PRELIMINARY DRAFT – FOR PUBLIC COMMENTS

California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Sorghum Ethanol

Stationary Source Division

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Version 2.0

Version 2.0 replaces version 1.0 and corrected several errors resulting in the higher estimated carbon intensity of sorghum to ethanol pathway.

DRAFT – FOR REVIEW

Preliminary draft version developed by Alternative Fuels Section of the California Air Resources Board for the Low Carbon Fuel Standard Methods 2A-2B Process

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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 Anhydrous Sorghum Ethanol

A Well-To-Tank (WTT) Life Cycle Analysis of a fuel (or fuel blendstock) pathway includes all steps from feedstock production to final finished product. For this analysis, the system boundary begins with the cultivation of sorghum and ends with the combustion of an ethanol/CARBOB blend in a motor vehicle. Finished ethanol is assumed to be shipped to California where it is blended with CARBOB. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. WTT and TTW analyses are combined to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)[1] model developed by Argonne National Laboratory was modified by Life Cycle Associates to create a GREET model called CA-GREET. For this analysis, the CA-GREET model was utilized to develop a WTW analysis of the conversion of sorghum into ethanol. The CA-GREET model and pathway documents published by ARB staff are available from the Low Carbon Fuel Standard (LCFS) website at www.arb.ca.gov/fuels/lcfs/lcfs.htm.

This document estimates the life cycle GHG emissions from the production of ethanol at Midwestern dry mill plants that use sorghum as a feedstock. These estimates are based on the energy use and chemical inputs required in the production process which are also estimated in this analysis. All values are calculated on an anhydrous ethanol basis (anhydrous ethanol is ethanol containing less than 1% water). The WTT components include sorghum farming, production and use of agricultural chemicals, feedstock transport, ethanol production, and transportation and distribution (T&D) of finished fuel. Figure 1 outlines the discrete components included in the sorghum ethanol system boundary. Not included in this pathway is the addition of a denaturant which is required before ethanol can be transported from a production facility to a blending station for use as a transportation fuel. Details of the blending and denaturant use are provided in a document for California Reformulated Gasoline, also available from the LCFS website.

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

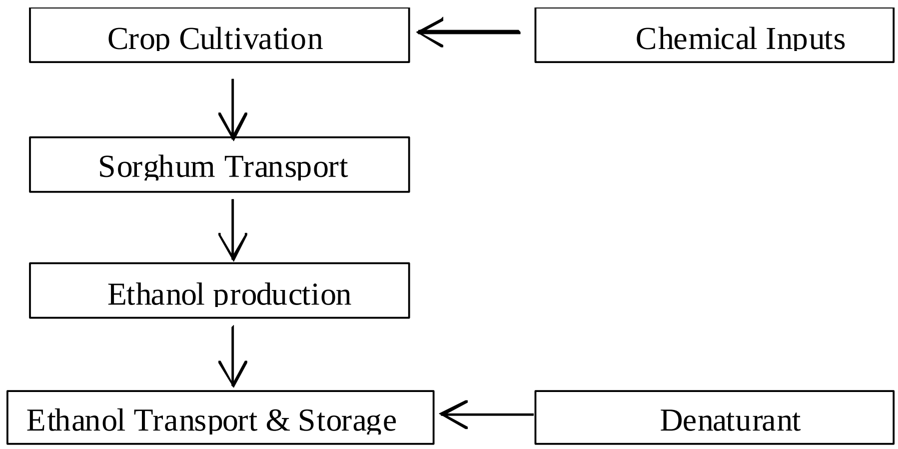


Figure 1. WTT Components for Ethanol Transported to California

Indirect land use change (ILUC) impacts have not been included in this document. ILUC inputs will be estimated separately and appended to the life cycle carbon intensity (CI) estimate from this analysis. Tailpipe emissions factors attributable to ethanol in CaRFG are not provided in this document. These will be made available in an addendum on the LCFS website. This addendum will contain carbon intensities for this analysis and will include impacts from land use change (if any) and contributions from tailpipe CH_4 and N_2O emissions.

The analysis that follows uses conventions and technical terms with specific meanings that are defined here:

- CA-GREET calculates energy consumption and GHG emissions recursively: calculated results are often used in subsequent calculation. For example, natural gas (NG) is used as a process fuel to recover natural gas. The total natural gas recovery energy consumption includes the direct natural gas consumption AND the energy associated with recovering that natural gas (which is the value being calculated).

- "Direct" energy use and GHG emissions refer to the energy released and the GHG emissions resulting from the use of fuel.

- "Upstream" energy use and GHG emissions refer to the energy required for, and the GHG emissions produced from, the production of fuel feedstocks and the production of fuel from those feedstocks.

- BTU/MMBTU is the energy input in BTU required to produce one million BTU of a finished (or intermediate) product. This unit is used consistently in CA-GREET for all energy calculations.

- gCO_2e/MJ is the unit used to express greenhouse gas emissions on a CO_2 equivalent per unit of energy (MJ) basis for a given fuel. International Panel on Climate Change (IPCC) coefficients are used to convert the non-CO_2 GHGs, nitrous oxide and methane, to a CO_2-equivalent value. For nitrous oxide and methane, these coefficients are 298 gCO_2-equivalents/gNO and 25 gCO_2-equivalents/gCH_4, respectively.

- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and CO_2-equivalent emissions are calculated using ratios that reflect the relative molecular weights of these GHGs.

- Process Efficiency throughout CA-GREET is defined as:

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

- Rounding of values has not been performed in several tables in this document. This allows stakeholders executing runs with the CA-GREET model to compare actual output values with the values appearing in those tables.

Table 1 summarizes the fuel cycle energy inputs by stage (BTU/MMBTU) and Table 2 summarizes the major GHG emission categories and intensities (gCO_2e/MJ) by stage. The Tables present energy and emission results relative to the energy content lower heating value (LHV) of anhydrous ethanol. The results are provided for dry mill plants producing 100% dry distiller's grain solubles (DDGS). Details of all energy inputs and GHG emissions are provided in Appendix A. A list of all inputs is provided in Appendix B.

Table 1. Energy Use Summary for Dry Mill, DDGS Sorghum Ethanol

Sorghum Ethanol Fuel Cycle Components		
	Energy* **(BTU/MMBTU)**	**% Energy Contribution**
Well-to-tank		
Sorghum Farming	30,864(148,656)	
Energy Inputs for Ag Chemicals	153,436	
Sorghum Transportation	28,814	
Ethanol Production	1,434,648	
Ethanol T&D	34,667	
Co-products	-154,548	
Total well-to-tank	1,527,881	**60.44%**
Total tank-to-wheel	1,000,000	**39.56%**
Tank-to-wheel		
Total well-to-wheel	**2,527,881**	**100%**

Table 2. GHG Emissions Summary for Dry Mill, DDGS Sorghum Ethanol

Sorghum Ethanol Fuel Cycle Components	GHG (gCO_2e/MJ)	GHG Contribution(%)
Well-to-tank		
Sorghum Farming	10.78	
Ag Chemicals Production and Use	23.91	
Sorghum Transportation	2.19	
Ethanol Production	38.27	
Ethanol T&D	2.63	
Co-Products	-11.54	
Total well-to-tank	**66.24**	**100%**
Carbon in fuel	0	0
Total Tank-to-wheel	**0**	**0**
Total well-to-wheel	**66.24**	**100%**

The ethanol production GHG emission values listed in Tables 1 and 2 are for plants producing 100% DDGS. Plants producing wet distiller's grain solubles (WDGS) will use less energy and produce less GHG emissions per unit of product. Table 3 lists GHG emissions for plants producing 100% DDGS or 100% WDGS.

Table 3. Total Well-to-Wheel GHG Emissions According to Co-product Produced

	100% DDGS	100% WDGS
Ethanol Production gCO_2e/MJ	**38.27**	**27.84**
Total well –to-wheel (gCO_2e/MJ)	**66.24**	**55.81**

Agricultural chemical production and use (**23.91 gCO_2e/MJ**) and ethanol production (**38.27 gCO_2e/MJ**) are the major contributors to GHG emissions for the sorghum ethanol pathway. Details of all energy inputs and GHG emissions for the dry mill, DDGS pathway are provided in Appendix A.

<u>SORGHUM FARMING</u>

Table 4 breaks down energy input by fuel type used in sorghum farming activities. Table 5 summarizes GHG emissions resulting from the energy use described in Table 4. Details of these calculations are provided in Appendix A.

Table 4. Total Energy Input by Fuel for Sorghum Cultivation

Fuel Type	**Total Energy**
Diesel fuel (BTU/bu)	11,667
Gasoline (BTU/bu)	6,187
NG (BTU/bu)	12,925
Electricity (BTU/bu)	65
Dry mill ethanol (BTU/bu, anhydrous basis)	**30,864**
Dry mill ethanol (BTU/MMBTU, anhydrous basis)	**148,656**

Table 5. GHG Emissions from Sorghum Farming

Sorghum Farming	
Emission Species	GHG
VOC (gCO_2e/MMBTU)	68.49
CO (gCO_2e/MMBTU)	696.66
CH_4 (gCO_2e/MMBTU)	935.61
N_2O (gCO_2e/MMBTU)	57.41
CO_2 (gCO_2e/MMBTU)	9,601
Total GHG (gCO_2e/MMBTU)	11,360
Total GHG (gCO_2e/MJ)	**10.78**

CHEMICAL INPUTS FOR AGRICULTURAL CHEMICALS

Table 6 summarizes the energy inputs required to produce the various chemicals used in the cultivation of sorghum. Table 7 provides details of the GHG emissions related to the production and use of these chemicals.

