California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Brazilian Sugar Cane Ethanol

Stationary Source Division

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The Staff of the Air Resources Board developed this preliminary draft version as part of the Low Carbon Fuel Standard Regulatory Process

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When reviewing this document, please submit comments directly to:
Anil Prabhu: aprabhu@arb.ca.gov
Chan Pham: cpham@arb.ca.gov
Alan Glabe: aglabe@arb.ca.gov
Jim Duffy: jduffy@arb.ca.gov

These comments will be compiled, reviewed, and posted to the LCFS website in a timely manner.

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SUMMARY

CA-GREET Model Pathway for Brazil Sugar Cane Ethanol

A Well-To-Tank (WTT) life cycle analysis of a fuel (or blending component of fuel) pathway includes all steps from feedstock production to final finished product. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. Together WTT and TTW analysis are combined together to provide a total Well-To-Wheel (WTW) analysis.

A life cycle analysis model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory has been used to estimate the energy use and greenhouse gas (GHG) emissions associated with the production of ethanol from Brazilian sugar cane. The ethanol is then transported via ocean tanker to a California port and transported to a blending terminal for use in a light-duty vehicle. The values, assumptions, and equations used in this document are from the GREET 1.8b model (released February 2009), which has been modified to reflect California specific values. This model labeled “the CA-GREET model v1.8b” is available for download from the Low Carbon Fuel Standard website at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

The values shown in this document are preliminary draft values and staff is in the process of evaluating them. The areas that staff may revise include emission factors, energy intensity factors, percent fuel shares, transport modes and their shares, agricultural chemical use factors, etc.

Note: At this time, analysis of land use change for sugar cane based ethanol has not been completed and results presented here do not include any potential land use change impacts. These impacts will be considered when the analysis for land use change is completed.

Figure 1 below outlines the discrete components that comprise the sugar cane ethanol pathway.

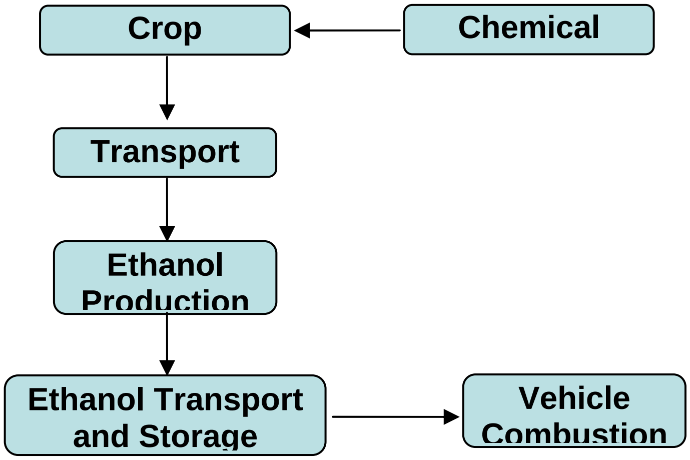

Figure 1. WTW Components for Sugar Cane Ethanol Produced in Brazil and Transported for Use in CA

Several general descriptions and clarification of terminology used throughout this document are:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the direct crude oil consumption AND the energy associated with crude recovery (which is the value being calculated).

- Btu/mmBtu is the energy input necessary in Btu to produce one million Btu of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC Global Warming Potential (GWP) values and included in the total.

- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights. This method is also used by the IPCC.

- Process Efficiency for any step in CA-GREET is defined as:

  Efficiency = energy output / (energy output + energy consumed)

- Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document.

Table A below summarizes the fuel cycle energy inputs by stage (Btu/mmBtu) and Table B summarizes the major GHG emission categories and intensities (gCO_2e/MJ). The tables present energy and emission results relative to the energy content (LHV) of anhydrous ethanol (see Appendix A for greater detail about energy and emissions). Figure 2 shows the percentage energy contributions from the various components of the ethanol pathway. From an energy viewpoint, ethanol production (48.6%) and carbon in fuel (44.4%) components dominate the sugarcane ethanol pathway. Figure 3 shows the GHG contributions from the various components of this pathway. From a GHG viewpoint, sugarcane farming impacts (37.2%) and production and use of agricultural chemicals (32.7%) components are the major contributors to the sugarcane ethanol pathway. Complete details of all energy inputs and GHG emissions are provided in Appendix A. A list of all inputs is provided in Appendix B.

Note: Since all the ethanol is produced from sugar cane which consists of CO_2 fixed via photosynthesis, the tailpipe emissions from combustion of ethanol is considered to be zero. This is since the CO_2 release from combustion was actually removed from the atmosphere by the feedstock. The addition of denaturant however does lead to contributions to CO_2 during combustion which is proportional to the amount of denaturant added to anhydrous ethanol. This value is not shown below in Table B under TTW category since the values are shown for anhydrous ethanol. The discussion and calculations are presented in Appendix A under TTW section. Since the use of anhydrous ethanol as a stand alone fuel is not permitted in CA, this document does not include tailpipe emissions of CH_4 and N_2O. An accompanying document for CaRFG (containing ethanol as an oxygenate in CARBOB) provides combined effects including tailpipe emissions of using reformulated gasoline in a light-duty vehicle.

Table A. Sugar Cane Ethanol Energy Use

Sugar Cane Ethanol Components	**Energy* (Btu/mmBtu) (Anhydrous)**	**% Energy Contribution**
Sugar Cane Farming	26,407	1.2%
Energy Inputs for Ag Chemicals	59,616	2.7%
Sugar Cane Transportation	25,722	1.1%
Ethanol Production	1,093,376	48.6%
Ethanol T&D	44,442	2%
Total Well-to-Tank	**1,249,563**	**55.6%**
Carbon in Fuel	1,000,000	44.4%
Total Tank-to-wheel	**1,000,000**	**44.4%**
Total Well-to-Wheel	**2,249,563**	**100%**

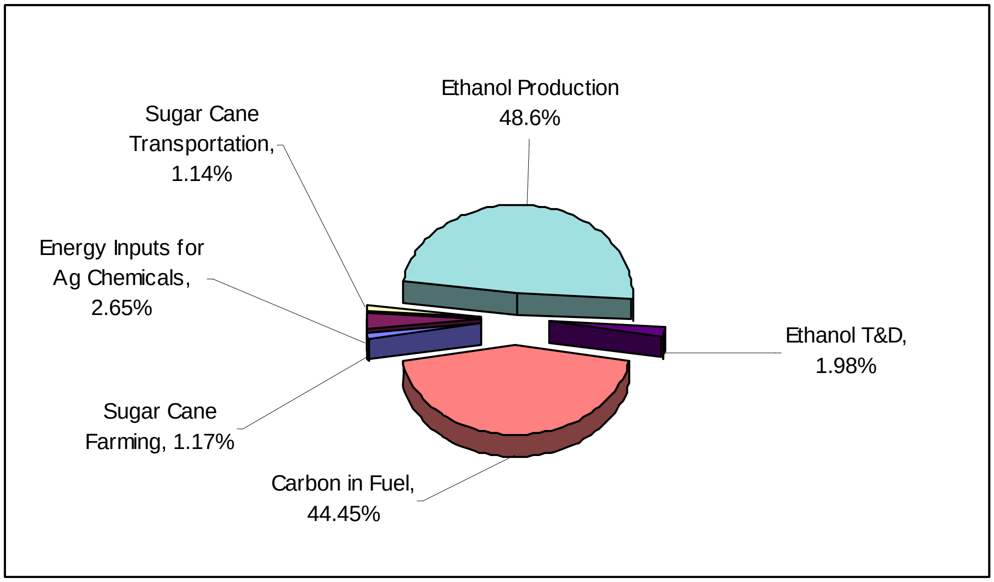

Figure 2. Percent Energy Contribution from WTW for Sugar Cane Ethanol

Table B. GHG Emissions Summary for Sugar Cane Ethanol

Sugar Cane Ethanol Components	**GHGs (g CO_2e/MJ)**	**% Emission Contribution**
Sugar Cane Farming *(incl. straw burning)*	9.9	37.2%
Ag Chemicals Production and Use Impacts	8.7	32.7%
Sugar Cane Transportation	2.0	7.5%
Ethanol Production	1.9	7.1%
Ethanol T&D	4.1	15.4%
Total Well-to-Tank	26.6	100%
Total Tank-to-wheel	0	0%
Total Well-to-Wheel	**26.60**	**100%**
Inclusive of Tailpipe Emissions and Land Use Change	**73.40***	

*Note: The value of **26.60** does not include contributions from CH_4 and N_2O when ethanol is blended with CARBOB and used as Reformulated Gasoline in a light-duty gasoline engine. The total GHG value including tailpipe contributions for sugarcane ethanol is **27.40 gCO_2e/MJ** when blended with CARBOB (approximately 10% by volume ethanol). Details of the calculation procedure is available in the CaRFG pathway document. Land Use change estimated value of **46.0 gCO_2e/MJ** is from the GTAP analysis and the details are presented in Chapter 4 of the Staff Report. Combined, the total WTW inclusive of Land Use Change is **73.40 gCO_2e/MJ** for sugarcane ethanol.

