Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Brazilian Sugarcane Ethanol Production Simulated by Using the GREET Model

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Abstract

By using data available in the open literature, we expanded the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory to include Brazil-grown sugarcane ethanol. With the sugarcane ethanol pathway added to the GREET model, we examined the well-to-wheels (WTW) energy use and greenhouse gas (GHG) emissions of sugarcane-derived ethanol produced in Brazil and used to fuel light-duty vehicles in the United States. Results for sugarcane ethanol were compared with those for petroleum gasoline. This paper documents the development of the sugarcane-to-ethanol pathway in the GREET model. The pathway comprises fertilizer production, sugarcane farming, sugarcane transportation, and sugarcane ethanol production in Brazil; ethanol transportation to U.S. ports and then to U.S. refueling stations; and ethanol use in vehicles. We developed and examined several sensitivity cases to test the effect of key parameters on WTW results for sugarcane ethanol. Our analysis revealed that sugarcane ethanol can reduce GHG emissions by 78% and fossil energy use by 97%, relative to petroleum gasoline.

1. Introduction

Brazil began its sugarcane fuel ethanol program in 1975 after the first oil crisis and has since expanded it significantly. Brazil is now the number 2 fuel ethanol producer and consumer after the United States. Ethanol has become a mainstream motor fuel in Brazil, accounting for 40% of its gasoline market. More than 80% of new cars sold in 2006 were ethanol flexible-fuel vehicles (FFVs).

Brazil has vast land available for sugarcane farming. About five million hectares of land are currently used for sugarcane farming in Brazil (Macedo 2005), and some in Brazil maintain that an additional five million hectares can be made available for sugarcane farming. Brazil expects that its sugarcane ethanol industry will continue to expand. In fact, companies from other countries are beginning to invest in the sugarcane ethanol industry in Brazil. In addition to its own consumption, Brazil seeks to export fuel ethanol to other countries, including the United States, the European Union, and Japan.

With the support of the U.S. Department of Energy (DOE), Argonne National Laboratory has been developing and applying the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model to examine energy and emission benefits of advanced vehicle technologies and new transportation fuels (see Brinkman et al. 2005 for the GREET model and its applications). The GREET model features many fuel ethanol production pathways from feedstocks such as corn, fast-growing trees, switchgrass, crop residues, and forest residues. As part of this effort, we added the production of sugarcane ethanol in Brazil and use of it in the United States to the GREET model.

2. System Boundary and Analysis Cases for the Sugarcane-to-Ethanol Pathway

We conducted a well-to-wheels (WTW) analysis of Brazilian sugarcane-derived ethanol based on the system boundary depicted in figure 1. The sugarcane-to-ethanol pathway simulated in this study comprises the following stages:

- Fertilizer production
- Sugarcane farming and harvesting
- Sugarcane transportation
- Ethanol production
- Ethanol transportation from sugarcane mills in Brazil to U.S. ports
- Ethanol transportation and distribution from ports to refueling stations within the United States
- Ethanol use in U.S. vehicles

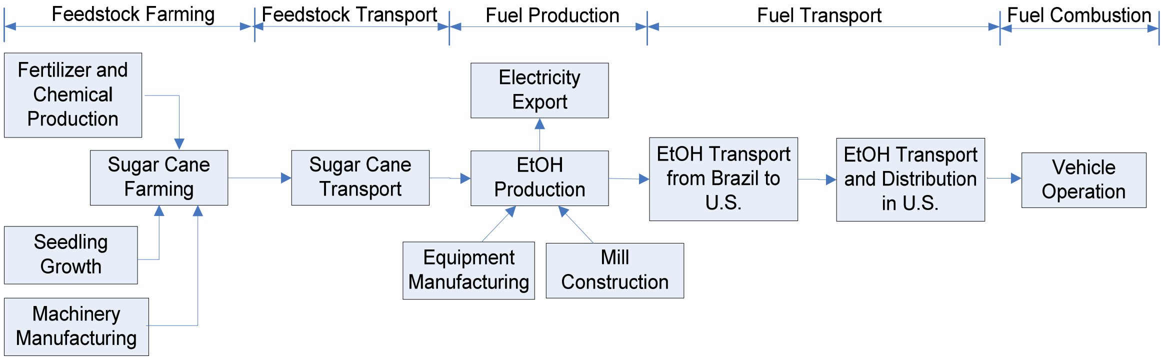


Figure 1. Stages of the Sugarcane-to-Ethanol Pathway

The life cycle of sugarcane-derived ethanol begins with the manufacture of fertilizer and farming machinery and the preparation of cane seedlings. Farming operations include chemical application, irrigation, tillage, and harvest. The current sugarcane farming practice involves open-field burning of sugarcane leaves and straws before and after harvest to facilitate the manual harvest and to control disease. Harvested sugarcane is transported via trucks to sugarcane mills, where it undergoes sugar juice extraction, followed by fermentation of juice for ethanol production (and/or sugar production).

The residues from juice extraction — called “bagasse” — are combusted in sugarcane mills to generate steam and electricity to meet the demand for heat and power. Since 2000, sugarcane mills have made major efforts to export their excess electricity to the electric grid. In addition to the manufacture of farming machinery and sugarcane mill equipment, construction of sugarcane mills was included in this analysis.

Ethanol is transported from sugarcane mills to Brazilian ports via rails and pipelines, to U.S. ports by ocean tankers, and then to U.S. refueling stations via trucks. Ethanol is used either in low-level blends such as E10 (mixture of 10% ethanol and 90% gasoline by volume) in regular gasoline vehicles or high-level blends such as E85 (mixture of 85% ethanol and 15% gasoline by volume) in FFVs.

The gasoline life cycle, on the other hand, begins with crude oil recovery in oil fields and ends in gasoline combustion in gasoline vehicles, a pathway that is already in the GREET model.

In this near-term (2006–2010) analysis of the sugarcane ethanol life cycle, many factors play a key role in determining the overall energy use and greenhouse gas (GHG) emissions of sugarcane ethanol. We examined these factors by developing several sugarcane ethanol cases, all of which produce ethanol and export electricity to the electric grid. In addition, we included petroleum gasoline, corn ethanol, and switchgrass ethanol for comparison.

The base case established for sugarcane ethanol was production in Brazil and use in the United States. Other cases were developed to test the importance of the following parameters: (1) whether sugarcane ethanol is used in the United States or Brazil (to assess the contribution of ocean tanker transportation of ethanol), and (2) whether energy embedded in farming equipment manufacturing and sugarcane mill construction makes a significant contribution to the WTW results of sugarcane ethanol. The sugarcane (SC) cases and the petroleum gasoline, corn ethanol, and switchgrass ethanol cases were as follows:

- SC Case 1 (the base case for sugarcane ethanol): sugarcane ethanol is produced in Brazil and used in the United States; energy embedded in farming equipment manufacturing and sugarcane mill construction is not included (This case is consistent with the petroleum gasoline pathway.)

- SC Case 2: same as SC Case 1 except that energy embedded in farming equipment manufacturing and sugarcane mill construction is included

- SC Case 3: same as SC Case 1 except that energy embedded in farming equipment manufacturing is included

- SC Case 4: same as SC Case 3 except that sugarcane ethanol is used in Brazil (This case shows the contribution of ocean tanker transportation of ethanol.)

- Petroleum gasoline production and use in the United States excluding energy embedded in all infrastructure-related activities

- Corn ethanol production and use in the United States, including energy embedded in farming machinery

- Cellulosic ethanol production and use in the United States with switchgrass as the feedstock and including energy embedded in farming machinery manufacture

3. Data Sources and GREET Assumptions

To develop the sugarcane ethanol pathway in GREET, we collected data for the activities associated with the sugarcane ethanol pathway from the open literature. The data were processed to derive input parameters for GREET.

Previous studies have been conducted to evaluate the GHG emission effects of sugarcane ethanol. Macedo et al. (2004) conducted a detailed analysis of the energy and emission effects associated with the production and use of sugarcane ethanol in Brazil. A study by Concawe et al. (2007) included sugar cane ethanol among many other transportation fuels; it relied on data developed by Macedo et al. and other studies.

