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Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use

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Abstract: Sugarcane is currently the main renewable energy source in Brazil. Due to the importance of the cane industry and its contribution to a wide range of biobased energy and other products, LCA studies regarding cane-derived products are needed to assess their environmental benefits. The main objective of this work was the assessment of life cycle energy use and greenhouse gas (GHG) emissions related to cane sugar and ethanol, considering bagasse and electricity surpluses as coproducts. We performed an overall balance for the Brazilian Center-South Region, adopting different methods to evaluate sugar and ethanol production separately. The GREET 1.8c.0 model was used for the 'well-to-wheels' calculations but adapted to the comprehensive set of Brazilian parameters that best represent the Center-South Region. For the reference case, fossil energy use and GHG emissions related to sugar production were evaluated as 721 kJ/kg and 234 g CO_2eq/kg, respectively. For the ethanol life cycle, these values were 80 kJ/MJ and 21.3 g CO_2eq/MJ. Special attention was paid to the variation of some parameters among producing units based on data collected by industry. The consequent uncertainties in ethanol life cycle emissions were assessed through a Monte Carlo analysis based on assigned distribution of probability curves for eleven selected parameters and informed by partial statistical data available from industry for distribution generation. Projections were also made for 2020 scenario parameters based on the best in current class technologies and technological improvements deemed commercially possible today. Published in 2011 by John Wiley & Sons, Ltd

Keywords: *Saccharum officinarum*; GHG emissions mitigation; global warming; energy balance; uncertainty analysis; sugarcane refineries

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Introduction

According to the 2009 World Energy Outlook,[1] energy-related CO_2 emissions of 29 Gt in 2007 would increase to 40 Gt in 2030 if business-as-usual scenarios continue, with potential increases in global average temperatures of about 6°C, even including 120 Mtoe (5 EJ) of global biofuels production. To stabilize the CO_2 concentration in the atmosphere at 450 ppm by the year 2100 (or a third of temperature increase), the scenario requires more than double of the biofuels production above including ethanol, biodiesel, and a variety of second-generation biofuels including renewable hydrocarbon biofuels for diesel and aviation fuels (about one-third). Half of the biofuels would be low carbon intensity such as ethanol from sugarcane or lignocellulosic biomass. Similarly, while global electricity production from biomass represents 1.7% in the business-as-usual case in 2007, it grows to 5% in the case of the stabilization scenario.

Mitigation alternatives will involve different types of energy sources, but a broader use of bioenergy sources is needed, especially in transport, a sector responsible for 23% of global emissions and also the fastest-growing source of emissions in OECD countries.[2] In this context, the environmental contribution of cane ethanol is already well documented, but the potential associated to other cane products still needs to be analyzed.

Since 2007, sugarcane is the main renewable energy source in Brazil, representing 18.2% of the country's total energy supply or 18.8% of the total primary energy in 2009. Ethanol provides 5.7% of the primary energy supply and sugarcane processing electricity is responsible for 4.75% (5.6 GW) of the total installed capacity in 2009.[3] Electricity is an important and strategic energy product for the country, as temporal and spatial (geographic) complementarities of bagasse-derived electricity and hydroelectricity (especially during the dry season) enable integration of renewable resources in electricity generation offsetting fossil resources that would otherwise be dispatched. Brazil is the world's largest producer and exporter of sugar: in 2008, production reached 31 M t, with exports close to 19.5 M t.[4] The sugarcane industry is expanding the production of renewable plastics and also the types of transport fuels provided, such as high energy content hydrocarbon fuels to replace other carbon-intensive fossil fuels.[5]

Part of the potential environmental benefits of cane-derived products can be investigated through life cycle assessment (LCA) studies. In this work, we assessed the life cycle energy use and greenhouse gases (GHG) emissions related to cane sugar and ethanol (the already large-scale, commercial products derived from sugarcane in Brazil), assuming bagasse and electricity surpluses as coproducts.

For ethanol, both national and international evaluations have been regularly published,[6–12] although frequently involving different methodologies and/or databases. To facilitate comparisons with other feedstock, a consolidated and widely used methodology was adopted in this study. The GREET 1.8c.0 model[13] was selected as an analysis tool since it already includes comprehensive datasheets. Nevertheless, for the specific case of sugarcane production and processing, we used the most recent, comprehensive set of parameters related to the Brazilian Center-South Region, which is responsible for nearly 90% of the sugarcane production in Brazil.

Different allocation methodologies were used in order to evaluate sugar and ethanol production separately. Special attention was paid to the uncertainties of ethanol life cycle emissions, which were assessed through a Monte Carlo analysis based on assigned probability curves of eleven selected parameters. Projected parameters were also used to capture the emission trends for a 2020 scenario.

Methodology

Database

A comprehensive countrywide database for the Brazilian sugarcane sector has not yet been fully established. Recent survey efforts[14] cover most part of Brazilian mills, but do not present important sugarcane agriculture parameters (e.g. fertilizers use). The last comprehensive studies[6,9,15] have used the database of the sugarcane technology center (CTC), which comprises several technical parameters related to cane cultivation, harvest, transport, and processing. It provides, for instance, the use of chemicals, productivities, harvested areas, total area under cane, cane quality, industrial efficiencies, etc. It is recognized for the reliability and traceability of the information it collects, even though for some parameters a relatively small number of mills used to be covered. In this study, the CTC database has been used, but now involving a considerably larger sample of mills, as CTC has increased the number of mills participating in its survey since 2005. For some parameters, the sample consisted of 168 mills.