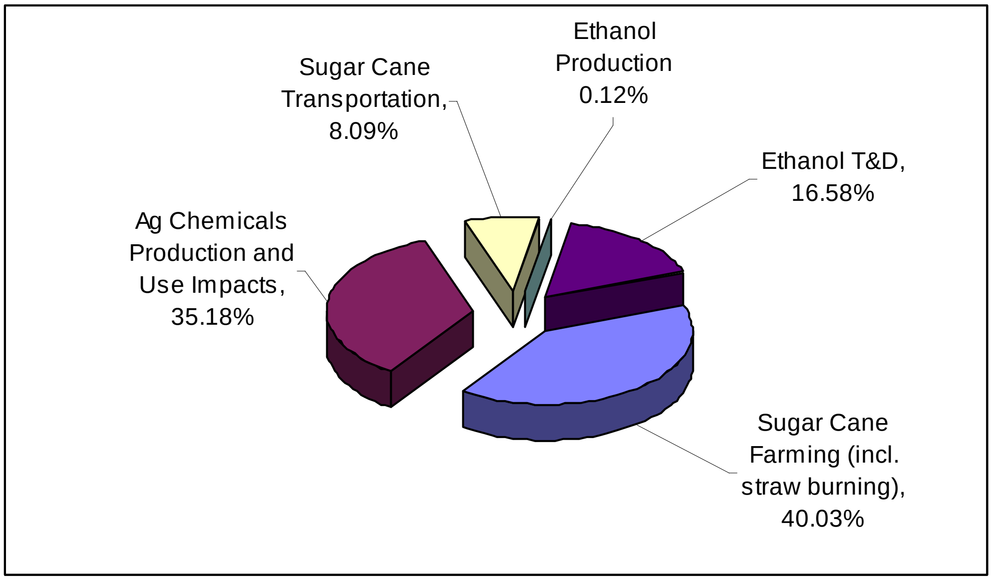

Figure 3. Percent GHG Contributions from WTW for Sugar Cane Ethanol

WTT Details

This section provides a breakdown of the energy and related GHG emissions for all the various WTT components of the ethanol pathway detailed in Figure 1. Complete details including calculations, equations, etc. are provided in Appendix A.

SUGAR CANE FARMING

Table C provides a breakdown of energy input from each fuel type used in sugar cane farming activities. Table D provides information on GHG emissions related to sugar cane farming. Additional details are provided in Appendix A.

Table C. Total Energy Input by Fuel Use for Sugar Cane Farming

Fuel Type	Total Energy (Btu/mmBtu)
Diesel fuel	10,247
Gasoline	3,401
Natural gas	5,213
Liquefied petroleum gas	4,790
Electricity	2,756
Total Energy for Sugar Cane Farming	**26,407**

See table 1.03

Table D. GHG Emissions from Sugar Cane Farming and Straw Burning

Emission Species	Farming	Straw Burning
CH_4	< 0.01	6.6
N_2O	0.01	2.1
VOC	< 0.01	2.2
CO	< 0.01	14.4
CO_2	1.69	163.20
Biogenic CO2 credit	n/a	(-180.31)
Total (gCO_2e/MJ)	**1.74**	**8.2**
Total GHG (gCO_2e/MJ)		**9.9**

See table 1.12

CHEMICAL INPUTS FOR AGRICULTURAL CHEMICALS

Table E provides details the energy inputs required to produce chemicals used in agricultural operations related to sugar cane farming. This includes fertilizers such as nitrogen, phophorus, potassium (potash), and calcium carbonate (lime) as well as herbicides and insecticides. Table F provides details of the associated GHG emissions related to the production of these chemicals as well as their use in sugar cane farming. N_2O and CO_2 emissions from the soil are based on the amount of fertilizer and lime applied respectively. Complete details are provided in Appendix A.

Table E. Energy Inputs for Agricultural Chemicals for Sugar Cane Farming

Chemical Type	**Energy Use, (Btu/mmBtu)**
Nitrogen Fertilizer	31,054
Phosphate Fertilizer	880
Potash	885
Lime	22,354
Herbicide	3,853
Insecticide	375
Total	**59,616**

See table 2.01

Table F Total GHG Emissions from Agricultural Chemical Use

Ethanol Pathway	**Agricultural Chemicals**			**Soil N_2O and NO**	**CO_2 from Application of Lime**	**Total**
	Fertilizers	**Herbicide**	**Pesticide**			
GHGs (gCO_2e/MJ)	3.7	0.3	0.03	3.5	1.2	**8.7**

See tables 2.03, 2.05, 2.06, and 2.07

SUGAR CANE TRANSPORT

Table G details the energy inputs required to transport sugar cane from the farm to the ethanol production plant using heavy duty trucks. Table H provides details of the associated GHG emissions related to transportation of sugar cane from the farm to the ethanol plant. Complete details are provided in Appendix A.

Table G. Sugar Cane Transport Energy

Transport Mode	Energy Consumption (Btu/mmBtu)
Total Energy for Sugarcane Transport	**25,722**

See table 3.02

Table H. Sugar Cane Transport – Total GHG Emissions

Transport Mode	GHG Emissions (gCO_2e/MJ)
VOC	< 0.01
CH_4	< 0.01
N_2O	< 0.01
CO	< 0.01
CO_2	2.0
Total GHGs	**2.0**

See table 3.04

<u>ETHANOL PRODUCTION</u>

Table I details the energy inputs required to produce ethanol from sugar cane. Table J provides details of the associated GHG emissions related to production of ethanol. Credit from bagasse is also shown in this table. Complete details are provided in Appendix A.

Table I. Ethanol Production Energy Use

Fuel Type	Total Energy
From Residual Oil (Btu/gal)	284
From Bagasse (Btu/gal)	83,132
Total Energy Input for Ethanol Production (Btu/gal)	83,415
Total Energy Input for Ethanol Production (Btu/mmBtu)	**1,093,743**

See table 4.02

Table J. GHG Emissions for Ethanol Production

GHG Species	**(gCO_2e/MJ)**
CO_2 from Residual Oil	0.03
CO_2 from Bagasse Burning	124.9
CO_2 credit for Bagasse	-122.97
CH_4	< 0.01
N_2O	< 0.01
VOC from Residual Oil	< 0.01
VOC from Bagasse Burning	0.02
VOC from non-combustion source	0.09
CO from Residual Oil	< 0.01
CO from Bagasse Burning	0.12
Total GHGs	**1.9**

See table 4.04

ETHANOL TRANSPORT AND DISTRIBUTION

Ethanol is transported within Brazil by rail or pipeline. It is then shipped to the US by ocean tanker. Several different denaturant blending options can apply to Brazilian ethanol. A significant fraction of ethanol imported to the U.S. is processed as hydrated ethanol (5% water) in the Caribbean where denaturant is also added. This delivery mode is not modeled in CA-GREET so the pathway based on delivering anhydrous ethanol to California is shown here. Once in CA, it is blended with CAROB and transported and distributed by heavy duty trucks. Table K details the energy inputs required to transport ethanol. Table L provides details of the associated GHG emissions related to ethanol transport and distribution. Additional details are provided in Appendix A.

Table K. Energy Use for Ethanol Transport and Distribution (T&D)

Transport Mode	**Btu/mmBtu**
Transportation within Brazil and to US Port	
By Ocean Tanker	21,510
By Rail	4,614
By Pipeline	3,056
Transportation within U.S	
By Heavy Duty Truck	10,251
Distribution within US	
By Heavy Duty Truck	2,460
Total Ethanol T&D	**44,442**

See table 5.02

Table L. GHG Emissions Related to Ethanol Transport

Transport Mode	g/MJ
Transportation within Brazil and to US Port	
By Ocean Tanker	1.81
By Rail	0.72
By Pipeline	0.45
Transportation within U.S	
By Heavy Duty Truck	0.81
Distribution within US	
By Heavy Duty Truck	0.32
T&D Total (Btu/mmBtu Ethanol)	**4.1**

See table 5.04

Since the CO_2 released from ethanol combustion is the carbon fixed during crop growth,the CO_2 emissions are not counted in the Life Cycle Analysis of sugarcane ethanol. Also, since ethanol is not used as a fuel but as an oxygenate in CaRFG, tailpipe emissions from use of anhydrous ethanol is not discussed in this document. Staff has provided a CaRFG (California Reformulated Gasoline) document which details the blending of ethanol into CARBOB for use as CaRFG and emissions from use of CaRFG.

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APPENDIX A

SECTION 1. SUGAR CANE FARMING

1.1 Energy Use for Sugar Cane Farming

This section presents the direct farming energy inputs for sugar cane farming. For farming, the CA-GREET model calculates energy and emissions based on the quantity of fuel (Btu) and chemicals used per bushel of sugar cane, rather than using energy efficiencies, as the petroleum pathways do in CA-GREET. The total input energy per tonne of sugar cane is **41,592** Btu (CA-GREET default) using a mix of fuel types shown in Table 1.01.

The Brazilian sugar cane ethanol pathway uses three different electricity mixes: Brazilian average, Brazilian marginal and U.S. average mix. The electricity mix used for sugar cane farming is the Brazilian average mix[2], and U.S. electricity is the assumed input for fertilizer production (see Sections 2.1 and 2.2). Marginal Brazilian electricity (natural gas) is the assumed electricity mix displaced by bagasse-fired exported electricity produced at the ethanol plant. Table 1.02 below shows generation shares of the three electricity mixes used in this fuel pathway.

