Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil

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Abbreviations	
BEN	Balanço Energético Nacional (National Energy Balance)
CMA	Controle Mútuo Agrícola (Agricultural Benchmark Program)
CMI	Controle Mútuo Industrial (Industrial Benchmark Program)
CTC	Centro de Tecnologia Copersucar (Copersucar Technology Center)
C-S	Center-South region (Brazil)
IPCC	Intergovernmental Panel on Climate Change
NIPE	Núcleo Interdisciplinar de Planejamento Energético – UNICAMP (Interdisciplinary Nucleus of Energy Planning – UNICAMP)
PAMPA	Programa de Acompanhamento Mensal de Performance Agrícola (Agricultural Monthly Performance Follow up Program)
SP	São Paulo State
UNICAMP	Universidade de Campinas (University of Campinas)
GHG	Greenhouse gases
GWP	Global warming potential
HHV	Higher heating value
LHV	Lower heating value
RS	Reducing sugars

Units	
cv	Metric horsepower (1cv = 0,7355 kW)
GJ	Gigajoule
ha	Hectare
h	Hour
kcal	Kilocalorie
kg	Kilogram
kWh	Kilowatt hour
l	Liter
MJ	Megajoule
Pol	Polarization (sucrose content)
t	Metric ton
TC	Metric ton of cane
TCH	Metric ton of cane per hour

	Chemical compounds
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2SO_4	Sulfuric acid
K_2O	Potassium fertilizers
N	Nitrogen
NH_4	Ammonium radical
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
P_2O_5	Phosphate fertilizers

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Preface

One of the main tasks of the Secretariat of the Environment of the State of São Paulo is the improvement of air quality in the State's urban areas. The addition to gasoline of 20-25% of ethanol is an important contribution to this end.

The substitution of gasoline by alcohol has another important consequence: the reduction of greenhouse gas emission (principally CO_2) provided that in the production of the ethanol, the fossil fuel contribution is minimized. This contribution stems from the energy needed to produce the raw materials used in farming and in the industrial process (fertilizers, lime, sulfuric acid, lubricants etc.) as well as electricity and fuels acquired by the producer (direct energy consumptions).

To consider ethanol as a renewable (or an "almost renewable") fuel, it is essential that the production fossil fuels' contribution is small, just as with the emission of greenhouse gases not directly associated with the use of fossil fuels in the entire cycle of production and usage.

Along the years evaluations of this contribution have been made by various groups of specialists, with highly encouraging results.

With the increase in the numbers of ethanol production units and with the advances of technology, the Secretariat of the Environment felt it to be necessary to seek from University of Campinas (UNICAMP) an updating of these evaluations. This update was carried out with data obtained also from the Copersucar Technology Center (CTC/Copersucar). This report is the result of this work.

Prof. José Goldemberg

Secretary of the Environment

Executive summary

Sugar cane energy products, ethanol and bagasse, have made a significant contribution to the reduction of greenhouse gas (GHG) emissions in Brazil, substituting fossil fuels, gasoline and fuel oil, respectively.

However, fossil fuels are used in the operations of planting, harvesting, transportation and processing of the sugar cane, resulting in GHG emissions. Energy and GHG balances are required to evaluate the net effects during the complete well-to-wheel cycle of ethanol, i.e. ethanol production from sugar cane and its use as fuel in the transport sector. To facilitate the comparison with other studies, the GHG data are presented as CO_2 equivalent emissions (CO_2eq.).

In the energy balance three levels of energy flows are considered, making it easier to compare with other energy balances.

Level 1 – Only the direct consumption of external fuels and electricity (direct energy inputs) is considered.

Level 2 – This is the additional energy required for the production of chemicals and materials used in the agricultural and industrial processes (fertilizers, lime, seeds, herbicides, sulfuric acid, lubricants, etc.).

Level 3 – This is the additional energy necessary for the manufacture, construction and maintenance of equipment and buildings.

Due to the diversity of the database for the technical parameters related to the sugar cane and ethanol production in Brazil, a limited but reliable database was prepared using the information available at Copersucar. This database has the advantage of traceability and consistent references.

Two cases have been considered in the evaluation of energy flows: Scenario 1 based on the average values of energy and material consumption and Scenario 2 based on the best values being practiced in the sugar cane sector (minimum consumption with the use of the best technology in use in the sector). In both Scenarios the balance is referred to one metric ton of cane (TC).

Under these conditions, the results obtained for energy consumption were: 48,208 kcal/TC and 45,861 kcal/TC in the agricultural sector for Scenarios 1 and 2, respectively, and 11,800 kcal/TC and 9,510 kcal/TC in the industrial sector for Scenarios 1 and 2, respectively. The total energy consumptions for Scenario 1, 60,008 kcal/TC, and Scenario 2, 55,371 kcal/TC, compare very favorably with the total energy production (ethanol and surplus bagasse) of 499,400 kcal/TC and 565,700 kcal/TC, for Scenarios 1 and 2, respectively. The ratios of output energy (renewable) to input energy (fossil) are 8.3 and 10.2, for Scenarios 1 and 2, respectively.

In the GHG balance the emissions have been divided into two groups: emissions derived from the use of non renewable energy (diesel and fuel oil) and emissions from other sources (cane trash burning, fertilizer decomposition).

For the first group the calculated values were 19.2 kg CO_2eq./TC and 17.7 kg CO_2eq./TC for Scenarios 1 and 2, respectively, while the values determined for the second group were 12.2 kg CO_2eq./TC for both Scenarios.

The emissions avoided due to the substitution of ethanol for gasoline and surplus bagasse for fuel oil, deducting the above values, gives a net result of 2.6 and 2.7 t CO_2eq./m^3 anhydrous ethanol and 1.7 and 1.9 t CO_2eq./m^3 of hydrous ethanol, for Scenarios 1 and 2, respectively.

Introduction

The Brazilian sugar cane agribusiness is an economic activity responsible for 2.2% of GDP, generating an income of over US$ 8 billion and creating approximately one million direct jobs: more than 400,000 in the State of São Paulo alone – the country's largest producer State – as well as fostering the economic development of a large number of municipalities and contributing to the employment of a large number of workers in the rural areas.

The activity has a positive environmental differential that is the efficient production of fuel grade ethanol from sugar cane. The extensive use of fuel ethanol in Brazil, whether as a 25% blend with gasoline (gasohol), or used as a neat fuel in vehicles equipped with dedicated alcohol engines or used in the newly produced flex fuel vehicles, which can operate on neat ethanol, gasohol or any intermediate blend, places Brazil as a leader in carbon emission reduction and Greenhouse Effect mitigation.

The production of ethanol in the 2003/2004 crop season will reach the significant volume of 14.4 billion liters and the Center-South region, which includes São Paulo State, will respond for 89.6% of the total.

In addition to the production of ethanol, the industrial processing of sugar cane generates bagasse, another valuable product. This residue also adds to the industry's positive environmental differential because it has been widely used to replace fossil fuels in the production of industrial heat and electricity in the sugar mills and distilleries thereby boosting the abatement potential of greenhouse gases emission.

The present work is a contribution to a better understanding of the renewable energy value and energy efficiency of this important industrial sector.

Objective

This work presents the life cycle analysis of the GHG emissions in the production and use of ethanol, under the typical conditions found in Brazilian sugar and ethanol mills. It also presents the emissions derived from fossil fuel consumption and those not related to the use of energy.

Data collected in 2002 have been used for the latest update of the analysis of energy consumption in the sugar cane ethanol production at Copersucar mills undertaken in 1985[1], then updated in 1998[2].

The observations made in the first report, especially those concerning the correct definition of the boundaries of the process analysed, remain valid. Some of the parameters defined at that time have been maintained in this report, due to the difficulties found in their updating. However this fact can be considered of little importance since it would have only a very small impact on the energy consumption figures.

The evaluation of the GHG emissions in the production and use of ethanol is also an update and a revision of previous work performed at the Copersucar Technology Center (CTC), whose studies were published in 1992[3] and revised in 1998, with 1996 data[4].

Methodology

The energy flows have been considered in two situations: one (Scenario 1), based on the average values of energy and chemicals' utilizations, and the other (Scenario 2), based on the best existing values (minimum consumption values resulting from the application of the best technology in use by the sector). The use of these scenarios allows not only the characterization of the present situation (Scenario 1) but also the estimation of a situation that may become reality in the medium term (Scenario 2) by the widespread use of good practices already being used in some mills. Technologies that are already developed, or in the process of being developed, but are not used in a significant degree today, have not been considered in this work.

Technologies in the process of gradual introduction, that may have significant impact on the GHG emissions, have been considered at the present degree of utilization. This is the case of mechanically harvested unburned cane, without trash recovery for power generation.

The energy flows have been considered in three levels, to facilitate the comparison with other studies:

Level 1 – Only the direct consumptions of external fuels and electricity (direct energy inputs) are considered.
Level 2 – The energy required for the production of chemicals and materials used in the agricultural and industrial processes (fertilizers, lime, seeds, herbicides, sulfuric acid, lubricants etc.) is added.
Level 3 – The energy necessary for the fabrication, construction and maintenance of equipment and buildings is added.

The parameter values recommended by the Intergovernmental Panel on Climate Change (IPCC)[7] have been used in the GHG emission calculations whenever available.

Database

A complete countrywide database for the sugar cane sector has not yet been fully established, thus the use of a database covering part of the sector but based on reliable and traceable information has been preferred. It is important to point out that this database is representative of the agricultural and industrial practices, especially of the Center-South region, accounting for approximately 85% of the sugar cane production in Brazil.