Table 6. Energy Inputs for the Production of Agricultural Chemicals Used in Sorghum Farming

Chemical Type	WTT Energy (BTU/MMBTU)
Nitrogen Fertilizer	96,813
Phosphate Fertilizer	6,834
Potash	736
Lime	14,315
Herbicide (average)	17,369
Insecticide (average)	17,369
Total	**153,436**

Table 7. GHG Emissions from Production and Use of Agricultural Chemicals

Fertilizers	Herbicide	Insecticide	$CaCO_3$	Urea	Soil N_2O	Total
7.47	1.29	1.50	0.72	0.66	12.27	**23.91**

SORGHUM TRANSPORT

Table 8 summarizes energy inputs required to transport sorghum from the farm to the ethanol production plant. The transport distances are assumed to be the same as those for the transport of Midwest corn from the farm to the ethanol plant. Table 9 provides GHG emissions related to the transportation of sorghum from the farm to the ethanol plant.

Table 8. Energy for Sorghum Transport

Transport Mode	Energy Consumption
Sorghum to Stack by Medium Duty Truck (BTU/bu)	1,454
Stack to Ethanol Plant by Heavy Duty Truck (BTU/bu)	4,528
Total (BTU/bu)	5,982
Total (dry mill) (BTU/MMBTU)	**28,814**

Table 9. GHG Emissions from Sorghum Transport

Transport Mode	GHG Emissions (gCO_2e/MJ)
Sorghum to Stack by Medium Duty Truck	0.54
Stack to Ethanol Plant by Heavy Duty Truck	1.68
Total	**2.19**

ETHANOL PRODUCTION

Table 10 summarizes the energy inputs required to produce ethanol from sorghum. Table 11 presents GHG emissions related to the production of ethanol from sorghum.

Table 10. Energy for Ethanol Production

Fuel Type	Energy
Natural Gas (BTU/gal)	34,598
Electricity (BTU/gal)	10,926
Energy from EtOH (BTU/gal)	63,983
Total energy input for ethanol production (BTU/gal)	109,507
Total energy input for ethanol production (BTU/MMBTU)	**1,434,648**

Table 11. GHG Emissions for Ethanol Production

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	38,471
VOC (gCO_2e/MMBTU)	14
CO (gCO_2e/MMBTU)	39
CH_4 (gCO_2e/MMBTU)	1,758
N_2O (gCO_2e/MMBTU)	100
Total GHGs (gCO_2e/MMBTU)	40,383
Total GHGs (gCO_2e/MJ)	**38.27**

ETHANOL TRANSPORT AND DISTRIBUTION

Transport from the ethanol plant to the bulk terminal or storage facility is accomplished primarily by rail with short truck delivery to the terminal or storage facility. Ethanol is transported by truck to a gasoline blending terminal where it is blended with gasoline to produce RFG. Table 12 presents energy inputs required for ethanol transport and distribution. Table 13 presents GHG emissions related to ethanol transport and distribution.

Table 12. Energy Use for Ethanol Transport and Distribution (T&D)

Transport Mode	BTU/MMBTU
Heavy Duty Truck	4,201
Rail	26,474
Total	29,415
Distribution by Truck	5,252
Total Energy for Transportation & Distribution	**34,667**

Table 13. GHG Emissions from Ethanol Transport and Distribution (T&D)

Transport Mode	CO_2 (g/MMBTU)	CH_4 (g/MMBTU)	N_2O (g/MMBTU)	CO_2e (g/MMBTU)	CO_2e (gCO_2e/MJ)
Rail	2,068	2.33	0.048	2,147	2.01
Medium Duty Truck	230	0.25	0.006	239	0.22
Heavy Duty Truck	411	0.45	0.01	427	0.40
Total	2709	3.03	.0064	2813	2.63

CO-PRODUCT CREDITS

The dry mill process generates DDGS which can replace corn as animal feed. Table 14 provides a summary of energy credits generated by assigning credits for DDGS. GHG emission credits corresponding to the energy credits are provided in Table 15 for the dry mill process. Details of the co-product analysis are provided in Appendix A.

Table 14. Sorghum Ethanol Co-Product Energy Credits

Ethanol Production Type	Displaced Product	Energy Credit (BTU/gal)	Energy Credit (BTU/MMBTU anhydrous)
Dry Mill	Feed corn	-6,230	-81,617
	Total co-product credit	**-6,230**	**-81,617**

Table15. Dry Mill Co-Product GHG Emission Credits

Displaced GHG	Feed corn
VOC (g/gal anhydrous)	-0.555
CO (g/gal anhydrous)	-5.007
CH_4 (g/gal anhydrous)	-0.575
N_2O (g/gal anhydrous)	-1.381
CO_2 (g/gal anhydrous)	-492
GHGs (g/gal anhydrous)	-927
GHG (gCO_2e/MMBTU anhydrous)	-12,145
GHG (g/CO_2e/MJ)	**-11.54**

APPENDIX A

SECTION 1. SORGHUM FARMING

1.1 Energy Use for Sorghum Farming

This section presents the direct farming energy inputs for sorghum cultivation. Instead of using energy efficiencies as it does for petroleum pathways, the CA-GREET model calculates energy input and GHG emissions based on the energy content of consumed fuel and chemicals used per quantity of product for sorghum farming. For the mix of fuel types shown in Table A-1, the total direct input energy for farming per bushel of sorghum is 27,257 BTU. The energy input is based on USDA data[2] for sorghum producing states in the Central Plains (Colorado, Nebraska, Kansas, Missouri, and South Dakota) and Southern Plains (Texas and Oklahoma). In CA-GREET we use the Midwest fuel shares shown in Table A-1.

Table A-1. Direct Energy Input by Fuel Type for Sorghum Farming

Fuel Type	Fuel Share (%)	Calculation	Direct Energy Input (BTU/bu)
Diesel fuel	36.7	0.367*27,257	10,006
Gasoline	18.8	0.188*27,257	5,132
Natural gas	44.4	0.444*27,257	12,097
Electricity	0.1	0.1*27,257	22
Total	**100**	**-**	**27,257**

[2] Economic Research Service, U.S. Department of Agriculture, February 1997, FBEI 97-1.

The energy inputs in Table A-1are direct inputs and are not the total energy required. CA-GREET accounts for the ‘upstream’ energy associated with fuels by using the formulas shown in Table A-2. Values for the coefficients used to calculate total energy in Table A-2 are shown in Table A-3. Table A-4 provides additional details for about the factors presented in Table A-3.

Table A-2. Calculating Total Energy Input by Fuel Type for Sorghum Farming

Fuel Type	Formula	Total Energy (BTU/bu)
Diesel fuel	$A*[1+((B*C+D)/10^6)]$	11,667
Gasoline	$E*[1+((B*F+G)/10^6)]$	6,187
Natural gas	$H*(1+I/10^6)$	12,925
Electricity	$J*(K+L)/10^6$	65
Total (dry mill, anhydrous basis)[a]	**-**	**30,864**
Total (dry mill, anhydrous basis)[a] (BTU/mmBTU)		**148,656**

[a] Anhydrous ethanol is “neat” fuel, typically 99.6% pure ethanol. The energy use for anhydrous ethanol is calculated by the following equation: Energy use = (Energy for sorghum farming (BTU/bu) / (Ethanol Yield (gal/bu) * LHV of Anhydrous Ethanol (BTU/gal)))*10^6. The LHV of anhydrous ethanol is 76,330 BTU/gal. Ethanol yields for dry mill sorghum ethanol are assumed to be 2.72 gal/bu in CA-GREET.

Table A-3. Values of Coefficients Used in Table A-2

Factor	Description	Value	Reference
A	Direct Diesel input	10,006 BTU/bu	calculated in Table A-1
B	Crude energy	40,630 BTU/MMBTU	CA-GREET calculated (cell B183, Petroleum Tab)
C	Diesel loss factor	1.0000	CA-GREET default value
D	Diesel energy	125,344 BTU/MMBTU	CA-GREET calculated (cell K183, Petroleum Tab)
E	Direct Gasoline input	5,132BTU/bu	calculated in Table A-1
F	Gasoline loss factor	1.0008	CA-GREET default
G	Gasoline energy	164,956 BTU/MMBTU	CA-GREET calculated (cell D183, Petroleum Tab)
H	Direct NG input	12,097BTU/bu	calculated in Table A-1
I	NG stationary energy	70,079 BTU/MMBTU	CA-GREET calculated (cell B124, NG Tab)
J	Direct electricity input	22 BTU/bu	calculated in Table A-1
K	Stationary electricity feedstock production	99,790 BTU/MMBTU	CA-GREET calculated (cell B84, Electric Tab)
L	Stationary electricity fuel consumption	2,877,173 BTU/MMBTU	CA-GREET calculated (cell C84, Electric Tab)

The factors listed in Table A-3 are derived from the energy contributions of all other fuels that were used to produce ethanol. Those fuels are shown in Table A-4 in two components: WTT energy (E) and Specific Energy (S) for each fuel type.

