analysis) of the total ligno-cellulosic material processed.

INFLUENCE OF THE CHARACTERISTICS OF THE RAW MATERIAL

In the last 20 years, the development of new cane varieties more adapted to specific soil and climate conditions, associated to better agricultural practices, has progressively enhanced cane productivity and quality (sugar content). During this period, the development of new varieties was essentially aimed at the enhancement of pest resistance and sugars productivity per hectare. However, as technology progresses and ligno-cellulosic products become more attractive, the development of high fiber content varieties may be also attractive. Today, varieties with high fiber content are still not desired, as they compromise the cane crushing capacity and lead to higher sugar losses in the juice extraction step. But the better use of the ligno-cellulosic material through advanced technologies may change this logic.

A sensitivity analysis presented in Seabra (2008) compares the impact of different cane's sugar and fiber contents on mill's performance, considering three different uses for bagasse (electricity cogeneration with steam cycles, biochemical conversion and FT synthesis). The analysis shows that, regarding the economics, the additional sugar loss due to the higher fiber content would be offset by the additional revenue related to electricity generation through the steam cogeneration cycle in the short term. In the long run, the high ethanol yield of the biochemical conversion technology would also make the production of ligno-cellulosic products more advantageous, while for the FT synthesis the preference for sugar instead of fiber prevails.

Despite that, reaching high fiber commercial varieties is not likely in the short term, although it is clear the interest for their utilization in the pool of varieties of the future sugarcane biorefineries. Independently, the average cane fiber content at the mill will probably rise in the next years, due to the higher impurity levels associated with the unburned cane harvesting. In this case, increasing the cane trash recovery level is one option to delivery more ligno-cellulosic material to the mill; but it is important to stress the additional logistic costs and higher mineral impurity levels associated to this alternative.

ENVIRONMENTAL ASPECTS: GHG EMISSIONS

The environmental benefits of sugarcane ethanol, considering the replacement of oil gasoline and greenhouse gases (GHG) emissions mitigation, are already acknowledged since the publication of the first studies involving the energy balance and GHG emissions in the ethanol lifecycle (Silva *et al.*, 1978; Macedo and Nogueira, 1985; Macedo, 1992). These balances were recently updated (Seabra, 2008; Macedo *et al*. 2008), using 2005/2006 average values related to 44 mills of Brazilian Center-South Region. Besides methodology and database update, the study also assessed a projected 2020 scenario, considering the trends for the sugarcane sector and the availability of advanced technologies for biomass use.

For 2005/2006 values, the energy ratio in ethanol production was 9.4, which is considerably greater than the value verified with 2002 data (Macedo *et al*., 2004). The ethanol lifecycle emissions were evaluated at 269 kg CO_2eq/m^3 anhydrous, including the emission credits of ethanol co-products (bagasse and electricity). For the future, the complete elimination of burning practices during cane pre-harvesting will lead to considerably lower emission levels (see Tables 3, 4 and 5). Actually, it is expected that the emission credits related to co-products will match (or even surpass) the emissions in the ethanol production and distribution. In the 2020 Steam cycle Scenario (based on conventional cogeneration, which is recognized as the most likely scenario), for instance, the employment of only today's commercial technologies would lead to ethanol lifecycle emissions of -409 kg CO_2eq/m^3 anhydrous.

The potential for emissions mitigation of sugarcane ethanol is even higher in the future. For the 2020 Steam cycle Scenario, the net avoided emission associated with the utilization of 1 m^3 of ethanol as E25 blend would be 2.5 t CO_2eq. In terms of sugarcane biomass, it means that the products derived from 1 tonne of cane (plus some trash) would lead to an emission reduction of 233 kg CO_2eq. In the same way, 1 hectare of cane would be responsible for the mitigation of 18.4 tonnes of CO_2eq per year, considering the utilization of the different sugarcane products assumed in the study.

It must be stressed that, in this analysis, the direct and indirect emissions related to land use change were assumed as zero. For the particular

TABLE 3 Energy balance for different technology options (MJ/t cane).

	2005/2006	2020 Scenarios[a]			
		Steam cycle[b]	Biochemical conversion[c]	BIG/GT-CC[d]	Thermochemical conversion[e]
Fossil energy ***Input***	234.2	262.6	267.8	264.1	264.3
Cane production	210.6	238.5	237.3	238.5	238.5
Cane processing	23.6	24	30.6	25.5	25.8
Renewable energy ***Output***	2,198.4	3,171.1	3,247	3,755.8	3,367
Ethanol	1,926.4	2,060.3	2,879.5	2,060.3	2,060.3
Electricity surplus[f]	96	1,110.8	367.5	1,695.5	814.3
Bagasse surplus	176	0	0	0	0
Synthetic fuels					492.3
Energy ratio	9.4	12.1	12.1	14.2	12.7

[a] Scenarios refer to different options for cane residual biomass use.
[b] 65 bar/480 ºC.
[c] Dilute acid + SSCF.
[d] Pressurized gasification in aggressive configuration (BIG-PR(AG)).
[e] FT liquids.
[f] Values are equivalent to the primary energy required by a Natural Gas thermoelectric plant to produce the same electricity surplus.