Table 1.01 Primary Energy Inputs by Fuel/Energy Input Type for Farm Operations

Fuel Type	Fuel Share	Formula	Primary Energy Input (Btu/tonne)	Primary Energy Input (Btu/mmBtu)
Diesel Fuel	38.3%	41,592*38.3%	15,930	9,858
Gasoline	12.3%	41,592*12.3%	5,116	3,166
Natural Gas	21.5%	41,592*21.5%	8,942	5,534
Liquefied Petroleum Gas	18.8%	41,592*18.8%	7,819	4,839
Electricity	9%	41,592*9%	3,743	2,316
Direct Energy Consumption for Sugar Cane Cultivation (unadjusted)			**41,550**	**22,681**

Note: To convert Btu/tonne (metric tonne) into the standard units of Btu/mmBtu, we use the following convention for anhydrous ethanol:

41,550 (Btu/tonne)/(24 (gallons/tonne)*76,330 Btu/gal) * 10^6 where :
41,550 is a calculated value in Table 1.01
24 (gallons/tonne) = sugar cane EtOH yield (CA-GREET default)
76,330 Btu/gal = Low Heating Value of anhydrous ethanol (CA-GREET default)

Table 1.02 General Shares of Electricity Mix

Fuel	**Brazilian Average Mix**	**U.S. Average Mix**	**Brazilian Marginal Mix**
Petroleum	1.2%	2.7%	0.0%
NG	5.0%	18.9%	100.0%
Coal	1.7%	50.7%	0.0%
Biomass	4.2%	1.3%	0.0%
Nuclear	3.0%	18.7%	0.0%
Hydro	82.9%	(Included in "Others")	0.0%
Others	2.0%	7.7%	0.0%

The primary energy inputs do not consider the upstream energy associated with the fuels. For example, the amount of energy associated with diesel does not include the energy and emissions associated with the making of the diesel. CA-GREET accounts for the 'upstream' energy associated with fuels by multiplying with appropriate factors. Calculations are shown in Table 1.03. The factors A, B, etc. used in table 1.03 are defined in Table 1.04. Table 1.05 provides additional details for values used in Table 1.04.

Table 1.03 Calculating Total Energy Input by Fuel for Sugar Cane Cultivation

Fuel Type	**Formula**	**Total Energy (Btu/tonne)**	**Total Energy (Btu/mmBtu)**
Diesel fuel	$A*[1+((B*C)+D/10^6)]$	18803	10247.
Gasoline	$E*[1+((B*F)+G/10^6)]$	6240.4	3400.8
Natural gas	$H*(1+I)/10^6$	9565.2	5212.7
LPG	$(J)*(K)*(1+(I*L+M)/10^6 +$ $(J)*(N)*(1+(P*O+Q)/10^6$	8789.3	4789.9
Electricity	$R*S/10^6$	5057.8	2756.3
Total Energy for Sugar Cane Cultivation		**48,456**	**26,407**

Note: Brazilian average electricity mix used. No energy inputs are included for agricultural machinery.

Table 1.04 Values Used in Table 1.03

Factor	Description	Value	Reference
A	Direct Diesel Input	15,930 Btu/tonne	calculated in Table 1.01
B	Crude Energy	31,657 Btu/mmBtu	CA-GREET calculated
C	Diesel Loss Factor	1.00004	CA-GREET default value
D	Diesel Energy	125,303 Btu/mmBtu	CA-GREET calculated
E	Direct Gasoline Input	5,116 Btu/tonne	calculated in Table 1.01
F	Gasoline Loss Factor	1.00081	CA-GREET default
G	Gasoline Energy	169,676 Btu/mmBtu	CA-GREET calculated
H	Direct NG Input	8,942 Btu/tonne	calculated in Table 1.01
I	NG Stationary Energy	72,626 Btu/mmBtu	CA-GREET calculated
J	Direct LPG Input	7,819 Btu/tonne	calculated in Table 1.01
K	NG for LPG Production Share	60%	CA-GREET default
L	NG to LPG Loss Factor	1.00006	CA-GREET default
M	NG to LPG Fuel Stage Energy	48,835 Btu/mmBtu	CA-GREET calculated
N	Petroleum for LPG Production Share	40%	CA-GREET default
O	Petroleum to LPG Loss Factor	1.00012	CA-GREET calculated
P	Petroleum to LPG Fuel Crude Energy	31,657 Btu/mmBtu	CA-GREET calculated
Q	Petroleum to LPG Fuel Energy	75,622 Btu/mmBtu	CA-GREET calculated
R	Direct Electricity Input	3,743 Btu/tonne	calculated in Table 1.01
S	Stationary Electricity Feedstock Production	1,347,391 Btu/mmBtu	CA-GREET calculated

The factors listed in Table 1.04 are derived from the energy contributions of all other fuels that were used in processing these fuels. Those fuels are shown in Table 1.05 below, in two components: WTT energy (E) and Specific Energy (S) for each fuel type.

Table 1.05 Energy Consumption in the WTT Process and Specific Energy

	WTT energy (Btu input/mmBtu product)	**S: Specific Energy (Btu input/Btu product)**
Crude Recovery	$\text{WTT}_{\text{Crude Recovery}}$ = 44,499 (CA-GREET calculated)	$\text{S}_{\text{Crude Recovery}} = 1+\text{WTT}_{\text{Crude Recovery}}/10^6$ = 1.028
B	$\text{WTT}_{\text{Crude}} = \text{WTT}_{\text{Crude Recovery}}*\text{LF}_{\text{T\&D}} + \text{WTT}_{\text{Crude T\&D}} + \text{WTT}_{\text{Crude Storage}}$= 28,249*1.00006 +3,406 = 31,657	$\text{LF}_{\text{T\&D}}$ = Loss Factor for Transport and Distribution = 1.00006 (CA-GREET default) $\text{WTT}_{\text{Crude T\&D}}$= 3,406 (CA-GREET calculated) $\text{WTT}_{\text{Crude Storage}}$ = 0.0 (CA-GREET default)
Residual Oil	$\text{WTT}_{\text{Res Oil}}$ = 55,561 (CA-GREET calculated)	$\text{S}_{\text{Res Oil}} = 1+(\text{WTT}_{\text{Crude}}*\text{LF}_{\text{Crude}}+ \text{WTT}_{\text{Res Oil}}) /10^6$ = 1.106 LF_{Crude} = 1.00000 (CA-GREET default)
D	$\text{WTT}_{\text{diesel}}$ = 124,812 (CA-GREET calculated)	$\text{S}_{\text{diesel}} = 1+(\text{WTT}_{\text{Crude}}*\text{LF}_{\text{diesel}} + \text{WTT}_{\text{diesel}})/ 10^6$ = 1.157. $\text{LF}_{\text{diesel}}$ = 1.00004 (CA-GREET default).
G	$\text{WTT}_{\text{gasoline}}$= 164,227 (CA-GREET calculated)	$\text{S}_{\text{gasoline}} = 1+(\text{WTT}_{\text{Crude}}*\text{Loss Factor}_{\text{gasoline}} + \text{WTT}_{\text{gasoline}})/ 10^6$ = 1.201 $\text{LF}_{\text{gasoline}}$ = 1.00081 (CA-GREET default)
I	$\text{WTT}_{\text{NG}}=(\text{WTT}_{\text{NG Recovery}}* \text{LF}_{\text{processing}} + \text{WTT}_{\text{NG Process}}) * \text{LF}_{\text{T\&D}} + \text{WTT}_{\text{T\&D}}$ = 69,664 (CA-GREET calculated)	$\text{S}_{\text{NG}} = 1+\text{WTT}_{\text{NG}}/10^6$ = 1.073 Natural Gas recovery, Process and T&D includes $\text{WTT}_{\text{NG Recovery}}$ = 31,125, $\text{WTT}_{\text{NG Process}}$ = 31,843, $\text{LF}_{\text{Processing}}$ = 1.00148 and $\text{WTT}_{\text{NG T\&D}}$ = 9,381. $\text{LF}_{\text{T\&D}}$ = 1.00367 (all CA-GREET calculated)
S	$\text{WTT}_{\text{electricity}}$ = 1,347,391	$\text{S}_{\text{Electricity}} = (\text{WTT}_{\text{feedstock}} + \text{WTT}_{\text{fuel}})/ 10^6$ = 2.347

Note: $\text{WTT}_{\text{Crude Recovery}}$: WTT energy for crude oil recovery, of self use of crude oil at the well, not include T&D. $\text{WTT}_{\text{Crude Storage}}$: WTT energy of crude storage

1.2 GHG Emissions from Sugar Cane Farming

CA-GREET calculates carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions for each component of the pathway and uses IPCC[3] **G**lobal **W**arming **P**otentials (GWP) to calculate CO_2 equivalent values for CH_4 and N_2O (see Table 1.06). For VOC and CO, CA-GREET uses a carbon ratio to calculate CO_2 equivalent values which are detailed in a note below Table 1.06. These are based on the oxidation of CO and VOC to CO_2 in the atmosphere. Note that CA-GREET v1.8b has updated GWPs for CH_4 and N_2O compared to CA-GREET v1.7b. The earlier GWPs of 23 and 296 for CH_4 and N_2O have been changed to 25 and 298 respectively in the current version of CA-GREET. This is to reflect updated IPCC values for these GHG species[4].