We have processed the data for some important parameters. An in-depth analysis of diesel consumption and fertilizer used in sugarcane production was conducted to ensure the consistency of the information received. Table 1 compiles the final parameters considered for sugarcane production for the 2008/2009 season, while sugarcane processing parameters are presented in Table 2. Chemical inputs presented in Table 2 include chemicals for sugar and ethanol production, which have been properly attributed to the respective final product in the life cycle assessment. For ethanol transport and distribution (T&D), we considered road transportation using heavy-duty trucks and a total transportation distance (including distribution) of approximately 340 km.

Table 1. Sugarcane production, harvesting, and transportation parameters in 2008.

Parameter	Value	Source
Cane productivity	86.7 t/ha	CTC (168 mills)
Harvested area % total area	72%	CTC
Total diesel consumption[a,b]	274 L/ha	CTC (27 mills)
Transportation distance[b]	21 km	CTC (32 mills)
Truck's energy efficiency[b]	55 t.km/L	CTC (24 mills)
Unburned cane harvesting[c]	35%	CTC (167 mills)
Mechanical harvesting	48%	CTC (167 mills)
Cane trash yield	140 kg_{dry}/t cane	Hassuani et al.[16]
Agr. inputs		
N	777 g/t cane	CTC (13 associates)
P_2O_5	249 g/t cane	CTC (13 associates)
K_2O	980 g/t cane	CTC (13 associates)
$CaCO_3$	5183 g/t cane	CTC (13 associates)
Herbicides	44 g/t cane	Adapted from SINDAG[d]
Insecticides	3 g/t cane	Adapted from SINDAG[d]
Acaricides	0.02 g/t cane	Adapted from SINDAG[d]
Fungicides	<0.01 g/t cane	Adapted from SINDAG[d]
Other defensives	0.96 g/t cane	Adapted from SINDAG[d]
Shares of N fertilizers		
Ammonia	14%	CTC (13 associates)
Urea	48%	CTC (13 associates)
Ammonium nitrate	37%	CTC (13 associates)
MAP	<1%	CTC (13 associates)
Shares of P_2O_5 fertilizers		
Acidulated phosphates	91%	CTC (13 associates)
Phosphate rock	<1%	CTC (13 associates)
MAP	9%	CTC (13 associates)

[a] Includes diesel consumption in all activities (sugarcane farming, harvesting, transportation, etc.).
[b] Values for the 2007 harvest season.
[c] In burned cane areas, we assumed that 90% of the cane trash is actually burnt to estimate GHG emissions. Note that burned cane can also be mechanically harvested.
[d] Specific defensive uses are derived from SINDAG[17] data on total defensive demands in 2008 for sugarcane crop. Total sugarcane demands for defensives (active ingredient) in 2008 were – herbicides: 24 857 t; insecticides: 1808 t, acaricides: 9 t; fungicides: 1 t; others: 538 t. To yield the uses per tonne of cane in Center-South, these values were divided by total planted area in Brazil (8.92 M ha),[4] adjusted to harvested area (72.44%), and divided by cane productivity (86.7 t/ha).

Table 2. Sugarcane processing parameters in 2008.[a]

Parameter	Value	Number of Mills
Sucrose % cane	14.0 %	166
Fiber % cane	12.8%	166
Bagasse % cane	26.4%	74
Industrial efficiency	86.2%	103
Chemicals[b] & lubricants		
Lubricants	10.3 g/t cane	65
Sulfur	156 g/bag	45
Lime	880 g/t cane	93
Sulfuric acid – fermentation	7.4 g/L	94
Soda – evaporators	65 g/t cane	52
Neutralization soda	2.1 g/L	53
Antibiotic – fermentation	9.3 g/m^3	88
Electricity surplus	10.7 kWh/t cane	124[c]
Bagasse sold / total produced	3.3%	74
Residues		
Stillage	11 L/L	85
Filtercake	31 kg/t cane	99
Boiler ashes	2 kg/t cane	[d]
Soot	12 kg/t cane	[d]

[a] From CTC.[18]
[b] Main chemicals used in the industry.
[c] UNICA members.
[d] From Copersucar.[19]

Energy balance and GHG emissions

In this analysis we adopted a well-to-wheels approach for ethanol evaluation, and a field-to-gate approach for sugar. For both products, the following energy flows were considered in the energy balance and GHG emissions evaluation: the direct consumption of external fuels and electricity (direct energy inputs, in terms of fossil primary energy); and the fossil primary energy required for the production of chemicals inputs in agricultural and industrial processes (e.g. fertilizers, limestone, pesticides, lubricants).

Many LCA studies also include the embodied energy in machinery and buildings. The evaluation of such flows, however, may add unnecessary complexity to the analysis, since they represent small shares of total emissions and energy use. For this reason, and to be consistent with other analyses

Table 3. Above-ground nitrogen availability related to crop and industrial residues returned to the soil.