Under these considerations the following documents have been selected as references for the energy balance of ethanol production in Brazil.

– Copersucar: Agricultural Benchmark Program (26 to 31 mills in the State of São Paulo) – These reports present dozens of performance parameters in the agricultural sector of a group of Copersucar associated mills. They have been prepared for many years, bring monthly and annual averages, and have been fully discussed among the participating mills.
– Copersucar: Industrial Benchmark Program (17 to 22 mills in the State of São Paulo) – These reports present the industrial sector performance parameters (efficiencies, consumption of chemicals etc.) of a selected part of Copersucar member mills. They have been also extensively discussed among the participants, and show the monthly and annual averages.
– Copersucar: Agricultural Monthly Performance Follow up Program (98 mills in the Center-South region) – These reports present the agricultural sector parameters for a larger number of participating mills in the Center-South region. However the traceability of the information and the uniformity of procedures have not the same level of accuracy as in the cases of the two previous sets of documents.

In the cases where weather conditions can have significant impacts on the results (such as the case of sugar cane productivity) the averages for five seasons in sequence (1998/99 to 2002/2003 seasons) have been used. In other cases, the 2001/2002 harvesting season has been used as reference for both agricultural and industrial performance data.

Systems and emission flows definition

To evaluate the GHG emission mitigation in the life cycle of ethanol produced from sugar cane, the concept of "autonomous distillery" has been adopted, meaning that the mill will process the sugar cane to produce ethanol only. In this way the effects of sugar production can be ignored.

The mitigation corresponds to the reduction of GHG emissions obtained by the production and use of ethanol (substituting for gasoline as a fuel). It is, therefore, the difference between the emissions in a situation where no ethanol is produced nor used and a situation with the actual emissions with ethanol: both of which situations reflect Brazilian conditions.

For the life cycle analysis the control volume used included the cane production area, the distillery and the final use of fuel ethanol.

To facilitate the calculations the GHG emissions have been divided into four groups.

Group 1:
Carbon flows associated with the uptake of atmospheric carbon by photosynthesis and its gradual release by oxidation.

1.a Uptake of atmospheric carbon (photosynthesis);
1.b Carbon release during cane field burning, before harvesting (around 80% of tops and leaves are burned with an efficiency of 90%);
1.c Oxidation of unburned residues, in the field;
1.d CO_2 release in the fermentation of sucrose to ethanol;
1.e CO_2 release by the combustion of all bagasse, for power and heat generation, in the boilers of the mills or in other industries boilers (surplus bagasse);
1.f CO_2 release by the combustion of ethanol in automobile engines.

These emission flows can be considered to be nearly neutral, for it is assumed that all fixed carbon is released again within the cycle of sugar cane production and the final use of ethanol and bagasse. An exception is the uptake of part of the carbon in the soil (in past decades the cane fields showed a positive average carbon uptake because land was generally poor in organic matter before being used to grow cane). In this study, due to the difficulties in estimating with a minimum accuracy the level of carbon fixed in the soil, this fraction has been ignored, which results in a conservative assumption.

Thus, the net contribution of the Group 1 carbon flows has been considered as zero which is a common assumption for cycles of biomass production and use.

Group 2:
Carbon flows associated with the use of fossil fuels in the production of all chemicals and inputs used in the agricultural and industrial sectors for the production of sugar cane and ethanol, as well as in the manufacture of equipment, construction of buildings and their maintenance:

2.a CO_2 release due to the use of fossil fuels in the cane fields: tillage, irrigation, harvesting, transportation etc.;
2.b CO_2 release due to the use of fossil fuels in the production of agricultural inputs (seeds, herbicides, pesticides, fertilizers, lime etc.);
2.c CO_2 release due to the use of fossil fuels in the production of agricultural equipment, spare parts and their maintenance;
2.d CO_2 release due to the use of fossil fuel for industrial inputs (lime, sulfuric acid, biocides, lubricants etc.);
2.e CO_2 release due to the use of fossil fuels in the manufacture of equipment, construction of buildings, and their maintenance in the industrial area.

These are negative flows since they contribute to emission increase.

Group 3:
The GHG flows not associated with the use of fossil fuels are mainly N_2O and methane; consideration was given to:

3.a Release of other GHG (non CO_2) in the process of cane field burning;
3.b Release of N_2O from the soil, due to fertilizer decomposition;
3.c Release of other GHG (non CO_2) in the combustion of bagasse in steam boilers;
3.d Release of other GHG (non CO_2) in the combustion of ethanol in engines.

These flows are also negative, that is, they contribute to the increase of GHG emissions.

Group 4:
This group includes what can be called "virtual" flows of GHG emissions; they would take place if, in the absence of ethanol, the fuel demand was met by gasoline and if in the absence of surplus bagasse, fuel oil was used.
These emissions can be characterized as:
4.a GHG avoided emission by substituting ethanol for gasoline;
4.b GHG avoided emission by substituting bagasse for fuel oil in other industrial sectors.

In the analysis that follows, the flows of Groups 2 to 4 will be evaluated; the flows of Group 1 will not be calculated since the net balance is zero. To facilitate the understanding of some simplifying assumptions, it is important to bear in mind that the emissions of Groups 2 and 3 are nearly ten times smaller than those of Group 4. This is normally true for fossil fuels or biomass systems where the energy embodied in equipment and buildings is small when the whole useful life is considered. The same applies to the energy inputs for the manufacture of chemicals and other materials used in the production process. There are some exceptions such as the case of ethanol from corn in the USA.

Use of fossil fuel in sugar cane production

The detailed analysis is presented in Annex 1. The three energy levels considered in sugar cane production are:

Level 1 – Diesel oil used in agricultural operations and sugar cane transportation.

Level 2 – Other inputs: fertilizers, lime, herbicides, pesticides, seeds.

Level 3 – Energy for production and maintenance of equipment and labor.

In Level 1, the energy consumption associated to fuel (diesel) can be calculated using the energy value of diesel (lower heating value, LHV = 9,235 kcal/l plus 2,179 kcal/l for production, transportation and processing) of 11,414 kcal/l. It should be pointed out that if the objective of the analysis was just to verify the fraction of self consumption of the same type of energy in the ethanol production, without regard to the life cycle, the diesel use should be considered as its LHV value. For fuel oil the energy values are equivalent to diesel[5]. Some additional comments on these values can be found in Annex 3, Note 1.

The summary of the results is presented in Table 1. In this summary, no distinction is made between the different forms of energy (usually electric energy is considered at its thermodynamic value, that is, the thermal energy used in its generation) but a complete discussion is presented in Annex 3, Note 2.

Use of fossil fuel in the industrial production of ethanol

The detailed analysis is shown in Annex 2.

In the industrial processing of sugar cane to produce ethanol there are three items that should be considered in the final energy balance:

Level 1 – Purchased electric energy, if any.

Level 2 – Energy required for the production of inputs to the industrial process (chemicals, lubricants).

Level 3 – Energy for the manufacture of equipment, construction of buildings and their maintenance.

Table 2 summarizes the results for the three levels and two Scenarios without distinction between the forms of energy (*see Annex 3, Note 2*).

It can be seen from the energy balance (Annex 2) that there is a surplus of energy being produced, in the form of surplus bagasse that will be considered in the overall analysis, amounting to 40,300 kcal/TC (Scenario 1) or 75,600 kcal/TC (Scenario 2).

A comparison between the energy produced in the process in the form of ethanol and surplus bagasse and the fossil energy consumed is shown in Table 3. It can be seen that the output energy to input

Table 1 – Energy consumption in sugar cane production

Level		Energy consumption	
		Scenario 1 (kcal/TC)	Scenario 2 (kcal/TC)
1	Fuel		
	Agricultural operations/harvesting (A2)	9,097	9,097
	Transportation (A3)	10,261	8,720
	Level total	**19,358**	**17,817**
2	Fertilizers (A4)	15,890	15,152
	Lime (A5)	1,706	1,706
	Herbicide	2,690	2,690
	Pesticides	190	190
	Seeds (A6)	1,404	1,336
	Level total	**21,880**	**21,074**
3	Equipment (A7)	6,970	6,970
	Level total	**6,970**	**6,970**
	Total	**48,208**	**45,861**

energy ratio is 8 to 10, considerably larger than in the case of ethanol from corn in the USA. The energy flows in and out of the control volume of the agricultural and industrial sectors are shown in Figure 1, for Scenario 1.