3.1. Sugarcane Farming

We analyzed energy use and emissions for activities involved in sugarcane farming, including fertilizer, lime, and chemical production; sugarcane seedling preparation; farming operations; farming equipment manufacturing; and open-field burning of sugarcane leaves and straws.

3.1.1. Chemical and Energy Inputs for Sugarcane Farming

Once sugarcane seedlings have been planted on sugarcane farms, the sugarcane can be harvested for five to seven seasons. After that, sugarcane farms are replanted. Table 1 presents the typical composition of sugarcane. Traditionally, sugarcane is harvested by laborers (“sugarcane cutters”); this harvest is often referred as to the manual harvest. To ease cutters’ efforts, sugarcane fields are burned before harvest. After harvest, the remaining stalks are often burned to control disease and promote seedling growth in the next season. Primarily because of concerns about air pollution caused by open-field burning, the state of Sao Paulo will phase out open burning completely by 2018. As a result, mechanical harvesting will replace manual harvesting. As of 2005, 65% of the sugarcane harvest in Brazil was manual and 35% was mechanical (Macedo 2005).

Table 1. Sugarcane Composition

Parameter	Value (%)
Sucrose content	14.5
Fiber content	13.5
H_2O content	72.0

Source: Macedo et al. 2004.

Table 2 summarizes the application rates of nitrogen (N) and phosphate (P_2O_5) fertilizer, potash (K_2O), lime ($CaCO_3$), herbicide, and pesticide on Brazilian sugarcane farms. Fertilizer and chemical use are usually reported in kilograms per hectare per year (kg/ha/yr); however, for GREET simulations, we need to use kilograms or grams of per metric ton (kg/MT) of sugarcane harvested. We converted the value by using a sugarcane yield of 68.6 MT/ha (Macedo et al. 2004). The types of nitrogen fertilizer used are 85% urea and 15% ammonium nitrate and sulfate together (Macedo 2007).

Table 2. Fertilizer and Chemical Inputs for Sugarcane Farming in Brazil

Input	Assuncao (2000)[a]	Macedo et al. (2004)[b]	GREET[e]
N fertilizer			
kg/ha/yr	77.2	71.6[c]/75[d]	
g/MT of sugarcane	1,152.2	1,042.2[c]/1,091.7[d]	1,091.7
P_2O_5			
kg/ha/yr		40.8[c]/8.3[d]	
g/MT of sugarcane		593.9[c]/120.8[d]	120.8
K_2O			
kg/ha/yr		120[c]/13.3[d]	
g/MT of sugarcane		1,746.7[c]/193.6[d]	193.6
Lime ($CaCO_3$)			
kg/ha/yr		366.7	
g/MT of sugarcane		5,337.7	5,337.7
Herbicide use			
g/MT of sugarcane		26.9	26.9
Pesticide use			
g/MT of sugarcane		2.21	2.21

[a] Assuncao assumed a nitrogen application of 28 kg/ha for planting of sugarcane and 87 kg/ha for each harvest season. We assumed a cycle of 6 years with five cuts. He further assumed a sugarcane yield of 80.4 MT/ha/cut, resulting in 67 MT/ha over the 6-year period. These values were used to derive nitrogen application per hectare per year and per metric ton of sugarcane harvested.

[b] Macedo et al. (2004) used a sugarcane yield of 68.7 MT/ha over a 6-year sugarcane cycle. We used this value to derive nitrogen application rates per metric ton.

[c] For farms that do not use filter mud cake and vinasse (the residues left in a still following distillation).

[d] For farms that use filter mud cake and vinasse.

[e] For GREET simulations, weighted average values between sugarcane fields without and with use of filter mud and vinasse would be ideal. Because of the lack of data regarding breakdown of the two types of sugarcane plantations, we adopted the values for the fields with use of filter mud and vinasse.

For sugarcane farming, energy use includes diesel fuels used to power farming equipment, energy spent preparing sugarcane seedlings, and energy embedded in farming equipment manufacturing (Table 3). Although GREET WTW analyses generally do not include energy embedded in equipment, we included it to be consistent with the pathways for ethanol production from different feedstocks, which include this energy. Nonetheless, we designed an option in GREET for including or excluding the energy embedded in farming equipment manufacturing and associated emissions.

Table 3. Inputs of Energy Use for Farming Operation, Seedling Preparation, and Farming Machinery Manufacturing for Sugarcane Farming

Input	Assuncao (2000)	GTZ (2005)	Macedo et al. (2004)	GREET
Farming operation[a]				
MJ[b]/MT of sugarcane	30.1	38	38	
Btu[b]/MT of sugarcane	28,531	36,019	36,019	36,019
Sugar cane seedling preparation				
MJ/MT of sugarcane	5.76	6	5.88	
Btu/MT of sugarcane	5,460	5,687	5,573	5,573
Energy embedded in farming machinery				
MJ/MT of sugarcane	33.1		29.1	
Btu/MT of sugarcane	31,346		27,583	27,583

[a] The farming energy data include energy use for sugarcane harvesting, as well as for other farming activities. Data from the three cited sources are for combinations of manual and mechanical harvest. Although manual harvest now accounts for more of the total harvest than mechanical harvest, in the long term, mechanical harvest will account for more. Energy use between the two harvest methods could be different, but no data showing the difference are available. The difference in harvest energy use may be small, because manual harvest collection and loading activities are still performed by machines to a large extent.

[b] MJ = millijoules; Btu = British thermal unit.

3.1.2. Open-Field Burning of Sugarcane Leaves and Tops

Sugarcane leaves and tops are typically burned in the field before and after harvest. Macedo et al. (2004) reported a yield of 280 kg of leaves and tops (with 50% moisture content, or 140 kg of dry leaves and tops) per metric ton of sugarcane harvest. At present, 80% of sugarcane farms in Brazil practice open-field burning. Because open-field burning will be gradually phased out, in developing the sugarcane ethanol pathway in GREET, we assumed burning of 80% of leaves and tops at present and 0% in 2020.

For the GREET simulation, we took into account emissions from open-field burning — in particular, emissions of two pollutants: methane (CH_4) and nitrous oxide (N_2O). Emissions of carbon dioxide ($CO_{2)}$ from open-field burning were not taken into account, because the CO_2 is uptaken during sugarcane growth. Emissions from open-field burning of sugarcane leaves and tops were estimated by assuming a leaf and top moisture content of 15%, which is similar to that of corn stover and switchgrass. The carbon content of leaves and tops is 50% on a dry-matter basis (Macedo et al. 2004).

Table 4 lists our estimates of emissions generated from open-field burning. These were based on three sources: summaries of Macedo et al. (2004) and Assuncao (2000); results in Andreae and Merlet (2001); and data included in the Intergovernmental Panel on Climate Change guidelines (IPCC 2006a). Average emissions values from open-field burning of agricultural residues listed in the IPCC guidelines appear higher than those from other sources. We used IPCC data as our base case for emission factors of CH_4, N_2O, carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter measuring

2.5 micrometers or less ($PM_{2.5}$). For PM_{10} (particulate matter measuring 10 micrometers or less), we estimated emission factors on the basis of a ratio of 2:1 between PM_{10} and $PM_{2.5}$, which was derived from coal combustion emission factors in GREET. Therefore, we used a value of 7.8 g/kg of leaves and tops burned for PM_{10}. For volatile organic compound (VOC) and sulfur oxides (SO_x) emission factors, we used values estimated by Andreae and Merlet (2001).

Table 4. Emission Factors of Open-Field Burning of Sugarcane Leaves and Tops

	Emission Factors (g/kg of dry leaves and tops burned)					
		Macedo et al. (2004)				
Pollutant	Andreae and Merlet (2001)	Low Value[a,b]	High Value[a,b]	Assuncao (2000)[a]	IPCC (2006a)	GREET
CO_2	1515 (±177)				1515 (±177)	NN[c]
CO	92 (±84)				92 (±84)	92
CH_4	2.7	0.1464	1.0214	0.2886	2.7	2.7
NO_x	2.5(±1)				2.5 (±1)	2.5
N_2O	0.07				0.07	0.07
$PM_{2.5}$	3.9					3.9
PM_{10}						7.8 [d]
VOC	7.0					7.0
SO_x	0.4					0.4

[a] These sources reported CH_4 emissions in kg/MT of sugarcane harvested. We used the yield of 280 kg of sugar cane leaves and tops with 50% moisture content per MT of sugarcane harvested to convert the original values into values in g/kg of leaves and tops burned.