Table A-4. Energy Consumption in the WTT Process and Specific Energy

	WTT Energy (BTU input/MMBTU product)	**Specific Energy (BTU input/MMBTU product)**
Crude	$WTT_{Crude\ Recovery}$ = 44,499 (CA-GREET calculated)[a]	$S_{Crude\ Recovery} = 1 + WTT_{Crude\ Recovery} / 10^6 = 1.045$
B	$WTT_{Crude} = WTT_{Crude\ Recovery} * LF_{T\&D} + WTT_{Crude\ T\&D} + WTT_{Crude\ Storage}$ = 44,499 * 1.0001 + 11,059 = 55,560	$LF_{T\&D}$ = Loss Factor for Transport and Distribution = 1.0001 (CA-GREET default) $WTT_{Crude\ T\&D}$ = 11,059 (CA-GREET calculated) $WTT_{Crude\ Storage}$ = 0.0 (CA-GREET default)
D	WTT_{Diesel} = 124,812 (CA-GREET calculated)	$S_{Diesel} = 1 + (WTT_{Crude} * LF_{Diesel} + WTT_{Diesel}) / 10^6$ = 1.180 LF_{Diesel} = 1.0000 (CA-GREET default).
G	$WTT_{Gasoline}$= 164,227 (CA-GREET calculated)	$S_{Gasoline} = 1 + (WTT_{Crude} * LF_{Gasoline} + WTT_{Gasoline}) / 10^6$ = 1.220 $LF_{Gasoline}$ = 1.0008 (CA-GREET default)
I	$WTT_{NG} = (WTT_{NG\ Recovery} * LF_{Processing} + WTT_{NG\ Processing}) * LF_{T\&D} + WTT_{T\&D}$ = (31,250 * 1.001 + 32,196) * 1.001 + 6,499 = 69,664 (CA-GREET calculated)	$S_{NG} = 1 + WTT_{NG} / 10^6 = 1.070$ WTT_{NG} includes $WTT_{NG\ Recovery}$ = 31,207, $WTT_{NG\ Processing}$ = 31,862, and $WTT_{NG\ T\&D}$ = 6,499. (all CA-GREET calculated)
Electricity		$S_{Electricity} = (WTT_{Feedstock\ Production} + WTT_{Fuel\ Consumption}) / 10^6$ = 2.649
K	$WTT_{Feedstock\ Production}$ = 87,341 (CA-GREET calculated)	
L	$WTT_{Feedstock\ Consumption}$ = 2,561,534 (CA-GREET calculated)	

[a] $WTT_{CrudeRecovery}$: WTT energy for Crude Oil Recovery, or use of crude oil at the well, does not include T&D.

1.2 GHG Emissions from Sorghum 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 Global Warming Potentials (GWP) to calculate CO_2 equivalent emissions for methane and nitrous oxide. The IPCC GWP values for CH_4 and N_2O are given in Table A-5. CA-GREET uses a carbon ratio of 3.1 for volatile organic compounds (VOC) and a carbon ratio of 1.6 for carbon monoxide (CO) to calculate CO_2 equivalent emissions for these species. These carbon ratios are based on the complete oxidation of VOC and CO to CO_2 in the atmosphere. The GHG emissions resulting from fuel use in the ethanol production process are shown in Table A-6. All emission factors listed are CA-GREET default values.

Table A-5. Global Warming Potentials for Gases[a]

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

[a] Conversions from MMBTU to MJ have been calculated using the factor 1 MMBTU = 1055 MJ

Table A-6. CO_2 Emission Calculated – WTT of All Fuels

Fuel	WTT CO_2e Emissions (gCO_2e/MMBTU fuel output)	Specific Emissions (gCO_2e/MMBTU fuel output)
Crude	$E_{Crude} = E_{Crude\ Recovery} * LF_{T\&D} + E_{Crude\ T\&D} + E_{Crude\ Storage}$ + (VOC and CO conversion) = 4,310 * 1.0000 * 1.0000 + 885 + 34 = 5,230	$SE_{Crude\ Recovery} = 1 + EF_{Crude\ Rrecovery}$
Residual Oil (RO)	E_{RO} = 5,623	$SE_{RO} = 1 + (EF_{Crude} * LF_{Crude} + EF_{RO})$
Conventional Diesel	E_{Diesel} = 9,395	$SE_{Diesel} = 1 + (EF_{Crude} * L\ F_{Diesel} + EF_{Diesel})$
Conventional Gasoline	$E_{Gasoline}$ = 12,131	$SE_{Gasoline} = 1 + (EF\ Crude * LF_{Gasoline} + EF_{Gasoline})$
Natural Gas (NG)	$E_{NG} = (E_{NG\ Recovery} * LF_{Processing} + E_{NG\ Processing} + EF_{T\&D}) * LF_{T\&D} + E_{T\&D} + E_{Non\text{-}combustion}$ + (VOC and CO conversion) = 5,214	$SE_{NG} = 1 + EF_{NG}$
	$E_{NG\ Recovery}$ = 1,722, $E_{NG\ Processing}$ = 1,859, $E_{NG\ T\&D}$ = 352, $E_{NG\ non\text{-}combustion}$ = 1,237, $LF_{T\&D}$ = 1.0008	
Electricity	$E_{Feedstock} + E_{Fuel}$ = (6,980 + 213,458) = 220,437	$SE_{Electricity} = (EF_{efeedstock} + EF\ efuel)$

The greenhouse gas 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/bushel) and the combustion and upstream emissions for the energy input. The CA-GREET model calculates emissions for each fuel input by multiplying fuel input (BTU/bushel) by the total emission factors for combustion, crude production and fuel production. The electricity emissions are calculated by multiplying the electricity input (BTU/bushel) by the total (feedstock plus fuel) emission factor associated with the chosen electricity mix (from the Electricity Tab in CA-GREET). For this pathway, sorghum farming uses Midwest electricity. Table A-7 below shows formulas and calculated CO_2 emissions by fuel type for sorghum farming. The same method is used to calculate CO_2 equivalent emissions associated with releases of CH_4 and N_2O, but these calculations are not presented.. Table A-8 provides values for parameters used in the formulas in Table A-7.

Table A-7. CA-GREET Calculations for CO_2 Emissions from Sorghum Farming[a]

Fuel	Formula	CO_2 Emissions
Diesel	$[(A)*[(B)*(C) + (D)*(E)+(F)*(G)+(H)*(I)+(J)*(K)+(L)]]/10^6$	907 g/bu
Gasoline	$[(M)*[(N)+ (J)*(O)+(P)]]/10^6$	337 g/bu
Natural gas	$[(Q)*[(R)*(S) + (T)*(U)+(V)*(W)+(X)*(Y)+(Z)]]/10^6$	747g/bu
Electricity	$[(AA)*[(BB)+(CC)]]/10^6$	5 g/bu
Total	-	1,993 g/bu
Total (dry mill, anhydrous basis)	-	9,601 g/MMBTU

[a] The calculations for CH_4 and N_2O are analogous. Relevant parameters here are calculated values in CA-GREET, except for technology shares, which are direct inputs.
To convert emissions from (g/bu) to (g/MMBTU), multiply the emissions in (g/bu) by the following factor: 10^6 / [Ethanol Yield * LHV of Anhydrous Ethanol] where the LHV of Anhydrous Ethanol is 76,330 BTU/gal and the Ethanol Yield is assumed to be 2.72 gal/bu for dry mill ethanol.

Table A-8. Description and Values of Factors Used in Table A-7[a,b]

Fuel	Relevant Parameters*	Reference
A	= Direct Diesel input = 10,006 BTU/bushel (table A-3)	CA-GREET default
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 = 20%	CA-GREET default
E	= IC Engine CO_2 Emissions =77,349 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 = 80%	CA-GREET default
I	= Tractor CO_2 emissions = 77,204 g/MMBTU	CA-GREET default
J	= Crude production CO_2 emissions = 3,956 g/MMBTU	CA-GREET calculation
K	= Diesel loss factor = 1.0000	CA-GREET default
L	= Diesel production CO_2 emissions = 9,480 g/MMBTU	CA-GREET calculation
M	= Direct Gasoline input = 5,132 (table A-3)	CA-GREET default
N	= Farming tractor CO_2 emission factor = 49,494 g/MMBTU	CA-GREET default
O	= Gasoline loss factor = 1.0008	CA-GREET default
P	= Gasoline production CO_2 emissions = 12,243 g/MMBTU	CA-GREET Calculation
Q	= Direct NG input = 12,097 BTU/bushel (table A-3)	CA-GREET default
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 = 5,214 g/MMBTU	CA-GREET Calculation
AA	= Direct Electricity input = 22 BTU/bu (table A-3)	CA-GREET default
BB	= Electricity feedstock CO_2 emissions = 7,755 g/MMBTU	CA-GREET Calc

Fuel	Relevant Parameters*	Reference
CC	= Electricity fuel CO_2 emissions = 233,154 g/MMBTU	CA-GREET Calculation

[a] The calculations for CH_4 and N_2O are analogous.
[b] Parameters presented here are calculated in CA-GREET, except for fuel shares, which are direct inputs.

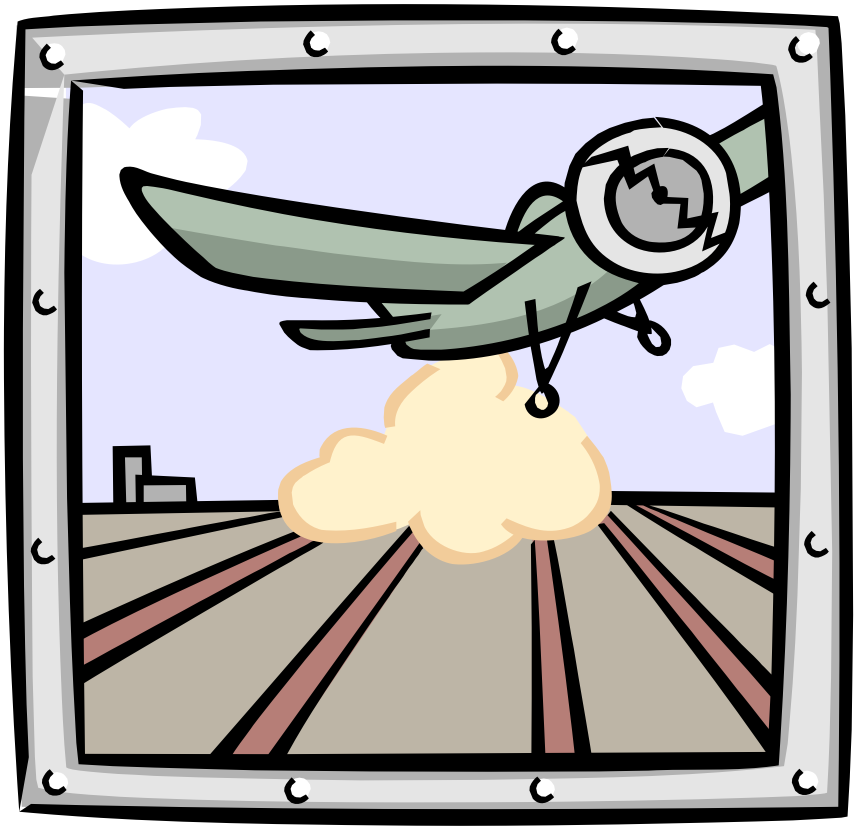
VOC, CO, CH_4, and N_2O emissions are calculated with the same formulas, energy input, and loss factors as CO_2 emissions calculations shown in Table A-7, but with different VOC, CO, CH_4, and N_2O emission factors. Table A-9 presents the calculated CO_2-equivalent GHG emissions from VOC, CO, CH_4, and N_2O in associated with sorghum farming. The sorghum farming emissions are shown on an energy (LHV anhydrous ethanol) basis for dry mill sorghum ethanol production.

Table A-9. GHG Emissions from Sorghum Farming

GHG Species	Emissions (g/bu)	Emissions (gCO_2e/MMBTU)[a]
VOC	4.56	68.49
CO	92.13	696.66
CH_4	7.77	935.61
N_2O	0.04	57.41
CO_2	1,993	9,601
Total GHG (gCO_2e/MMBTU)		10,849
Total GHG (gCO_2e/MJ)		**10.78**

[a] To convert CO_2 emissions from (g/bu) to (g/MMBTU), multiply the emissions in (g/bu) by the following factor:
10^6 / (Ethanol Yield * LHV of Anhydrous Ethanol) where the LHV of Anhydrous Ethanol is 76,330 BTU/gal and the Ethanol Yield is assumed to be 2.72 gal/bu for dry mill ethanol.
To convert VOC and CO emissions from (g/bu) to (gCO_2e/MMBTU), multiply the emissions in (g/bu) by the following factor:
(10^6 * Carbon Ratio) / (Ethanol Yield * LHV of Anhydrous Ethanol) where the Carbon Ratio is 3.1 for VOC and 1.6 for CO and other terms are the same as above.
To convert CH_4 and N_2O emissions from (g/bu) to (gCO_2e/MMBTU), multiply the emissions in (g/bu) by the following factor:
(10^6 * GWP) / (Ethanol Yield * LHV of Anhydrous Ethanol) where GWP is the appropriate Global Warming Potential from Table A.5 and other terms are the same as above.

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 to CA_GREET on a g-nutrient/bushel basis for fertilizer and a g-product/bushel basis for herbicide and pesticide. Table A-10 presents the USDA[3] chemical inputs per bushel of sorghum, the total energy required to produce the chemical product and the calculated upstream energy required to produce a bushel of sorghum using these inputs. Both chemical input values and product energy values are CA-GREET defaults.

[3] USDA, 2003, http://www.ers.usda.gov/data/arms/cropoverview.htm.

Table A-10 Sorghum Farming Chemical Input, Product Input Energy, and WTT Energy Per Bushel (BTU/bu) and BTU/MMBTU Anhydrous Ethanol

Chemical Type	Chemical Usage (g/bu)	Input Energy (BTU/g)	WTT Energy (BTU/bu)[a]	Dry Mill WTT Energy (BTU/MMBTU)[b]
Nitrogen fertilizer	433.1	46.41	20,100	96,813
Phosphate fertilizer	102.3	13.87	1,419	6,834
Potash	16.95	9.02	153	736
Lime	357.6	8.31	2,972	14,315
Herbicide (average)	13.1	275.27	3,606	17,369
Insecticide (average)	13.1	275.27	3,606	17,369
Total				**153,436**

[a] WTT Energy = (Chemical Input) * (Product Input Energy). Both are CA-GREET defaults.
[b] Dry Mill WTT Energy = (WTT Energy * 10^6) / (Ethanol Yield * LHV of Anhydrous Ethanol]) where the LHV of Anhydrous Ethanol is 76,330 BTU/gal and the Ethanol Yield is assumed to be 2.72 gal/bu for dry mill ethanol.

CA-GREET treats nitrogen fertilizer as a weighted average of ammonia (70.7%), urea (21.1%) and ammonium nitrate (8.2%) fertilizers. As Table A-10 shows, nitrogen fertilizer input accounts for more than half of total chemical energy input. The input energy for herbicide is a weighted average of four types of commonly used herbicides: atrazine (31.2% usage), metolachlor (28.1%), acetochlor (23.6%) and cyanazine (17.1%). For insecticide, the input energy represents the energy for a hypothetical average insecticide, rather than a calculated weighted average of energy input for specific insecticides. Because the energy required to produce nitrogen fertilizers, herbicides or insecticides does not vary significantly by category, the use of average energy inputs is deemed appropriate.

2.2 GHG Calculation for Production of Chemical Inputs

This calculation accounts for all upstream GHG emissions related to manufacturing agricultural chemical products. Upstream GHG emissions, which includes emissions from the production, processing and transport of product, are calculated in units of grams per ton of product in the Ag Inputs sheet of CA-GREET. These emissions are converted to units of grams per ton of nutrient by dividing by the ratio of nutrient to product. The final calculation step converts energy units to BTU and emissions units to g GHG/ g nutrient for fertilizer and g GHG/g product for herbicide and insecticide. Upstream GHG emissions for nitrogen fertilizer are modeled as a weighted average of emissions from three fertilizers. Average upstream GHG emissions for herbicide are calculated using a weighted average of emissions from four herbicides, and GHG emissions from insecticide production are based on a single insecticide. Table A-11 shows the upstream GHG emissions for agricultural chemicals. The formulas are complex and not shown here since agricultural inputs apply to large variety of crop cultivation and are not specific to sorghum cultivation.

Table A-11. Calculated GHG Emissions Associated with the Production of Agricultural Chemicals

GHG Species	Nitrogen fertilizer[a]	P_2O_5	K_2O	$CaCO_3$	Herbicide[b]	Pesticide
	g/g nutrient				g/g product	
CH_4	0.0021	0.0014	0.0009	0.0008	0.03	0.0307
N_2O	0.0016	0	0	0	0	0.0002
CO_2	2.3944	0.9864	0.6645	0.6062	20.84	24.1752
Total (gCO_2e/g)	**2.9**	**1.0**	**0.7**	**0.6**	**21.6**	**25.0**

[a] Upstream GHG emissions for nitrogen fertilizer are modeled as a weighted average of emissions from three nitrogen fertilizers.
[b] Upstream GHG emissions for herbicide are calculated using a weighted average of emissions from four herbicides.

In the CA-GREET model, the GHG emission factors of agricultural inputs are multiplied by chemical input factors (in the Ethanol sheet) and a loss factor (from the Ag Inputs sheet) to yield GHG emissions in g/bu of sorghum. Table A-12 shows the calculations for CO_2-equivalent emissions associated with the use of chemical inputs. The method for calculating CO_2-equivalent GHG emissions from VOC, CO, CH_4 and N_2O emissions during chemical production is the same as presented above and is not shown. Table A-13 presents values of the factors used in Table A-12.

Table A-12. Calculated CO_2 Emission Factors Associated with Production of Agricultural Chemicals

Chemical Product	Formula	CO_2e Emissions	
		g/bu	Dry Mill (g/MMBTU)
Nitrogen fertilizer	(A)*(B)*(C)	1,037	4,998
P_2O_5	(D)*(E)*(F)	101	486
K_2O	(G)*(H)*(I)	11	54
$CaCO_3$	(J)*(K)*(L)	217	1,045
Herbicide	(M)*(N)*(O)	273	1,314
Insecticide	(P)*(Q)*(R)	317	1,527
Total	-	1,956	9,424
Total (gCO_2e/MJ)			**8.93**

Table A-13. Description and Values of Factors Used in Table A-12

Chemical Product	Relevant Parameters	Reference
A	= Nitrogen input = 433.1 g/bu	CA-GREET default
B	= Nitrogen chemical cycle emissions = 2.3944 g/g	CA-GREET calculation
C	= Nitrogen loss factor = 1.0000[a]	CA-GREET default
D	= P_2O_5 input = 102.3 g/bu	CA-GREET default
E	= P_2O_5 chemical cycle emissions = 0.9864 g/g	CA-GREET calculation
F	= P_2O_5 loss factor = 1.0000 [a]	CA-GREET default
G	= K_2O input = 17.0 g/bu	CA-GREET default
H	= K_2O chemical cycle emissions = 0.6645 g/g	CA-GREET calculation
I	= K_2O loss factor = 1.0000 [a]	CA-GREET default
J	= $CaCO_3$ input = 357.6 g/bu	CA-GREET default
K	= $CaCO_3$ chemical cycle emissions = 0.6062 g/g	CA-GREET calculation
L	= $CaCO_3$ loss factor = 1.0000 [a]	CA-GREET default
M	= Herbicide input = 13.12 g/bu	CA-GREET default
N	= Herbicide chemical cycle emissions = 20.84 g/g	CA-GREET calculation
O	= Herbicide loss factor = 1.0 [a]	CA-GREET default
P	= Insecticide input = 13.12 g/bu	CA-GREET default
Q	= Insecticide chemical cycle emissions = 24.1752 g/g	CA-GREET calculation
R	= Insecticide loss factor = 1.0000	CA-GREET default

[a] Loss occurs during transportation due to evaporation, venting, etc.

Table A-14 shows the GHG emissions from the production of chemicals used in sorghum farming based on the calculations shown in Table A-12. The upstream GHG emissions associated with the release of VOC, CO, CH_4 and N_2O during chemical production that are shown in Table A-14 are calculated with the same formula as CO_2 emission calculations, except the CO_2 emission factor is replaced by an appropriate emission factor. Table A-14 also shows the WTT GHG emissions for dry mill sorghum ethanol.

Table A-14. Calculated GHG Emissions from Production of Agricultural Chemicals

GHG Species	Nitrogen fertilizer[a]	P_2O_5	K_2O	$CaCO_3$	Herbicide[b]	Pesticide	Total
	g/bu						
VOC	2.63	0.04	0.002	0.03	0.04	0.06	3
CO	2.55	0.12	0.01	0.20	0.20	0.29	3
CH_4	0.90	0.14	0.01	0.32	0.36	0.43	2
N_2O	0.70	0.001	0.00	0.00	0.00	0.00	1
CO_2	1,036	100	11	217	273	317	1,954
Total	1,279	104	11	225	282	328	2,229
Total GHG Dry Mill (g/MMBTU)[c]	**6,243**	**501**	**53**	**1,084**	**1,358**	**1,579**	**10,740**
Total GHG Dry Mill (gCO_2e/MJ)	**5.91**	**0.48**	**0.05**	**1.03**	**1.29**	**1.50**	**10.26**

[a] Upstream GHG emissions for nitrogen fertilizer are modeled as a weighted average of emissions from three nitrogen fertilizers.
[b] Upstream GHG emissions for herbicide are calculated using a weighted average of emissions from four herbicides.
[c] To convert from g/bu to g/MMBTU, multiply the emissions in g/bu by the following factor:
10^6 / (Ethanol Yield * LHV of Anhydrous Ethanol) where the LHV of Anhydrous Ethanol is 76,330 BTU/gal and the Ethanol Yield is assumed to be 2.72 gal/bu for dry mill ethanol.

CA-GREET was used to calculate direct field and downstream N_2O emissions resulting from nitrogen fertilizer use. There are two main inputs for this calculation: fertilizer input (g/bu) and percent conversion of nitrogen input to N_2O. The CA-GREET model assumes that 1.3% of fertilizer nitrogen is ultimately converted to N_2O. A mass ratio of N_2O to N_2 of 44/28 is also assumed; N_2 is used in this ratio because two fixed nitrogen atoms are required for every N_2O molecule formed. Table A-15 shows the inputs for calculating the N_2O emissions and the calculated GHG emissions in units of gCO_2e/MMBTU and gCO_2e/MJ anhydrous ethanol for the dry mill production of ethanol from sorghum. It can be seen from Table A-15 that soil N_2O is the dominant source of N_2O emissions and a significant component of net fuel cycle GHG emissions.

Table A-15. Inputs and Calculated Emissions for Soil N_2O from Sorghum Farming

Fertilizer nitrogen input (g/bu)[a]	Nitrogen conversion to N_2O (%)	Nitrogen mass ratio (g/g)	Nitrogen converted (g/bu)	Soil N_2O emissions (gN_2O/bu)[b]	GHG Emissions (gCO_2e/MMBTU)[c,d]	GHG Emissions (gCO_2e/MJ)
433.1 + 141.6	1.3	1.57	8.75	9.02	12,947	**12.27**

[a] Total Nitrogen = Fertilizer Nitrogen + Biomass Nitrogen = 433.1 g N/bu + 141.6 g N/bu
[b] Soil N_2O emissions = (433.1 + 8.3 g N/bu) * (0.013) * (1.57 g N_2O/g N_2) = 9.02 gN_2O/bu
[c] GHG Emissions (gCO_2e/bu) = 9.02 gN_2O/bu* 298 gCO_2e/gN_2O = 2,687 gCO_2e/ bu
[d] GHG Emissions (gCO_2e/MMBTU = 2,687 gCO_2e/ bu*(bu/ 2.72 gallons ethanol) * (gallons ethanol / 76,330 BTU) *10^6 = 12,947 gCO_2e/MMBTU)

The CA-GREET model assumes that all carbon in added lime is fully oxidized to CO_2 and that 357.6 g of lime is required for each bushel of sorghum produced. GHG emissions from lime application in sorghum farming are calculated as follows:

CO_2 emissions = (357.6 $gCaCO_3$/bu) * (44 g CO_2/100 g $CaCO_3$) = 157.3 gCO_2/bu

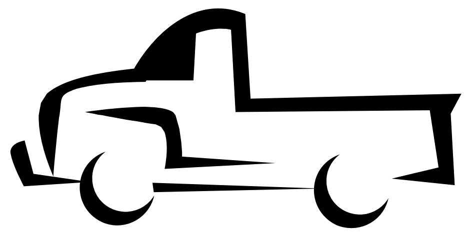
After converting units, the calculated CO_2 emissions of 157.3 gCO_2/bu can be shown to equal to 0.72 gCO_2e/MJ.

The total GHG emissions from agricultural chemical use in dry mill sorghum ethanol production are presented in Table A-16. Emissions from fertilizer, herbicide and pesticide usage from Table A-14 and emissions from soil N2O from Table A-15 are combined with CO_2 emissions associated with lime application to yield the total GHG emissions from agricultural chemical use in sorghum farming in Table A-16.

Table A-16. Total GHG Emissions from Agricultural Chemical Use in Dry Mill Sorghum Ethanol Production (g CO_2e/MJ)

	Fertilizer	**Herbicide**	**Pesticide**	**$CaCO_3$**	**Urea**	**Soil N_2O**	**Total**
GHG Emissions	**7.47**	**1.29**	**1.50**	**0.72**	**0.66**	**12.27**	**23.91**

SECTION 3. SORGHUM TRANSPORT



3.1 Energy for Sorghum Transportation

Transport of sorghum from the field to stack and from the stack to the ethanol plant is accomplished entirely by diesel trucks. To calculate the total energy needed to transport sorghum, the CA-GREET model assumes that medium duty trucks are used for transport from the field to the sorghum stack and that heavy duty trucks are used for transport from the stack to the fuel production facility using heavy duty trucks. The assumed sorghum transportation distance and energy inputs are provided in Table A-17; all values are CA-GREET defaults. Capacities of medium and heavy duty trucks are assumed to be 8 tons and 15 tons, respectively. The default transport distance from the field to the stack is assumed to be 10 miles and the distance from the stack to the ethanol plant is assumed to be 40 miles. CA-GREET calculates the diesel energy per ton-mile based on the cargo capacity of the truck and the truck's fuel economy. It is also assumed that empty trucks returning from delivery use the same energy as loaded trucks.

Table A-17. Assumptions for Calculating Energy Use for Sorghum Transport

Transport Mode	Energy intensity (BTU/ton-mile)	Distance (mi)	Truck capacity (tons)	Fuel economy (mi/gal)	Energy consumption of Truck (BTU/mi)	Diesel fuel fraction (%)
Field to stack by medium duty truck	2,199	10	8	7.3	17,596	100
Stack to plant by heavy duty truck	1,713	40	15	5	25,690	100

The calculated sorghum transport energy on a BTU per ton and BTU per bushel of sorghum basis is shown in Table A-18.

Table A-18. Calculated Sorghum Transport Energy

Transport Mode	Transport energy (BTU/ton)	Transport energy (BTU/bu)[a]
Field to stack by medium duty truck	51,924[b]	(51,924 BTU/ton)* (56 lbs/bu) / (2,000 lbs/ton) = 1,454
Stack to plant by heavy duty truck	161,727[c]	(161,727 BTU/ton) * (56 lbs/bu) / (2,000 lbs/ton) = 4,528
Total	213,651	5,982
Total	-	**28,814 BTU/MMBTU[d]**

[a] One bushel of sorghum weighs 56 pounds.
[b] For medium duty truck: (10 miles one-way distance) * (2,199 BTU/ton-mile origin to destination + 2,199 BTU/ton-mile return trip) * (Diesel share 100%) * (1 + Diesel WTT Energy 0.180 BTU/BTU) = 51,924 BTU/ton
[c] For heavy duty truck: (40 miles one-way distance) * (1,713 BTU/ton-mile origin to destination + 1,713 BTU/ton-mile return trip) * (Diesel share 100%) * (1 + Diesel WTT Energy 0.180 BTU/BTU) = 161,727 BTU/ton
[d] (5,982 BTU/bu) * (bu / 2.72 gal) * (gal / 76,330 BTU) *10^6 = 28,814 BTU/MMBTU

3.2 GHG Emissions Calculations from Sorghum Transportation

GHG emissions from sorghum transportation are calculated using the same assumptions about transportation mode, distance traveled, truck capacity, truck fuel economy and fuel type presented in Table A-17. Again, all values used in these calculations are CA-GREET default values. Table A-19 present the assumptions used to calculate GHG emissions from sorghum transport to dry mills and calculated GHG emissions from sorghum transport are presented in Table A-20.

Table A-19. Assumptions for Calculating GHG Emissions from Sorghum Transport

Transport mode	Energy Intensity (BTU/ton-mile)	Distance (mi)	CO_2 Emission Factors of Truck (g/mi)	CO_2 Emission Factors of Diesel used as transportation fuel (g/MMBTU)	CO_2 Emission Factors of Diesel Combustion (g/MMBTU)
Field to stack by medium duty truck	2,199	10	1,371	14,625	77,912 (77,890) [a]
Stack to plant by heavy duty truck	1,713	40	1,999 (2,002)[a]	14,625	77,809 (77,912) [a]

[a] Values in parentheses are for return trips.

Table A-20. Calculated CO_2 Emissions from Sorghum Transport

Transport Mode	CO_2 Emissions (g/ton)	CO_2 Emissions (g/bu)	CO_2 Emissions (g/MMBTU)
Field to stack by medium duty truck	4,018[a]	113	544[b]
Stack to plant by heavy duty truck	12,509	350	1,687
Total	16,527	462	2,231
Total (gCO_2/MJ)	**-**	**-**	**2.11**

[a]Example calculation of CO_2 emissions from medium duty truck:
Departing trip: [((77,912 gCO_2/MMBTU) + (14,625 gCO_2/MMBTU) * (100% diesel used)) * 2,199 (BTU/ton- mile)] *10 miles / (10^6 MMBTU/BTU) = 2035 gCO_2/ton
For Returning trip: [((77,890 g/MMBTU) + (14,625 g/MMBTU) * (100% diesel used)) * 2,199 (BTU/ton-mile)] *10 miles / (10^6 MMBTU/BTU) = 2009 gCO_2/ton
Medium duty truck total: =(2009 gCO_2/ton) + (2009 gCO_2/ton) = 4,018 gCO_2/ton
[b](4,018 g/ton / 2,000 lbs/ton) * (56 lbs/bushel) = 113 g/bushel
[(113 g/bushel) / ((2.72 gal/bushel) * (76,330 BTU/gal))] * (10^6 MMBTU/BTU) = 544 g/MMBTU

Emissions of CH_4, N_2O, VOC, and CO are calculated using the same methods and assumptions as the CO_2 emissions calculations, but with different emission factors for each species. These calculated non-CO_2 GHG emissions are shown in Table A-21. Table A-22 presents these emissions as CO_2-equivalent GHG emissions after the application of appropriate global warming potentials and carbon ratios.

Table A-21. Non-CO_2 GHG Emissions from Sorghum Transport

Transport Mode	CH_4 (g/MMBTU)	N_2O (g/MMBTU)	VOC (g/MMBTU)	CO (g/MMBTU)
Field to stack by medium duty truck	0.60	0.02	0.26	0.80
Stack to plant by heavy duty truck	1.87	0.04	0.71	3.18
Total	**2.47**	**0.06**	**0.97**	**3.97**

Table A-22. GHG Emissions from Sorghum Transport

Transport Mode	CH_4	N_2O	VOC and CO	CO_2	Total GHG	Total GHG
	($gCO_2e/MMBTU$)					($g\ CO_2e/MJ$)
Field to stack by medium duty truck	15.05	5.41	2.07	549	571	0.54
Stack to plant by heavy duty truck	46.78	12.47	7.20	1,709	1,775	1.68
Total	**61.75**	**17.87**	**9.27**	**2,231**	**2,320**	**2.19**

SECTION 4. ETHANOL PRODUCTION

4.1 Ethanol Production

As for the sorghum farming energy calculations, CA-GREET uses energy input values and fuel shares to calculate direct energy input for for dry mill sorghum ethanol in BTU/gallon of anhydrous ethanol and uses fuel shares to allocate this direct energy input to process fuels. For this document, the energy used and the GHG emissions emitted from the production of sorghum-derived ethanol are assumed to be equal to those for producing corn-derived ethanol[4]. For the fuels used in dry mill ethanol production, Table A-23 shows the share of each fuel used and the energy input per gallon of anhydrous ethanol product. For dry mill ethanol production, electricity consumption is 1.08 kWh/gal (3,670 BTU/gal). Dry mill ethanol plants that produce WDGS as the co-product require less energy and have lower GHG emissions per gallon of product.

Table A-23. Share of Fuel and Primary Energy Input by Fuel Type for Dry Mill Sorghum Ethanol Production

Fuel	Fuel share (%)	Primary energy input (BTU/gal)
Natural gas	89.8	32,330
Electricity	10.2	3,670
Total	**100**	**36,000**

CA-GREET uses the direct, primary energy inputs for ethanol production to calculate the total energy required to deliver each primary energy input. Table A-24 shows the CA-GREET formulas and parameters used to calculate energy usage by fuel type for dry mill sorghum ethanol production. The energy per gallon of ethanol produced for each fuel type is also presented in this table.

[4] See LCFS corn ethanol pathway document at www.arb.ca.gov/fuels/lcfs/022709lcfs_cornetoh.pdf

Table A-24. Calculation of Total Energy Input for Dry Mill Sorghum Ethanol Production

Fuel Type	Formula	Relevant Parameters	Energy Input (BTU/gal)
Natural gas	(Direct NG input)* (1+ (NG Stationary energy) / 10^6)	Direct NG input = 32,330 BTU/gal NG Stationary energy = 70,154 MMBTU	34,598
Electricity	(Direct electricity input)*((Stationary electricity feedstock stage energy)*(Stationary electricity fuel stage energy))/10^6	Direct electricity input = 3,670 BTU/gal Stationary electricity feedstock stage energy = 99,970 BTU/MMBTU Stationary electricity fuel stage energy = 2,887,173 BTU/MMBTU	10,926
Ethanol	76,330 * (1 / 0.524 - 1)	-	63,983
Total	-	-	109,507
Total (BTU/MMBTU)	-	-	**1,434,648**[a]

[a] (109,507 BTU/gal) / (76,330 BTU/gal) * 10^6 = 1,434,648 BTU/MMBTU

4.2 GHG Emissions from Ethanol Production

GHG emissions from dry mill ethanol production are calculated using the assumptions presented in Table A-25; the values in this table are CA-GREET defaults. In the Midwest, natural gas is commonly used as the fuel for both large and small boilers during dry mill ethanol production from sorghum. These boilers use 89.8% of the total plant energy. Electricity is used for all other the processes and contributes about 10.2% of the total input energy. The direct energy input for each fuel used is calculated by multiplying the total process input energy of 36,000 BTU/gal by the fractional fuel share.

Table A-25. Process Shares and GHG Emission Factors (EF)
For Dry Mill Sorghum Ethanol Production Equipment

Production Equipment and Fuel Used	Equipment usage (%)	CO_2 EF (g/MMBTU)	VOC EF	CO EF	CH_4 EF	Fuel share (%)	Energy input (BTU/gal)
Natural gas large industrial boiler (>100 MMBTU/hr)	50	58,198	1.557	16.419	1.1	89.8	32,330
Natural gas small industrial boiler (10-100 MMBTU/hr)	50	58,176	2.417	28.822	1.1		
Electricity at user sites (as Feedstock)		7,755				10.2	3,670
Electricity (as Fuels)		233,154					

Calculated GHG emissions from ethanol production are shown in Table A-26. These emissions include direct CO_2 emissions from natural gas combustion in boilers, natural gas WTT GHG emissions, and fuel cycle electricity GHG emissions assuming a Midwest electricity generation mix. All values are CA-GREET defaults unless explicitly indicated.

Table A-26. Calculated GHG Emissions for Dry Mill Sorghum Ethanol Production

	Calculations CO_2 in g/gal [a]		**Conversion to CO_2e g/MMBTU**	**Results**
Natural Gas				
large industrial boiler	32,330*50%*58,198/10^6 = 940.7	2,051	(2,051 g/gal) /(76,330 BTU/gal)*10^6 *1.001 = 26,892 (where 1.001 is loss factor of ethanol)	26,880
small industrial boiler	32,330*50%*58,176/10^6 = 940.4			
WTT NG	32,330*5,245/10^6 = 170.0			
Electricity				
As feedstock	3,670*7,794/10^6 = 29	884	(884 g/gal) /(76,330 BTU/gal)*10^6 *1.001 = 11,591	11,591
As fuel	3,670*233,154/10^6 = 856			
VOC[a]	(Direct Energy use of NG and electricity)* VOC EF	0.354	(0.354 g/gal)* (0.85/0.27)/77,254*10^6*1.001	14
CO[a]	(Direct Energy Use of NG and electricity)* CO EF	1.908	(1.908 g/gal)* (0.43/0.27)/77,254*10^6 *1.001	39
CH_4[a]	(Direct Energy Use of NG and electricity)* CH_4 EF	5.366	(5.366 g/gal)*25 /77,254*10^6	1,758
N_2O[a]	(Direct Energy Use of NG and electricity)* N_2O EF	0.026	(0.026 g/gal)*298 /77,254*10^6	100
Total GHGs (gCO_2e/MMBTU)				**40,375**
Total GHGs (gCO_2e/MJ)				**38.27**

[a] Similar calculations for these emissions are shown in this example:
VOC from NG boilers: 32,330*50%*(1.557+2.417+6.284) = 0.354 g/gal
Direct NG input: 32,330 (table 4.01)
% shares of each boiler: 50% (table 4.03)
VOC EF of two kinds of boilers (table 4.03): 1.557 and 2.417 g/MMBTU
VOC EF of NG as stationary fuel: 6.284 g/MMBTU

Ethanol plants that sell their DGS co-product in the wet form use less natural gas per gallon of ethanol produced than those that dry their DGS co-products using natural gas. The total natural gas energy required for ethanol production is 22,430 BTU/gal for wet DGS producing plants compared to 32,330 BTU/gal for dry DGS producing plants. Using this lower natural gas energy value and the same value as dry DGS producing plants for electricity usage (3,670 BTU/gal), total GHG emissions for plants producing 100% wet DGS are calculated to be 27.84 gCO_2e/MJ. GHG emissions from plants producing 100% dry DGS and 100% wet DGS are compared in Table A-27.

Table A-27. Calculated GHG Emissions from Ethanol Plants Producing 100% Dry DGS and 100% Wet DGS

Type of Ethanol Plant	GHG Emissions ($g\ CO_2e/MJ$)
100% Dry DGS	38.27
100% Wet DGS	27.84

Detailed descriptions of GHG emission facvtors associated with natural gas and coal use are shown in Tables A-28 through A-33.

Table A-28. Details of GHG Emission Factors for Natural Gas and Electricity Presented in Table A-25

Fuel	Formulas	Calculations	Result (g/MMBTU)
NG	(NG Density/(NG LHV) * (10^6 *Carbon ratio of NG) - (VOC Emission Factor of the large boiler * Carbon ratio of VOC) +(CO Emission Factor of the large boiler*Carbon Ratio of CO) +CH_4 Emission Factor of the large boiler * Carbon Ratio of CH_4)] / Carbon ration of CO_2	[((20.4 g/SCF) / (930 BTU/SCF)) * (10^6 * 0.724) – ((1.757 * 0.85) + (16.419 * 0.43) + (1.1 * 0.75))] / 0.27	58,198
	(NG Density / (NG LHV) */(10^6 *Carbon ratio of NG) -[(VOC Emission Factor of the small boiler * Carbon ratio of VOC) + (CO Emission Factor of the small boiler * Carbon Ratio of CO) + (CH_4 Emission Factor of the small boiler * Carbon Ratio of CH_4)] / Carbon ratio of CO_2	[((20.4 g/SCF) / (930 BTU/SCF)) * (10^6 * 0.724) – ((2.417 * 0.85) + (28.822 * 0.43) + (1.1 * 0.75))] / 0.27	58,176
Electricity	As Feedstock	(for details, see Table A-31)	7,755
	As Fuel (See Table A-32)	(for details, see Table A-34)	233,154

Table A-29. Detailed CO_2 Emissions from Feedstock Consumption Contributions for Electricity Shown in Tables A-29 and A-32

Feedstock As Fuel	Direct Input from fuels (UNITS)	Calculation	GHG Emissions (gCO_2/MMBTU)
Natural gas	935,557	935,557 * (D) / 10^6	4,820
Coal	1,646,650	1,646,650 * (E) / 10^6	2,404
Biomass (farmed trees)	195,568	195,568 * (F + G + H + I + J + K + L + M) / N * 100%	483
VOC conversion [a]	18.9	18.9 * 0.85 / 0.27	59
CO conversion [a]	17.7	17.7 * 0.23 / 0.27	28
Total	-	-	**7,755**

[a] See Table A-5 for VOC and CO conversion factors.

Table A-30. Calculations of Direct Energy Inputs of Fuels for Electricity Generation

Fuel	Fuel share (%)	Formula for Plant Efficiency[a]	Calculation	Direct Energy Input (BTU/MMBTU)
Natural gas	33.5	10^6 / (Residual NG Power Plant Efficiency) / (1-Transmission Loss) * (Fuel Share for Stationary Applications)	10^6 / 0.39 / (1 – 0.081) * 0.335	935,557
Coal	51.6	10^6 / (Residual Coal Power Plant Efficiency) / (1-Transmission Loss) * (Fuel Share for Stationary Applications)	10^6 / 0.341 / (1 - 0.081) * 0.516	1,646,650
Biomass	1.3	10^6 / (Residual Biomass Power Plant Efficiency) / (1-Transmission Loss) * (Fuel Share for Stationary Applications)	10^6 / 0.321 / (1 – 0.081) * 0.013	195,568
Others	9.1	10^6 / (Residual Power Plant Efficiency) / (1-Transmission Loss) * (Fuel Share for Stationary Applications)	10^6/100%/(1-8.1%)* 9.1%	99,397

[a] Process Efficiency in CA-GREET is defined as:
(Energy in output product) / [(Energy of input material + Energy consumed to produce product)]

Table A-31. Descriptions and Values of Factors Presented in Table A-29

Factor	Value	Description
A	5,445	CO_2 from crude consumed (g/MMBTU), see Table A-6)
B	1.0000	Loss factor of crude used, CA-GREET default)
C	5,678	CO_2 from residual oil consumed (g/MMBTU), see Table A-6
D	5,153	CO_2 from natural gas consumed for power generation (g/MMBTU), CA-GREET calculation
E	1,460	CO_2 from coal consumed for power generation (g/MMBTU), CA-GREET calculation
F	23,628	CO_2 from farmed trees (g/dry ton), CA-GREET calculation
G	1,957	CO_2 from nitrogen used for tree fertilizer (g/dry ton), CA-GREET calculation
H	193	CO_2 from P_2O_5 used for tree fertilizer (g/dry ton), CA-GREET calculation
I	232	CO_2 from K_2O used for tree fertilizer (g/dry ton) CA-GREET calculation
J	516	CO_2 from herbicide (g/dry ton), CA-GREET calculation
K	50	CO_2 from insecticide (g/dry ton), CA-GREET calculation
L	14,957	CO_2 from farmed tree transportation (g/dry ton), CA-GREET calculation
M	0	CO_2 from farmed tree farming land use change (g/dry ton)
N	1,681,100	Farmed tree LHV (BTU/ton)

Table A-32. Detailed CO_2 Emissions from Fuel Consumption Contributions for Electricity Generation Shown in Table A-29[a]

Power Plants Types	CA-GREET calculated CO_2 EF of Stationary Use	Power Plant Emissions (g/KWh) Calculations	Conversion to CO_2e	gCO_2/MMBTU
Biomass-Fired	(1,087 – 1,087) * 5.8% = 0	730/(1-8.1%) = 794	$(794*10^6/3412)$	232,824
NG-Fired	510*33.5% = 171			
Coal-Fired	1084*51.6%= 559.3			
Total	730			
VOC		0.02/(1-8.1%) = 0.02	$(0.02*10^6/3412)$ *0.85/0.27	14.7
CO		0.63/(1-8.1%) = 0.68	$(0.63*10^6/3412)$ *0.23/0.27	315.2
Total				**233,154**

[a]To calculate CO_2 emissions:
CO_2 emission from power plant + VOC and CO emissions conversion from power plant, where:
CO_2 from power plant = (Specific Power Plant Emission Factor)* % of generation mix/(1- % assumed loss in transmission)/10^6, then convert from g/kWh to gCO_2e/MMBTU by multiplying g/kWhr by $(10^6/3412)$.
Biomass has zero net CO_2 emissions because all CO_2 emissions are biogenic and climate neutral.

Table A-33. Power Plant Equipment Used in Table A-32

Description	Combustion Shares	Power Plant Energy Conversion Efficiencies by CA-GREET default	Emission Factor (gCO_2/MMBTU) by CA-GREET default	g/kWh
Natural Gas, large turbine[a]	20%	34.8%	58,198	114
Natural Gas, simple-cycle gas turbine[b]	36%	31.5%	58,179	227
Natural Gas, combined-cycle gas turbine[c]	44%	51.8%	58,171	172
Coal, utility Boiler[d]	100%	34.1%	137,356	697
Biomass, utility boiler[e]	100%	32.1%	102,224	1,087

[a] NG large turbine: $(20\%*58,198/34.8\%)/10^6*3412$ = 114 g/KWh
[b] NGsimple-cycle gas turbine: $(36\%*58,179/31.5\%)/10^6*3412$ = 227 g/KWh
[c] NGcombined-cycle gas turbine: $(44\%*58,171/51.8\%)/10^6*3412$ = 172 g/KWh
[d] Coal-fired Plant: $(100\%*137,356/34.1\%)/10^6*3412$ = 697 g/KWh
[e] Biomass Plant: $(100\%*102,224/32.1\%)/10^6*3412$ = 1,087 g/KWh

SECTION 5. ETHANOL TRANSPORT AND DISTRIBUTION

5.1 Energy for Ethanol Transportation and Distribution

Once ethanol is produced, it is transported to California where it is blended with gasoline to make reformulated gasoline (RFG). The RFG is then delivered to local fueling stations for use in passenger vehicles. Transport of ethanol from the production plant to a California blending terminal is accomplished primarily by rail, with some transport by heavy duty diesel truck. Transport of RFG from a blending terminal to a fueling station is accomplished by heavy duty diesel truck. Based on AB1007 analyses, the distance for ethanol transport by rail is typically 1,400 miles and the total distance for ethanol transport by heavy duty truck is 40 miles. The estimated distance for trucking RFG to a fueling station is 50 miles.

Instead of calculating the WTT values on a per ton basis as for the sorghum transport component, CA-GREET calculates WTT energy required per MMBTU of fuel (anhydrous ethanol) transported. Table A-34 below shows the major inputs used in calculating transport energy and Table A-35 presents the CA-GREET formulas used to calculate the ethanol transport energy for each transport mode.

Table A-34. Inputs and Calculated Fuel Cycle Energy Requirements for Ethanol Transport to Bulk Terminals

Transport Mode	Energy Intensity (BTU/ton-mile)	Distance (mi)	Truck Capacity (tons)	Fuel Economy (mi/gal)	Energy Used by Truck (BTU/mi)	Diesel share (%)	Fuel Transported (%)
Plant to blending terminal by heavy duty Truck	1,028	40	25	5.0	25,690	100	70
Plant to blending terminal by rail	370	1,400	n/a	n/a	n/a	100	100
Blending terminal to fueling station by heavy duty truck	1,028	50	25	5.0	25,690	100	100

Table A-35. CA-GREET Calculations for Ethanol Transport Energy (BTU/MMBTU Anhydrous Ethanol) by Transport Mode[a]

Transport Mode	CA-GREET Formula	Relevant Parameters	BTU/MMBTU
Transport By HDD Truck	[(10^6/76,330)*(2,988/(454*2000)))*(40*1028*2)*(100%)*(1+0.185) [b]	76,330 BTU/gal = Ethanol Low Heating Value 2,988 g/gal= Ethanol density 40 = Miles traveled for ethanol transportation Energy intensity = 2*(1,028 BTU/ton-mile) both ways 100% = %Diesel Share 0.185 BTU/BTU = Diesel energy	4,201
Transport Rail	[(10^6/76330)*(2,988/(454*2000)))*(1400*370)*(100%)*(1+0.185)	1,400= Miles traveled 370 BTU/ton-mile = rail energy intensity =	26,474
Transport Total	(70%)(4,201 BTU/MMBTU) +(100%)(26,474 BTU/MMBTU)	70% = % Fuel transported by truck 100% = % Fuel transported by rail	29,415
Distribution By HDD truck	[(10^6/76330)*(2,988/(454*2000)))*(50*1028*2)*(100%)*(1+0.185) [b]	50 = Miles traveled for ethanol distribution	5,252
T&D Total (BTU/MMBTU)			**34,667**

[a] Well-to-tank T&D energy on an anhydrous ethanol basis.
[b] Note that 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 sorghum T&D, ethanol T&D to bulk terminal is assumed in CA-GREET by rail cars and then to destination by truck. All the key assumptions are the same as for sorghum T&D and are shown in Table A-35.

Table A-36 Key Assumptions in Calculating GHG Emissions from EtOH Transportation [a]

Transport Mode	1-way Energy Intensity (BTU/ton-mile)	Distance from Origin to Destination (mi)	CO_2 Emission Factors (g/mi)	CO_2 Emission Factors of Diesel used as transportation fuel (g/MMBTU)	CO_2 Emission Factors of Diesel Combustion (g/MMBTU)
100% Rail	370	1,400		14,931	77,664
70% Heavy Duty Truck	1,713	40	1,999	14,931	77,809
100% Heavy Duty Truck	1,713	50	1,999	14,931	77,809

[a] Assumed all locomotives use diesel

The results are shown in Table A-36. 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. 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.

Table A-37. EtOH Transport - CO_2e Emissions in g/MMBTU

Transport Mode	CO_2 Emission (g/MMBTU anhydrous)	CH_4 to CO_2e (g/MMBTU anhydrous)		N_2O to CO_2e (g/MMBTU anhydrous)		CO_2e (g/MMBTU anhydrous)
Transported by Rail	2,068 [a]	2.33	58.3	0.048	14.5	2,141
Transported by Heavy Duty Truck	230	0.25	6.3	0.006	1.7	238
Distributed by Heavy Duty Truck	411	0.45	11.3	0.01	3.0	425
Total	2,709		76		19	2,804
VOC and CO Emissions (gCO_2e/MJ)						**0.01**
Total (gCO_2e/MJ)						**2.63**

[a] Rail CO_2 emissions = (Ethanol density 2,988 g/gal)/(Ethanol LHV 76,330 BTU/gal)/[(454 g/lb)*(2,000 lbs/ton)]*[(Diesel emission factor 77,664 g/BTU)+(Diesel WTT emissions 14,931 g/MMBTU)]*(370 BTU/ton-mile)*(miles transported) = 2,068 g/MMBTU ethanol.

SECTION 6. CO-PRODUCTS CREDITS

6.1 Energy Credit for Ethanol Co-Products

Ethanol production pathways result in a variety of co-products. In general, all fermentation approaches result in solids from spent yeast organisms and unfermentable solids. In addition, sorghum ethanol and other starch-based crops contain a significant oil and protein fraction, which are converted to a variety of food and animal feed products. The typical co-products for sorghum ethanol are shown below in Table A-38. Ethanol produced using the dry-milling process results in solid and liquid co-products—distillers grains and thin stillage—which are generally mixed together and sold as animal feed, most commonly without drying the mixture to produce WDGS.

Table A-38. Co-Products Generated for Sorghum Ethanol Production

Process	Feedstock	Co-Products
Dry mill	Sorghum	Wet or dry distillers grains and solubles (DGS)

The default CA-GREET configuration uses the displacement method to calculate energy and emission credits based on co-product displacement ratios. For this document, a 1 lb of DDGS (or WDGS) replacing 1 lb of feed corn has been used for dry mill co-product. This is to be consistent with an analysis being conducted for Land Use Change using the GTAP model from Purdue[5]. This treatment is different from the Argonne model which provides some credit to other products being replaced. Table A-39 shows the important parameters, formulas and values for dry mill co-products.

[5] https://www.gtap.agecon.purdue.edu/

Table A-39. CA-GREET Input Parameters, Formulas and Values for Dry Mill Sorghum Ethanol Co-Products [a]

Parameter	Formula	Parameters	Value	Reference
DGS yield (dry lbs/gal anhydrous EtOH)	(44.658-11.083*2.72)/2.72	44.658 lbs/bu EtOH 11.08 lbs/gal DGS 2.72 gal.bu EtOH yield	5.34 (CA-GREET default)	CA-GREET Default
Total feed corn displaced (lb/gal an. EtOH)[1]	(DGS yield lbs/gal)*(1.0)	DGS yield = 5.34 lbs/gal (CA-GREET default)	5.34	CA-GREET Default
Existing feed corn displacement (excludes new markets) (lb/gal an. EtOH)	(Total feed corn displaced lbs/gal)*(1-(% Co-products for new demand))	Total feed corn displaced = 5.34 lbs/gal % Co-products for new demand = 0.0%	-5.335	CA-GREET Calculation
N in urea displacement (lb/gal)	((CGM yield lbs/gal)*(CGM/nitrogen in urea displacement ratio lb/lb)+(CGF yield lbs/gal)*(CGF/nitrogen in urea displacement ratio lb/lb))*(1-(% Co-products for new demand))	CGM yield = 0.992 lbs/gal CGM/nitrogen in urea displacement ratio = 0.023 lb/lb CGF yield = 4.275 lbs/gal CGF/nitrogen in urea displacement ratio = 0.015 lb/lb % Co-products for new demand = 0%		-0.088
Soy Oil displacement (lb/gal)	(Sorghum Oil Yield lb/gal)	Sorghum oil yield = 0.794 lb/gal		-0.794

[a] All values and formula are CA-GREET default

The parameters in the previous table are used to calculate the energy and emission credits on a BTU/gal and g/gal basis, respectively. The co-product energy credit calculations are shown below in Table A-40.

Table A-40. Sorghum Ethanol Co-Product Energy Credit Calculations and Values

Ethanol Production	**Displaced Product**	**Formula**	**Relevant Parameters**	**Energy Credit (BTU/gal)**	**Energy Credit (BTU/MMBTU)**
Dry Mill	Feed corn	(Total farming energy BTU/bu)/(standard lbs/bushel)*(Feed corn displaced lb/gal)*(1-DGS used as fuel)	Total farming energy = 56,047 BTU/bu Standard lbs/bushel = 48 Feed corn displaced = -5.335 lb/gal	-6,230	-81,617
Total co-product credit for dry mill sorghum ethanol (BTU/MMBTU)					**-81,617**

6.2 Co-product Emissions Credits

Table A-41 presents the greenhouse gas emission credits based on the co-product yields and other inputs discussed in section 6.1. The calculation for the CO_2 credit associated with feed corn displaced by DDGS is shown below.

Dry Mill CO_2 example calculations:
Feed corn CO_2 credit = (Total farming emissions 4,422 g/bu)/(48 lbs/bu corn)*(Feed corn displaced -5.34 lb/gal) = -492 g/gal neat ethanol

Table A-41. Dry Mill Co-Product Emission Credits Based on Parameters Presented in Section 6.1

Displaced Product	**Dry Mill**
	Feed corn
VOC	-0.555
CO	-5.007
CH_4	-0.575
N_2O	-1.381
CO_2	-492
GHGs (g/gal anhydrous)	-927
GHG (gCO_2e/MMBTU anhydrous)	-12,145
GHG (g/CO_2e/MJ anhydrous)	**-11.54**

When using the Argonne approach for co-product credit (which credits feed corn, soybean meal and urea), the total WTW GHG value is lower by 3.4% for dry mill sorghum ethanol (for CaRFG blending at 3.5% oxygenate, the impact is 0.3%).

APPENDIX B

ETHANOL PATHWAY INPUT VALUES (FROM MIDWEST SORGHUM)

Ethanol made in Midwest from Midwest sorghum and transported to California for blending

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.1	
CO		1.6	
Sorghum Farming			
Fuel Use Shares			
Diesel		36.7%	
Gasoline		18.8%	
Natural Gas		44.4%	
LPG		0.0%	
Electricity		0.1%	
Cultivation Equipment Shares			
Diesel Farming Tractor		80%	
CO_2 Emission Factor	g/MMBTU	77,204	
Diesel Engine		20%	
CO_2 Emission Factor	g/MMBTU	77,349	
Gasoline Farming Tractor		80%	
CO_2 Emission Factor	g/MMBTU	49,494	
NG Engine		100%	
CO_2 Emission Factor	g/MMBTU	56,551	
LPG Commercial Boiler		100%	
CO_2 Emission Factor	g/MMBTU	68,036	
Sorghum Farming			
Sorghum energy use	BTU/bu	27,257	
Sorghum harvest	lbs/bu	56	Grain Sorghum
	bu/acre	69.2	
Sorghum T&D			
Transported from Sorghum Field to Stack			
by medium truck	miles	10	2,199 BTU/mile-ton Energy Intensity
fuel consumption	mi/gal	7.3	capacity 8 tons/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-ton Energy Intensity
fuel consumption	mi/gal	5	capacity 15 tons/trip
CO_2 emission factor	g/mi	1,999	
Chemicals Inputs			
Nitrogen	g/bu	433.1	
NH_3			
Production Efficiency		82.4%	
Shares in Nitrogen Production		70.7%	

Parameters	Units	Values	Note
CO_2 Emission Factor	g/g	2.475	
Urea			
Production Efficiency		46.7%	
Shares in Nitrogen Production		21.1%	
Ammonium Nitrate			
Production Efficiency		35%	
Shares in Nitrogen Production		8%	
P_2O_5	g/bu	102.3	
H_3PO_4			
Feedstock input	tons	n/a	
H_2SO_4			
Feedstock input	tons	2.674	
Phosphor Rock			
Feedstock input	tons	3.525	
K_2O	g/bu	16.95	
$CaCO_3$	g/bu	357.6	
Herbicide	g/bu	13.1	
Pesticide	g/bu	13.1	
CO_2 from $CaCO_3$ use	g/bu	157	
Co-Product Credit			
EtOH Production			
Dry mill (shares of total)		80%	
Dry EtOH Yield	gal/bu	2.72	
Energy use for Dry Mill EtOH (DDGS)	BTU/gal	36,000	
Energy use for Dry Mill EtOH (WDGS)	BTU/gal	26,102	
NG used for dry mill		92.7%	
Large NG Boiler	g/MMBTU	58,198	50% usage
Small NG Boiler	g/MMBTU	58,176	50% usage
Electricity used for dry mill		7.3%	
EtOH T&D			
Transported by rail	miles	1,400	370 BTU/mile-ton Energy Intensity
Transported by HHD truck	miles	40	1,028 BTU/mile-ton Energy Intensity both ways
Distributed by HHD truck	miles	50	1,028 BTU/mile-ton Energy Intensity both ways
Fuels Properties	**LHV (BTU/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	
Residual Oil	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,868	2,651	As liquid
EtOH	76,330	2,988	Anhydrous ethanol (neat)
EtOH	77,254	2,983	Denatured ethanol
Still Gas	128,590		

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