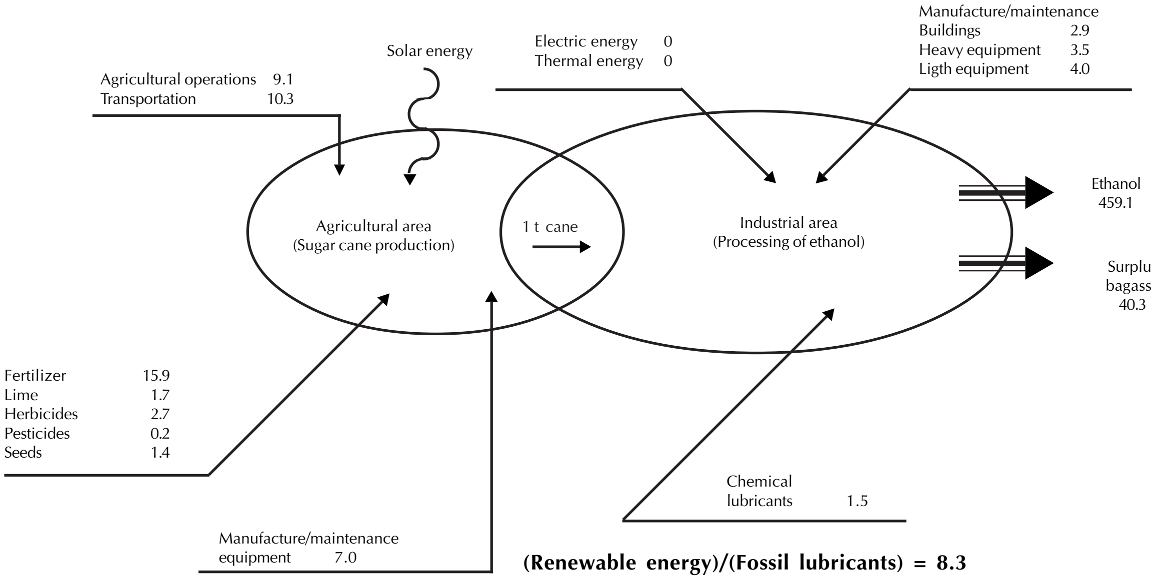
Table 2 – Energy consumption in the production of ethanol

	Level	Energy consumption	
		Scenario 1 (kcal/TC)	Scenario 2 (kcal/TC)
1	Electric energy	0	0
2	Chemicals and lubricants (A9)	1,520	1,520
3	Buildings (A10)	2,860	2,220
	Heavy equipment	3,470	2,700
	Light equipment	3,950	3,070
	Total	**11,800**	**9,510**

Table 3 – Energy generation and consumption in the production of sugar cane and ethanol

Activity	Energy consumption			
	Scenario 1 (kcal/TC)		Scenario 2 (kcal/TC)	
Sugar cane production (total)	**48,208**		**45,861**	
Agricultural operations	9,097		9,097	
Transportation	10,261		8,720	
Fertilizers	15,890		15,152	
Lime, herbicides, pesticides etc.	4,586		4,586	
Seeds	1,404		1,336	
Equipment	6,970		6,970	
Ethanol production (total)	**11,800**		**9,510**	
Electricity	0		0	
Chemicals, lubricants	1,520		1,520	
Buildings	2,860		2,220	
Equipment	7,420		5,770	
External energy flows	**Input**	**Output**	**Input**	**Output**
Agriculture	48,208	-	45,861	-
Factory	11,800	-	9,510	-
Ethanol produced	-	459,100	-	490,100
Surplus bagasse	-	40,300	-	75,600
Total	**60,008**	**499,400**	**55,371**	**565,700**
Output/input	**8.3**		**10.2**	

Figure 1 – Energy balance – Scenario 1 (Mcal/TC)



GHG emissions due to the use of fossil fuels

All fossil fuel use listed in Tables 1 and 2 has been considered here, including direct and indirect uses. The values of indirect uses of energy for fuels, as well as the carbon emission coefficients for their combustion, can be found in Annex 3, Note 2.

Diesel has been considered in the agricultural operations, cane harvesting and transportation and fuel oil for the production of chemicals and the energy embodied in equipment, buildings and their maintenance. This simplification is acceptable considering the structure of the energy use in such applications and the small magnitudes involved.

Total diesel oil consumption: 19,358 kcal/TC and 17,817 kcal/TC, for Scenarios 1 and 2, respectively.

Total fuel oil consumption: 40,650 kcal/TC and 370,554 kcal/TC, for Scenarios 1 and 2, respectively.

The corresponding GHG emissions, as CO_2 equivalent (CO_2eq.), are: 19.2 and 17.7 kg CO_2eq./TC, for Scenarios 1 and 2, respectively.

Other GHG emissions in the production and use of ethanol

In this category are included the emissions associated with sugar cane production, cane processing for ethanol and final use of ethanol (as fuel) that are not derived from use of fossil fuels. The most important are:

– Methane and N_2O emissions from the burning of sugar cane trash before harvesting;

– N_2O soil emissions;

– Methane emissions from bagasse burning in boilers;

– Methane emissions from ethanol combustion in vehicle engines, compared with those from gasoline combustion.

Emissions from sugar cane trash burning in the field.

The calculation have been done considering emission coefficients measured in a wind tunnel simulating the cane field burning[6] and alternatively the average values for agricultural residues recommended by IPCC[7] (*see Annex 3, Note 4*).

The IPCC values led to higher emissions values and, being on the conservative side, have been adopted; the results for methane and N_2O, shown in detail in Annex 3, Note 4, are: 9.0 kg CO_2eq./TC

N_2O soil emissions

Evaluations based on the use of nitrogen fertilizers (Annex 3, Note 5) considered that for the Center-South region conditions around 28 kg N/ha are used in cane planting and 87 kg N/ha for each ratoon, which gives an average value of 75 kg N/(ha.year) for the whole cane cycle. Most of the fertilizer used is of the NH_4 type.

The resulting emissions are 1.76 kg N_2O/(ha.year). Since N_2O has a global warming potential 296 larger than CO_2, this results in 521 kg CO_2eq./(ha.year) or 6.3 kg CO_2eq./TC

Methane emissions from bagasse burning in boilers.

Significant unburned organic compound emissions, including methane, in bagasse fired boilers take place only during operational transients or uncontrolled disturbances in the combustion process. Because of almost continuous operation during the crop season, which is the ethanol production period, such transients and disturbances are relatively small in the ethanol distilleries and sugar mills, and this substantially reduces methane emissions. Therefore, this type of emissions will be ignored in this study.

Methane emissions from automotive engines fueled with ethanol or gasoline/ethanol blends, compared with those from pure gasoline engines.

It is shown in Annex 3, Note 6, that although it is difficult to measure differences between emissions from ethanol and gasoline engines (since there are no engines in use in Brazil that operate on ethanol-free gasoline), the technological evolution of the engines fueled with ethanol and gasoline/ethanol blends has made it possible for these engines to meet current tight legal emission limits. It has also brought the methane emissions to very low levels.

These values are very small when compared with other items considered in this study. In Annex 3 the beneficial aspects of the use of ethanol in automobile engines are also discussed.

Avoided emissions

GHG emissions are avoided by the use of surplus bagasse as fuel in other industrial sectors, substituting for fuel oil, as well as by the use of ethanol as an automotive fuel, substituting for gasoline. In a near future, a fraction of the bagasse produced (and the trash) could be used to generate considerable amounts of surplus electric energy or more ethanol, via hydrolysis, contributing even more to reducing the GHG emissions.

Surplus bagasse

An analysis of the surplus bagasse situation is presented in Annex 3, Note 7.

On average, 280 kg of bagasse/TC are produced with a moisture content of around 50%. The surplus is estimated as 8% in Scenario 1 and 15% in Scenario 2; therefore, the energy corresponding to these amounts of bagasse are 40,300 and 75,600 kcal/TC, for Scenarios 1 and 2, respectively (*see Annex 2*).

To estimate the avoided emissions when this bagasse is substituting for fuel oil, operating conditions have been established for both bagasse and fuel oil fired boilers. Under these conditions (*see Annex 3, Note 7*), the 8% and 15% of surplus bagasse correspond, in terms of end energy use, to 3.2 and 6.1 kg fuel oil/TC being displaced.

The total avoided emissions (including indirect emissions) related to the fuel oil displaced are 12.5 and 23.3 kg CO_2eq./TC, for Scenarios 1 and 2, respectively.

Ethanol

Considering the average productivity and efficiencies of the mills and distilleries, the total emissions (direct and indirect) of the displaced gasoline (Annex 3, Note 8) and the fuel equivalence of Brazilian automobile engines, the avoided emissions due to the use of ethanol were calculated for hydrous and anhydrous ethanol. The details are presented in Annex 3, Note 8.
The resulting avoided emissions are:
2.82 kg CO_2/l anhydrous ethanol
1.97 kg CO_2/l hydrous ethanol
Referring to metric ton of cane, the figures are:
Anhydrous ethanol: 242.5 or 259 kg CO_2eq./TC, for Scenarios 1 and 2, respectively
Hydrous ethanol: 169.4 or 180.8 kg CO_2eq./TC, for Scenarios 1 and 2, respectively.

Balance of emissions and conclusions

The results presented above are summarized in Table 4.

The values are alternative, which means that 242.5 kg CO_2eq./TC is avoided if anhydrous ethanol is produced or 169.4 kg CO_2eq./TC with the production of hydrous ethanol.

For many applications it is more convenient to have the emission data referred to as cubic meters of ethanol (net value), whether it is anhydrous or hydrous. The conversion can be done using the sugar cane productivity of the two scenarios, leading to:
Anhydrous ethanol: 2.6 and 2.7 t CO_2eq./m^3 ethanol, for Scenarios 1 and 2 respectively
Hydrous ethanol: 1.7 and 1.9 t CO_2eq./m^3 ethanol, for Scenarios 1 and 2, respectively.

The values for Scenario 1 (current average), should be preferred for GHG emissions evaluations because they reflect realistic conditions.

Figure 2 shows the emission flows related to the Agricultural Production, Industrial Processing and Ethanol Bagasse Utilization control volumes (Scenario 1).

Taking as a base case that Brazilian fuel ethanol consumption is around 12 million m^3 per year, in approximately equal shares of anhydrous and hydrous ethanol, it can be estimated that the use of ethanol as a fuel in Brazil reduces the GHG emissions by 25.8 million t CO_2eq./year or 7.0 million t Carbon eq./year.