[b] Macedo et al. (2004) maintained that the low values represented the average Brazilian emission rates, and the high values were adopted from the IPCC guidelines.

[c] Data are not needed here. CO_2 emissions are calculated in GREET by using the carbon balance of sugar cane leaves and tops; see Section 4.1.

[d] Data were not available. This value was estimated on the basis of the ratio of PM_{10} versus $PM_{2.5}$ for coal combustion.

3.1.3. N_2O Emissions from Sugarcane Fields

A major source of N_2O emissions from sugarcane farming is nitrification and denitrification of nitrogen fertilizer applications. In Brazil, the most frequently used type of nitrogen fertilizers is urea (Macedo 2007), from which N_2O is emitted directly and indirectly. When applied to soil, nitrogen fertilizer is volatilized and converted to N_2O; when oxidized, some of it is emitted directly to the air as N_2O. A large amount of nitrogen fertilizer leaches to groundwater or rivers through surface runoff, during which some of it is converted to N_2O via microbial nitrification and denitrification. Macedo et al. (2004) estimated that on an annual basis, 75 kg of nitrogen in nitrogen fertilizer applied to a 1-ha sugarcane field resulted in 1.76 kg of N_2O emissions in the Central-South region of Brazil, which resulted in 1.5% in weight (wt%) of nitrogen in N_2O per weight unit of nitrogen in nitrogen fertilizer applied.

N_2O emissions from soil are highly uncertain; they depend on various conditions such as the amount of nitrogen fertilizer applied, soil type, soil moisture content, and temperature. According to the IPCC guidelines (2006b), the following are the N_2O emission factors for nitrogen in N_2O generated from the nitrogen in nitrogen fertilizer for generic applications: 1% for direct N_2O-N emissions, with a range of 0.3–3%; 1% for N_2O emissions from volatilization, with a range of 0.2–5% and a volatilization rate for nitrogen input of 10%, with a range of 3–30%; and 0.75% N_2O emissions from leaching and runoff, with a range of 0.05–2.5% and a leaching and runoff rate for nitrogen input of 30%, with a range of 10–80%. Using the average values in the IPCC guidelines (2006b), we derived a total N_2O-N rate of 1.325% (1% + 1% × 10% + 0.75% × 30%), which is close to the value of 1.5% derived from Macedo et al. (2004). We used the rate of 1.5% in our analysis.

The types of nitrogen fertilizer used are 85% urea and 15% ammonium nitrate and sulfate together (Macedo 2007). A gram of urea (NH_2CONH_2) contains 0.2 g of carbon, resulting in 0.43 g of carbon per gram of nitrogen in urea. This results in 1.577 g of CO_2 per gram of nitrogen in urea. We included this CO_2 emission source in the GREET simulation.

3.1.4. Sugarcane Transportation from Farms to Sugarcane Mills

Harvested sugarcane contains about 70% water. Because sugarcane is bulky and heavy, sugarcane mills are built in the midst of sugarcane farms to minimize transportation distance. Sugarcane is transported via trucks (see figure 2) an average one-way distance of 20 km (Macedo et al. 2004). The payload of a truck is 40–50 MT (Moreira and Goldemberg 1999). With these inputs, past studies in Brazil concluded that energy use for transporting sugarcane from farms to mills is 31–43 MJ/MT of sugarcane (Assuncao 2000; GTZ 2005; Macedo et al. 2004).

Figure 2. A Truck Carrying Sugarcane to Sugarcane Mill

For GREET simulations, we assumed that sugarcane is transported by a diesel truck with a payload of 40 MT for a 20-km one-way trip from field to mill. Furthermore, we assumed a fuel economy of 4 miles per gallon of diesel fuels for trucks transporting sugarcane. On the basis of these assumptions, the GREET model estimated an energy consumption of 24.4 MJ/MT of sugarcane transported. This value is lower than the values in the cited studies; those studies may have included direct energy use (as was the case in our estimate) and energy embedded in manufacturing the trucks.

3.2. Ethanol Production in Sugarcane Mills

In sugarcane mills, sugarcane is washed and crushed, and cane juice is extracted. The juice is then treated to produce ethanol and/or sugar. The split between the two products is based on market demand. The stream for ethanol production is then fermented, and the fermentation broth is subject to distillation, yielding product ethanol. CO_2 is emitted during fermentation. Figure 3 is a schematic of the sugarcane ethanol production process. To simplify this analysis, we assumed that a sugarcane ethanol mill is operated with 100% feed for ethanol production. The primary source of process fuel is bagasse with additional lubricant oil to support machinery operation.

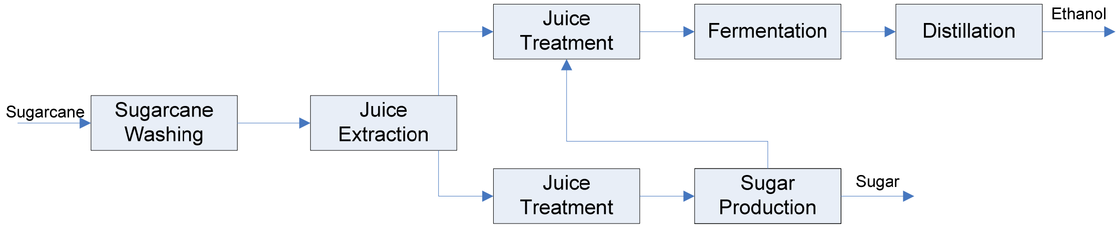


Figure 3. Schematic Representation of the Sugarcane Ethanol Production Process

3.2.1. Ethanol Yield

Table 5 presents a summary of ethanol yield from several studies. We used a yield of 91 L of ethanol/MT of sugarcane, based on the best value reported in Macedo et al. (2004).

Table 5. Summary of Ethanol Yield in Sugarcane Mills[a]

Source	Ethanol Yield (L/MT)	Notes	GREET Input (L/MT)/(gal/MT)[b]
Moreira and Goldemberg (1999)	79.5	1996/97 season yield	
Assuncao (2000)	73	1985 season yield	
	85.4	2000 season yield	
GTZ (2005)	80		
Macedo et al. (2004)	86	Average value	
	91	Best value	91/24

[a] Assuming that all sugarcane goes to ethanol production.
[b] Based on wet metric ton of sugarcane.

3.2.2. Energy Requirements in Sugarcane Mills

Table 6 shows the amounts of electric, thermal, mechanical, and chemical energy required for production of ethanol in sugarcane mills. Sugarcane mills are self-sufficient in terms of thermal energy and electricity use. Heat demand represents the majority of energy use and is met through bagasse combustion. Most sugarcane mills generate their own electricity for internal use. The use of bagasse as the process fuel is discussed in Section 3.2.4. We selected values for GREET input parameters on the basis of the latest data from the open literature. We estimated total electricity use by the sugarcane mill to be 28.85 kWh/MT of sugarcane processed. Of this total, 16.84 kWh/MT is used to drive mechanical work with a conversion efficiency of 95% (Table 7).

Table 6. Energy Consumption in Ethanol Production Process

Parameter	MJ/MT of Sugarcane	Data Source	GREET Input (MJ/MT of Sugarcane)
Energy Use			
Electricity	43.20	Macedo 2005	43.20
Mechanical energy	57.60	Macedo 2005	57.60
Thermal energy	1,188.00	Macedo 2005	1,188.00
Chemical and Lubricant Use			
	7.34	Assuncao 2000	
	6.00	GTZ 2005	
	6.36	Macedo et al. 2004	6.36
Energy Embedded in Sugar Mill Construction			
Average value	10.78	Assuncao 2000	
Average value	12.00	GTZ 2005	
Best value	8.07	Assuncao 2000	
Best value	9.00	GTZ 2005	
Average value	11.97	Macedo et al. 2004	
Best value	9.29	Macedo, 2004	9.29
Energy Embedded in Sugar Mill Equipment			
Average value	27.96	Assuncao 2000	
Average value	31.00	GTZ 2005	
Best value	20.98	Assuncao 2000	
Best value	24.00	GTZ 2005	
Average value	31.07	Macedo et al. 2004	
Best value	24.16	Macedo et al. 2004	24.16

We assumed that the thermal energy (1,188 MJ, or 1.126 million Btu, per MT of sugarcane) is supplied by bagasse combustion in a biomass boiler to produce steam with an efficiency of 80%. There is 1.408 million Btu of bagasse per MT of sugarcane, or 58,546 Btu/gal of ethanol produced (Table 7). A small amount of lubricants (6.36 MJ/MT of sugarcane) is used in sugarcane mills, which we assumed to be similar to residual oil in terms of energy and emission profiles. Therefore, we approximated the energy use of lubricant oil to that of residual oil.

Table 7. Process Energy Use in Sugarcane Mills for Ethanol Production

	MJ/MT of Sugar cane	KWh/MT of Sugarcane	KWh/gal of EtOH[a]	Btu/MT of Sugarcane	Btu/gal of EtOH[a]
Electricity	43.2[b]	12.00	0.50		
Mechanical	57.6[b]	16.84[c]	0.70		
Thermal	1,188[b]			1,407,583	58,546
Lubricant oil	6.36[b]			6,028	251
Mill construction	9.29[b]				366
Equipment manufacturing	24.16[b]				953
Total		28.85	1.20		

[a] The conversion from sugarcane processed to ethanol produced is based on the ethanol yield of 91 L/MT of wet sugarcane.

[b] Data source: see Table 6.

[c] We assumed a conversion efficiency of 95% from electric energy to mechanical energy.

Macedo et al. (2004) estimated a life-cycle energy use of 9.29 MJ/MT of sugarcane processed in construction of sugarcane mills and 24.16 MJ/MT in manufacture of sugarcane mill equipment (that is, embedded energy in mill equipment). We included these values in the GREET model. The equipment used was assumed to be 100% steel. Emissions from equipment manufacturing were estimated on the basis of process fuel shares for steel production as presented in GREET 2.7.

3.2.3. Bagasse as the Process Fuel in Sugarcane Mills

Bagasse is the residue of sugarcane after the juice has been extracted. Because of its high carbon content (46.3 wt% on a dry matter basis), it serves as an excellent source of process fuel in sugarcane mills. We assumed that bagasse is combusted in a biomass boiler to produce steam to meet the plant demand for steam and to generate electricity with a steam turbine to meet the plant requirement for electricity and for electricity export.

We used a bagasse yield of 280 kg (50% moisture content) per MT of sugarcane, which was reported by Macedo et al. (2004). The lower heating value (LHV) of bagasse in references ranged from 7.530 to 7.736 MJ/kg (with 50% moisture content, Macedo et al. 2004; Garcia 2007). One heating value reported by Assuncao (2000), 9.449 MJ/kg, was 2 MJ higher and was not specified as either high heating value (HHV) or LHV. We compared the data with Perry's *Chemical Engineers' Handbook* (Perry and Green 1997) which listed an HHV of 8.37–11.63 MJ/kg for bagasse, suggesting that the value of 9.448 MJ/kg is most likely the HHV. For sugarcane ethanol simulations in GREET, we used a LHV of 7.53 MJ/kg (with 50% moisture) for bagasse. On a dry-matter basis, the LHV for bagasse is 15.06 MJ/kg, or 12,947,320 Btu/ton.

The steam and electricity balance for sugarcane ethanol processing is presented in Table 8. The total energy provided by bagasse, 83,124 Btu/gal of ethanol produced, was determined by using a bagasse energy yield of 280 kg/MT sugarcane × 7.53 MJ/kg at an ethanol yield of 0.024 gal/kg of sugarcane (91 L/MT). The steam needed for plant operation is 58,546 Btu/gal of ethanol, which is based on a boiler efficiency of 80% (Table 7).

We assumed the surplus steam, 24,578 Btu/gal of ethanol, is used to generate electricity. With an electricity generation efficiency of 30% (the current Brazil industrial average), a total of 2.16 kWh of electricity can be generated for each gallon of ethanol produced. After 1.20 kWh (Tables 7 and 8) has been consumed in the process, an excess of 0.96 kWh/gal of ethanol is available for export.

Table 8. Ethanol Plant Steam and Electricity Energy Balance (per gallon of ethanol)

Bagasse Energy Yield (Btu)	Internal Steam Needs (Btu)	Extra Btu for Electricity Generation (Btu)
83,124[a]	58,546	24,578
Electricity Generated from Extra Bagasse Energy (KWh)	Internal Electricity Needs (kWh)	Extra Electricity for Export (kWh)
2.16[b]	1.20	0.96

[a] This value is calculated as follows. One MT of sugarcane results in 280 kg of bagasse with 50% moisture content and 91 L of ethanol. Thus, a gallon of ethanol is associated with 11.66 kg of bagasse, which contains 87.70 MJ of energy, or 83,124 Btu of energy.

[b] Based on a power generation efficiency of 30%.

3.2.4. Bagasse Combustion Emissions

The IPCC guidelines (2006b) specify emission factors of CH_4 and N_2O from biomass combustion; see Table 9. Because of the large variations in the CH_4 and N_2O emission factors, we adopted the IPCC average values for GREET simulations.

Table 9. Emission Factors of Bagasse Combustion

Pollutant	Emission Factors (g/mm Btu of bagasse)			
	From IPCC Guidelines (2006b)			GREET Inputs
	Low	Average	High	
CH_4	11.00	31.65	105.50	31.65
N_2O	1,58	4.22	15.83	4.22

3.3. Ethanol Transportation from Sugarcane Mills to Refueling Stations

While some Brazilian sugarcane ethanol is exported to Japan, the European Union, and the United States, the majority of the sugarcane ethanol produced in Brazil is used in the Brazilian domestic market. For a U.S. perspective of Brazilian sugarcane ethanol, we examined the case in which sugarcane ethanol is produced in Brazil and used in the United States market so that we could compare its effects directly with those of ethanol production pathways already examined for the United States.

For the case of the domestic use of ethanol in Brazil, we assumed that ethanol is transported via pipeline and rail for 350 miles (in each mode) from sugarcane mills to bulk terminals and then via truck for 50 miles to refueling stations, where it is used either in its pure form or blended with gasoline.

For the case of ethanol exported to the United States, we accounted for ethanol transportation in both Brazil and the United States. Ethanol is first transported from mills to Brazilian ports in Southern Brazil. For this analysis we selected a representative port, Santos, a major port in Brazil. Most sugarcane mills are located in the two southern states near the Santos port that provide about 50% of the nation's ethanol. In particular, we assumed that ethanol is transported via pipeline and rail on an average of 500 miles (in each mode) from sugarcane mills to the Santos port, where it is loaded onto ocean tankers for transporting to the United States. We chose two U.S. ports, New York and Los Angeles, as entry points for Brazilian ethanol to the U.S. market. We used the average distance of 6,449 nautical miles from Santos to New York and from Santos to Los Angeles (see www.distance.com). Inside the United States, we assumed that ethanol is distributed regionally on the East and West Coasts, while the rest of the country receives domestic corn ethanol from the U.S. Midwest. In particular, we assumed that the imported ethanol is transported 100 miles by truck to blending and storage facilities and further distributed to refueling stations.

3.4. Extraction and Production of Process Fuels and Electricity Generation Mix

For individual stages of the sugarcane ethanol pathway in Brazil, such as sugarcane farming, cane transportation, ethanol production, and ethanol transportation to U.S. ports, the energy use and emissions of primary energy recovery and processing, including coal, natural gas, and oil, were not available at the time of this study. We used GREET default values, which are based on U.S. industry averages. These values may be updated once Brazilian data become available.

To estimate energy and emission credits of the exported electricity generated at sugarcane mills in Brazil, energy and emissions associated with electricity use in Brazil were estimated by assuming the electricity exported from sugarcane mills would replace electricity generation in natural gas plants. It is believed that natural gas power plants are marginal power plants in Brazil. In comparison, Table 10 shows the average power generation mix in Brazil.