Table 1.06. Global Warming Potentials for Gases

GHG Species	**GWP (relative to CO_2)**
CO_2	1
CH_4	25
N_2O	298

Carbon ratio of VOC = 0.85 grams CO_2/MJ so grams VOC*(0.85)*(44/12) = 3.1
Carbon ratio of CO = 0.43 grams CO_2/MJ so grams CO/mmBtu*(0.43)*(44/12) = 1.6

The GHG emissions for farm energy use are determined separately for CO_2, CH_4 and N_2O in CA-GREET using the direct energy inputs presented in Section 1.1 (Btu/tonne) and the combustion and upstream emissions for the energy inputs. CA-GREET calculates the emissions for each fossil fuel input by multiplying fuel input (Btu/tonne) by the total emissions from combustion, crude production and fuel production. The electricity emissions are calculated by multiplying the electricity input (Btu/tonne) by the total (feedstock plus fuel) emissions associated with the chosen electricity mix (from the *Electricity* Tab in CA-GREET). Note that U. S. average emission factors are used for Brazilian fuel use and electricity generation. Table 1.07 below shows equations and calculated values by fuel type for sugar cane farming CO_2 emissions. Equations and values for CH_4 and N_2O are not shown, but use the same structure. Table 1.08 provides values for parameters used in equations shown in Table 1.07.

Table 1.07 CA-GREET Calculations for CO_2 Emissions from Sugar Cane Farming

Fuel	**Formula**	**CO_2 Emissions (g/tonne)**	**CO_2 Emissions (g/mmBtu)**
Diesel	[(A)*[(B)*(C) + (D)*(E)+(F)*(G)+ (H)*(I)+(J)*(K)+(L)]]/10^6	1,435	782
Gasoline	[(M)*[(N)+ (J)*(O)+(P)]]/10^6	466	254
Natural Gas	[(Q)*[(R)*(S) + (T)*(U)+(V) *(W)+(X)*(Y)+(Z)]]/10^6	552	301
LPG	[(AA)*[(BB)+((J)*(CC)+(DD)+(EE)*(FF) +(GG))/2]]/10^6	599	326
Electricity	[(HH)*(II)]/10^6	69	38
Total CO_2 Emissions		**3,120**	**1,701**

To convert from g/tonne to g/mmBtu use:

3,120 (g/tonne)/(24 (gallons/tonne)*76,330 Btu/gal) * 10^6
where :
24 (gallons/tonne) = sugar cane EtOH yield (CA-GREET default)
76,330 Btu/gal = Low Heating Value of anhydrous ethanol (CA-GREET default)
10^6 is to convert to mmBtu

Table 1.08 Input Values for Calculations in Table 1.06

	Relevant Parameters*	Reference
A	= Diesel input = 15,930 Btu/tonne	Table 1.01
B	= % Fuel share diesel boiler = 0%	CA-GREET default
C	= Boiler CO_2 emissions = 78,167 g/mmBtu	CA-GREET default
D	= % Fuel share diesel stationary engine = 0%	CA-GREET default
E	= IC Engine CO_2 Emissions =77,401 g/mmBtu	CA-GREET default
F	= % Fuel share diesel turbine = 0%	CA-GREET default
G	= Turbine CO_2 emissions 78,179 g/mmBtu	CA-GREET default
H	= % Fuel share diesel tractor = 100%	CA-GREET default
I	= Tractor CO_2 emissions = 77,411 g/mmBtu	CA-GREET default
J	= Crude production CO_2 emissions = 3,260 g/mmBtu	CA-GREET
K	= Diesel loss factor = 1.00004	CA-GREET default
L	= Diesel production CO_2 emissions = 9,387 g/mmBtu	CA-GREET default
M	= Gasoline input = 5,116 Btu/tonne	Table 1.01
N	= Farming tractor CO_2 emission factor = 75,645 g/mmBtu	CA-GREET default
O	= Gasoline loss factor = 1.00081	CA-GREET default
P	= Gasoline production CO_2 emissions = 12,122 g/mmBtu	CA-GREET calculation
Q	= NG input = 8,942 Btu/tonne	Table 1.01
R	= % Fuel share NG engine = 100%	CA-GREET default
S	= Engine CO_2 emission factor = 56,551 g/mmBtu	CA-GREET default
T	= % Fuel share NG large turbine = 0%	CA-GREET default
U	= Turbine CO_2 emission factor = 58,179 g/mmBtu	CA-GREET default
V	= % Fuel share NG large boiler = 0%	CA-GREET default
W	= Large boiler CO_2 emission factor = 58,198 g/mmBtu	CA-GREET default
X	= % Fuel share small NG boiler = 0%	CA-GREET default
Y	= Small boiler CO_2 emission factor = 58,176 g/mmBtu	CA-GREET default
Z	= WTT stationary NG CO_2 emissions = 5,218 g/mmBtu	CA-GREET calculation
AA	= LPG input = 7,819 Btu/tonne	Table 1.01
BB	= Commercial boiler CO_2 emission factor = 68,036 g/mmBtu	CA-GREET default
CC	= LPG loss factor = 1.00012	CA-GREET default
DD	= LPG production CO_2 emissions = 5,708 g/mmBtu	CA-GREET calculation
EE	= LNG feedstock CO_2 emissions = 4,882 g/mmBtu	CA-GREET calculation
FF	= NG to LPG loss factor = 1.00006	CA-GREET default
GG	= NG to LPG fuel CO_2 emissions = 3,162 g/mmBtu	CA-GREET calculation
HH	= Electricity input = 3,743 Btu/tonne	Table 1.01
II	= Electricity CO_2 emissions = 18,504 g/mmBtu	CA-GREET calculation

Note: The calculation for CH_4 and N_2O are analogous
*Relevant parameters here are calculated values in GREET, except for technology shares, which are direct inputs.

Other GHGs, including VOC, CO, CH_4, and N_2O emissions are calculated with the same equations, energy input, and loss factors as CO_2 emissions calculations shown in Tables 1.07 and 1.08, but with different VOC, CO, CH_4, and N_2O emission factors. Table 1.09 shows the results of the calculations of VOC, CO, CH_4, and N_2O in (g/tonne) then converted to g/mmBtu. The conversion is performed as shown in the note below Table 1.07.

Table 1.09 GHG Emissions from Sugar Cane Farming

Emission Species	**Emissions[1] (g/tonne)**	**GHGs (gCO_2e/mmBtu)**	**GHGs (gCO_2e/MJ)**
CH_4	7.82	106.5	0.1
N_2O	0.08	11.9	0.01
CO_2	3,035	1,654	1.57
Total GHG		**1,772**	**1.7**

[1] Emissions in grams of gaseous species per tonne. To convert all VOC, CO, CH_4 and N_2O (g/tonne) to (g/mmBtu) = (g/tonne)/(Ethanol Yield (gal/tonne) * LHV of Anhydrous Ethanol (Btu/gal))*10^6. Note that for non-CO_2 gases when expressed as GHG in gCO_2e/mmBtu, the appropriate conversion using GWPs has been performed.

1.3 GHG Emissions from Straw Burning in Field

The sugar cane field is burned prior to harvesting by hand. The fire removes dry leaves and straw and kills any pests present while leaving the wet, sugar-rich stalks undamaged. The CA-GREET model uses the input assumptions shown below in Table 1.10 and emission factors presented in Table 1.11 to calculate emissions from field burning. An emission credit is also calculated in grams of CO_2/tonne cane, assuming that all carbon in burned residue is converted to CO_2.

Table 1.10 Inputs for Calculating Field Burning Emissions

Sugar Cane Straw Burning Input Parameters	**Straw Yield (Dry tonne straw/tonne cane)**	**Straw C Ratio (% by weight)**
	0.190	50.%

Table 1.11 Sugar Cane Straw Burning Emission Factors

Emission Species	**CO_2 EF**	**VOC EF**	**CO EF**	**CH_4 EF**	**N_2O EF**
Emission Factor (g/kg straw burned)	1,660	7.0	92.0	2.7	0.07

The straw burning emissions for CO_2 are calculated as follows:

(1,660 g/kg straw)(0.190 dry tonne straw/tonne cane)(1,000 kg/tonne) = 315,973

The CO_2 emission credit is calculated as follows:
-(0.190 dry tonne straw/tonne cane)*(50.0% C content by wt.)*(1,000 kg/tonne)*
(1,000 g/Kg)*(44/12) = -349,067

Table 1.12 shows all emission species calculated the same way as CO_2 example above.

Table 1.12 Sugar Cane Straw Burning Emissions

Emission Species	Emissions (g/tonne Cane)	GHG (gCO_2e/mmBtu EtOH)	GHG (gCO_2e/MJ EtOH)
VOC	1,332.80	2,287	2.2
CO	17,516.80	15,204	14.4
CH_4	514.1	7,003.90	6.6
N_2O	13.3	2,164.50	2.1
CO_2	315,973	172,195	163.2
Biogenic CO_2 Credit	-349,067	-190,230	-180.3
Total GHG		23,226	
GHG (gCO_2e/MJ)			**8.2**

The same notes under Table 1.09 apply for this table.

Total GHG emissions from sugarcane farming and straw burning is therefore **1.74 + 8.2 = 9.9 gCO2/MJ**.