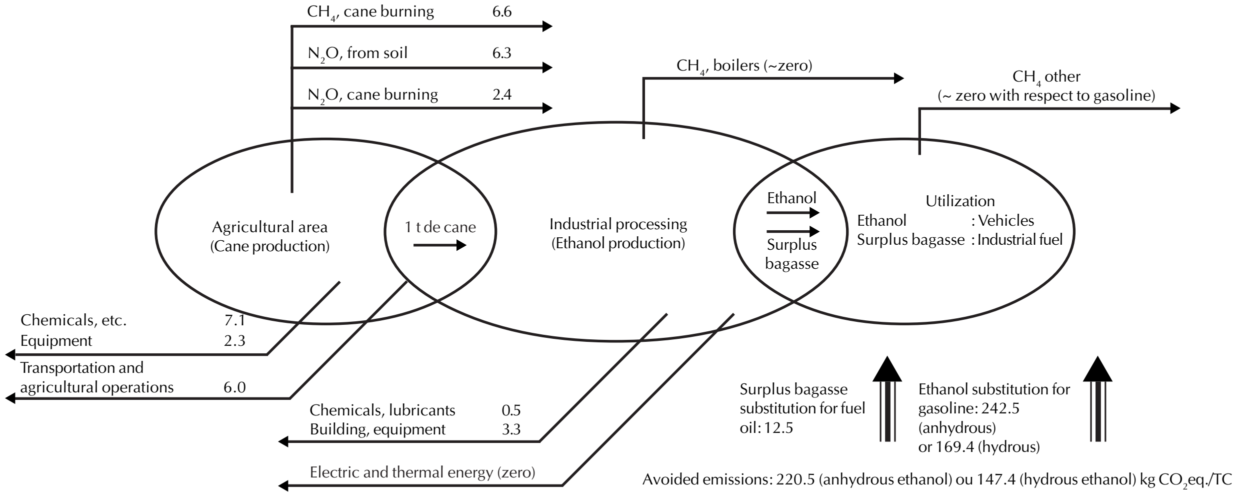
Table 4 – Ethanol life cycle emissions

	(kg CO_2eq./TC)	
	Scenario 1 (average)	Scenario 2 (best values)
Type		
Fossil fuels	19.2	17.7
Methane and N_2O from trash burning	9.0	9.0
Soil N_2O	6.3	6.3
Total emissions	34.5	33.0
Avoided emissions		
Surplus bagasse use	12.5	23.3
Ethanol use	242.5 (A); 169.4 (H)	259.0 (A); 180.8 (H)
Total avoided emissions	255.0 (A); 181.9 (H)	282.3 (A); 204.2 (H)
Net avoided emissions	220.5 (A); 147.4 (H)	249.3 (A); 171.1 (H)

(A): Anhydrous ethanol

(H): Hydrous ethanol

Figure 2 – GHG (*) Emissions – Scenario 1 (kg CO_2eq./TC)



(*) Photosynthesis cycle is not included since all carbon fixed by the cane is released as CO_2 (bagasse burning, burning/oxidation of trash, ethanol burning, fermentation; except for a small fraction that is fixed into the soil).

Annex 1 – Sugar cane production

Introduction

The data used in this analysis refers to the year 2002 for the Copersucar associated mills. In the present situation some of the basic parameters for harvest and sugarcane quality used were:

1. Sugar cane harvest – present situation[8]

Type of harvest	São Paulo (%)	Center-South (%)
Manual	63.8	65.2
Mechanical	36.2	34.8
Burned sugar cane	75.0	79.1
Unburned sugar cane	25.0	20.9

Considering that approximately 85% of the Brazilian ethanol production occurs in the Center-South, the following situation was assumed for Brazil:

Mechanical harvest	35%
Manual harvest	65%
Burned sugar cane harvest	80%
Unburned cane harvest	20%

For simplicity all the unburned cane harvested was considered to be mechanized harvest. It is important to mention that this simplification results in a more conservative analysis.

These data were used to determine the necessary equipment for the agricultural operations.

2. Pol and Fiber

Considering the average of five consecutive harvest seasons (1998/99 to 2002/03) the following data were obtained[9]:

Average Pol % cane	14.53%
Average Fiber % cane	13.46%

A1: Agricultural yield

The averages for various regions and sugar cane varieties (Copersucar Technology Center – CTC) are:

Table 5 – Sugar cane yield (averages for harvest seasons 1998/99 to 2002/03)

Harvest		Yield (t/ha)
1st – Plant cane (18 months)	113 (80%)	$\bar{X}$weighed = 106
Plant cane (12 months)	77 (20%)	
2nd – (1st ratoon)		90
3rd – (2nd ratoon)		78
4th – (3rd ratoon)		71
5th – (4th ratoon)		67
Average of 5 harvests		82.4 t/ha (68.7 t/ha.year)

Average age of plow out[9]:

99/00 harvest season	5.13 harvests
00/01 harvest season	5.18 harvests
01/02 harvest season	5.33 harvests

Normally 5 harvests are carried out (average of 82.4 t/ha). The ratoons are cut after one year and the plant cane two years after harvesting the previous ratoon for “18 month cane”. Therefore the average for a full cycle of 5 harvests is 68.7 t/ha.year.

A2: Agricultural operations and harvest

a) Agricultural operations
The agricultural operations, the equipment used and their capacities are listed in Table 6.

Table 6 – Agricultural operations: equipment

Nº	Equipment	Power (cv)	Implements	Capacity (ha/h)	Consumption (l diesel/h)
1	MF 290	78	Lime distributing wagon	1.61	6.0
2	CAT D-6	165	Heavy harrow, 18 discs x 34"	1.30	27.6
3	CAT D-6	165	5 shanks subsoiler	1.00	26.0
4	CAT D-6	165	Heavy harrow, 18 discs x 34"	1.35	27.6
5	Valmet 1780	165	Light harrow, 48 discs x 20"	1.60	15.0
6	MF 680	170	2 row furrower – fertilizer	1.10	15.0
7	MF 275	69	Planting wagon	0.60	4.0
8	MF 275	69	2 row furrow coverer	1.80	4.8
9	MF 275	69	Herbicide pump	2.50	4.0
10	MF 292	104	Cultivator	1.30	8.0
11	MF 275	69	Trash rake	1.50	4.0
12	Valmet 1580	143	Triple cultivator	1.30	9.2
13	Valmet 1580	143	Mechanical ratoon eliminator	1.10	12.2
14	Case A7700	330	Combine sugar cane harvester	45.0 t/h	40.4
15	MF 290 RA	78	Sugar cane grab loader	46.0 t/h	7.1
16	MB 2318	180	Sugar cane transport (8%)	2.2 km/l	-
17	MB 2325	250	Sugar cane transport (25%)	1.6 km/l	-
18	Volvo	360	Sugar cane transport (67%)	1.2 km/l	
19	MB 2318	180	Dumpster (skip tipper) truck	2.0 km/l	-
20	MB 2213	130	Flat bed fertilizer transport	2.0 km/l	-
21	MB 2318	180	Vinasse transport	2.2 km/l	-
22	MB 2220	200	Vinasse transport	2.0 km/l	-
23	Volvo	360	Vinasse transport	1.3 km/l	-
24	Diesel pump	120	Vinasse application	120 m^3/h	14.0
25	Valtra BH 180	180	Tractor hauler/transloader	35.0 t/h	9.0

The data for Table 6 were obtained from the research and development database[10]. The normal sequence for agricultural operations is given in Table 7.

Observations:

- *The previous analysis of soil compaction permits the reduction of 30% in subsoiling area.*
- *The mechanical cultivation (ridge removal) is approximately 70% of the planted area and is done after the chemical cultivation.*

The total consumption of energy in agricultural operations can be estimated based on Table 7.

Table 7 – Consumption of diesel oil in agricultural operations

Nº	Agricultural operations	Equip.	Capacity (ha/h)	Specific consumption (l/ha)	Fraction of area worked
	Land preparation and planting operations (20% of total area)				
1	Lime application	1	1.61	3.73	1.00
2	Mechanical elimination of ratoons	13	1.10	11.09	0.30
3	Chemical elimination of ratoons	9	2.50	1.60	0.30
4	Heavy harrowing I	2	1.30	21.23	0.90
5	Subsoiling	3	1.00	26.00	0.70
6	Heavy harrowing II	4	1.35	20.44	0.70
7	Heavy harrowing III	4	1.35	20.44	0.30
8	Light harrowing	5	1.60	9.38	0.90
9	Furrowing and fertilizing	6	1.10	13.64	1.00
10	Seed cane distribution	7	0.60	6.67	1.00
11	Closing furrows and insecticide application	8	1.80	2.67	1.00
12	Chemical tillage (herbicide application)	9	2.50	1.60	1.00
13	Mechanical tillage	10	1.30	6.15	0.70
	Ratoon tillage operations (80% of total area)				
1	Trash raking	11	1.50	2.67	0.25
2	Triple operation tillage	12	1.30	7.08	1.00
3	Chemical tillage (herbicide application)	9	2.50	1.60	0.85

The values for consumption in agricultural operations are equivalent for Scenarios 1 and 2:
Plant cane: C_p = 102.6 l/ha
Ratoon cane: C_r = 9.1 l/ha

b) Harvest
For the equipment 14, 15 and 25 (Table 6) and an average yield of 82.4 t/ha the results are shown in Table 8.