Source: Seabra (2008).

TABLE 4 GHG emissions associated to ethanol production for different technology options (kg CO_2eq/m^3 anhydrous)[a].

	2005/2006	2020 Scenarios			
		Steam cycle	**Biochemical conversion**	**BIG/GT-CC**	**Thermochemical conversion**
Emissions					
Fossil fuels	263	264	205	265	265
Trash burning	84	0	0	0	0
Soil emissions	146	129	92	129	129
Sub-total	**493**	**393**	**297**	**395**	**395**
Credits[b]					
Electricity surplus	-74	-803	-190	-1,225	-588
Bagasse surplus	-150	0	0	0	0
Synthetic fuels					-451
Subtotal	**-224**	**-803**	**-190**	**-1,225**	**-1,039**
Total	**269**	**-409**	**107**	**-831**	**-645**

[a] Emissions for hydrous ethanol are about 5% less than the values for anhydrous ethanol.
[b] In the future, considering the consolidation of sugarcane biorefineries, it will more appropriate to use allocation methods for the evaluation of ethanol co-products credits. Emissions mitigation associated to ethanol use considering an allocation methodology is presented in Macedo and Seabra (2008).

Source: Seabra (2008).

TABLE 5 Avoided emissions (t CO_2eq/m^3 hydrous or anhydrous ethanol).

	Ethanol use[a]	**Avoided emissions[b]**	**Net emissions[c,d]**
2006	HDE	-2	**-1.7**
	E25	-2.1	**-1.8**
2020 – Steam cycle	HDE	-2	**-2.4**
	FFV	-1.8	**-2.2**
	E25	-2.1	**-2.5**
2020 – Biochemical conversion	HDE	-2	**-1.9**
	FFV	-1.8	**-1.7**
	E25	-2.1	**-2**
2020 – BIG/GT-CC	HDE	-2	**-2.8**
	FFV	-1.8	**-2.6**
	E25	-2.1	**-2.9**
2020 – Themochemical conversion	HDE	-2	**-2.6**
	FFV	-1.8	**-2.4**
	E25	-2.1	**-2.8**

[a] HDE: hydrous-dedicated engines; E25: ethanol-gasoline blend with 25% anhydrous ethanol; FFV: flexible fuel vehicles (ethanol-gasoline), in Brazil.
[b] Avoided emissions (negative values) due to ethanol substitution for gasoline, considering fuel equivalences in Brazil (see Macedo *et al*., 2008).
[c] Net emissions = (Avoided emissions) + (Ethanol production emissions). Note that negative values indicate emissions mitigation.
[d] See note "a" in Table 4.

Source: Seabra (2008)

conditions of cane ethanol expansion in Brazil in the last years and the projections for 2020, this hypothesis is justified (Zuurbier and van de Vooren, 2008).

FINAL CONSIDERATIONS

Today we can say that the current Brazilian sugarcane mills are important precursors of the future biorefineries, using sugarcane biomass to produce different products, but with a still inefficient use of the ligno-cellulosic material. Besides sugar and ethanol, several other products with higher added value (e.g., amino acids and food additives) can be produced from cane's sugars in a competitive way, due to the low cost of sugar and large energy availability.

As for the ligno-cellulosic fraction, current advanced cogeneration systems can lead to a better energy use, and also represent an attractive business option for cane mills. In the middle-long term, the biochemical conversion and gasification technologies will enable even higher efficiencies, but not necessarily with as good economic performances. For the options and conditions assumed here, the ethanol production via biochemical conversion is the most attractive alternative, though it is also the one that possibly presents the largest technical challenges to reach the complete mature level. In general, we can say that all these alternatives have an interesting potential to be adopted in the Brazilian sugarcane mills thanks to the large biomass availability at relatively low cost. It is also important to point out that even greater performances could be achieved through the full integration of these technologies with the mill.

Finally it must be remarked the great environmental contribution that the optimized use of cane biomass can represent. Nowadays, cane ethanol is one of the best alternatives to mitigate GHG emissions, and its environmental benefits shall improve, as mills use more efficiently the residual cane biomass. This, added to the social-economic benefits promoted by the sugarcane sector activity, underlines the contribution of this sector for the sustainable development.

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