Residue	Availability[a] (kg/t cane)	N content[b] (%)	Total N (g/t cane)
Unburned trash	40[c]	0.60[d]	237
Stillage	570[e]	0.36[f]	205
Filtercake	31	0.84	264
Boiler ashes	2	0.01	<1
Soot	12	0.16	19
Total			**725**

[a] From Table 2.
[b] From Copersucar.[18]
[c] Dry basis. The availability was calculated assuming that 80% of the trash in unburned cane areas remains on soil. Total dry trash yield: 140 kg/t cane; unburned cane area: 35% (see Table 2).
[d] From Linero and Lamônica.[23]
[e] L/t cane. Estimated by the multiplication of stillage yield by total ethanol production, divided by total cane processed (related to the Center-South Region).
[f] kg/m^3, from Macedo.[24]

performed for fossil fuels,[8] or recommended for biofuels[20] these flows were not considered here. Moreover, for the specific case of Brazil, fossil embodied energy tends to be even smaller, due to the large share of renewable sources (47%) in the primary energy matrix.[3]

In addition to fossil fuels utilization, emissions from cane trash burning and from the field due to fertilizers/limestone application and crop/industry residues returned to soil are included. For residues returned to the soil, Table 3 presents the total above-ground nitrogen available, for which it is assumed that a fraction is emitted as N_2O. Methane emissions from stillage and bagasse degradation were not considered, since current storage and application conditions adopted in Brazil reduce substantially the promotion of anaerobic digestion.[9] Carbon emissions from direct and indirect land-use change (LUC and iLUC) were not included either. For the direct LUC effects, the data for the specific land-use changes for sugarcane expansion in the last decade indicates that less than 1% occurred over native vegetation areas (with higher C stocks) and the overall effect may actually be of increasing the C stocks in soil – for the expansion occurred in the 2002–2008 period, LUC emissions have been estimated as –118 kg CO_2eq/m^3 ethanol.[21] As the growth scenarios for 2020 indicate the need for relatively small areas compared to the availability, the trend is the use of more pasture lands and less crop areas in the expansion. So very little impact (if any) on LUC emissions are expected. For the iLUC effects, there is no scientific consensus on a methodology to evaluate these emissions. The large area availability in Brazil and the intensification of the cattle-raising systems, together with the current AgroEcological Zoning legislation restricting areas for sugarcane expansion (http://www.cnps.embrapa.br/zoneamento_cana_de_acucar/), indicate that the iLUC effects could also be very small.[22]

The GREET 1.8c.0 model was used to evaluate energy use and GHG emissions in the ethanol life cycle, with recent production parameters of the Brazilian Center-South Region. Some default parameters were changed to better reflect Brazilian conditions. For instance, the energy required to produce agricultural limestone was based on a sample of seven production units in Brazil, with an average consumption of 7 kWh (electricity) plus 2.6 liters of fuel diesel per tonne of limestone produced. These values differ substantially from the original GREET parameters, which are assumed to be similar to K_2O mining values.[25]

In addition, for chemical inputs, we performed a separate analysis based on aggregated information from the Brazilian Chemical Industry Association.[26] Emissions and energy use were assessed through the total use of chemicals in ethanol production and the overall emission and energy use factors available (350 kg CO_2/t; 0.157 toe/t; 50.5% from renewable sources).

To evaluate the GHG emissions mitigation obtained by using ethanol instead of gasoline, we considered the average fuel mileage equivalences verified in São Paulo State, for the different ethanol uses, as presented in Table 4.

Table 4. Fuel economy equivalences for different ethanol uses in Brazil.

Fuel	Fuel economy[a] (km/L)	Equivalence[b]	L etOH/ L gas[c]
Gasoline (reference)[d]	n.a.	100%	
E22[e]	11.3	106%	1.3
Ethanol[f]	8.6	139%	1.4
Flex-Ethanol[g]	7.7	155%	1.6

[a] Averages verified in 2005 for new light vehicles in São Paulo State.[27,28]
[b] Equivalence with respect to gasoline (set as 100%).
[c] Represents the equivalence between ethanol and gasoline for each technology employed. In terms of lower heating value, the equivalence would be approximately 1.5 L/L for anhydrous ethanol.
[d] Gasoline mileage is not available (n.a.) since gasoline is not used as neat fuel in Brazil. For comparison purposes, we assumed gasoline fuel economy as 11.9 km/L, based on Joseph Jr.[29] Such value was estimated from the gasohol (E22) mileage with respect to gasoline, which is reported as 105.5%.[29]
[e] Gasoline-ethanol blend: 78% gasoline, 22% anhydrous ethanol (volume basis). The ethanol-gasoline equivalence was estimated as follows: (0.22 x 106%) / (1 – 0.78 x 106%) = 1.3 L/L.
[f] Hydrous ethanol (E100) fueling dedicated ethanol engines.
[g] Represents flex-fuel vehicles operating with hydrous ethanol. In Brazil, flex-fuel vehicles are designed to run with any mixture between gasohol and hydrous ethanol.

For the sugar production analysis, we allocated the sugarcane production flows (evaluated with the GREET model) according to the methodology described below. The flows associated with use of chemicals in industry were evaluated separately, both for sugar and ethanol. Emissions from bagasse boilers and lubricants' use, however, were based on GREET parameters.

Energy and emissions allocation

The main products of the Brazilian sugarcane industry are sugar (for the food market), anhydrous ethanol, which is used as fuel (blended with gasoline), and hydrous ethanol, which is used as neat fuel (in dedicated engines and flex-fuel vehicles (FFV)) and also destined for a small non-energy market. The more than 400 registered sugarcane mills in Brazil[30] can be classified into three different groups: sugar mills, for sugar production only; sugar mills with adjacent distilleries, which produce sugar and ethanol; and autonomous distilleries for ethanol production only. Sugarcane mills with adjacent refineries comprise about 60%, autonomous distilleries make up about 37%, and the remaining are sugar mills only.

For cane ethanol, exclusive LCA studies have been consistently performed, due to the long Brazilian experience with autonomous distilleries. But when the coproduction of sugar is considered, a proper methodology to allocate energy and GHG and other emissions' flows related to cane production has to be adopted, as sugar and ethanol 'compete' for cane's sugars, with similar consumption of sugar.