Table 8 – Harvest equipment

Equipment	Operational capacity (ha/h)	Specific consumption (l/ha)
Case harvester	0.5461	74.0
Santal cane loader	0.5583	12.7
Tractor hauler/transloader	0.4248	21.2

Calculations:

Case Harvester

$$\text{Operational capacity} = 45\ \frac{t}{h} \times \frac{1}{82.4}\ \frac{ha}{t} = 0.5461\ ha/h$$

$$\text{Specific consumption} = 40.4\ \frac{l}{h} \times \frac{1}{0.5461}\ \frac{h}{ha} = 74.0\ l/ha$$

Santal Loader:

$$\text{Operational capacity} = 46.0\ \frac{t}{h} \times \frac{1}{82.4}\ \frac{ha}{t} = 0.5583\ ha/h$$

$$\text{Specific consumption} = 7.10\ \frac{l}{h} \times \frac{1}{0.5582}\ \frac{h}{ha} = 12.7\ l/ha$$

Tractor hauler/transloader:

$$\text{Operational capacity} = 35.0\ \frac{t}{h} \times \frac{1}{82.4}\ \frac{ha}{t} = 0.4248\ ha/h$$

$$\text{Specific consumption} = 9.0\ \frac{l}{h} \times \frac{1}{0.4248}\ \frac{h}{ha} = 21.2\ l/ha$$

The present situation can be described as:

In a 6 year cycle: one cane elimination, four ratoon crops and five harvests, 35% of which mechanically (15% unburned and 20% burned) and 65% manually with mechanical grab loading are effected[8]. The annual diesel oil consumption in agricultural operations and in harvesting is given by:

$$C_{AC}(l/TC) = \frac{1}{P_A}\ \{0.17C_P+0.67C_S+0.83[0.35(C_{CC}+C_{TR})+0.65(C_{CM}+\tfrac{2}{3}C_{TR})]\}$$

Here, C_{CC} and C_{CM} (l/ha) are the consumption in mechanical and manual harvesting respectively. C_{TR} is the consumption of the hauler tractors or transloaders and P_A is the annual cane yield, TC/(ha.year).

Observation: For manual harvesting, the transport of cane was considered to be made by triple trailer trucks, which implies a participation of haulers in 2/3 of the total cane.

The results obtained are:

Scenarios 1 and 2: $C_{AC} = 0.797$ l/TC

A3: Transportation

All the values for capacity and consumption are given in reference 9.

Sugar cane transportation from the field to the mill

The specific consumption values vary according to the type of truck and distance. The mean harvested area distance is 20 km. Based on Table 6 and in the proportion of each type of truck used in cane transport: Single truck (15 t) = 8%, Double wagon (28 t) = 25%, Triple wagon (45t) = 67% it is estimated, for Scenario 1 the value of 20.4 l/t.km.

Calculations:

$$\textbf{Single Truck} = \frac{1}{2.2}\ \frac{l}{km} \times \frac{1}{15t} \times 1{,}000\ \frac{ml}{l} = 30.3\ \frac{ml}{t.km}$$

$$\textbf{Double Wagon} = \frac{1}{1.6}\ \frac{l}{km} \times \frac{1}{28t} \times 1{,}000\ \frac{ml}{l} = 22.3\ \frac{ml}{t.km}$$

$$\textbf{Triple Wagon} = \frac{1}{1.2}\ \frac{l}{km} \times \frac{1}{45t} \times 1{,}000\ \frac{ml}{l} = 18.5\ \frac{ml}{t.km}$$

$$\overline{X}\text{weighed} = 20.4\ \frac{ml}{t.km}$$

$$\text{Four Wagon/58 t} = \frac{1}{1.1}\ \frac{l}{km} \times \frac{1}{58\ t} \times 1{,}000\ \frac{ml}{l} = 15.7\ \frac{ml}{t.km}$$

The use of trucks with a larger transport capacity decreases the values, as is the case with the four Wagon Volvo FH (specific consumption= 15.7 ml/t.km) used as a reference in Scenario 2.

Results:

Scenario 1: C_{TC} = 0.816 l/TC **Scenario 2:** C_{TC} = 0.628 l/TC

Seed cane transportation

For the use of 12 t of seed cane/ha, at an average distance of 20 km, the MB2318 consumes C_{TM} = 17.4 l/ha

Truck with 12 t of load: 2.3 km/l $\longrightarrow \frac{1}{2.3} \times 40 = 17.4$ l/ha

Filter mud cake

Where filter mud cake is used, it is applied in 30% of the planted area. In the present situation, only Scenario 2 considers the application of filter mud cake.

A dumpster truck (MB2213) with an average load of 8 t and a consumption of 2.5 km/l is used for the application of filter mud cake in the fields; the average distance is 8km and the application rate is 12 t (wet)/ha (5 t dry/ha).

Results: C_{TT} = 9.6 l/ha

Vinasse

To be conservative, only Scenario 2 considers vinasse application in 30 % of the ratoon area. The types of applications are:

Direct application with tanker trucks – 6% of the area – rate 100m^3/ha (MMB2318 truck with 15 m^3 tank), average distance is 7 km;

Sprinkler (water cannons) system – 63% of the area – rate 150 m^3/ha (diesel pumps with channel);

Trucks combined with cannons – 31 % of the area – rate 100 m^3/ha with Volvo Tanker (two 30 m^3 tanks, distance up to 12 km.

Calculations:

$$\textbf{Direct application with tanker trucks} = \frac{1}{2.2}\ \frac{l}{km} \times \frac{14\ km}{15\ m^3} \times 100\ \frac{m^3}{ha} = 42.4\ \frac{l}{ha} \times 0.06 = 2.54\ \frac{l}{ha}$$

$$\textbf{Sprinkler system (channels + water cannons)} = 16\ \frac{l}{h} \times \frac{h}{120\ m^3} \times 150\ \frac{m^3}{ha} = 20\ \frac{l}{ha} \times 0.63 = 12.6\ \frac{l}{ha}$$

$$\textbf{Tanker truck + water cannons} = \frac{1}{1.3}\ \frac{l}{km} \times \frac{24\ km}{60\ m^3} \times 100\ \frac{m^3}{ha} = 30.8\ \frac{l}{ha} \times 0.31 = 9.55\ \frac{l}{ha}$$

$$\overline{X}\text{weighed} = 24.7\ \frac{l}{ha}$$

Results: C_{TV} = 24.7 l/ha

Fertilizers

For Scenario 2 it was considered a 30% reduction in area of fertilizer application due to the use of vinasse and filter mud cake. Values used for calculations are found in Table 9.

Typically a MB2213 (cargo weight of 12 t, 2.5 km/l) is used. For an average distance of 20 km and a cycle of 6 years, we have:

Scenario 1: 2,500 kg fertilizer/ha, C_{TA} = 3.33 l/ha
Scenario 2: 1,200 kg fertilizer/ha, C_{TA} = 1.60 l/ha

Table 9 – Fertilizer applicaton

	Plant cane	Ratoon	Total
Scenario 1	500 kg/ha (6-24-24)	500 kg/ha (16-5-24)	2,500 kg/ha (in 6 years)
Scenario 2*	400 kg/ha (0-125-200)	200 kg urea	1,200 kg/ha (in 6 years)

*areas with filter mud cake and vinasse application (30%).

The amount of fertilizers is calculated considering that, at present, only 30% of the area can be treated with vinasse and filter mud cake.

The different consumptions can be associated with agricultural yields, leading the total consumption in transport to:

Scenario 1: $C_T = C_{TC} + \frac{1}{P_A}\{0.17C_{TM}+0.83C_{TA}\} = 0.899$ l/TC

Scenario 2: $C_T = C_{TC} + \frac{1}{P_A}\{0.17C_{TM}+0.7(0.83C_{TA}) + 0.3\,(0.17C_{TT} + 0.67C_{TV})\} = 0.764$ l/TC

A4: Fertilizers

There is a large variation in application rate due to different soil types. Average values are listed in Table 10.

Scenario 1 represents the conventional fertilization, while Scenario 2 considers the use of filter mud cake in plant cane and vinasse in ratoons.

Considering that only 30% of these areas can be treated, the final figures for the 2 scenarios are presented in Table 11 *(page 26)*.

The specific energy costs are known^5.

Table 10 – Rate of fertilizer application

Macronutrient	Rate (kg/ha)			
	Plant cane		Ratoon	
	Scenario 1	Scenario 2*	Scenario 1	Scenario 2*
Nitrogen – N	30	–	80	90
Phosphorus – P_2O_5	120	50	25	–
Potassium – K_2O	120	80	120	–

*areas with the application of filter mud cake and vinasse (30%).

Table 11 – Enery in fertilizers

	Nutrient	Annual rate of application (kg/ha.year)	Energy (kcal/kg)	Energy/ha (Mcal/ha.year)	Energy/TC (Mcal/TC)	Total (Mcal/TC)
Conventional	N	58.3	14,700	857.50	12.48	15.9
	P_2O_5	36.7	2,300	84.33	1.23	
	K_2O	100.0	1,600	150.00	2.18	
With vinasse and mud cake (30%, Scenario 2)	N	60.0	14,700	882.00	12.84	13.4
	P_2O_5	8.3	2,300	19.17	0.28	
	K_2O	13.3	1,600	21.33	0.31	

Final results:

Present situation

Scenario 1: E_f = 15,890 kcal/TC

Scenario 2: E_f = 15,890 x 0.7 + 13,430 x 0.3 = 15,152 kcal/TC

A5: Lime, herbicides and insecticides

Lime

Application rate of 2,200 kg/ha in 6 year cycles; energy cost of lime in the field is 313.4 kcal/kg[5].

Results:

E_c = 1,706 kcal/TC

Herbicides

As a reference the values for the 1996 study were maintained due to the lack of information regarding the energy cost (kcal/kg) of specific herbicides (*see Annex 3, Note 3*).