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SECTION 2. CHEMICAL INPUTS FOR AGRICULTURAL CHEMICALS

2.1 Energy Calculations for Production of Chemical Inputs

Chemical inputs, including fertilizer, herbicide and insecticide, are input on a g-nutrient/tonne (fertilizer) or g-product/tonne (herbicide and pesticide) basis. Table 2.01 below presents the CA-GREET chemical inputs per bushel of sugar cane, the total energy required to produce the chemical product and the calculated upstream energy required to produce a bushel of sugar cane using these inputs. Both chemical input values and product energy values are CA-GREET defaults.

Table 2.01. Sugar Cane Farming Chemical Inputs

Chemical Type	**Chemical Input (Btu/g)**	**Product Input Factors (g/tonne)**	**WTT Energy (Btu/tonne)**	**WTT Energy (Btu/mmBtu)**
Nitrogen Fertilizer	45.9	1,091.7	50,133	31,054
Phosphate Fertilizer	13.3	120.8	1,604	880
Potash	8.4	193.6	1,624	892
Lime	7.7	5,337.7	41,019	22,512
Herbicide (average)	262.8	26.9	7,070	3,898
Insecticide (average)	311.3	2.21	688	379
Total				**59,616**

Note: Ethanol yields for sugar cane ethanol are assumed to be 24 gal/tonne in CA-GREET. The WTT energy = chemical input (g/tonne)* product input energy (Btu/g).

Example Calculation:

For Nitrogen Fertilizer: WTT Energy (Btu/tonne) = 45.9 (Btu/g) * 1,092 (g/tonne) = 50,133 Btu/tonne

To convert Btu/tonne into the standard units of Btu/mmBtu, we use the following:

(50,133 Btu/tonne)/((24 gallons/tonne)*76,330 Btu/gal) * 10^6 where :
50,133 is a calculated value in Table 2.01
24 gallons/tonne = sugar cane EtOH yield (CA-GREET default)
76,330 Btu/gal = Lower Heating Value of anhydrous ethanol (CA-GREET default)

CA-GREET models nitrogen fertilizer as a weighted average of ammonia (70.7%), urea (21.1%) and ammonium nitrate (8.2%) fertilizer. As Table 2.01 shows, nitrogen fertilizer input accounts for more than half of total chemical energy input. The herbicide production energy is a weighted average of four types of herbicides used: atrazine (31.2%), metolachlor (28.1%), acetochlor (23.6%) and cyanazine (17.1%). The insecticide inputs represent an “average” insecticide, rather than an explicitly weighted average of specific insecticides. The energy required to produce nitrogen fertilizers, herbicides or pesticides does not vary significantly by category, attesting to the validity of using average energy inputs.

2.2 GHG Calculation from Production and Use of Agricultural Chemicals

This component includes all of the upstream emissions related to the manufacturing of agricultural chemical products. It also includes impacts from the use of agricultural chemicals in farming. Upstream emissions are calculated in CA-GREET per tonne of product, including the production, process and transportation emissions associated with manufacturing chemicals; these intermediate calculations take place in the Ag Inputs sheet. These values are converted to emissions per tonne of nutrient using the ratio of nutrient to product.

Nitrogen fertilizer greenhouse emissions are modeled as a weighted average of 3 types of N-fertilizers modeled in CA-GREET. Energy and emissions are converted to Btu or grams greenhouse gases per g of nutrient (fertilizer) or product (herbicide and pesticide). Average herbicide emissions are calculated using a weighted average of 4 herbicides and pesticide emissions are based on a single pesticide type. Table 2.02 below shows the greenhouse emissions for agricultural chemicals in grams per gram of nutrient for fertilizers and per gram of product for herbicides and pesticides. The equations are complex and not shown here since agricultural inputs apply to large variety of crop cultivation and are not specific to sugar cane cultivation.

Table 2.02 Calculated GHG Emissions (g/g) Associated with Production of Agricultural Chemicals

GHG Type	**Nitrogen (weighted average)**	**P_2O_5**	**K_2O**	**$CaCO_3$**	**Herbicide (weighted average)**	**Pesticide**
CH_4	<0.01	<0.01	<0.01	<0.01	0.03	0.03
N_2O	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CO_2	2.39	0.98	0.66	0.60	20.53	23.87
Convert to GHG (g/g)	**2.9**	**1.0**	**0.7**	**0.6**	**21.3**	**24.84**

The greenhouse emissions of agricultural inputs are multiplied by chemical input factors (g/tonne) in the *Ethanol* sheet and a loss factor from the "*Ag_Inputs*" sheet to yield fertilizer emissions in grams per bushel of sugar cane produced. Table 2.03 below shows the calculations for CO_2 emissions associated with the use of chemical inputs in g/tonne of sugar cane produced. Table 2.04 details the values used in calculations in Table 2.03. The equations for CH_4 and N_2O are analogous to these calculations and are not shown. Table 2.05 shows the emission results for all greenhouse gases for chemical use, based on the calculations shown in Table 2.03.

Table 2.03 Calculated CO_2 Emissions Associated with Production of Agricultural Chemicals

Chemical Product	**Formula**	**CO_2 Emissions**		
		(g/tonne)	**(g/mmBtu)**	**(gCO_2/MJ)**
Nitrogen (weighted average)	(A)*(B)*(C)	2,971	1,619	
P_2O_5	(D)*(E)*(F)	118	64	
K_2O	(G)*(H)*(I)	127	69	
$CaCO_3$	(J)*(K)*(L)	3,210	1,749	
Herbicide	(M)*(N)*(O)	552	301	
Pesticide	(P)*(Q)*(R)	53	29	
Total CO_2 emissions		**7,031**	**3,832**	**3.63**

Table 2.04. Calculated GHG Emissions (g/g) Associated with Production of Agricultural Chemicals

Variable	**Relevant Parameters**	**Reference**
A	= Nitrogen input = 1,091.7 g/tonne	CA-GREET default
B	= Nitrogen chemical cycle emissions = 2.39 g/g	Table 2.02
C	= Nitrogen loss factor = 1.0	CA-GREET default
D	= P_2O_5 input = 120.8 g/tonne	CA-GREET default
E	= P_2O_5 chemical cycle emissions = 0.98 g/g	Table 2.02
F	= P_2O_5 loss factor = 1.0	CA-GREET default
G	= K_2O input = 193.6 g/tonne	CA-GREET default
H	= K_2O chemical cycle emissions = 0.66 g/g	Table 2.02
I	= K_2O loss factor = 1.0	CA-GREET default
J	= $CaCO_3$ input = 5,337.7 g/tonne	CA-GREET default
K	= $CaCO_3$ chemical cycle emissions = 0.60 g/g	Table 2.02
L	= $CaCO_3$ loss factor = 1.0	CA-GREET default
M	= Herbicide input = 26.9 g/tonne	CA-GREET default
N	= Herbicide chemical cycle emissions = 20.53 g/g	Table 2.02
O	= Herbicide loss factor = 1.0	CA-GREET default
P	= Pesticide input = 2.21 g/tonne	CA-GREET default
Q	= Pesticide chemical cycle emissions = 23.87 g/g	Table 2.02
R	= Pesticide loss factor = 1.0	CA-GREET default

Note: Loss Factor occurs during transportation due to evaporation, venting, etc.

Table 2.05 shows the emission results (g/tonne) for all GHG emissions for production of chemicals used in agriculture based on the calculations shown in Table 2.03. The CH_4 and N_2O emissions results shown in Table 2.05 are calculated with the same equations as CO_2 emission calculations, except that CO_2 emission factors are replaced by CH_4 and N_2O emission factors. Table 2.05 also shows the WTT emissions on an energy basis. Note that converting from g/tonne to g/mmBtu is shown in a note below Table 2.05. To convert from g/mmBtu to gCO_2e/mmBtu, non-CO_2 gasses are adjusted using their respective GWPs. For CO and VOC, see note below Table 1.08.

Table 2.05 Calculated GHG Emissions from Production of Agricultural Chemicals

GHG Type	Nitrogen (weighted average)	P_2O_5	K_2O	$CaCO_3$	Total Fert.	Herbicide (weighted average)	Pesticide	Total
CH_4 (g/tonne)	3.1	0.2	0.2	4.9		0.8	0.1	9.3
N_2O (g/tonne)	1.8	<0.01	<0.01	0.05		<0.01	<0.01	1.8
CO_2 (g/tonne)	2,971	118	127	3,210		552	53	6,743.4
GHGs (g/tonne)	3,579	124	133	3,344		574	55	7524.2
GHGs (g/mmBtu)	**1,951**	**68**	**72**	**1,822**	**3,913**	**313**	**30**	**4,256**
GHGs (g/MJ)	**1.85**	**0.06**	**0.07**	**1.73**	**3.70**	**0.30**	**0.03**	**4**

Note: To convert (g/tonne) to (g/mmBtu) = (g/tonne)/(Ethanol Yield (gal/tonne) * LHV of Anhydrous Ethanol (Btu/gal))*10^6. LHV of denatured ethanol is 76,330 Btu/gal and ethanol yield is assumed to be 24 gal/tonne.