To evaluate the environmental burden associated with each of these main products, a virtual subdivision method was used, which creates three pathways for cane processing, as illustrated in Fig. 1. This method applies the same logic as the physical causality as allocation principle. The proposed

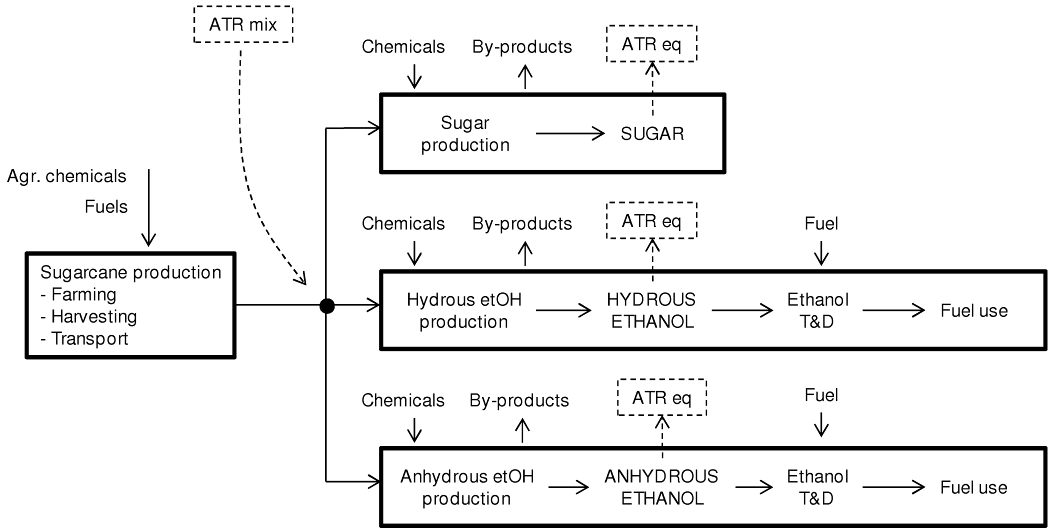

Figure 1. Sugar and ethanol pathways.

method is based on the mass balance regarding the total recoverable sugars (the Portuguese acronym ATR will be used) associated to each sugar-derived product of the mill, i.e. the *ATR mix*.

In the Consecana methodology, established within the context of the independent sugarcane suppliers payment system, ATR is a function of the content of cane sugars and industrial efficiencies.[31] It is based on very reliable data since it is established jointly by cane suppliers and industry owners, and it plays an essential role in establishing the payment for the sugarcane supplied. Sugar and ethanol (final products) can also be converted into their corresponding equivalent ATR through this methodology, using specific coefficients so that we can estimate how much of the total ATR 'available' in the mill has been respectively destined to sugar, hydrous, and anhydrous ethanol production. This method also enables the assessment of cane used for sugar and ethanol. In this work, the overall ATR balance of Brazilian Center-South Region in 2008 was used in the subdivision method proposed (Table 5).

Allocation methodologies based on the energy content and market values of the products were also considered in the sensitivity analysis. The energy-based method used the lower heating values of sugar and ethanol, while the market-value method considered the 2008 average prices at the mill gate, estimated from CEPEA.[32]

Coproduct credits

The main coproducts of ethanol and sugar production are bagasse and electricity. Nowadays, energy generation in most sugarcane mills is based on 'pure' cogeneration cycles (at pressures of 22 bar), which are able to meet the whole energy demand of the mills and still produce small bagasse and electricity surpluses (0–10 kWh/t cane). Even though an established bagasse market does not exist in Brazil, many industries acquire surplus bagasse to use it as fuel, avoid-

Table 5. Overall ATR balance in the Brazilian Center-South Region in 2008.

Product[a]	Production[b] (Mt or hm^3)	ATR factor[c] (kg/kg or L)	ATR[d] (Mt)	Mix
Sugar[e]	27.1	1.0495	28.4	**40%**
Hydrous ethanol	16.7	1.6913	28.2	**39%**
Anhydrous ethanol	8.5	1.7651	15.1	**21%**

[a] In 2008, total sugarcane production for sugar and ethanol in the Center-South Region was 500.2 M t.[4]
[b] From MAPA.[4]
[c] Converts final products into ATR equivalent. This analysis was based on ATR factors given by Consecana-SP.[31]
[d] ATR = Production x ATR factor.
[e] Considered as white sugar.

ing, thus, the use of fuel oil. Such practice, however, has been progressively reduced, as the interest for using bagasse for electricity generation in cane mills grows. About 100 mills currently export electricity to the grid today, and this number is increasing.

At the end of the 1990s, with the change in the Brazilian energy sector regulation, the mills' power section started generating surplus electricity for sale. A strong modernization process started, involving the acquisition of high-pressure boilers, combined with process improvements to reduce energy demand.[33,34] As a consequence, the electricity surplus commercialized by the mills has increased, and has the potential to produce ten times greater levels than those currently generated in the near future, considering the use of trash as additional fuel to bagasse.[33,35]

The environmental emissions may be assigned to coproducts and main products in many different ways. The more suitable way depends on the specific coproduct in each case. The emissions' assignment may consider different methodologies: the displacement method, physical causalities, the market value, or a specific reference scenario for the biomass/processes under consideration.

When bioenergy is the main product, the displacement method is usually selected, as recommended by the ISO standards[36,37] for LCA methodology. Usually, it takes into account the service offered by the coproduct and how (the net emissions) that service would have been delivered in the absence of the coproduct. These net emissions are credited to the biomass product chain for providing the coproduct.