Results:

Eh = 2,690 kcal/TC

Insecticides

In sugar cane, insecticides are used in the control of soil pests and leaf cutting ants. The energy cost of previous studies was maintained for these controls (190 kcal/TC).

A6: Seed cane

The average consumption is of 12 t of seed cane per hectare for each cycle of 6 years, that is: 0.0299 TC/TC. Admitting that the procedures for the production of seed cane are essentially equivalent to those for commercial cane, 3% global energy cost represents the equivalent for seed cane.

Scenario 1: 1,404 kcal/TC (= 3% X 46,804 kcal/TC)
Scenario 2: 1,336 kcal/TC (= 3% X 44,525 kcal/TC)

A7: Agricultural machines and equipment

The present situation is based on a survey of a typical Copersucar mill with the results presented in Table 12[10].

Table 12 – Use of agricultural equipment

Equipment	Mean density of use (kg/ha)
Tractors and harvesters	41.8
Implements	12.4
Trucks	82.4
Total	136.6

The method suggested by Pimentel[5] is used to calculate the energy cost associated with equipment. Basically the hypotheses are:

1) Considering the energy incorporated in the materials (steel, tires) and the production and maintenance. The incorporated energy is essentially in the steel (15,000 kcal/kg) and tires (20,500 kcal/kg). The energy consumed for the production of the various equipments is evaluated by weight (excluding tires).
2) The energy for maintenance corresponds to 1/3 of the cumulative total repairs (ASAE[5] estimates the values for each class of equipment).
3) The useful life of the equipment corresponds to 82% of the total life (due to interruptions) and the energy cost is calculated, per year, using these values. These hypotheses lead to the results in Table 13.

With the data for density of use, estimated useful life and the yield of sugar cane the results presented in Table 14 are obtained.

Table 13 – Energy for the production and maintenance of equipment

Equipment	Energy of the material (kcal/kg)	Weight of tires (fraction of total weight)	Energy of production (kcal/kg)	Total accumulated repairs (%)	Energy of repairs (fraction of material energy + production energy)
Tractors	11,814	0.179	3,294	89.1	0.297
Implements	15,000	-	2,061	92.6	0.309
Trucks	15,000 steel 20,500 tires	0.06	3,494	60.7	0.202

Table 14 – Energy cost of equipment

Equipment	Energy of material (kcal/ha)	Production energy (kcal/ha)	Energy for repairs (kcal/ha)	Energy mat. + production corrected for useful life (kcal/ha)	Total energy (kcal/ha)	Useful life (years)	Energy cost (kcal/TC)
Tractors	493,825	113,043	180,240	497,632	677,872	5	1,973
Implements	185,550	25,495	65,213	173,057	238,269	8	434
Trucks	1,263,170	270,631	309,828	1,257,717	1,567,545	5	4,563

Results for the present situation:

E_e = 6,970 kcal/TC

A8: Labor

For this study, the energy in labor is not considered as an energy cost and it is therefore not included in the calculations. In the 1984 balance, the estimated value was 1,880 kcal/TC. Currently it is certainly less than that due to the increase in mechanical harvesting.

Annex 2 – Use of energy in the industrial processing of cane to ethanol

Introduction

This work is an updating of the industrial area parameters used in a 1995 study for Copersucar member mills. Reference 11 provided the values used to assess the industry performance data; the values related to the 2001/29002 crushing season were selected as reference. It is important to point out that these values compare very closely with the five year average of the crushing seasons 1998/1999 through 2002/2003.

RS (reducing sugars)	0.545%
Mill extraction efficiency	96.2%
Juice treatment efficiency	99.2%
Sugar loss in cane washing	0.61%
Fermentation efficiency	91.1%
Distillation efficiency	99.6%

Industrial sector energy balance

The present situation of the ethanol production has been analyzed using efficiency and energy consumption average values for Copersucar member mills. These values are important to determine the operating equilibrium condition for the co-generation system used, and to verify the surplus and deficits of energy.

Specific consumptions per ton of processed sugar cane have not changed much in the conventional areas of the mills. A few major changes due to new processes (such as the substitution of cyclohexane for benzene as dehydration agent) have been considered. The effects of the more efficient technologies such as bagasse gasification/gas turbine have not been evaluated, simply because they are not in use.

Industrial conversion efficiency

Based on a pol % cane = 14.53[8] and the RS and efficiencies listed above, the following conversion rates have been determined:

Scenario 1: 88.7 l/TC (anhydrous ethanol)
Scenario 2: 91.8 l/TC (anhydrous ethanol)

Although these values have been calculated based on performance data shown in Copersucar Benchmark Program[11], it would be reasonable to apply them to the sugar cane industry in the State of São Paulo or even to the whole Center-South region. However, to be on the safe side in the energy and CO_2 balances the conversion rate value of 86 l anhydrous ethanol/TC has been used for Scenario 1 as representative of Brazilian sugar cane sector. This value is a weighed estimate of various specialists of the sector who suggested 88 l anhydrous ethanol/TC for the Center-South region and 75 l anhydrous ethanol/TC for the Northeast region (ethanol production can be divided as 85% in Center-South and 15% in the Northeast. For Scenario 2, the value of 91.8 l anhydrous ethanol/TC was maintained. Accordingly, the values used in the energy/CO_2 balance are:

Scenario 1: 86.0 l/TC (anhydrous alcohol)
Scenario 2: 91.8 l/TC (anhydrous alcohol)

Utilisation of electricity

The mills increased the internal production of electrical energy during the 2001/02 harvest[11] (average generation: 16.83 kWh/TC; maximum: 29.13 kWh/TC). Consequently, bagasse excess was reduced (average: 5.8%; maximum: 17%). Mills exist with large excesses and complete electricity self-sufficiency.

The average electricity consumption was 12.90 kWh/TC and the minimum, 9.64 kWh/TC.

Electricity bought (average) was 0.26 kWh/TC, which indicates 98% self-sufficiency. On the other hand, the average sale of electric power was 5.86 kWh/TC (maximum: 16.98 kWh/TC). These statistics refer to 2001/2002[11] crop season.

It follows that the hypothesis of the totality of the mills on average neither acquiring nor exporting electricity is no longer absolutely valid: there is in fact an increase in energy export (though relatively unimportant in the context of its potential).

There are two methods of evaluating (to evaluate emissions) the mills' exports of electricity (still incipient): we either consider the export to be small, and compute its value as mitigation of emission and consider the resulting real bagasse excess, or we consider only the excess bagasse (conservatively). As the excess statistics refer to the joint production of sugar and ethanol (it being currently unrealistic to separate them), the securest option is the conservative one, though adopting a slightly higher average figure (in the production of ethanol, the bagasse excesses are larger than for sugar).

Thus, the values used for excess electricity are zero and from 8% (average) to 15% (maximum) for surplus bagasse (see commentaries in the following section).

Energy used in milling sugar cane

An estimate of consumption can be made from the installed capacity together with some observations of milling conditions, in some mills. The bigger mills have on the average a lower installed specific power capacity (22.1 cv/TC for mills with milling capacity of over 300 tons of sugar cane per hour - TCH). As in general they also have better cane preparation it is to be expected that the actual power used would be very close to that installed. Although minimum values of 17 cv/TCH (installed power) were identified, analysis of the whole sector shows that an average value of 20 cv/TCH is a good estimate of the power actually used in the mills with good cane preparation and milling. The relationship between power used in milling and in preparation is approximately 1.5.

Energy consumption in the processes: sugar and ethanol

The conditions found in the Brazilian mills make it difficult to analyze "average" values due to the variations in the sugar/ethanol production ratios and the diversity of operating procedures in ethanol production, as well as the differences in levels of energy conservation. Techniques to reduce energy consumption in sugar production have been established and used for many years. In Brazil today the simultaneous production of sugar and alcohol makes the sugar production easier, since it is not necessary to exhaust the molasses.

The potential to increase the production of surplus bagasse (or electric energy) has been analyzed and the results are impressive. However, for the objective of this work only two Scenarios have been considered, the first with the present average values and the second with the best values achieved today.

For the sugar/ethanol mills, the values considered today are still:

– Average surplus bagasse of 5%, reaching 15% in the best cases;

– No outside electric power needed, for an average power consumption of 12.9 kWh/TC. (Most mills are self sufficient in energy).

It is quite reasonable to assume that for the production of ethanol only (autonomous distillery) a higher percentage of surplus bagasse can be obtained; therefore 8% is assumed as average value and 15% as best value.

With an average fiber content of 13.5% and a bagasse with 50% moisture content, 280 kg of bagasse with a LHV = 1800 kcal/kg is obtained. A summary of the bagasse and electric power situation is shown in Table 15.

Table 15 – Surplus bagasse energy

Scenario 1:		
Surplus bagasse	8%	40,300 kcal/TC
External electric energy	0	0
Scenario 2:		
Surplus bagasse	15%	75,600 kcal/TC
External electric energy	0	0

A9: Chemicals and materials for industrial sector

The main chemicals and lubricants used in the ethanol industrial production process are listed in Table 16, with the corresponding average utilization and associated energy consumption. These averages refer to the 2002/2003 crushing season but they reflect well the averages for the last five years[11].