Impact of soil N_2O emissions resulting from nitrogen fertilizer use on WTT GHG emissions

CA-GREET also calculates direct field and downstream N_2O emissions resulting from nitrogen fertilizer input. Table 2.06 below shows the two main inputs: fertilizer input (g/tonne) and percent conversion of N-input to N_2O. The table shows the N_2O emissions on an energy basis. CA-GREET v1.8b assumes 2.0% of fertilizer-N is ultimately converted to N_2O. The calculation also uses the mass ratio of N_2O to N_2 (44/28). Table 2.06 provides total GHG impacts from soil N_2O emissions.

Table 2.06 Inputs and Calculated Emissions for Soil NO and N_2O from Sugar Cane Farming

	Fertilizer N input (g/tonne)	Percent conversion to N_2O-N	N_2O formed/ N_2O-N (g/g)	N Converted (g/tonne)	N_2O or NO Emissions (g/tonne)	GHG Emissions (g/mmBtu)	GHG Emissions (gCO_{2e}/MJ)
N_2O	1,091.7	1.3%	44/28	14.5	22.7	3,691	**3.5**
						Total	**3.5**

Note: Soil N_2O emissions = (1,091.8 g N/tonne)(1.3%)(44 g N_2O/28 g N_2) = 22.7 g N_2O/tonne
N_2O Emissions: N in N_2O as % of N in N fertilizer and biomass: CA-GREET default of 1.3%

Effect of Lime ($CaCO_3$) added to soil on GHG emissions

CA-GREET assumes that all of the carbon in added lime is emitted as CO_2. This results in the following CO_2 emission: Soil CO_2 emissions = (5,337.7 g $CaCO_3$/tonne)*(44 g CO_2/100 g $CaCO_3$) = 2,349 g CO_2/tonne = 1,282 g CO_2/mmBtu = 1.2 g CO_2/MJ.

Tables 2.05, 2.06 and emissions from adding lime to soil are combined to provide the total GHG emissions and are detailed in Table 2.07.

Table 2.07 Total GHG Emissions from Agricultural Chemical Use for Sugar Cane Ethanol

Ethanol Pathway	**Fertilizers**	**Herbicide**	**Pesticide**	**Soil N_2O and NO**	**CO_2 from $CaCO_3$**	**Total (gCO_{2e}/MJ)**
GHGs (gCO_2e/MJ)	3.7	0.3	0.03	3.5	1.2	**8.7**

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SECTION 3. SUGAR CANE TRANSPORT

3.1 Energy for Sugar Cane Transportation

CA-GREET calculates the total energy needed (Btu/tonne) to transport sugar cane from the field to the ethanol production facility using heavy duty trucks. Table 3.01 below shows the sugar cane transportation distance and energy inputs. The calculations are based on heavy duty truck capacities of 17 tonnes. The default transport distance is 12 miles. CA-GREET calculates the diesel energy per tonne mile based cargo capacity of the truck and its fuel economy and assumes that truck trips carrying sugar cane and returning empty use the same energy. All values are CA-GREET default values.

Table 3.01 Sugar cane Transport Inputs

Transport Mode	Energy Intensity (Btu/tonne-mile)	Distance from Origin to Destination (mi)	Capacity (tonnes)	Fuel Consumption (mi/gal)	Energy Consumption of Truck (Btu/mi)	Shares of Diesel Used
Field to Ethanol Plant	1,511	12	17	5	25,690	100%

The calculated sugar cane transport energy on a Btu per tonne of sugar cane basis is shown below in Table 3.02 using the values in Table 3.01.

Table 3.02 Sugar Cane Transport Energy

Transport Mode	Energy Consumption (Btu/ton)
Field to Ethanol Plant	(12 miles one-way distance)*(1,511 Btu/ton-mile origin to destination + 1,511 Btu/ton-mile back-haul)*(Diesel share 100%)*(1+Diesel WTT Energy 0.157 Btu/Btu) /0.907 (tones/ton)= 47,200 Btu/ton
Total	47,200 (Btu/ton)
Total (anhydrous ethanol)	**25,722 (Btu/mmBtu)**

Note: To convert (Btu/ton) to (Btu/mmBtu) = (Btu/ton)/(0.907 tonnes/ton)/(Ethanol Yield (gal/tonne) * LHV of Anhydrous Ethanol (Btu/gal))*10^6. Diesel WTT energy is a CA-GREET calculation

3.2 GHG Calculations from Sugar Cane Transportation

GHG from sugar cane transportation are calculated from section 3.1 above with the same transportation mode, miles traveled, etc. as indicated by Table 3.01 above. Tables 3.03 below detail key assumptions of calculating GHG from sugar cane transportation. All values used in calculations are CA-GREET default values.

Table 3.03 Key Assumptions in Calculating GHG Emissions from Sugar Cane

Transport Mode	Energy Intensity (Btu/tonne -mile)	Distance from Origin to Destination (mi)	CO_2 Emission Factors of Truck (g/mi)	WTT Transport Diesel Emissions (g/mmBtu)	CO_2 Emission Factors of Diesel Combustion (g/mmBtu)
Sugar cane to plant by heavy duty truck	1,511	12	1999 (2,002)*	12,647	77809 (77,913)*

Note: *values in parenthesis are for the return trips.

Sugarcane transport emissions is first calculated on a g/ton basis and then finally converted to g/mmBtu and is shown in Table 3.04 below.

Table 3.04 Sugar Cane Transport - CO_2 Emissions in g/mmBtu

Transport Mode	CO_2 Emission (g/tonne)	CO_2 Emission (g/mmBtu)
Sugar Cane to Ethanol Plant by Heavy Duty Truck	3,701	2,017
Total (gCO_2/MJ anhydrous)		**2.0**

Note: Example formula to calculate CO_2 emission of Heavy Duty Truck above:
[((77,809 g/mmBtu)+(12,647 g/mmBtu)*(100% diesel used))*1,511 (Btu/ton-mile)+ ((77,913 g/mmBtu)+(12,647 g/mmBtu)*(100% diesel used))*1,511 Btu/ton-mile]*12 miles/0.907 ton/tonne/(10^6 mmBtu/Btu) = 3,710 g/tonne.
To convert (g/tonne) to (g/mmBtu) = (g/tonne)/(Ethanol Yield (gal/tonne) * LHV of Anhydrous Ethanol (Btu/gal))*10^6.

Similarly, CH_4, N_2O, VOC, and CO are calculated the same way (with different emission factors for each species) and shown in Table 3.05. Then all emissions are converted to CO_2 equivalent are also shown. The emissions are shown on an anhydrous ethanol basis.

Table 3.05 Sugar Cane Transport – Other GHG Emissions

Emissions Units	CH_4	N_2O	VOC	CO	CO_2	GHG (gCO_2e/MJ) anhydrous
(g/tonne)	4.078	0.088	1.493	6.553	3,701	
(g/mmBtu)	2.222	0.048	0.814	3.571	2,017	2,087
(g/MJ)	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**2.0**	**2.0**

SECTION 4. ETHANOL PRODUCTION

4.1 Ethanol Production

Like the sugar cane farming energy calculations, CA-GREET uses energy input values for sugar cane ethanol in Btu/gallon of anhydrous ethanol and uses fuel shares to allocate this direct energy input to process fuels. Part of the bagasse, the fiber material remaining after squeezing the juice of the plant, is currently burned at the mill to provide heat for distillation and electricity to run machinery at the plant. This allows ethanol plants to be energetically self-sufficient and even sell surplus electricity to utilities in some cases.

Note: A major portion of the energy used in sugarcane ethanol plant in Brazil is from bagasse (a fiber material of the sugar cane plant). Sucrose accounts for little more than 30% of the chemical energy stored in the mature plant; 35% is in the leaves and stem tips, which are left in the fields during harvest, and 35% are in the fibrous material (bagasse) left over from pressing.

Table 4.01 below shows the ethanol production fuel shares and energy inputs per gallon of anhydrous ethanol. The electricity input is represented in Btu/gal and added to the process fuel consumption to determine the fuel shares. Additional details are shown in Table 4.02.

Table 4.01 Sugar Cane Ethanol Fuel Shares and Primary Energy Inputs (Btu/gallon Anhydrous Ethanol)

Fuel Type	Fuel Share	Primary Energy Input (Btu/gallon)
Bagasse	99.65%	83,132
Residual Oil	0.35%	278
Total	**100%**	**83,409**

Note:
For Bagasse : 0.00642 dry tonne bagasse/gal ethanol *12,947,318 (Btu/tonne) LHV = 83,132 Btu/gal
For Residual oil: Oil use in sugarcane ethanol plants is from lubricant use. For CO2 calculation, it is assumed that 10% of lubricants is burned.

Tables 4.02 and 4.03 below show the CA-GREET equations, parameters and energy inputs for ethanol production. The Tables show the total input energy per mmBtu of anhydrous ethanol. For this document, ethanol transported from Brazil is considered as anhydrous which is subsequently blended to make denatured ethanol in CA.