Table 10. Average Electricity Generation Mix in 2004 in Brazil

Plant Fuel	Average Electricity Generation Mix in Brazil (%)
Petroleum	1.2
Natural gas	5.0
Coal	1.7
Biomass	4.2
Nuclear	3.0
Hydro	82.9
Others	2.0

Source: Ministry of Mine and Energy of Brazil (2005).

4. Key Issues in WTW Analysis of Sugarcane Ethanol

4.1. CO_2 Credits

During their growth, sugarcane plants take CO_2 from the air for the photosynthesis process. The carbon taken in by sugarcane plants resides in them and is further converted to carbon in CO_2, CO, VOC, and CH_4, which are generated through various chemical and biological routes (fermentation, combustion, and the like) when sugarcane is processed to produce ethanol. The CO_2 from sugarcane that is emitted through a combustion process or through ethanol combustion on vehicles is considered zero CO_2 emissions to the air, since this is the carbon from the air during sugarcane plant growth. In this case, the renewable carbon from sugarcane, rather than fossil fuel carbon, is used for combustion. Similarly, direct CO_2 emissions from sugar fermentation to ethanol are considered to be zero CO_2 emissions to the air.

We examined the fate of the renewable carbon in sugarcane beginning with harvested sugarcane by making several assumptions:

- All carbon in sugarcane plants is from atmospheric CO_2.
- Emissions from carbon in sugarcane plants end in four sources: CO_2, CO, VOC, and CH_4.
- CO and VOC, which are emitted to the air during combustion of sugarcane tops and leaves in sugarcane fields and combustion of bagasse in ethanol plants, are

converted to CO_2 in the air in a short time; these CO_2 sources, together with direct CO_2 emissions from these combustion processes, are not included in CO_2 emission calculations for sugar cane ethanol, since they are ultimately from the air.

- CH_4 from these combustion processes remains in the air for a long time, and these CH_4 emissions are accounted for as a GHG emission source for sugarcane ethanol.
- The organic carbon content of soil in sugarcane farms remains constant; however, this may not be the case if sugarcane ethanol production is expanded significantly and certain land uses are changed to accommodate such expansion.

Figure 4 is a schematic diagram of the fate of atmospheric carbon in the sugarcane ethanol pathway. The renewable carbon in sugarcane is utilized (combusted) in the sugarcane-to-ethanol pathway via three major routes: open-field burning of sugarcane leaves and tops, bagasse combustion in ethanol plants, and ethanol combustion during vehicle operation. All four forms of carbon emissions from these sources — CO_2, CO, VOC, and CH_4 — originate in carbon uptake from the air by sugarcane plants during growth. Among them, CO and VOC typically are oxidized to CO_2 within a few days after being released to the air. The amount of CO_2 generated is basically the carbon transformed from atmospheric CO_2; that is, the CO_2 emission sources shown in figure 4 are actually CO_2 from the air during sugarcane growth.

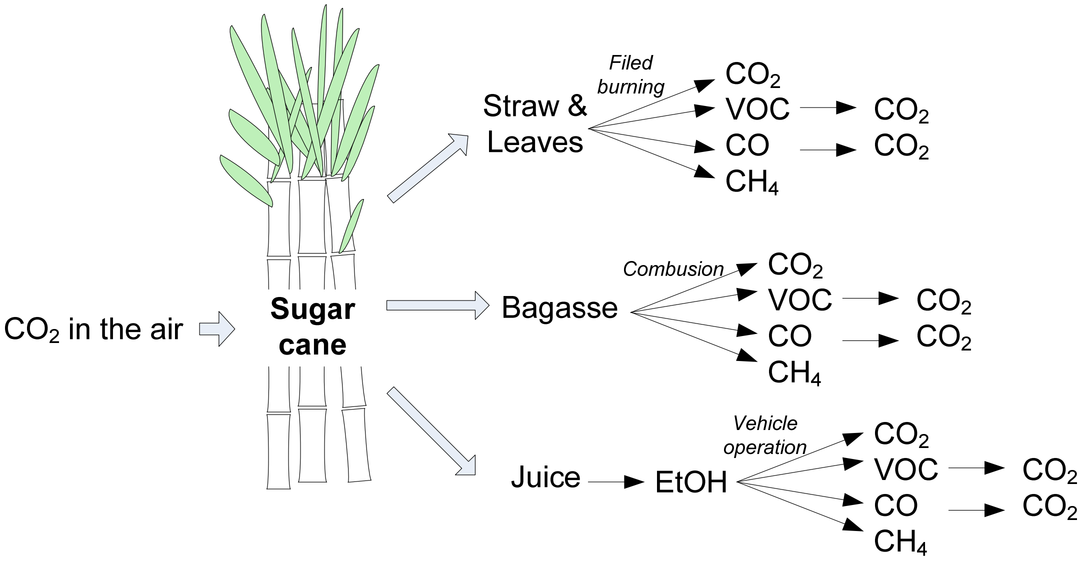


Figure 4. Fate of Renewable Carbon in the Sugarcane Ethanol Pathway

4.2. Energy and Emission Credits of Exported Electricity

Bagasse is combusted to provide steam for meeting process heat requirements at sugarcane mills, and excess steam generates electricity to satisfy plant internal power demand. Excess power could be exported to the electric grid. In some cases, mills may not be connected to the electric grid; thus, power export may not be an option. In the

GREET model, we designed two options for the sugarcane ethanol pathway: (1) ethanol production with no electricity export; and (2) ethanol production with excess electricity exported to the electric grid.

In the case in which excess electricity is exported to the electric grid (the case we considered in our simulations), electricity generated from sugarcane mills is assumed to displace electricity generated with natural gas electric power plants. On the other hand, if the exported electricity is assumed to displace the electricity with the Brazilian average electric generation mix, which is largely hydropower (82.9%, see table 10), the energy and emission credits of the exported power would be smaller. In other words, the fact that the renewable power generated from bagasse displaces another primary renewable power reduces the benefit of the exported electricity from sugarcane ethanol plants.

5. Results and Discussions

As indicated in Section 2, we established a base case for production of sugarcane ethanol in Brazil and use of it in the United States (SC Case 1). Three sensitivity cases were developed from the base case. For comparison, we selected the base case to compare sugarcane ethanol with corn ethanol, switchgrass-based cellulosic ethanol, and petroleum gasoline, since evaluation of these three cases does not include energy embedded in corn ethanol plants and petroleum refineries. WTW results of energy use and GHG emissions are presented in figures 5–11 and in Table 11. Energy and GHG emission results are expressed for each million Btu of fuel produced and used.

Energy use results for sugarcane ethanol, corn ethanol, and cellulosic ethanol are presented together in this section. While results for sugarcane and corn ethanol are based on operational data of many plants, results for cellulosic ethanol from switchgrass are based on projections and engineering simulations of switchgrass growth and cellulosic ethanol production. Note that in terms of commercial readiness, cellulosic ethanol is not at the same stage of development as sugarcane and corn ethanol.

5.1 Fossil and Petroleum Energy Use Results

Ethanol produced from Brazilian sugarcane achieves substantial reductions in fossil energy use (97%) relative to petroleum gasoline (Figure 5). The reductions are 2.6 times as much as those by corn ethanol. Fossil energy includes petroleum, natural gas, and coal energy; thus petroleum energy use presented here is a subset of fossil energy use.

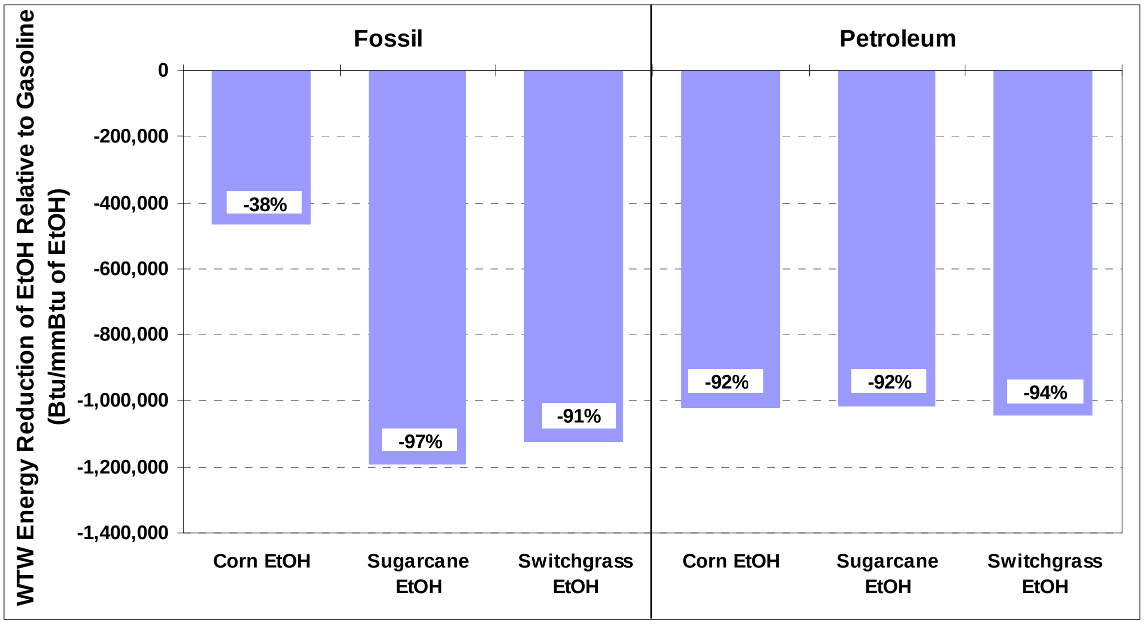
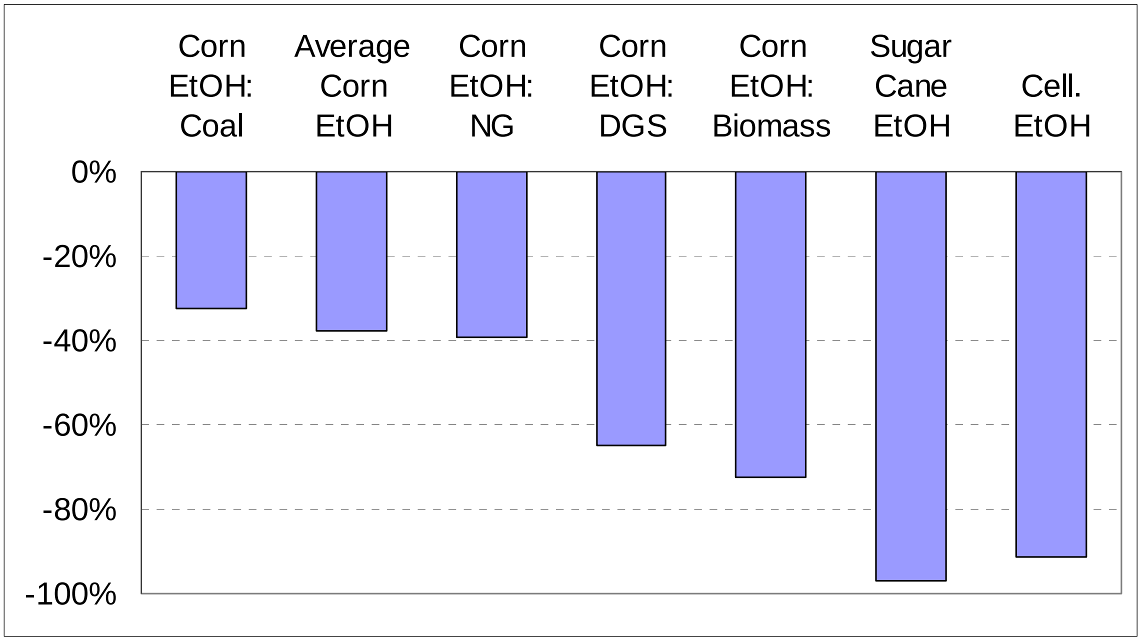


Figure 5. WTW Fossil Energy and Petroleum Reductions by Ethanol Relative to Petroleum Gasoline

Figure 5 shows that ethanol can provide reductions of more than 90% in petroleum energy compared to gasoline, regardless of the feedstocks for ethanol production (corn, sugarcane, or switchgrass). Figure 6 compares sugarcane ethanol with various ethanol production and feedstock options. Among the ethanol production and feedstock options evaluated, fossil energy reduction by sugarcane ethanol is similar to that by cellulosic ethanol. Figure 7 presents the net energy balance values of various ethanol production options and petroleum gasoline per million Btu of fuel produced. The net energy balance (NEB) is the difference between the Btu content of a fuel and the fossil Btu input to the fuel production pathway. A positive value of NEB represents an energy surplus for a fuel, while a negative value shows an energy deficiency. All the ethanol options show positive NEB values. For each million Btu of ethanol produced from sugarcane grown in Brazil and utilized in the United States, there is a net gain of 0.96 million Btu, in contrast to a net gain of 0.23 million Btu for corn ethanol and 0.89 million Btu for switchgrass-derived ethanol.



(Corn ethanol and cellulosic ethanol results are from Wang et al. (2007); each corn ethanol type represents the corn ethanol plants fueled with a given process fuel.)

Figure 6. WTW Fossil Energy Reductions of Various Ethanol Production Options Relative to Petroleum Gasoline

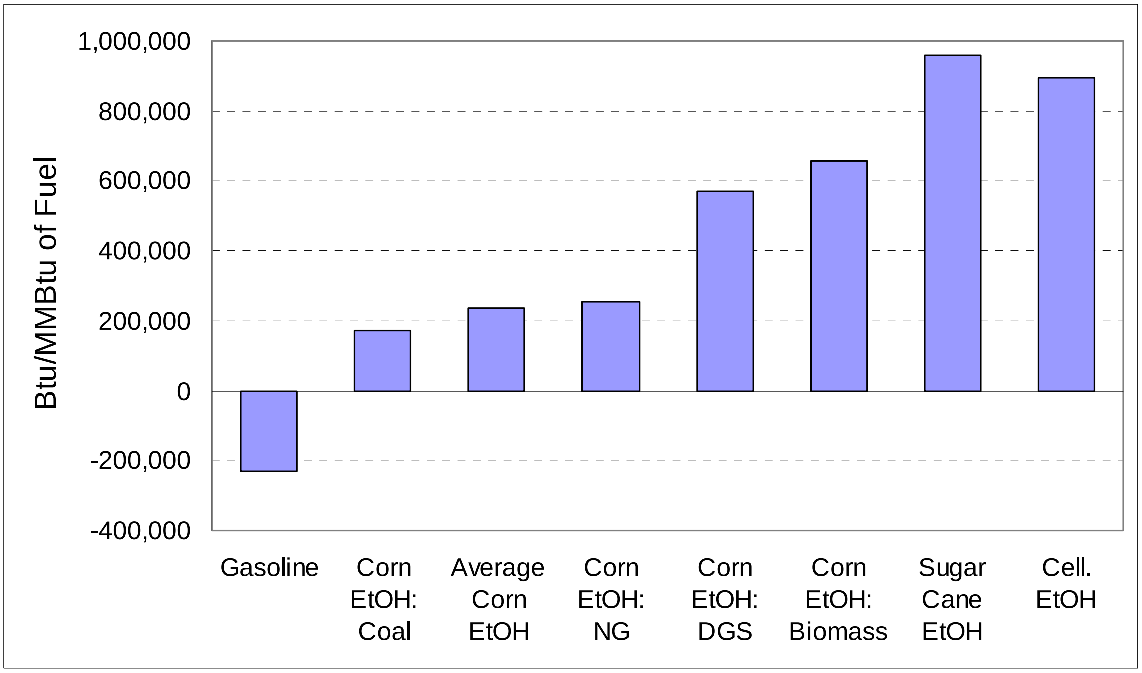


Figure 7. Net Energy Balance of Ethanol and Petroleum Gasoline:

The unique advantage of the sugarcane ethanol pathway is that ethanol production in sugarcane mills is self-sustaining in terms of energy need: the juice is used for ethanol production and bagasse is used for heat and power generation. As a result, ethanol production requires 58,546 Btu of heat demand and 1.20 kWh of electricity per gallon of ethanol. In addition, renewable power at the rate of 0.96 kWh can be exported to the electric grid. This reduction in fossil energy use is the main cause of the marked difference in WTW results between sugarcane ethanol and corn ethanol. Table 11 illustrates that approximately 100,785 Btu of natural gas and 163,609 Btu of coal per million Btu of ethanol are saved by sugarcane ethanol production compared to corn ethanol. Recently, designers and operators started to address the issue of process fuel demand in corn ethanol plants by considering renewable sources such as wood chips or distiller's grains and solubles (DGS). With these renewable energy sources, corn ethanol could reduce an additional 27% (DGS as the process fuel) or 34% (wood chips as the process fuel) of fossil energy use (Figure 6).

Table 11. WTW Fossil Energy Use for Ethanol (Btu/Million Btu of Ethanol)

Fossil Energy	Corn EtOH	Sugarcane EtOH
Natural Gas	468,709	–96,097[a]
Coal	206,284	42,675
Petroleum	90,398	92,596
Total	765,391	39,174

[a] The negative value represents the reduction of natural gas-based electricity generation that is displaced with the electricity exported from sugar cane mill.

Sensitivity analysis of sugarcane ethanol with the four sugarcane ethanol production options (as presented in Figure 10) indicates that (1) energy embedded in sugarcane mills contributes 0.3% of total fossil energy use; (2) energy embedded in farming equipment contributes 2.3%; and (3) transportation of ethanol from Brazil to the United States contributes 3.0%.

5.2. GHG Emissions Results

Figure 8 shows WTW GHG emission reductions by sugarcane ethanol and several other ethanol production options, compared to petroleum gasoline. The GHG emission reductions by sugarcane ethanol are 3.8 times as much as those by corn ethanol and rank second only to those by cellulosic ethanol.

For the five corn ethanol production options, GHG emission changes range from a 3% increase to a 52% reduction, depending on the process fuel used.

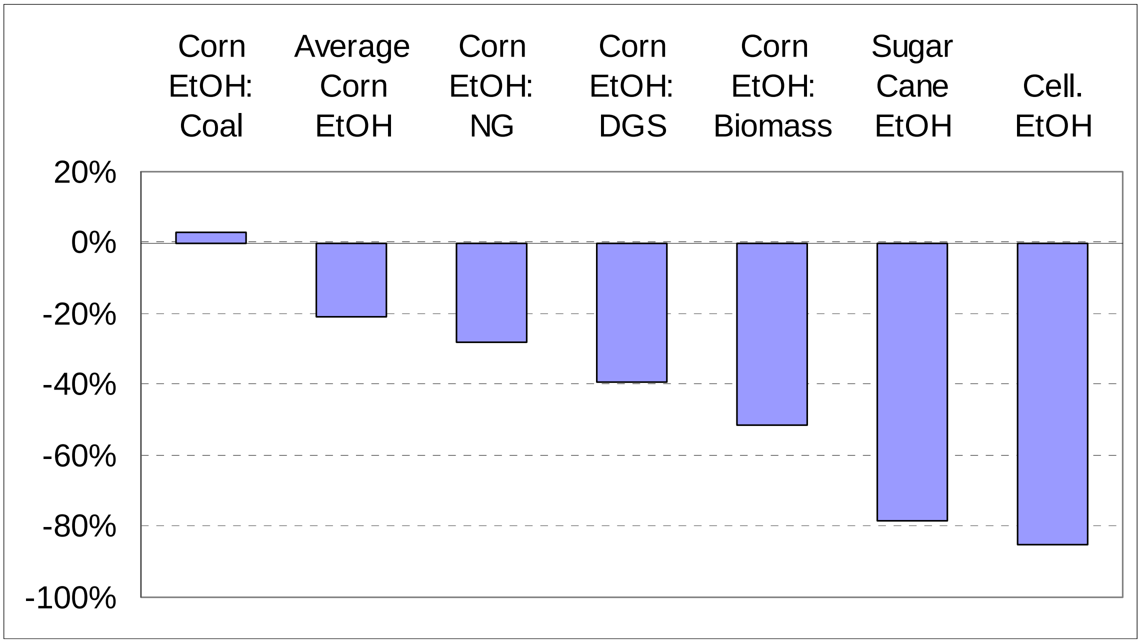


Figure 8. WTW GHG Emission Reductions by Various Ethanol Production Options Relative to Petroleum Gasoline

We examined key stages of the sugarcane ethanol pathway for their contributions to total GHG emissions. Similar to that for cellulosic ethanol, the sugarcane ethanol pathway generates heat and power from bagasse in sugarcane mills to displace natural gas or coal use. However, sugarcane farming differs considerably from cellulosic biomass farming. For example, sugarcane farming is associated with open-field burning of sugarcane tops and leaves, a practice not used in either corn farming or cellulosic biomass farming. CH_4 and N_2O emissions from open-field burning alone are responsible for 24% of total GHG emissions for sugarcane ethanol (Figure 9). In particular, the five major contributors to sugarcane ethanol GHG emissions are open-field burning (24%), N_2O emissions from sugarcane fields (14%), fertilizer production (16%), GHG emissions from sugarcane mills (17%), and sugarcane farming (9%); together these make up 80% of the total WTW GHG emissions of sugarcane ethanol.

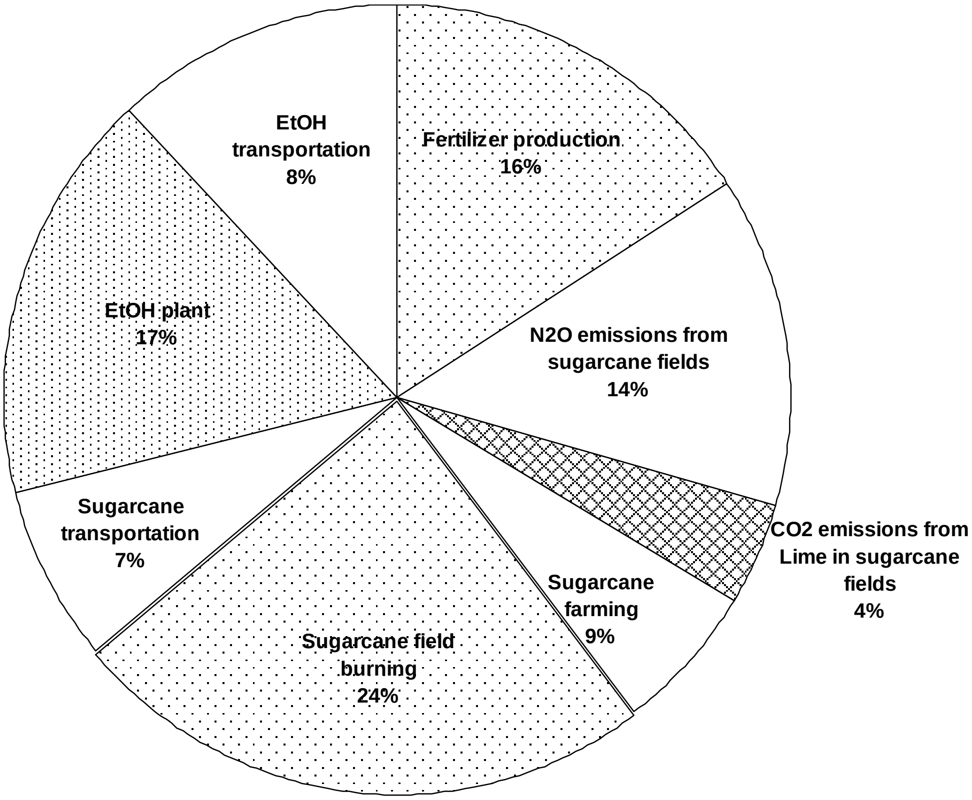


Figure 9. Shares of GHG Emissions of Sugarcane Ethanol Pathway Activities

5.3. Sensitivity Cases of Sugarcane Ethanol

We developed four sugarcane ethanol cases in this study to show variations in energy and GHG emission effects of sugarcane ethanol. The difference between Cases 1 and 2 shows the contribution of energy embedded in farming equipment production and sugarcane mill construction; that between Cases 1 and 3 shows the contribution of energy embedded in farming equipment production; and that between Cases 1 and 4 shows the contribution of transporting ethanol from Brazil to the United States.

Figures 10 and 11 show the effects of these factors. In particular, inclusion of energy embedded in farming equipment and sugarcane mill construction lowers fossil energy reductions by sugarcane ethanol by 2.6 percentage points and GHG emission reductions by 2.8 percentage points. Inclusion of energy embedded only in farming equipment lowers fossil energy reductions by1.3 percentage points and GHG reductions by 1.2 percentage points. These results imply that energy embedded in farming equipment and sugarcane mills contributes in equal proportion to total sugarcane ethanol results.

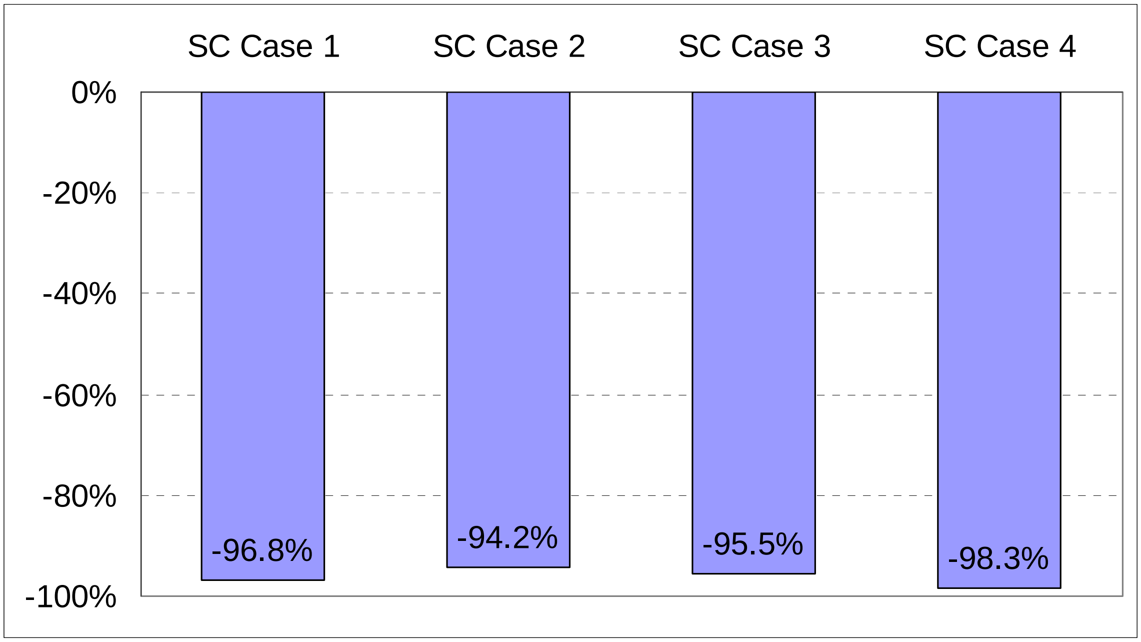


Figure 10. Fossil Energy Reductions by Four Sugarcane Ethanol Cases Relative to Petroleum Gasoline

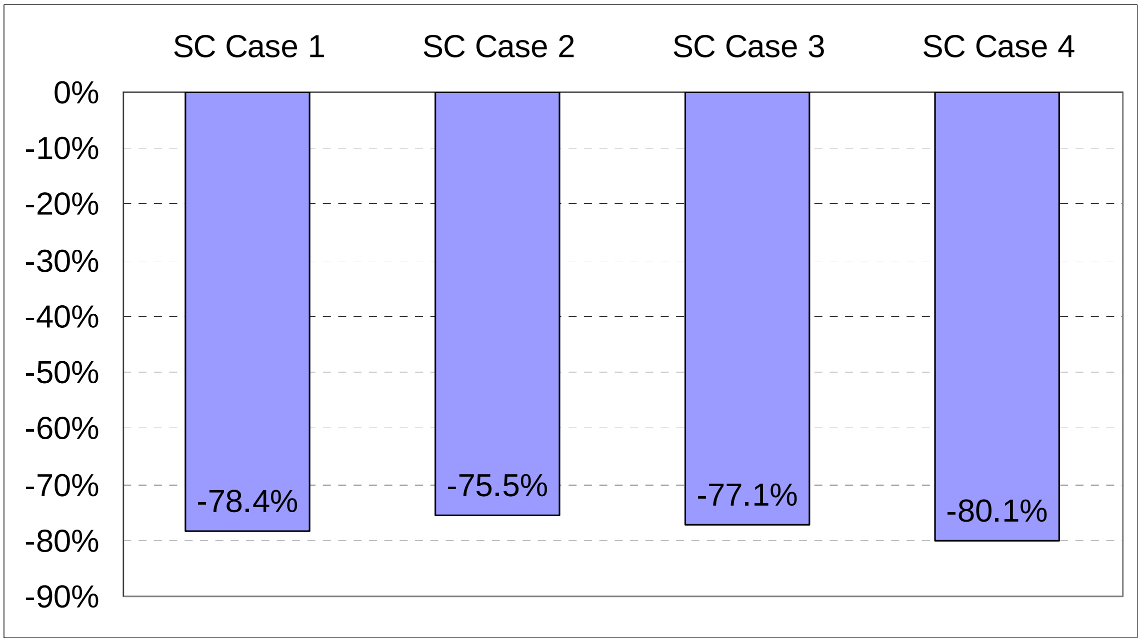


Figure 11. GHG Emission Reductions by Four Sugarcane Ethanol Cases Relative to Petroleum Gasoline

The difference between Cases 1 and 4 indicates that transportation of sugarcane ethanol from Brazil to the United States contributes to a 1.5-percentage-point difference in fossil energy use and a 1.7-percentage-point difference in GHG emissions for sugarcane ethanol.

We also developed two cases for open-field burning — one with 100% burning and the other with 0% burning (this is compared with the assumed 80% open-field burning for all four sugarcane ethanol cases examined in this study). The results of the two cases showed a difference in GHG emission reductions of 9 percentage points. Because Brazil is going to phase out open-field burning in the future, this will certainly help further reduce GHG emissions of sugarcane farming, together with reductions in emissions of criteria pollutants such as NO_x and PM_{10}.

CH_4 emissions from open-field burning are subject to great uncertainty (Table 4). Use of a CH_4 emission factor of 0.15 g/kg of biomass instead of 2.7 g/kg helps increase GHG emission reductions of sugarcane ethanol by 5.2 percentage points.

We assumed in our analysis that the exported electricity from sugarcane ethanol plants will displace electricity generated in natural gas electric power plants, which are believed to be the marginal electric power plants in Brazil. On the other hand, if the exported electricity displaces the average electricity in Brazil (83% of which is from hydro-power), GHG emission benefits of sugarcane ethanol are reduced by up to 8 percentage points.

6 Conclusions

By using the GREET model, our WTW analysis of the pathway of producing ethanol from sugarcane in Brazil and using it in the United States reached the following conclusions. Sugarcane ethanol could achieve fossil energy reduction as much as 97% relative to petroleum gasoline. The large reduction is a result of use of bagasse in sugarcane mills in place of coal or natural gas to generate the heat and power needed for plant operation. This and other factors such as low sugarcane farming energy and fertilizer use contribute to a positive net energy balance of 0.96 million Btu per million Btu of ethanol produced.

Sugarcane ethanol could achieve a reduction of 78% in GHG emissions relative to those of petroleum gasoline. This reduction is similar to that of cellulosic ethanol. Even when energy embedded in farming equipment and sugarcane mills is included, GHG emission reductions by sugarcane ethanol are still more than 75%. The large reductions can be attributed to the use of bagasse in sugarcane mills. Of the total GHG emissions associated with sugarcane ethanol, the five major contributors are open-field burning of sugarcane tops and leaves, N_2O emissions from sugarcane fields, fertilizer production, sugarcane mill operation, and sugarcane farming.

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