In this analysis, sugar and ethanol pathways were created, with surplus electricity and bagasse as coproducts. These coproducts are used as suppliers of commercial energy, and they correspond to a relatively small value today. The displacement method is then adopted as the reference case.

For bagasse, we considered the substitution of bagasse-fired boilers (79% LHV efficiency) for fuel-oil-fired boilers (92% LHV efficiency), which is the most common application in Brazil.[6] These emission credits are not included in the GREET model, so here they were estimated apart from the model, but considering GREET emissions factors for residual oil.

For electricity, substitution criteria are more complex and need further explanation. In this case, the basic question is: what is the amount of additional net GHG emissions that would have been produced by the Brazilian power system to provide the same energy, in the absence of the surplus electricity supplied by sugarcane processing?

To answer this question we have to consider the characteristics of the Brazilian power system. It consists of 80% hydropower generation (in an average hydrology year), and the remaining 20% are mostly from thermal power,[38] to complement the national interconnected system (SIN) demand, to assist in eventual (localized) transmission restrictions, and to supply the isolated systems (SI). Wind energy also plays a (small) role, and distributed energy systems (renewable, cogeneration) are part of the system as well.

Projections for the expansion of the generation system indicate that from 2008 to 2017 the installed capacities for hydroelectricity will decrease from 81.9 to 70.9%, with substantial increase in fuel oil based power (0.9 to 5.7%).[39] This trend is in part to decrease environmental impact of large hydro power projects. Environmental restrictions to the flooding of large areas for use as water reservoirs for the new hydroelectric power stations has led to a much larger seasonal variation in power availability in the last years. New hydroelectricity units have (relatively) much smaller water-storage capacity in the dams.[40, 41] This has strongly limited the capacity for multi-annual regulation of the large reservoirs in Brazil, forcing increased installation and dispatch of thermal power to help the supply system throughout the dry season.

The dispatch order in Brazil is: (i) hydroelectric; (ii) wind; (iii) nuclear; (iv) imports from other subsystems (ordered by increasing cost); and (v) thermal power (ordered by increasing cost). The bagasse-based generation units are classified as 'inflexible thermal-based systems', in the sense that they are always dispatched. They are in the lowest range of unit variable cost for the thermal systems.[39] The National Electric System Operator (ONS) considers that the energy they supply to the grid allows for the reduction of other thermal power plants' use, with higher costs, which would have been dispatched for security reasons.

Surplus energy is produced by the sugar mills in the dry season, thus reducing the need for thermal power complementation. Since the bagasse-based surplus energy will remain at a level lower than 10% of the total electricity needs, in this decade, it is essentially reducing the use of fuels in the Operating Margin (OM). Hence, the emissions avoided by the bagasse-derived electricity today are well represented by the emission factor for the OM. Some methodologies have been used for its evaluation (simple or adjusted OM; dispatch data analysis; average OM),[42] but the use of the dispatch data is the most recommended. The emission factor may then be calculated as the weighted average of the emission factors for the power generation units supplying the 10% (of total dispatched energy) at the lowest priority dispatch (calculated each hour).

Considering the predominant use of natural gas thermal plants in the Brazilian OM generation mix (Figure 2), we adopted the natural gas emission factors for electricity credits evaluation in the reference scenario. Alternatively, an energy-based allocation method was considered as sensitivity, assuming an arbitrary heat rate of 9 MJ/kWh for the electricity surplus.

The methodology proposed within the European Directive on renewable energy use[43] suggests a separation between cogenerated electricity and total excess electricity produced in a biorefinery. In the sugarcane context, it is natural to assign all bagasse-derived electricity as credit to sugar and ethanol, due to the relatively small electricity production, and the fact that bagasse is an industrial residue. The scenario is different, however, when the recovery of field residues is considered for electricity generation. In terms of potential, commercial technology options for electricity generation exclusively from bagasse can lead to surpluses greater than 60 kWh/t cane.[44,34] Thus, for electricity surpluses up to

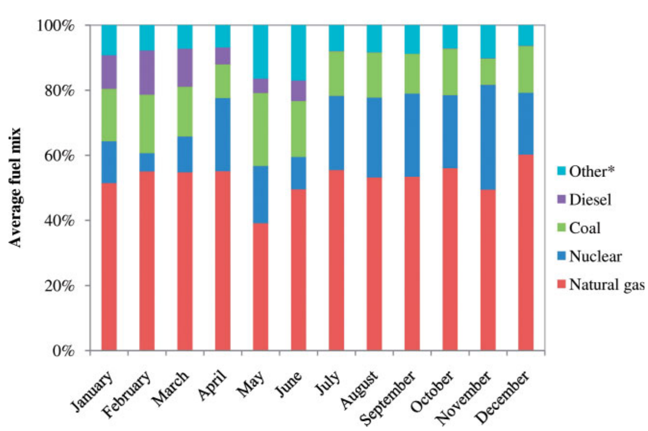

Figure 2. Average fuel mix for electricity generation in Brazilian SIN Operating Margin in 2008 (Based on MCT).[45] *Includes hydro, wind, fuel oil, and gas coke.

60 kWh/t cane, it is reasonable to assign all excess electricity as credit to sugar and ethanol production, instead of the adoption of allocation methods.

Uncertainty analysis of ethanol life cycle emissions

The advantages and importance of sugarcane ethanol as a tool for GHG emissions mitigation are well explored in literature,[46,47] but studies of the uncertainties related to such mitigation are not very common in the literature. One example from Finland shows large uncertainties in mitigation values using commercial or developing technologies.[48]

In this work, we used a Monte Carlo analysis to assess the uncertainties of ethanol life cycle emissions. Uncertainty distributions were generated for eleven parameters (Table 6) based mostly on the CTC database for the 2008 season, taking into consideration that different parameters had different numbers estimates from sugarcane mills. The uncertainties related to fossil fuels life cycle emissions were not considered in this analysis.

Projections were also made for a 2020 scenario (based on experts' estimates), but assuming different averages and probability distributions. This was based on best-in-class technologies and technological improvements commercially possible today.

Results

Fossil energy use and GHG emissions from sugar production are presented in Table 7. Fossil energy use was estimated at 721 kJ/kg, including the credits related to electricity and bagasse surpluses. Because bagasse is used for energy there is no demand for fossil fuels in the industrial phase. As a result, there is a strong benefit not only to the energy balance, but also in the GHG emissions associated to sugar production. GHG emissions were estimated at 234 g CO_2eq/kg, with a large contribution from trash burning and field emissions, accounting for 42% of total gross emissions (excluding credits).

As for anhydrous ethanol life cycle, fossil energy use and emissions were evaluated respectively as 80 kJ/MJ and 21.3 g CO_2eq/MJ (Table 8). Additional emissions compared to sugar are due to ethanol T&D and tailpipe emissions. Field emissions and trash burning are similarly important emissions sources, although the use of diesel for cane farming and transportation is the main GHG emitter (which is also true

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Table 6. 2008 input parameter for Monte Carlo analysis.

Parameter	Distribution	Units	Values[a]
Cane productivity	Normal	t/ha	(86.7, 13.4)
Harvested area	Normal	%	(72, 6)
Diesel consumption	Normal	L/ha	(274, 75)
Nitrogen application	Triangular	g/t cane	(39, 1515)
N_2O emission factor[b]	Triangular	%	(0.4, 4)
$CaCO_3$ application	Triangular	g/t cane	(162, 13 755)
Trash burning	Triangular	kg/t cane	(3, 126)
Ethanol yield[c]	Normal	L/t cane	(81.1, 4.3)
Electricity surplus	Exponential	kWh/t cane	(10.7, –)
Bagasse surplus	Exponential	kg/t cane	(8.7, –)
Ethanol T&D distance[d]	Normal	km	(340, 100)

[a] Normal distribution (mean, standard deviation), triangular (min, max), exponential (mean, –).
[b] Based on Hsu *et al.*[49]
[c] Ranges were estimated from reported industrial efficiencies.
[d] An arbitrary standard deviation was assumed.

Table 7. Fossil energy use and GHG emissions from sugar production (2008).

	Fossil energy use (kJ/kg)	GHG emissions (g CO_2eq/kg)
Sugarcane farming	1109	85
Trash burning		48
Field emissions[a]		85
Agr. inputs production	508	48
Sugarcane transportation	237	18
Sugar production	37	31
Credits		
Electricity[b]	–754	–46
Bagasse[c]	–416	–35
Total	**721**	**234**

[a] Includes emissions from the soil due to fertilizers, residues and limestone application.
[b] Displacement of NG thermoelectricity generation.
[c] Displacement of fuel oil fired boilers. We assumed 10% bagasse losses in handling and storage.

Table 8. Fossil energy use and GHG emissions in the anhydrous ethanol life cycle (2008).

	Fossil energy use (kJ/MJ)	GHG emissions (g CO_2eq/MJ)
Sugarcane farming	88	6.8
Trash burning		3.8
Field emissions[a]		6.7
Agr. inputs production	40	3.8
Sugarcane transportation	19	1.4
Ethanol production	4	2.6
Ethanol T&D	22	1.8
Tailpipe emissions		0.8
Credits		
Electricity[b]	–60	–3.7
Bagasse[c]	–33	–2.7
Total WTW	**80**	**21.3**

[a] Includes emissions from the soil due to fertilizers, residues and limestone application.
[b] Displacement of NG thermoelectricity generation.
[c] Displacement of fuel oil fired boilers. We assumed 10% bagasse losses in handling and storage.

for sugar). In Brazil, today, the diesel fuel is actually a blend of fossil diesel and biodiesel (B5).[50] The use of B5, instead of fossil diesel exclusively, was not considered in this analysis, but significant benefits can be expected in the future as larger levels of biodiesel are used in sugarcane production.

The embodied energy in machinery, equipment, and buildings and associated emissions were not accounted for in this analysis, to be consistent with most of the analyses for other fuels. In the estimate presented in Macedo *et al.*,[6] based partially on foreign coefficients dated prior to 1980, these flows were evaluated as 5.6 kg CO_2eq/t cane

(~3 g CO_2eq/MJ) ethanol, which is probably overestimated for the conditions today[9]. But given the low emissions level in the ethanol life cycle this value would be somewhat significant.

As presented in Figure 3, the method used to allocate the emissions' burden of sugarcane production between sugar and ethanol affects the final values. The adoption of an energy-based method leads to higher emissions from sugar production, lowering, thus, ethanol emissions. The effect is the opposite when an ATR-based method is adopted.

The allocation methods used to deal with coproducts (bagasse and electricity surpluses) impact final emissions as well (Figure 4). These impacts are small today, but can be increasingly important in the next years, as electricity exports will represent a significant share of the total energy output of the plant. In this case, the adoption of allocation methods (e.g. separating the electricity related to the condensing portion of the combined heat and power cycle) could be appropriate, due to the importance of electricity as an additional sugarcane product. This highlights the fact that allocation choices influence carbon intensity of renewable fuels, which is a relevant aspect to be considered in regulatory analyses.

Compared to other feedstock (like sugarbeet or corn), we can say that sugarcane is a more effective option for emissions mitigation, as already illustrated in literature.[51] The use of bagasse as energy source in part explains this comparative advantage. One example is presented in Figure 5, comparing the GHG emissions from sugar production using sugarbeet and sugarcane as feedstock. Values

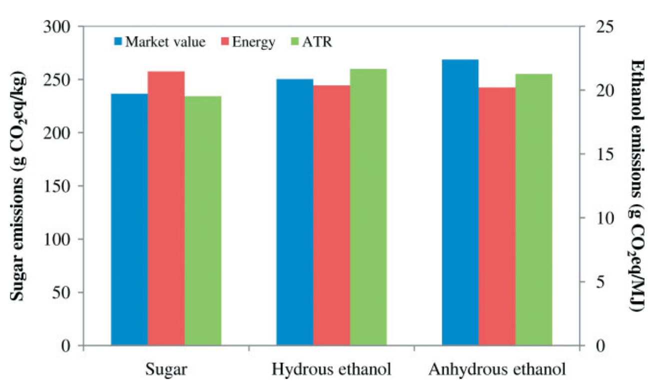

Figure 3. Impacts of different methods to allocate sugarcane emissions between sugar and ethanol.

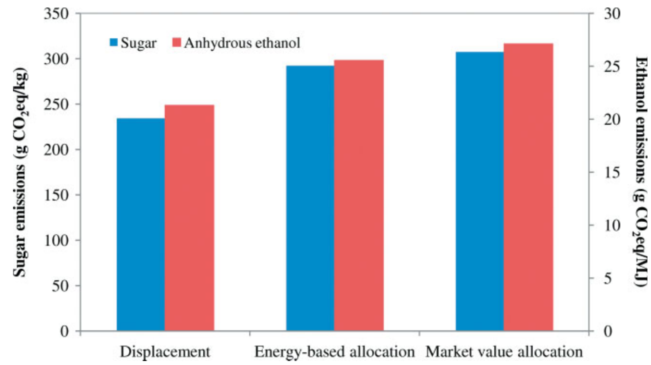

Figure 4. Impacts of different methods to deal with sugar and ethanol coproducts allocation (electricity and bagasse surplus).

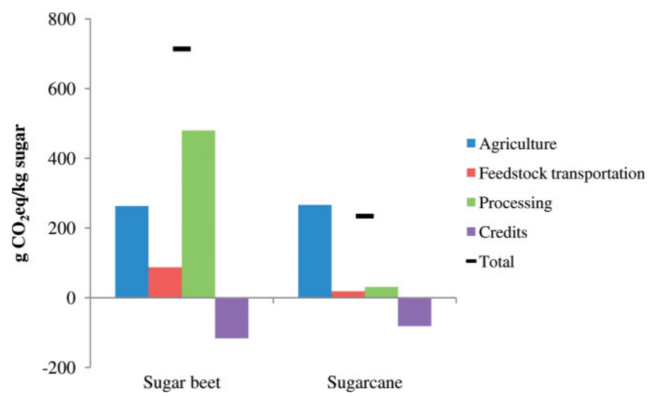

Figure 5. GHG emissions from sugar production using sugar beet and sugarcane as feedstock.

presented here for sugarbeet are derived from RFA[52] for beet production and transportation, while values for beet processing (for one unit using heavy fuel oil) are derived from Krajnc *et al.*[53] Emission credits due to the coproduction of beet pulp and lime were also estimated using emission factors from RFA.[52] To yield the final emissions per kg of sugar, we allocated the total emissions between sugar and molasses based on the sugar mass balance of these output streams.

For sugarcane ethanol, the environmental benefits are internationally acknowledged.[11,12,42] Considering the 2008 average conditions in the Center-South Region, the use of anhydrous ethanol in Brazil mitigates around 80% of gasoline GHG emissions (Figure 6), but the uncertainties (due to differences among producing units) must be highlighted (Figure 7). The results of the Monte Carlo analysis show that the 90% confidence interval (i.e. 5th percentile and the 95th

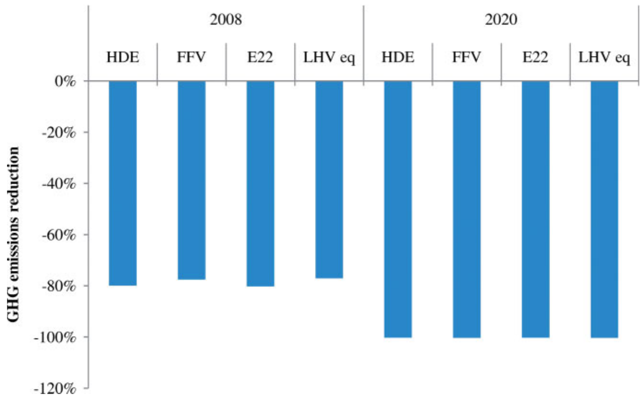

Figure 6. GHG emissions reduction relative to conventional petroleum gasoline (92.5 g CO_2eq/MJ) for different ethanol uses in Brazil. HDE: dedicated hydrous ethanol engines; E22: anhydrous ethanol in blends with gasoline (22% ethanol); FFV: flex-fuel vehicles operating with hydrous ethanol; LHVeq: lower heating value equivalence between gasoline and anhydrous ethanol.

percentile) for anhydrous ethanol emissions in the current conditions is 12 g CO_2eq/MJ to 35 g CO_2eq/MJ. For the 25th to 75th percentiles the data are between 20 and 28 g CO_2eq/MJ and are practically symmetric around the median value. The red X point indicates the averages used in the analysis called reference case.

The reference case and the median values are not coincident essentially because of the uncertainty distribution assumed for the N_2O emission factor. The reference cases resulted from the average parameters; as the mean resulted from the triangular distribution is greater than the IPCC default value (used for the reference cases), higher emissions are verified in the uncertainty analysis. It is worth mentioning that for Brazilian conditions, the averages verified for the N_2O emission factor are even lower than the default value recommended by Intergovernmental Panel on Climate Change (IPCC).[54]

Uncertainties related to variation of parameters over time also exist (mostly due to varying climatic conditions). Variations in cane quality and productivity, for instance, may impact emission averages in different ways from year to year. Nevertheless, a clear trend can be identified for the next decade, when the 90% confidence interval of ethanol emissions is expected to be –10 g CO_2eq/MJ to 14 g CO_2eq/MJ and the 25th to the 75th percentile are between –3 and 7 CO_2eq/MJ. Due to the complete elimination of cane trash burning, rational use of residues in agriculture and, mainly, high level of electricity exports, ethanol net emissions could be close to zero on average in 2020.

We used the displacement method to assess the electricity credits. This is appropriate for the current conditions since the cogeneration level (10.7 kWh/t cane) is still much lower than the 'limit' cogeneration (40–60 kWh/t cane) for the process thermal energy needs. For the future, allocation procedures can be more appropriate as mills produce greater electricity surplus, especially due to the use of cane trash as supplementary fuel to bagasse. In that case, emissions mitigation promoted by electricity (or any other coproduct)

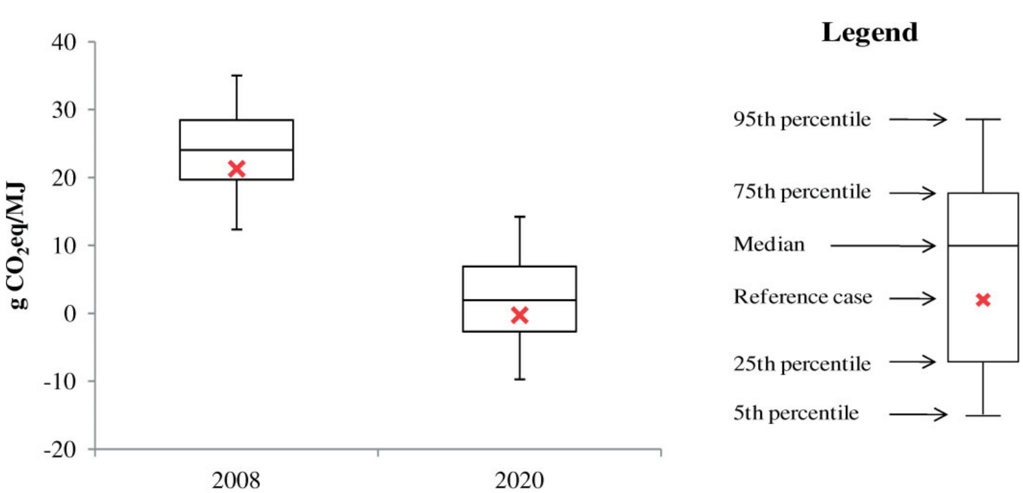

Figure 7. Boxplot of the Monte Carlo uncertainty analysis results for ethanol life cycle emissions.

must be accounted for in other sectors, but assigned back to sugarcane.

Conclusion

This work evaluated the energy use and GHG emissions in the life cycle of sugar and ethanol from cane, considering bagasse and electricity surpluses as coproducts. We performed an overall balance for the Brazilian Center-South Region, adopting an allocation method based on the total recoverable sugars (ATR), which allowed a proper evaluation of sugar and ethanol production separately. Alternative methods were evaluated as well, showing that the energy-based method would increase the sugar emissions' burden and lead to lower ethanol emissions.

Different methodologies to deal with coproducts also lead to some impact on final results for sugar and ethanol. For the near future, however, as mills start to produce much greater electricity surplus, more drastic impacts may be verified. Especially for those cases involving trash recovery, and other future coproducts, partial allocation methods may be considered. For averages under 60 kWh/t cane, credits based on displacement of operating margin mix are more appropriate for the Brazilian case.

Through a consolidated analysis tool and a comprehensive database, we verified the comparative advantages of sugarcane products. For sugar production, GHG emissions were estimated at 234 g CO_2eq/kg, which is considerably less than what is verified for beet sugar produced in Europe, for instance. As for anhydrous ethanol, life cycle emissions were evaluated as 21.3 g CO_2eq/MJ, which leads to an emission mitigation of 80% (compared to conventional gasoline), considering ethanol use in blends with gasoline (E22).

The Monte Carlo analysis showed the effects of a relatively high variation for some parameters among the production units (some of this is due to inherent conditions, like soil quality; some to operational procedures); but there is a clear trend for the next few years, when the credits associated to electricity exports are expected to offset all ethanol life cycle emissions. For the mid to long term, further reductions can be projected as advanced technologies for biomass utilization (e.g. biochemical conversion or gasification routes) become commercially available and are employed at significant levels in the sugarcane sector.

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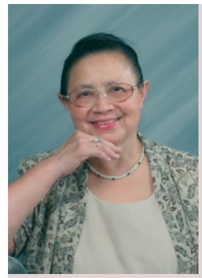

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