Table 16 – Energy in the chemicals and lubricants used in the industrial sector

Item	Consumption	Energy (kcal/TC)
Sulfuric acid	9.05 g/l	740
Cyclohexane	0.60 kg/m^3 anhydrous	130
Sodium hydroxide	–	180
Lubricants	13.37 g/TC	170
Lime	930 g/TC	300
Total	–	1,520

A10: Buildings, equipment and installations of the industrial sector

The evaluation of the energy used in the construction and erection of an ethanol distillery can be done in a simplified way for the objective of this study, because it does not represent a significant fraction of the energy flows involved in the ethanol production. This energy is used in the construction of buildings, working areas and in the fabrication and erection of industrial equipment.For this evaluation, an ethanol distillery with a nominal capacity of 120,000 l/day, operating 180 days per year was used as reference.The energy embodied in the building and working areas is detailed in Table 17[5].

Table 17 – Energy in the buildings and working areas

	Area (m^2)	Energy used (10^6 kcal/m^2) (a)	Total energy (10^9 kcal)
Industrial buildings	5,000	2.7	13.50
Offices	300	4.5	1.35
Repair shops, laboratories	1,500	1.7	2.55
Storage	4,000	0.5	2.00
Total			19.40

There are large variations in the industrial equipment installed in the various mills; a typical case has been used as reference. The results are shown in Table 18.

Table 18 – Energy in equipment fabrication

	Weight (t)	Total energy (10^9 kcal)	Notes
Cane belt conveyor (30 m)	45	0.75	(c)
Bagasse belt conveyor (200 m)	180	3.9	(c)
Cane feed table and acessories	42	0.70	(c)
30″x54″ mills tandem, 5 mills	220	6.16	(d)
Turbine, turbine generator, speed reducing train	50	0.9	
Boilers	310	4.34	(e)
Distillery			
– Stainless steel	76	1.67	(f)
– Carbon steel	400	6.64	(g)
Total		24.16	

It must be pointed out that for each piece of equipment there are two components in the energy cost: the energy required for the production of the raw material (steel, iron) and the energy required to manufacture the equipment (b). From Tables 17 and 18, the total energy necessary for the installation of the industrial sector can be estimated as 43x10^9 kcal. An analysis of this set of equipment has shown that some of the main equipment (mill tandem and distillery) have a processing capacity adequate for 180,000 l ethanol/day.

The useful lives of the items in Table 17 and 18 have been assumed as:

Buildings: 50 years
Heavy equipment (mills, boilers): 25 years
Light equipment: 10 years

For maintenance, the energy cost has been considered as 4%/year of the total cost. With these assumptions the specific energy costs per ton of cane (TC) can be estimated. Table 19 presents the results.

Table 19 – Energy use related to equipment and buildings in the industrial area

	Total energy (10^9 kcal)	Useful life (years)	Energy/ year (10^9 kcal)	Energy/year (maintain) (10^9 kcal)	Total energy (10^9 kcal/year)	kcal/(TC/year) Scenario 1	Scenario 2
Buildings	19.40	50	0.348	0.696	1,044	2,860	2,221
Heavy equipment	15.85	25	0.634	0.634	1,268	3,474	2,698
Light equipment	10.31	10	1,031	0.412	1,443	3,953	3,070
Total					3,755	10,290	7,989

For the best case condition (Scenario 2) the operating conditions of several good distilleries have been evaluated. The most energy efficient have indicated that the same equipment considered in the tables above for the typical mill, with minor modifications, could produce 240,000 l anhydrous ethanol/day. Adopting these values leads to the following results:

Scenario 1: 180,000 l/day and 377,000 TC/year
Equipment energy use: 10,290 kcal/TC

Scenario 2: 240,000 l/day and 470,000 TC/year
Equipment energy use: 7,989 kcal/TC

Notes:
a) Data from Hannon[12].
b) The energy necessary to produce raw steel varies according to the process used. A summary of data collected from many sources[13] (P.F. Chapman, *The energy cost of materials*, Energy Policy, March, 1975) shows a variation from 9,000 kcal/kg to 14,300 kcal/kg for six independent studies in the 70's. In this work the value of 9,030 kcal/kg has been used (Statistical Year Book, 1972[14]). Values for the finished product (including the energy for equipment fabrication) can be estimated based on the available data[15].
c) Essentially structural steel.
d) In this case, the mill capacity is larger than required by the factory. It has been considered as forged steel to estimate the energy cost.
e) Values estimated for "tractors and combines". It could be one 65 t steam/h boiler or two 45 t steam/h boilers.
f) A,B,C,P columns; condensers; k heat exchanger.
g) Conventional distillery with wine and water tanks, condensers at 25 m height; fermentation vats, tanks, piping, cooling coils (carbon steel) structures.This distillery had a nominal capacity of 120,000 l/day but could reach, with minor improvements, 240,000 l/day of anhydrous ethanol.

Table 20 – Energy cost for different equipment and materials

	Energy cost (kcal/kg)	Note
Forged steel	28,000	Finished product
Structural steel	16,600	Finished product
Turbine generator	9,500	Fabrication only
Tractor	14,350	Finished product
Combine	13,160	Finished product
Stainless steel (pipes, vessels)	16,200 to 22,000	Finished product

Note 1: Life cycle CO_2 emissions of fossil fuels used (or replaced) by sugar cane products (ethanol and bagasse).

The analysis includes not only the direct emissions (such as CO_2 emissions per liter of diesel used in the agricultural operations) but also the indirect emissions (emissions in oil extraction, its transportation to the refinery, refining, transportation to the consumers, evaporation). For petroleum derived fuels the indirect emissions represent between 10 to 20% of the total emissions.

There are variations in the values of indirect emissions due to several factors: differences in transportation distances and means (ships, pipeline, trucks), refining process and refining profile.

However, it is reasonable to use the simplifying assumption that the total emission of the petroleum cycle is equally divided among the products, with respect to the corresponding LHV.

An example is shown in[16] for diesel:

Indirect emissions	(kg CO_2/kg diesel)
Extraction and transportation of oil	0.06
Refining	0.16 – 0.26
Transportation to consumers	0.02
Evaporation	0.25 – 0.35
Direct emissions	3.15
Total emissions	3.40 – 3.49

Therefore in this case, the indirect emissions are 9% of the direct emissions.

In a classic reference in the 80's, Pimentel[5] indicated that the direct fuel energy is 81% of the total energy; the same value applying for gasoline, diesel and fuel oil.

	Direct (kcal/l)		Indirect (kcal/l)		Total(kcal/l)
Gasoline:	8,179	+	1,930	=	10,109
Diesel, fuel oil:	9,235	+	2,179	=	11,414

For Brazil, some important points should be considered such as oil extraction technology (most of the oil comes from deep water), oil type (mostly heavy oil) which may result in a higher energy consumption for extraction and refining.

In this study, the 81% value for the direct energy has been used in conjunction with the heating values and densities presented in BEN 2002[17]. For the carbon content the IPCC[7] values have been used. Table 21 presents the main results.

Table 21 – Fossil fuel emissions

	Density (kg/l)	LHV (MJ/kg)	Direct carbon IPCC – 2001 (kg C/GJ)	Direct emissions (kg C/t)	Total emissions (kg C/m^3)
Gasoline	0.742	44.8	18.9	846	776
Diesel	0.852	42.7	20.2	862	908
Fuel oil	1.013	40.19	21.1	848	1,061

Note 2: Forms of energy used in the production of agricultural and industrial chemicals and materials, and embodied in equipment, buildings and structures

Energies embodied in the manufacture of equipment (field and industry) and construction of buildings/structures are, as expected, small compared to the energy flows in the systems dedicated to energy generation. They can, therefore, be estimated in a simplified way based on the weight and type of material used in the equipment (steel, iron, aluminum) and in some cases, such as tractors and trucks, with some specific considerations. For buildings and others facilities the estimate is made based on the covered area and type of construction (warehouse, office).

The tables used show the total energy value (kcal/kg of material, for example); in these values are included the direct use of thermal energy (heat, transportation fuel) and the thermodynamic equivalent of electric energy (in general, converted using the thermal efficiency of the local thermal power plants). Thus, the CO_2 equivalent emissions are estimated based on the fuels used (fuel oil, natural gas, mineral coal), including electric energy. To identify the fraction corresponding to electric energy it is necessary to investigate to what extent electric energy is used in all involved sectors in Brazil.

To estimate the emissions, it would be adequate in the case of Brazil to separate electric energy from others types of energy since today more than 90% of the country's electric power comes from hydro power plants (with nearly zero GHG emissions). It is important to notice that many sectors involved (steel, iron) generate most of the electric energy they need, partly in a renewable way.

In any case, the values are small. BEN-2002[17] provides data to establish the following: (electric power has a thermal energy equivalent of 1 kWh = 3,132 kcal for fuel oil fired thermal power plants):

– Mining/pelletizing sector
Electric energy: 60%; thermal energy: 40% (fuel oil, coal, NG, diesel)

– Iron/steel sector:
Electric energy: 25%; thermal energy: 75% (charcoal, coke, mineral coal, others).
Renewable energy: around 25%

– Steel alloy sector:
Electric energy: 75%; thermal energy: 25% (charcoal, wood, others)
Renewable thermal energy: around 85%

– Cement sector
Electric energy: 31%; thermal energy: 69% (fuel oil, coal, diesel, others)
Renewable thermal energy: around 5%

– Ceramics sector
Electric energy: 23%; thermal energy: 67% (wood, LPG, fuel oil)
Renewable thermal energy: around 60%

Considering the relative participation of each sector above, the participation of each type of energy in the manufacture of equipment and construction of buildings can be estimated as:

Buildings/constructions
Electric energy: 30%; thermal energy: 70%

Equipment
Electric energy: 30%; thermal energy: 70%.

It must be understood that electric energy has been converted in equivalent thermal energy (1 kWh = 3,142 kcal) and that in the mining, iron and steel sectors there is a lot of co-generation involved. This separation of types of energy is considered for information only and is roughly estimated. For the emissions balance all the energy involved in this section has been assumed as thermal energy derived from fossil fuels (an important fraction of renewable energy has been ignored).

In the production of chemicals, for agriculture and industry, thermal energy is the major part of the total energy. For instance, for ammonia, electric energy participation is only 1%.

In the Brazilian case, where more than 90% of electricity comes from hydro power plants, to consider the total energy cost of chemicals as being from thermal origin is the conservative assumption used is this study.

Note 3: Energy in the production of herbicides and pesticides

It is difficult to define values for this item since the products are frequently changing and there is little information about energy use in the production process. This area in Brazil has inclined to develop biological controls (as in the cases of cane borer and froghopper) with a significant reduction in the use of pesticides.

Data from the 80's for the herbicides and pesticides used in cane fields indicate that (6): herbicides averaged 99,910 kcal/kg and insecticides averaged 86,000 kcal/kg.

Based on these energy values and product consumption of the mid 90's, the emission values have been estimated and considered to be very small.

Note 4: Methane emissions from trash burning, before harvest

There is only one complete study covering methane emissions from the trash (cane leaves) burning before the cane harvest. This study developed an adequate methodology and simulated trash burning conditions in a wind tunnel in 1994[6]. IPCC[7] recommends the use of generic values for the emissions from the burning of agricultural residues when specific data are not available; because these values are substantially higher than those presented in reference[6], the IPCC[7] values for GWP-100 are used to convert in CO_2 equivalent emissions.

Table 22 presents the results for both reference[6] and IPCC[7].

Table 22 – Methane emissions from cane field burning

	Emission coefficient (kg CH_4/t trash)	Trash burned (t trash/TC) (*)	Emissions (kg CH_4/TC)	GWP–100	Emission (kg CO_2 eq./TC)
IPCC[7]	2.83	0.101	0.286	23	6.6
Jenkins[6]	0.41	0.101	0.041	23	0.94

(*) 140 kg (DM) of trash/TC, with 82.4 TC/ha; 80% of cane burned with an efficiency of 90% (incomplete burning)

To maintain a conservative position, the IPCC values have been used, leading to 6.6 kg CO_2eq./TC. The N_2O emissions from trash burning can be estimated using IPCC (7) values for agricultural residues burning in general, as follows:

Residue carbon content:
0.50 kg C/kg residue (DM)

Residue nitrogen content:
N/C = 0.010 – 0.020

N_2O emission coefficient:
0.007 kg N/kg N in the residue

Considering 0.101 t trash/TC and assuming N/C = 0.15, results:

Carbon in the trash = 0.50 kg C/kg trash x 0.101 kg trash/TC = 50 kg C/TC

Nitrogen content in the trash = 0.015 x 50 = 0.75 kg N/TC

N_2O emissions = 0.75 kg N (trash)/TC x 0.007 kg N/kg N (trash) = 0.00525 kg N/TC = 0.00825 kg N_2O/TC

Using IPCC value for GWP – 100 = 296, the CO_2 equivalent is N_2O emissions = 2.4 kg CO_2eq./TC

Therefore, the total GHG emissions due to trash burning before harvest is 9.0 kg CO_2eq./TC.

Note 5: N_2O soil emissions (nitrogen fertilizer)

Although there are not many studies available on N_2O soil emissions, the value for sugar cane culture can be estimated using some assumptions[18]:

1. N_2O emissions depend on the quantity of nitrogen fertilizer used, the application technology (NO_3 or NH_4) and soil conditions.
2. The emissions amount to 0.5% to 1.5% (in weight N/N) of the fertilizer used; the higher values refer to NH_4 type.

For the Center-South region in Brazil, around 28 kg N/ha is used during cane planting and 87kgN/ha for each ratoon, resulting in 75 kg N/ha year for the whole cycle. Most of the fertilizers used is of the NH_4 type.

The resulting N_2O emissions are therefore 1.76 kg N_2O/ha year which is equivalent to 521 kg CO_2eq./ha.year or 6.3 kg CO_2eq./TC.

Note 6: Methane emissions from automotive engines fueled with ethanol, in comparison with gasoline fueled engines.

From 1980 to 1996 the regulated emission limits for automotive engines were changed considerably, in two phases (1986 and 1992)[19]. The analysis of the average emissions from 1986 and 1992 shows that carbon monoxide (CO) emissions have always been lower in ethanol engines compared with gasohol engines (gasoline/ethanol blends). In this same period, NO_x emissions were similar in both cases and the organic compound emissions, expressed as hydrocarbons (HC), were similar or lower. Based on the lower CO emissions it can be said that the use of ethanol in automotive engines is beneficial in terms of reducing GHG emissions since CO is a gas with indirect effect in the formation of GHG (can be oxidized to CO_2 or participate in the generation of ozone, which is also GHG). With respect to HC and NO_x, the combination of these gases results in the formation of ozone. However, there are no consistent studies in Brazil that would allow the conclusion that the use of ethanol has had the beneficial effect of reducing ozone in the lower atmosphere, although there are indications in the literature[20] that this may be true. One fact that favors this line of reasoning is that in USA, ethanol is one of the oxygenates used in the production of Reformulated Gasoline, that has as the main objectives the reduction of toxic emissions and the reduction of ozone formation. In spite of the referred indication of positive impacts it has been decided not to claim any benefit in this area from the use of ethanol in cars.

One point that deserves attention is the characterization of the HC's formed in the combustion process, especially with respect to the presence of CH_4. It is known that the mass ratio CO_2/CH_4 for internal combustion engines is, typically, around 4,700 for gasoline and diesel and around 3,900 for methanol and ethanol[21,23] which permits the statement that the relative importance of methane emission is very small, even considering its GWP = 23.

Data from Cetesb[22] show that with the different technologies existing in 1993, the ratio ethanol/HC in ethanol engines was in the range of 0.70 to 0.85, and the non ethanol HC's emissions were around 0.6 g/km. Assuming that 30% of HC is methane, the result would be 15 kg CO_2eq./m^3 ethanol. Using a similar reasoning for the gasohol engine emissions, the result would be no higher than 3.75 kg CO_2eq./m^3 ethanol (for 25% ethanol in the gasohol). These figures represent less than 1% of the avoided emissions which can be considered to be negligible.

It is very difficult to compare methane emissions from ethanol and gasoline engines in Brazil since there are no engines in the country that operate on pure gasoline.

For today's technology (electronic engine management, multipoint fuel injection, 3-way catalysts) in use since 1997 due to the introduction of tighter emission limits, methane emission level is 0.05 g/km [23]. If this level is reached, the emission would be no higher than 0.9 kg CO_2eq./TC, thus, still negligible.

Due to the above reasons automotive methane emissions are not included in the CO_2 balance.

Note 7: Use of surplus bagasse substituting for fuel oil in other industries (orange juice, pulp and paper)

It has been shown that an average of 280 kg bagasse/TC, with 50% moisture content is produced in cane milling. The LHV is 1,800 kcal/kg and the HHV is 2,260 kcal/kg.

The estimated surpluses are 8% and 15% for Scenarios 1 and 2, respectively; accordingly, the energy of this surplus bagasse is 40,300 and 75,600 kcal/TC for Scenarios 1 and 2, respectively (*see Annex 2*).

To estimate the avoided emissions when this surplus bagasse displaces fuel oil, the following operating conditions are assumed for the two systems:

Bagasse: boiler average efficiency of 78.7% (LHV) and 10% losses to account for fuel conditioning, start ups and shut downs.

Fuel oil: boiler efficiency of 92% (LHV); LHV = 49.19 MJ/kg under these conditions the 8% and 15% surplus bagasse would correspond, in terms of final energy use, to 3.2 and 6.1 kg of fuel oil/TC, displaced.

The total emissions, including the indirect ones, related to these amounts of fuel oil are 12.5 and 23.3 kg CO_2eq./TC, for Scenarios 1 and 2, respectively.

Note 8: Use of ethanol, substituting for gasoline, in E-100 engines (hydrous ethanol) and gasoline/ethanol blend engines (anhydrous ethanol).

Scenario 1: 86.0 l anhydrous ethanol/TC
Scenario 2: 91.8 l anhydrous ethanol/TC

With the same amount of cane, the production of hydrous ethanol is approximately 3% larger.

The gasoline direct CO_2 emissions, calculated from the Brazilian data (density = 0.742 kg/l; LHV = 44.8 MJ/kg and IPCC emission data (Annex 3, Note 1: 18.9 kg CO_2/GJ, LHV), are 628 g carbon/m^3. Adding the indirect emissions[5] (Annex 3, Note 1), the total value to be considered is 0.77 kg C/l or 2.82 kg CO_2/l gasoline.

Although a direct comparison between ethanol, gasohol and gasoline engines in Brazil is not possible, the equivalence that is widely accepted today, as a function of the relative performance of new vehicles, is as follows:

1 l of hydrous ethanol (E-100 engine) = 0.7 l of gasoline
1 l of anhydrous ethanol (E-25 engine) = 1 l of gasoline

Under these conditions, the avoided emissions are:

2.82 kg CO_2/l anhydrous ethanol
1.97 kg CO_2/l hydrous ethanol

or referring to sugar cane production:

Anhydrous ethanol: 242.5 or 259 kg CO_2/TC, for Scenarios 1 and 2, respectively.
Hydrous ethanol: 169 or 181 kg CO_2/TC, for Scenarios 1 and 2, respectively.

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