Table 4.02 Sugar Cane Ethanol Formulas, Parameters and Total Energy

Fuel Type	Formula	Relevant Parameters	Total Energy
Bagasse	Dry tonne bagasse/gal ethanol *Bagasse LHV	Dry tonne bagasse/gal ethanol = 0.00642 tonne/gal Bagasse LHV = 12,947,318 Btu/tonne (CA-GREET default)	83,132 (Btu/gal)
Residual Oil	(Direct Residual Oil Input)*(1+(WTT Crude Oil Energy*Loss Factor + WTT of residual oil)/10^6)	Direct residual oil input = 251 Btu/gal WTT crude oil energy = 31,657 Btu/mmBtu Loss Factor = 1 WTT of residual oil = 74,001Btu/mmBtu	284 (Btu/gal)
Total energy input for ethanol production (Btu/gal)			83,415
Total energy input for ethanol production (Btu/mmBtu anhydrous ethanol)		**83,415 Btu/gal / (76,330 Btu/gal) *10^6*1.001 Btu/mmBtu**	**1,093,376**

Note: 1.001 is the loss factor by CA-GREET default

4.2 GHG Emissions from Ethanol Production

Sugar cane mill ethanol production in Brazil is assumed here to use dry bagasse as fuel for small boilers (99.65%). A relatively small amount of residual oil is also utilized in the process (about 0.35%). GHG from ethanol production by burning bagasse is calculated based on the assumptions in Table 4.03 below and the results are shown in Table 4.04. The CO_2 emissions shown in Table 4.03 include the direct boiler emissions (118,834 g/mmBtu) of bagasse; residual oil emissions include emissions from an industrial boiler (85,045 g/mmBtu) and direct WTT residual oil use in the boiler. CO_2 is credited to the ethanol production process resulting from biomass (bagasse) burning.

Table 4.03 Process Shares and Emission Factors (EF) of Ethanol Production

EtOH Production Equipment and Fuel Used	% Shares of Equip. Usage	CO_2 EF (g/mmBtu of fuel burned)	VOC EF	CO EF	CH_4 EF	N_2O EF	Assumed % of Fuels used at the EtOH Plant	Direct Energy Use (Btu/gal)
Small industrial boiler (10-100mmBtu/hr input) to burn bagasse	100%	118,834	5.34	76.8	31.6	4.2	99.65%	83,132
Residual oil industrial boiler	10%	85,045	0.9	15.8	3.2	0.4	0.35%	284

Table 4.04 Calculated GHG Emissions for Ethanol Production Using CO_2 Factors from Table 4.03

Calculations CO_2 in g/gal			**Conversion to g/mmBtu**	**Results g- CO_2e/mmBtu**
Bagasse burning in EtOH Production				
CO_2 Small industrial boiler	(Direct energy use of bagasse, Btu/gal) *(118,834 g/mmBtu)*1.001/10^6	9,881	9,881 g/gal/(76,330 Btu/gal)*10^6	129,519
CO_2 credit from bagasse burning	Bagasse burning = -(0.00642 tonne/gal *46.3% carbon content *2000lbs/tonne*454 g/lbs)*44/12	-9,897	-9,897 g/gal/(76,330 Btu/gal)*10^6	-129,732
EtOH Production				
CH_4		34.52		963.5
N_2O		4.6		1,395
Total GHG EtOH Production (g CO_2e/mmBtu) (after converting CO and VOC to GHG)				**2,021**
Residual Oil				
CO_2 of small industrial boiler	(Direct energy use of residual oil, Btu/gal) *10%* (85,045 g/mmBtu) /10^6	2.1	(2.1 g/gal) /(76,330 Btu/gal)*10^6	28.0
CO_2 for WTT of crude oil	(Direct energy use of residual oil, Btu/gal) *10%* (3,260 g/mmBtu)*1/10^6	0.1	(0.1 g/gal) /(76,330 Btu/gal)*10^6	1.1
CO_2 for WTT of residual oil	(Direct energy use of residual oil, Btu/gal) *10%* (5,607 g/mmBtu)/10^6	0.1	(0.16 g/gal) /(76,330 Btu/gal)*10^6	1.8
VOC	(Direct energy use of residual oil, Btu/gal)*(0.9 g/mmBtu) /10^6	<0.01	(<0.01 g/gal)/ (76,330 Btu/gal)*(3.1)*10^6	<0.01
CO	(Direct energy use of residual oil, Btu/gal) * (15.8 g/mmBtu) /10^6	<0.01	(<0.01 g/gal)/ (76,330 Btu/gal)*(1.6)*10^6	0.08
Total GHGs for Residual Oil (gCO_2e/mmBtu)				**31.0**
Total GHGs for ethanol production (gCO_2e/mmBtu)				**2,021**
Total GHGs for ethanol production (gCO_2e/MJ)				**1.9**

Note: Feed Loss Factor is assumed at 1. Small amounts of CH_4 and N_2O are negligible.
Carbon ratio of bagasse is 46.3% by CA-GREET default.
The 10% allocation of residual oil to ethanol is a CA-GREET default value. The 10% is to account for lubricating oil that is used not as a combustion source but is lost during the operation of the machinery involved in ethanol production. For this document, the lubricating oil is modeled as residual oil and its WTT emissions are used as a surrogate for lubricating oil.

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SECTION 5. ETHANOL TRANSPORT AND DISTRIBUTION

5.1 Energy for Ethanol Transportation and Distribution

For CA-GREET pathway, the default sugarcane ethanol transport and distribution (T&D) from Brazil to the U.S is divided as follows:

- From ethanol plant in Brazil to U.S ports:
    - Inside Brazil: 50% by rail (500 miles) and 50% by pipeline (500 miles)
    - From Brazilian ports to U.S ports by ocean tanker (7,416 miles)
- From U.S ports to distribution centers inside U.S
    - 100% by Heavy Duty Truck (100 miles)
- For distribution within U.S
    - 80% by truck (50 miles)
    - 20% directly from ports to blending terminals

Instead of calculating the WTT values on a per tonne basis as CA-GREET does for the sugar cane transport component, CA-GREET calculates WTT energy required per mmBtu of fuel (anhydrous ethanol) transported. Table 5.01 below shows the major inputs used in calculating transport energy and Table 5.02 presents the CA-GREET formulas used to calculate the ethanol transport energy for each transport mode.

Table 5.01 Inputs and Calculated Energy Requirements for Ethanol Transport to Bulk Terminals

Transport	**Mode**	**Energy Intensity** (Btu/tonne-mile)	**Distance from Origin to Destination** (mi)	**Capacity** (tonnes)	**Fuel Used** (mi/gal)	**Energy Used** (Btu/mi for truck) (Btu/hp hr for ship)	**Shares of Diesel Used**	**% Fuel Transported by Mode**
Brazil Plant to Brazil port	Pipeline	253	500	110	n/a	n/a	20%	50%
	Rail	370	500	n/a	n/a	n/a	100%	50%
Brazil port to U.S port	Ocean Tanker	32	7,416	150,000	19	4,620	100%	100%
		29	7,416	150,000	19	4,691	100%	100%
U.S port to distribution center inside U.S	Heavy Duty Truck	1,028	100	33	5	25,690	100%	100%
Distribution to blending terminal inside U.S	Heavy Duty Truck	1,028	50	33	5	25,690	100%	80%

Note: Pipeline use 20% diesel, 6% electricity, 24% natural gas, the remaining 50% is residual oil. Ocean tanker travel from origin and back has different energy consumption. For ethanol distributed in the U.S, 20% ethanol is directly transported to blending terminal by CA-GREET default.

Table 5.02 CA-GREET Calculations for Ethanol Transport Energy (Btu/mmBtu Anhydrous Ethanol) by Transport Mode

Transport Mode	CA-GREET Formula	Relevant Parameters	Btu/mmBtu
Transport Pipeline within Brazil	- 6% electricity use: (10^6/A)*B)/((g/lb)*(lb/tonne)*(C)*(D)*[6%*(H)*100%] = 440 - 20% diesel use: (10^6/A)*B)/((g/lb)*(lb/tonne)*(C)*(D)*[20%*100%*(1+(F)] = 1,260 - 50% residual oil: (10^6/A)*B)/((g/lb)*(lb/tonne)*(C)*(D)*[50%*100%*(1+(G)] = 3,010 - 24% NG Use: 10^6/A)*B)/((g/lb)*(lb/tonne)*(C)*(D)*[24%*100%*(1+(K)] = 1,402	A = Ethanol LHV = 76,330 Btu/gal B = Ethanol density = 2,988 g/gal C = Mi traveled = 500 D = Energy intensity = 253 (Btu/tonne-mile) E = %Diesel Share = 20% F = Diesel energy = 0.157 Btu/Btu G = Residual oil energy = 0.106 Btu/Btu H = Electricity Energy in Brazil = 1.347 Btu/Btu K= NG energy = 0.073 Btu/Btu	6,202
Transport Rail within Brazil	100% diesel use: 10^6/A*B/((g/lb)*(lb/tonne)*I*K*[E*(1+F)]	I = Mi traveled = 500 J = % Electricity share = 0% K = Rail energy intensity = 370 Btu/tonne-mile	9,414
Transport Ocean Tanker to U.S ports	10^6/A*B((g/lb)*(lb/tonne)*(L*(M+N)*100%(1+G)	L = Mi travel = 7,416 miles M = energy intensity from origin = 32 Btu/tonne-mile N = energy intensity from destination = 29 Btu/tonne-mile	21,992
Total EtOH Transportation used in Brazil = 50%*6202 + 50%*9414 + 21992 =			29,800
Transport Within U.S	10^6/A*B((g/lb)*(lb/tonne)*(O*(P+P)*100%(1+F)	O = Mi travel = 100 miles P = energy intensity = 1,028	10,459
Total EtOH Transportation			**40,259**
Distribution	10^6/A*B((g/lb)*(lb/tonne)*(Q*(P+P)*100%(1+F)*80%	Q = Mi traveled = 50 80% = shares of truck travel	4,183
T&D Total (Btu/mmBtu ethanol)			**44,442**

Note: The energy intensity for heavy duty trucks is multiplied by 2 to account for return trip.

5.2 GHG Calculations from Ethanol Transportation and Distribution

Similar to sugar cane T&D, ethanol T&D to bulk terminal is assumed in CA-GREET model by rail and pipeline inside Brazil, then ocean tanker from Brazilian ports to U.S ports, and finally from trucks to terminal within U.S. All the key assumptions are the same as sugar cane T&D's and are shown in Table 5.03. The values in this table do not reflect the mode shares.

Table 5.03. Key Assumptions in Calculating GHG Emissions from EtOH Transportation

Transport Mode	Transport Fuel	1-way Energy Intensity (Btu/tonne-mile)	Distance from Origin to Destination (mi)	WTT Fuel CO_2 Emissions of transportation fuels (g/mmBtu)	CO_2 Emission Factors of Diesel Combustion (g/mmBtu)
50% Rail	Diesel	370	500	12,647	77,623
50% Pipeline	Electricity	253	500	18,504	-
	Diesel			12,647	Turbine: 78,179 Reciprocating Engine: 77,337
	Residual Oil			8,867	Turbine: 85,061 Reciprocating Engine: 84,219
	Natural Gas			5,218	Turbine: 58,044 Reciprocating Engine: 56,013
100% Ocean Tanker	Residual Oil	32 (29)	7,416	8,867	84,102
100% Heavy Duty Truck	Diesel	1,713	100	12,647	77,809 (77,913)
80% Heavy Duty Truck	Diesel	1,713	30	12,647	77,809 (77,913)

Note: It is assumed that all locomotives use diesel. Values in parenthesis are for the return trips

The results are shown below in Table 5.04. The WTT emissions shown in the Table for each GHG species is calculated in the *T&D* tab of CA-GREET. The equation for CO_2 from rail is shown below and the calculations for the other transport modes and GHG gases are done similarly. VOC and CO emissions are not shown in Table 5.04, which contribute 8.7 g/mmBtu and 18.6 g/mmBtu (on a CO_2-equivalent basis), respectively. CA-GREET also includes 19.7 g/mmBtu VOC fugitive emissions (62 g/mmBtu CO_2-equivalent). Note that only one-way rail emissions are counted, whereas an extra term exists in the calculation for truck transport to account for the return truck trip; emissions from the return trip are assumed to be equal to emissions for the trip from the origin to destination.

Sample Calculation: Rail CO_2 emissions = (Ethanol density 2,988 g/gal)/(Ethanol LHV 76,330 Btu/gal)/[(454 g/lb)*(2,000 lbs/tonne)]*[(Diesel emission factor 77,623 g/Btu)+(Diesel WTT emissions 12,647 g/mmBtu)]*(370 Btu/tonne-mile)*(500 miles)*(50% mode share) = 360 g/mmBtu anhydrous ethanol (see Table 5.04).

Table 5.04 EtOH Transport and Distribution - CO_2e Emissions in g/mmBtu

Transport Mode	**CO_2 Emissions, Excluding VOC and CO (g/mmBtu)**	**CH_4 Emissions (g/mmBtu)**		**N_2O Emissions (g/mmBtu)**		**CO_2e (g/mmBtu)**
		actual	**as CO_2e**	**actual**	**as CO_2e**	
Transported by Pipeline	449	0.77	0.77*25=19	0.01	0.01*298=3	471
Transported by Rail	737	0.83	0.83*25=21	0.02	0.02*298=6	764
Transported by Ocean Tanker	1,856	1.97	1.97*25=49	0.04	0.04*298=12	1,917
	2,449*					3,152
Transported by Heavy Duty Truck	820	0.9	23	0.02	6	859
Distributed by Heavy Duty Truck	328	0.2	5	0.00	1	334
Total	3,597	3.9	98	0.1	24	4,345
Total (gCO_2e/MJ, anhydrous ethanol)						**4.1**

Note: *In Brazil, assumed 50% EtOH transportation travel by rail and 50% by truck

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APPENDIX B

ETHANOL PATHWAY INPUT VALUES (FROM BRAZIL SUGAR CANE)

Scenario: Ethanol made in Brazil from Brazil sugar cane and transported to alifornia.

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.1	
CO		1.6	
Sugar Cane Cultivation			
Fuel Use Shares			
Diesel		38.3%	
Gasoline		12.3%	
Natural Gas		21.5%	
LPG		18.8%	
Electricity		9%	
Cultivation Equipment Shares			
Diesel Farming Tractor		80%	
CO_2 Emission Factor	g/mmBtu	77,411	
Diesel Engine		20%	
CO_2 Emission Factor	g/mmBtu	77,349	
Gasoline Farming Tractor		80%	
CO_2 Emission Factor	g/mmBtu	75,645	
NG Engine		100%	
CO_2 Emission Factor	g/mmBtu	57,732	
LPG Commercial Boiler		100%	
CO_2 Emission Factor	g/mmBtu	68,036	
Sugar Cane Farming			
Sugar Cane energy use	Btu/tonne	41,592	
Sugar Cane harvest yield	lbs/tonne		
	tonne/acre		
Land Use from Sugar cane farming	g/tonne	195	
Sugar cane T&D			
Transported from Sugar Cane Field to Stack			
by medium truck	miles	10	2,199 Btu/mile-tonne Energy Intensity
fuel consumption	mi/gal	7.3	capacity 8 tonnes/trip
CO_2 emission factor	g/mi	1,369	
Transported from Stack to EtOH Plant			
by heavy duty diesel truck	miles	40	1,713 Btu/mile-tonne Energy Intensity
fuel consumption	mi/gal	5	capacity 15 tonnes/trip
CO_2 emission factor	g/mi	1,999	
Chemicals Inputs			
Nitrogen	g/tonne	1,092	
NH3			
Production Efficiency		82.4%	
Shares in Nitrogen Production		70.7%	
CO_2 Emission Factor	g/g	2.475	
Urea			

Parameters	Units	Values	Note
Production Efficiency		46.7%	
Shares in Nitrogen Production		21.1%	
Ammonium Nitrate			
Production Efficiency		35%	
Shares in Nitrogen Production		8%	
P_2O_5	g/tonne	149	
H_3PO_4			
Feedstock input	tonnes	n/a	
H_2SO_4			
Feedstock input	tonnes	2.674	
Phosphor Rock			
Feedstock input	tonnes	3.525	
K_2O	g/tonne	193.6	
$CaCO_3$	g/tonne	5,337.7	
Herbicide	g/tonne	8.1	
Pesticide	g/tonne	2.21	
CO_2 from $CaCO_3$ use	g/tonne	2,349	
Sugar Can Straw Burning Credit	g/tonne	-349,067	
EtOH Production			
Yield			
EtOH Yiel	gal/wet tonne	24	
Sugar Cane Straw Yield	Dry tonne/tonne sugar cane	0.19	CA-GREET Default
Bagasse Burning/gal EtOH Yield	Dry tonne/gal	0.00642	CA-GREET Default
Production			
Energy use for Sugar Cane Mill EtOH	Btu/gal	251	CA-GREET Default
From Residual Oil		0.3%	
Residual Oil Industrial Boiler	g/mmBtu	85,045	CA-GREET Default
From Bagasse burning		99.7%	
Bagasse –burned, small Industrial Boiler	g/mmBtu	118,834	CA-GREET Default
EtOH T&D			
Transported by rail – inside Brazil	miles	500	370 Btu/mile-tonne Energy Intensity
Transported by pipeline – inside Brazil	miles	500	253 Btu/mile-tonne Energy Intensity
Transported by Ocean Tanker to U.S.	miles	7,416	26 Btu/mile-tonne Energy Intensity from original
From U.S. back to Brazil	miles	7,416	39 Btu/mile-tonne Energy Intensity from destination
Transported by HHD truck to distribution center	miles	100	1,028 Btu/mile-tonne Energy Intensity both ways
Transpoted by HHD truck to blending terminal	Miles	50	1,028 Btu/mile-tonne Energy Intensity both ways
Fuels Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	CA-GREET Default
Residual Oil	140,353	3,752	CA-GREET Default
Conventional Diesel	128,450	3,167	CA-GREET Default
Conventional Gasoline	116,090	2,819	CA-GREET Default
CaRFG	111,289	2,828	CA-GREET Default
CARBOB	113,300	2,767	CA-GREET Default
Natural Gas	83,868	2,651	As liquid
EtOH	76,330	2,988	Anhydrous ethanol (neat)
EtOH	77,254	2,983	Denatured ethanol (2.5% by volume)
Bagasse (Btu/dry tonne)	12,947,318	n/a	CA-GREET Default

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[1] GREET Model: Argonne National Laboratory:
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

[2] Brazilian Average Electricity Mix: http://www.eia.doe.gov/emeu/cabs/Brazil/Full.html

[3] Intergovernmental Panel on Climate Change a scientific intergovernmental body tasked to evaluate the risk of climate change caused by human activity established by United Nations in 1988.

[4] "*IPCC Technical Report 2007*" – Table TS-2 – page 33
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf