Draft

CA-GREET 3.0 Supplemental Document and Tables of Changes

Table of Contents

List of Tables

Changes made to the Argonne GREET1 2016 model to create a California version of the model called CA-GREET 3.0 for use in the Low Carbon Fuel Standard Program

The Low Carbon Fuel Standard program uses a well-to-wheel lifecycle analysis to calculate greenhouse gas emissions of all transportation fuels. The greenhouse house emissions are primarily calculated using a California modified version of Argonne National Laboratory's GREET.[1] This model is termed CA-GREET. The CA-GREET model uses additional inputs from the OPGEE[2] and GTAP/AEZ-EF[3] models to calculate emissions from crude oil and land use change respectively.

CARB staff used Argonne's GREET 1 2016 version and modified it to create a California specific version called CA-GREET 3.0. This document provides details of modifications made to the Argonne version of GREET. Although most of this document consists of a series of tables which compare changes made to Argonne's version of the model, it also includes details of fuel-related data which do not exist in Argonne's model. In addition, information is also included for comparison with a previous version of California model, CA-GREET 2.0.

The following bulleted list highlights critical modifications of GREET1 2016 in creating the California version CA-GREET 3.0. Complete details are provided in sections to follow.

- Unlike Tier 1 Calculators of the CA-GREET 2.0 model, where user inputs were used to the Argonne version specified in yellow cells of the T1 Calculator tab, CA-GREET 3.0 doesn't include this tab, but only the Region Selection tab. This tab allows user to select feedstock, the electricity mix, crude basket, and natural gas production parameters of the intended region.

- U.S. electricity resource mixes for various regions in the country are based on the U.S. EPA's, Emissions & Generation Resource Integrated Database (eGRID 2014), v1.0 (which describes 2014 electrical generation mixes). Staff has incorporated these resource mixes into the CA-GREET 3.0 model in addition to U.S average, User Defined, Brazilian, and Canadian electricity resource mixes.

- Tailpipe emission factors from the use of California Reformulated Gasoline (CaRFG) and ultra-low sulfur diesel (ULSD) are derived from 2010 California's Greenhouse Gas Inventory[6] and the mobile source emission inventory from EMFAC2014[7].

1 GREET refers to Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
2 OPGEE refers to the Oil Production Greenhouse Gas Estimator model.
3 GTAP/AEZ-EF refers to the Global Trade Analysis Project and Agro-Ecological Zone Emission Factor, both models together used to calculate land use change emissions for crop-derived biofuels.

- Staff added used cooking oil (UCO) and Corn Oil as pathway feedstocks for biodiesel and renewable diesel.

- Staff added cellulosic ethanol from corn fiber using Edeniq's[4] process.

- The baseline year of the LCFS program continues to be 2010 as specified in the LCFS regulation. In this version of CA-GREET, staff used outputs from the Oil Production Greenhouse Gas Emissions Estimator Version 2.0 (OPGEE)[5] for calculating the carbon intensity (CI) of crude oil used in California refineries in 2010. Refinery efficiencies and carbon intensities for CARBOB and ULSD are calculated from Argonne's data for California refineries.

- The regasification-processing step for liquefied natural gas (LNG) to compressed natural gas (CNG) pathway in the previous CA-GREET 2.0 model is eliminated for LNG produced in the U.S. LNG is gasified to CNG at the stations by utilizing the change of temperature from sub-cold (about -270ºF) to ambient temperature. However, the final compression to CNG is accounted in the model.

- Staff used the 2006 IPCC GHG Inventory Guide[24] Tier 1 default emission factors for N in N_2O as a % of N in N-fertilizer and biomass (crop residues). The EFs are determined using Equations 11.1, 11.6, and Table 11.3 from IPCC[24] resulting in a total (direct + indirect) EF of 1.325% for N-fertilizer, and 1.225% for crop residues. GREET1 2016 assumes 1.220% for Brazilian sugarcane and 1.225% for all other biomass-based feedstocks for N in N_2O as a % of N in N-fertilizer and biomass. All the feedstocks listed above apply the respective decomposition values for nitrogenous fertilizer as stated above.

Section 1: Tailpipe Emission Factors

a. Tailpipe Emission Factors for Combustion of CaRFG and ULSD:

   Tailpipe emission factors for California specific baseline fuels are not available in GREET 1 2016 and these factors are shown in Table 1.

   i. Because 2010 is the baseline of the California LCFS, staff continue to use emission factors derived from the 2010 data in California's Greenhouse

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[4] https://www.edeniq.com/products/

[5] El-Houjeiri, H.M., Vafi, K., Duffy, J., McNally, S., and A.R. Brandt, Oil Production Greenhouse Gas Emissions Estimator (OPGEE) Model Version 1.1 Draft D, October 1, 2014.

Gas Inventory[6] and the mobile source emission inventory, EMFAC2010[7] to calculate emission factors for CaRFG and ULSD.

ii. The tailpipe CO_2 emission factor for CaRFG is calculated by converting the carbon-content of CARBOB to CO_2, and subtracting the carbon emitted as CH_4 (Petroleum Tab, Cell E309). This is the same approach used in CA-GREET 2.0.

iii. The tailpipe CO_2 EF for ULSD is similarly corrected for carbon emitted as methane. This is the same approach used in CA-GREET 2.0.

Table 1. Tailpipe Emission Factors from Combustion of CaRFG and ULSD

<table>
<tr><th>Parameter</th><th>CA-GREET 2.0</th><th>GREET1 2016</th><th>CA-GREET 3.0</th></tr>
<tr><td>CARBOB (or CaRFG)</td><td>CARBOB Results Tab, Cells: F20:F24
<table>
<tr><th>Emission</th><th>g/MJ</th></tr>
<tr><td>CH4</td><td>0.14</td></tr>
<tr><td>N2O</td><td>0.91</td></tr>
<tr><td>CO2</td><td>72.89</td></tr>
<tr><td>CO2e</td><td>73.71</td></tr>
</table></td><td>Not included</td><td>Petroleum Tab, Cells E305:E311
<table>
<tr><th>Emission</th><th>g/MJ</th></tr>
<tr><td>CH4</td><td>0.14[6]</td></tr>
<tr><td>N2O</td><td>0.91[6]</td></tr>
<tr><td>CO2</td><td>72.89</td></tr>
<tr><td>CO2e</td><td>73.94</td></tr>
</table></td></tr>
<tr><td>ULSD</td><td>These values can be found in the CARB ULSD Pathway Document[8]
<table>
<tr><th>Emission</th><th>g/MJ</th></tr>
<tr><td>CH4</td><td>0.03</td></tr>
<tr><td>N2O</td><td>0.72</td></tr>
<tr><td>CO2</td><td>74.10</td></tr>
<tr><td>CO2e</td><td>74.86</td></tr>
</table></td><td>Not included</td><td>Petroleum Tab, Cells O305:P311
<table>
<tr><th>Emission</th><th>g/MJ</th></tr>
<tr><td>CH4</td><td>0.03[6]</td></tr>
<tr><td>N2O</td><td>0.72[6]</td></tr>
<tr><td>CO2</td><td>74.94</td></tr>
<tr><td>CO2e</td><td>75.70</td></tr>
</table></td></tr>
</table>

b. Tailpipe Emission Factors for Combustion of CNG and LNG

The emission factors for combustion of natural gas (CNG and LNG) in vehicles in CA-GREET 3.0 uses the same calculation methodology as CA-GREET2.0. The CO_2 emissions presented in Table 2 from fuel combustion is calculated based on the carbon

[6] California Environmental Protection Agency, Air Resources Board, "2014 Edition of California's 2000-2012 Greenhouse Gas Emissions Inventory Technical Support Document, (May, 2014), http://www.arb.ca.gov/cc/inventory/doc/methods_00-12/ghg_inventory_00-12_technical_support_document.pdf

[7] California Environmental Protection Agency, Air Resources Board, EMFAC2011 and EMFAC2014. http://www.arb.ca.gov/msei/categories.htm

[8] California Air Resources Board, "Detailed California-Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) from Average Crude Refined in California Version 2.1", 2009. http://www.arb.ca.gov/fuels/lcfs/022709lcfs_ulsd.pdf

content of the fuel (assuming complete oxidation of VOC and CO to CO_2). Carbon emitted as CH_4 is subtracted from this calculation; CH_4 is estimated and reported separately and discussed in section below Table 2.

Table 2. Tailpipe Carbon Dioxide Emissions for CNG and LNG Vehicles

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
CNG Tailpipe CO_2 Calculated from carbon content of Natural Gas (see Fuel Specs tab)	72.4% gC/gNG * 22.0 gNG/ft^3 * 44/12 gCO$_2$/gC / 983 Btu/ft^3 * 10^6 Btu/MMBtu = 58,853.58 gCO$_2$/MMBtu Correction for C as CH_4: 58,853.58 – 203.31*(44/16)/1055.06 = **55.78 gCO$_2$/MJ** NG Tab, Cell B119:C123	22.0 g/ft^3 / 983 Btu/ft^3 * 4,528 Btu/mile * 72.4% gC/gNG / 0.27 C ratio in CO2 = **264 g/mi** (corrected for C as CH_4 gCO$_2$/MJ) Vehicles Tab, Cell F79	72.4% gC/gNG * 22.0 gNG/ft^3 * 44/12 gCO$_2$/gC / 983 Btu/ft^3 * 10^6 Btu/MMBtu = 58,853.58 gCO$_2$/MMBtu Correction for C as CH_4: 58,853.58 – 203.31*(44/16)/1055.06 = **55.78 gCO$_2$/MJ** NG Tab, Cell B133:C134
LNG Tailpipe CO_2 Calculated from carbon content of Natural Gas (see Fuel Specs tab)	75.0% gC/gLNG * 1,621 gLNG/gal * 44/12 gCO$_2$/gC / 74,720 Btu/gal * 10^6 Btu/MMBtu = 59,089.51 gCO$_2$/MMBtu (correction for C as CH_4: 59,089.51 – 207.23*44/16 /1055.06 = **56.01 gCO$_2$/MJ** NG Tab, Cell D119:E123	22.0 g/ft^3 / 983 Btu/ft^3 * 5,047 Btu/mile * 72.4% gC/gNG / 0.27 C ratio in CO2 = **295 g/mi** (correction for C as CH_4 gCO$_2$/MJ) Vehicles Tab, Cell G71	75.0% gC/gLNG * 1,621 gLNG/gal * 44/12 gCO$_2$/gC / 74,720 Btu/gal * 10^6 Btu/MMBtu = 59,089.51 gCO$_2$/MMBtu (correction for C as CH_4: 59,089.51 – 207.23*44/16 /1055.06 = **56.01 gCO$_2$/MJ** NG Tab, Cell D133:E134

c. Methane and Nitrous Oxide Emissions from CNG and LNG for LDVs and MDVs

Methane and nitrous oxide emissions from alternative fuel vehicles are estimated using scale factors to adjust the fuel economy and emission factors of comparable gasoline and diesel-fueled vehicles, a method utilized by Argonne National Labs, EPA[9] and Lipman and Delucchi (2002)[10]. The general formula used is given in

[9] United States Environmental Protection Agency, "Climate Leaders Greenhouse Gas Inventory Protocol Core Module Guidance: Direct Emissions from Mobile Combustion Sources", EPA430-K-08-004, May 2008. http://www.epa.gov/climateleadership/documents/resources/mobilesource_guidance.pdf

[10] Lipman, Timothy E., and Mark A. Delucchi. "Emissions of nitrous oxide and methane from conventional and alternative fuel motor vehicles." *Climatic Change* 53, no. 4 (2002): 477-516. http://rael.berkeley.edu/sites/default/files/very-old-site/Climatic_Change.pdf

Equation 1; letters A through E in bold denote variables referred to in subsequent tables.

Equation 1. General Formula for Tailpipe Emission Factor Calculation

$$\left(\boldsymbol{A}\ \textit{Species Emission Factor}\ \frac{\text{g species}}{\text{mi}} \times \mathbf{B}\ \textit{NG Vehicle Scale Factor}\ \%\right) \times \left(\boldsymbol{C}\ \textit{Baseline Fuel Economy}\ \frac{\text{mi}}{\text{gal}} \times \mathbf{D}\ \textit{NG Vehicle Scale Factor}\ \%\right)$$

$$\times\ \mathbf{E}\ \textit{GGE (or DGE)}\ \frac{gal}{\text{Btu}} \times 10^6\ \frac{\text{Btu}}{\text{MMBtu}} = \boldsymbol{F}\ \textit{Species Emission Factor}\ \frac{\text{g Species}}{\text{MMBtu}}$$

Scale factors for fuel economy are provided relative to gasoline for all light and medium duty vehicles in Table 3. Tables 4 and 5 provide additional details of calculations for LDVs and MDVs which use NG as a fuel. The lower heating value of U.S. Gasoline as given in the GREET Fuel Specs tab (112,194 Btu/gal) is used to convert fuel economy to a fuel throughput basis.

Table 3. NG Vehicle Fuel Economy and Scale Factors by Vehicle Class for Light to Medium Duty Vehicles

Light to Medium Duty Vehicles (relative to gasoline baseline vehicle)	**Baseline Fuel Economy** Equation 1 **C)**	**Fuel Economy Scale Factor**[11,12] Equation 1 **D)**	**Source**
Class 2b Heavy-duty pickup trucks and vans	17.20	95%	ANL HDV, 2015.
Class 2a Light Duty Trucks (LDT2)	16.43	95%	LDT2_TS tab, cells C16, C156, and C173
Light Duty Trucks (LDT1)	20.06	95%	LDT1_TS tab, cells C16, C156, and C173

[11] Personal email communication with Argonne National Laboratory, Systems Assessment Group, Energy Systems Division. May 15, 2015. PDF saved as Cai(ANL)Alexiades(ARB)_PC_GREET1_2014_NGV_Tailpipe_EFs.pdf Argonne's analysis indicates that the relative fuel economy of model year 2010 light-duty vehicles has not improved as anticipated, therefore 95% is applied here, instead of 103% as given in the LDT1-, LDT2-, and Car Time Series tabs (cells C125 and C138) in CA-GREET2.0.

[12] Argonne provides two references for the alternative fuel vehicle fuel economy scale factors in GREET: (1) Norman Brinkman, Michael Wang, Trudy Weber, Thomas Darlington, "Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems— A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions", May 2005. https://greet.es.anl.gov/publication-4mz3q5dw. (2) A. Elgowainy, J. Han, L. Poch, M. Wang, A. Vyas, M. Mahalik, A. Rousseau, "Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles", June 1, 2010. https://greet.es.anl.gov/publication-xkdaqgyk

Light to Medium Duty Vehicles (relative to gasoline baseline vehicle)	Baseline Fuel Economy Equation 1 **C)**	Fuel Economy Scale Factor[11,12] Equation 1 **D)**	Source
Gasoline Cars	26.08	95%	Cars_TS tab, cells C16, C156, and C173

Table 4. NG Vehicle Emissions and Scale Factors by Vehicle Class for Light to Medium Duty Vehicles. Relative to Gasoline baseline vehicle (GGE = 112,194 Btu/gal)

Light to Medium Duty Vehicles	Baseline Vehicle CH_4 (g/mi) Equation 1 **A)**	NGV CH_4 Scale Factor Equation 1 **B)**	Source	Baseline Vehicle N_2O (g/mi) Equation 1 **A)**	NGV N_2O Scale Factor Equation 1 **B)**	Source
Class 2b Heavy-duty pickup trucks and vans	0.0209	1000	ANL HDV, 2015	0.0086	100	ANL HDV, 2015
Class 2a Light Duty Trucks (LDT2)	0.0170	1000	LDT2_TS tab, cells N16, N156, N173	0.041	100	LDT2_TS tab, cells O16,O12, O138
Light Duty Trucks (LDT1)	0.0126	1000	LDT1_TS tab, cells N16, N156, N173	0.010	100	LDT1_TS tab, cells O16,O156, O173
Cars	0.0106	1000	Cars_TS tab, cells N16, N156, N173	0.008	100	Cars_TS tab, cells O16,O156, O173

Table 5. Light to Medium Duty NG Vehicle Emissions (from equation (1))

Light to Medium Duty Vehicles (relative to gasoline baseline vehicle)	NGV CH_4 (g/MMbtu) Equation 1**)**	NGV CH_4 (g/MJ)	NGV N_2O (g/MMBtu) Equation 1**)**	NGV N_2O (g/MJ)	NGV CH_4 and N_2O (gCO_2e/MJ)
Class 2b Heavy-duty pickup trucks and vans	30.44	0.029	1.247	1.18E-03	1.07

Light to Medium Duty Vehicles (relative to gasoline baseline vehicle)	**NGV CH_4 (g/MMbtu)** Equation 1**)**	**NGV CH_4 (g/MJ)**	**NGV N_2O (g/MMBtu)** Equation 1**)**	**NGV N_2O (g/MJ)**	**NGV CH_4 and N_2O (gCO_2e/MJ)**
Class 2a Light Duty Trucks (LDT2)	23.66	0.022	5.765	5.46E-03	2.19
Light Duty Trucks (LDT1)	20.24	0.019	1.619	1.53E-03	0.94
Cars	19.08	0.018	1.682	1.59E-03	0.93

d. Methane and Nitrous Oxide Emissions from CNG and LNG for HDVs

The 2015 ANL HDV report[13] provides methane emission factors on a fuel throughput basis, rather than per mile, for ten representative HDVs, therefore the scale factor approach is used only for N_2O emissions from HDVs in CA-GREET2.0. NG vehicle fuel economy is provided in Btu/mile for these vehicles, eliminating the need for a scale factor adjustment to that parameter. Equations 2 and 3 are used to derive methane and nitrous oxide emission factors respectively for heavy duty vehicles using CNG as a fuel.

Equation 2. Heavy Duty Vehicles Methane Emission Factor Calculation

$$(Tailpipe + Crankcase) CH_4 \ Emission \ Factor \ \frac{\mathrm{g} \ CH_4}{\mathrm{MMBtu\ NG}} = Vehicle \ CH_4 \ Emission \ Factor \ \frac{\mathrm{g} \ CH_4}{\mathrm{MMBtu\ NG}}$$

Equation 3. Heavy Duty Vehicles Nitrous Oxide Emission Factor Calculation

$$\left(\mathrm{A\ \ Baseline\ Vehicle\ N2O\ Emission\ Factor}\ \frac{\mathrm{g\ N2O}}{\mathrm{mi}} \times \mathrm{B\ NG\ Vehicle\ Scale\ Factor\ \%}\right) \div \left(\mathrm{C\ NG\ Vehicle\ Fuel\ Economy}\ \frac{\mathrm{Btu}}{\mathrm{mi}}\right) \times 10^6 \ \frac{\mathrm{Btu}}{\mathrm{MMBtu}} = \boldsymbol{D} \ Vehicle \ N2O \ Emission \ Factor \ \frac{\mathrm{g\ N2O}}{\mathrm{MMBtu}}$$

13 Argonne National Laboratory, “The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles” May 27, 2015, https://greet.es.anl.gov/publication-heavy-duty

Tables 6-8 provide details of fuel economy, methane emissions, nitrous oxide emissions respectively for NG use in HDVs. Table 9 summarizes calculated emissions factors for HD vehicles which use CNG as a fuel.

Table 6. NG Vehicle Fuel Economy by Vehicle Class for Heavy Duty Vehicles from ANL HDV, 2015 Table 23

Heavy Duty Vehicles	**NGV Fuel Economy (Btu/mi)**
Class 8b Combination long-haul trucks	23,586
Class 8b Combination short-haul trucks	23,206
Class 8b Heavy Heavy-Duty vocational vehicles	23,586
Class 6 Medium-Heavy Duty vocational vehicles	20,312
Class 4 Light-Heavy Duty vocational vehicles	16,741
Class 8a Refuse trucks	31,737
Class 8 Transit Buses	39,466
Class 6 School Buses	21,763
Class 8 Intercity Buses	23,979

Table 7. NG Vehicle Methane Emissions for Heavy Duty Vehicles

Heavy Duty Vehicles	Tailpipe CH_4 (g/MMBtu)	Crankcase CH_4 (g/MMBtu)	NGV CH_4 (g/MMbtu)
Class 8b Combination long-haul trucks	49.0	59.5	108
Class 8b Combination short-haul trucks	45.0	54.5	99
Class 8b Heavy Heavy-Duty vocational vehicles	45.0	54.5	99
Class 6 Medium-Heavy Duty vocational vehicles	114.0	138.9	252
Class 4 Light-Heavy Duty vocational vehicles	114.0	138.9	252
Class 8a Refuse trucks	114.0	138.9	252
Class 8 Transit Buses	114.0	138.9	252
Class 6 School Buses	114.0	138.9	252
Class 8 Intercity Buses	45.0	54.5	99

Table 8. NG Vehicle Nitrous Oxide Emissions and Scale Factors by Vehicle Category for Heavy Duty Vehicles from ANL HDV, 2015 Table 23. Relative to diesel baseline vehicle

Heavy Duty Vehicles	Baseline Vehicle N_2O EF (g/mi)	NGV N_2O Scale Factor	NGV N_2O (g/MMBtu)
Class 8b Combination long-haul trucks	3.44E-04	25	0.004
Class 8b Combination short-haul trucks	3.81E-04	25	0.004
Class 8b Heavy Heavy-Duty vocational vehicles	4.91E-04	25	0.005
Class 6 Medium-Heavy Duty vocational vehicles	4.91E-04	25	0.006
Class 4 Light-Heavy Duty vocational vehicles	4.91E-04	25	0.007
Class 8a Refuse trucks	3.78E-04	25	0.003
Class 8 Transit Buses	4.01E-04	25	0.003
Class 6 School Buses	4.68E-04	25	0.005
Class 8 Intercity Buses	3.71E-04	25	0.004

Table 9. Results for Heavy Duty NG Vehicle Emissions

Heavy Duty Vehicles	NGV CH_4 (g/MMbtu) (Equation 2 Result)	NGV CH_4 (g/MJ)	NGV N_2O (g/MMBtu) (Equation 3 Result)	NGV N_2O (g/MJ)	NGV CH_4 and N_2O (gCO2e/MJ)
Class 8b Combination long-haul trucks	108	0.102	0.004	3.45E-06	**2.56**
Class 8b Combination short-haul trucks	99	0.094	0.004	3.89E-06	**2.35**
Class 8b Heavy Heavy-Duty vocational vehicles	99	0.094	0.005	4.94E-06	**2.35**
Class 6 Medium-Heavy Duty vocational vehicles	252	0.239	0.006	5.73E-06	**5.97**
Class 4 Light-Heavy Duty vocational vehicles	252	0.239	0.007	6.95E-06	**5.97**
Class 8a Refuse trucks	252	0.239	0.003	2.82E-06	**5.97**
Class 8 Transit Buses	252	0.239	0.003	2.41E-06	**5.97**
Class 6 School Buses	252	0.239	0.005	5.10E-06	**5.97**
Class 8 Intercity Buses	99	0.094	0.004	3.67E-06	**2.35**

Note that these emission factors are applied to both CNG and LNG vehicles. Thus, the final EF for CNG and LNG are distinguished from one another only by the distribution of vehicles.

e. Fuel Consumption-Weighted Average NGV Emission Factor

Table 10 depicts the challenge of aligning the available data on California fuel consumption shares by NGV type with the emission factors calculated above for the 13 Classes and subcategories available from ANL (nine HDVs and four light-to-medium duty vehicles). The most descriptive and complete data set for NG fuel consumption in California that was identified by staff is from the U.S. EIA[14]. The EIA dataset contains nine distinctive vehicle categories; however, the most recent data available is data year 2011. More recent, 2014 CNG and LNG volumes used as transport fuel in California is captured in the LCFS Reporting Tool (LRT); however, the vehicle categories are broad, distinguishing only between vehicles of greater or less than 14,000 Gross Vehicle Weight Rating (GVWR) (lb.s), and do not align well with the ANL HDV Classes. These

[14] U.S. Energy Information Administration, "Renewable & Alternative Fuels, Alternative Fuel Vehicle Data" website tool, Accessed on October 21, 2014. http://www.eia.gov/renewable/afv/users.cfm. See also vehicle category Definitions: http://www.eia.gov/renewable/alternative_transport_vehicles/pdf/defs-sources-notes.pdf

two sources were combined in order to estimate the proportion of fuel consumed by each vehicle type, as described below and in Table 11 and Table 12.

Vehicle Class 4 to 8 all fall within the broad weight range defined as heavy duty in LRT. These classes include not only a wide range of body types, engines, and pay loads, but duty cycle was determined to play an important role in determining fuel economy – a long-distance truck or intercity bus, for example, will achieve far greater efficiency than a refuse truck or transit bus of similar size, weight and engine type. Figure 1 shows comparison of vehicle categorization among data sources: EIA, EPA, GREET, and LRT of LCFS.

Table 10. Alignment of Vehicle Categories in GREET (source of emission factors) and EIA AFV User database a Reporting Tool database (source of fuel consumption shares)

MOVES 2014 Vehicle Categories	GREET Vehicle Categories	EPA GVWR Rating	EPA GVWR (lbs)	LCFS Reporting Tool Vehicle Categories	EIA Vehicle Categories	EIA Vehicle Types
	Cars	N/A		Light & Medium Duty GVWR ≤ 14,000 lbs	Light Duty GVWR ≤ 8500 lbs	Automobiles Other
Light Duty Trucks	LDT 1	LDT 1 & 2	Up to 6,000			
Light Duty Trucks	LDT 2	LDT 3 & 4	6,000 - 8,500			
Class 2b passenger trucks or light commercial trucks	Heavy-duty pickup trucks and vans	HDV Class 2b	8,500 - 10,000		Medium Duty 8,501 <GVWR≤ 26,000	Trucks Vans Pickups
Class 4 and 5 light heavy duty single unit short- or long-haul trucks	Light heavy-duty vocational vehicles	HDV Class 4	14,000 - 16,000	Heavy Duty GVWR > 14,001 lbs		
Class 6 and 7 medium heavy duty single unit short- or long-haul trucks	Medium heavy-duty vocational vehicles	HDV Class 6	19,500 - 26,000			
Class 6 and Class 7 school buses	School buses	HDV Class 6 or 7	19,500 - 33,000			
Class 8 heavy heavy duty single unit short- or long-haul trucks	Heavy heavy-duty vocational vehicles	HDV Class 8b	> 60,000		Heavy Duty GVWR> 26,000 lbs	Trucks Transit Buses School Buses Intercity Buses
Class 8 refuse trucks	Refuse trucks	HDV Class 8a	33,000 - 60,000			
Class 8 combination long-haul trucks	Combination long-haul trucks	HDV Class 8b	> 60,000			
Class 8 combination short-haul trucks	Combination short-haul trucks	HDV Class 8b	> 60,000			
Class 8 transit buses	Transit buses	HDV Class 8a	33,000 - 60,000			
Class 8 intercity buses	Intercity buses	HDV Class 8a	33,000 - 60,000			

Figure 1. Comparison of vehicle categorization among data sources used in this analysis

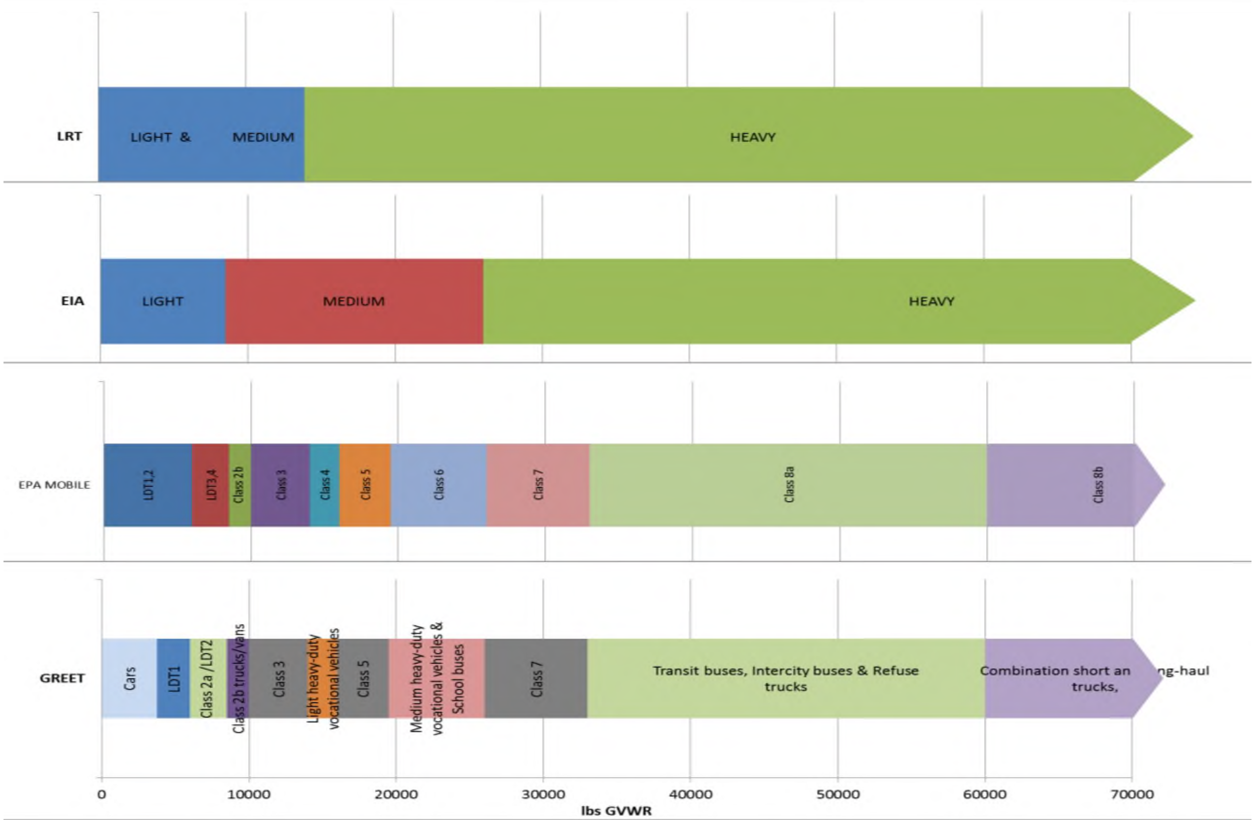

Table 11. Adjustment of 2011 EIA fuel shares as a proportion of LRT 2014 consumption in CNG heavy and light-to-medium duty vehicles

CNG Fuel Consumption by Vehicle Category [LCFS Reporting Tool Database, 2014]:			CNG Fuel Consumption by Vehicle Type [EIA AFV User Database, 2011]:			Adjustment to CNG Shares for this analysis
LRT Vehicle Category	**Fuel Consumption (Mscf)**	**Fuel Consumption Shares**	**EIA Vehicle Type and GVWR**	**Fuel Consumption (1,000 GGE/yr)**	**Fuel Consumption Shares [EIA, 2011]**	**Composite shares (EIA fuel shares as proportion of LRT)**
Heavy Duty (>14,000 lbs)	9,338,519	83.22%	Trucks (GVWR >26,000)	7,392	7.00%	7.82%
			Trucks (8500 < GVWR < 26,000)	3,201	3.03%	3.39%
			Transit Buses (GVWR >26,000)	77,800	73.66%	82.28%
			School Buses (GVWR >26,000)	4,700	4.45%	4.97%
			Intercity Buses (GVWR >26,000)	395	0.37%	0.42%
			Vans (8500 < GVWR < 26,000)	1,065	1.01%	1.13%
Light & Medium Duty (<14,000 lbs)	1,882,890	16.78%	Medium Duty Pickups (8500 < GVWR < 26,000)	2,754	2.61%	24.88%
			Light Duty Other (GVWR < 8500 lb) *	5,834	5.52%	52.70%
			Light Duty Automobiles ** (GVWR < 8500 lb)	2,483	2.35%	22.43%
			Sum total:	**105,624**		

* Light Duty Other includes pickups, SUVs, trucks, light duty vans, minivans and a category of “other.”

** Light Duty Automobiles includes subcategories of compact, subcompact, mid-size, and full-size passenger cars.

Table 12. 2011 EIA fuel consumption shares in LNG heavy and light-to-medium duty vehicles

LNG Fuel Consumption by Vehicle Category [LCFS Reporting Tool Database, 2014]:			LNG Fuel Consumption by Vehicle Type [EIA AFV User Database, 2011]:		
LRT Vehicle Category	Fuel Consumption (Gallons)	Fuel Consumption Shares	EIA Vehicle Type and GVWR	Fuel Consumption (1,000 GGE/yr)	Fuel Consumption Shares
Heavy Duty (>14,000 lbs)	55,045,693	100%	Trucks (GVWR >26,000)	5,688	39.80%
			Trucks (8500 < GVWR < 26,000)	37	0.26%
			Transit Buses (GVWR >26,000)	8,568	59.95%
Light & Medium Duty (<14,000	0	0%	Medium Duty Pickups	0	0%
			Light Duty Other *	0	0%
			Light Duty Automobiles **	0	0%
			Sum total:	**14,293**	

* Light Duty Other includes pickups, SUVs, trucks, light duty vans, minivans and a category of “other.”

** Light Duty Automobiles includes subcategories of compact, subcompact, mid-size, and full-size passenger cars.

Alignment of vehicle types from the EIA classification within the LRT Categories was straightforward, with the exception of three EIA vehicle types which span both LRT Categories: Trucks (8500 < GVWR < 26,000), Vans (8500 < GVWR < 26,000) and Pickups (8500 < GVWR < 26,000). Rationale for this choice is presented in the following explanation of how EIA-LRT composite data is matched with ANL vehicle classes.

Table 13 details matching ANL emission factor with each Composite Vehicle Category. Two categories required averaging as no further distinction was possible among the fuel volumes consumed by medium and heavy duty trucks. While EIA’s public database did not provide distinction among buses, data was provided to staff[15] to quantify fuel consumption in school, transit and intercity buses.

15 Personal email communication with EIA AFV User Database Collection Manager. May 15, 2015. PDF saved as EIA_AFV_Bus-Fuel_05-15-2015.

Table 13. Emission factors applied to each EIA category and composite fuel share

EIA Vehicle Type and GVWR	ANL Emission Factors
Trucks (GVWR >26,000)	Average of Class 8a and 8b trucks (n=4)
Trucks (8500 < GVWR < 26,000)	Average Class 4 and 6 (n=2)
Transit Buses (GVWR >26,000)	Class 8 Transit Buses
School Buses (GVWR >26,000)	Class 6 School Buses
Intercity Buses (GVWR >26,000)	Class 8 Intercity Buses
Vans (8500 < GVWR < 26,000)	Class 2b HD pickup/van
Pickups (8500 < GVWR < 26,000)	LDT2
Other (GVWR < 8500 lb)	LDT1
Automobiles (GVWR < 8500 lb)	Cars

Aligning the fuel consumption shares with the 13 vehicle categories in GREET required careful consideration and judgement, specifically with regard to the following EIA Medium Duty (MD) categories: MD Trucks, MD Vans, and MD Pickups which span a wide range of GVWR (8,500 to 26,000 lbs.). The average EF for Classes 4 and 6 Trucks (14,000 to 26,000 lbs.) was designated to represent the EIA category of MD Trucks; Class 2b (heavy duty pickup trucks and vans, 8,500 to 10,000 lbs.) was matched to EIA category of Medium Duty Vans; and the EF for Light Duty Trucks_2 (up to 6,000 lbs. GVWR) was applied to the share of fuel consumed by pickups in EIA's MD Pickups category. A sensitivity analysis was performed to ensure that these choices were not a major factor in determining the final EF representing CNG vehicles.

Equation 4. Fuel Consumption-Weighted Average Vehicle Emission Factor Calculation

$$\sum\left(Emission\ Factor_{i,j}\,\frac{\mathrm{g}\ species}{\mathrm{MMBtu}}\times fuel\ consumption\%_{i,j}\right)$$

Where *i* = fuel (CNG or LNG),

and *j* = Vehicle category (HDT, MDT, Transit Bus, School bus, Intercity bus, MD Vans, MD Pickups, LDT2, LDT1, LD Other, Automobiles. Table 14 details the results from fuel consumption weighted emission factors for CNG and LNG vehicles in CA-GREET 3.0.

Table 14. Results for the fuel consumption-weighted average NGV emission factor representing the California fleet of CNG and LNG vehicles in CA-GREET3.0

LRT Vehicle Category	g CH_4/MMbtu		g N_2O/MMbtu		g CO_2e/MJ	
	Category average CH_4	**Fleet-weighted average CH_4**	**Category average N_2O**	**Fleet-weighted average N_2O**	**Category Average Vehicle CH_4 and N_2O**	**Fleet-weighted average CH_4 and N_2O**
Heavy Duty CNG	240.07	203.308	0.02	0.307	5.693	**4.90**
Light & Med Duty CNG	20.980		1.744		0.990	
Heavy Duty LNG		207.23		0.003		**4.91**

Section 2: Electricity

The U.S. electricity resource mixes available in CA-GREET 3.0 are based on the U.S. EPA's, Emissions & Generation Resource Integrated Database (eGRID), 9th edition Version 1.0 (which describes 2010 electrical generation mixes). Staff used the same mixes associated with the 26 eGRID sub-regions.[16] Staff selected average electricity resource mixes primarily due to the uncertainty in determining the marginal resource mix accurately for each sub-region. It is highly speculative to attempt to define and distinguish marginal electricity sources; for example, natural gas has become increasingly common as a baseload power source, hydroelectric capacity can vary with precipitation patterns, and though most areas experience growth in electricity demand over time, individual sources of demand may expire as new sources of demand are created. Staff determined that the simplest, most equitable and defensible method is to apply the regional average across all pathways. Staff modified GREET1 2016, which used the 2010 10-region North American Electric Reliability Corporation (NERC) regions. The conversion to the 26 eGRID subregional mixes in CA-GREET 3.0 was accomplished by modifying the electricity resource mixes and sub-regions in the Fuel_Prod_TS tab of CA-GREET 3.0 and the associated links to the Inputs tab. Staff also added U.S Average, User-defined, Brazilian, and Canadian Mixes in addition to the 26 eGRID sub-regions.

a. Summary of Changes to GREET1 2016 Electricity Parameters

   i. GREET1 2016 allows users to choose between two sets of power plant emission factors. The first set consists of GREET-calculated factors found in the EF tab. The second set is taken from the EPA and EIA emission factor database. For the LCFS fuel pathways, only stationary electricity resource mixes in CA-GREET 3.0 are considered. Details of electricity emission factors incorporated in CA-GREEET 3.0 are discussed below. Staff restructured the available GREET1 2016 regional electricity resource mixes to allow fuel producers to use more representative sub-regional electricity resource mix to obtain a more representative CI for the sub-region. Staff modified the Electric Tab in GREET1 2016 to enable calculation of the regional combustion technology shares and power plant energy conversion efficiencies to match with the 26 sub-regions (see BO26:BP53, Electric tab).

   ii. Table 15 compares the sub-region categories used in CA-GREET 3.0 to the NERC region categories used in GREET1 2016.

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[16] United States Environmental Protection Agency, eGRID 9th edition Version 1.0: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

Table 15. Electricity Resource Mix Selections Available in the Three Models

CA-GREET 2.0				**GREET 1 2016**		**CA-GREET 3.0**			
Electricity Mix Stationary Use				**Electricity Mix Stationary Use**		**Electricity Mix Stationary Use**			
1	U.S Ave	16	SRTV	1	U.S.	1	U.S Ave	16	SRTV
2	User Defined	17	SRSO	2	ASCC	2	User Defined	17	SRSO
3	CAMX	18	NEWE	3	FRCC	3	CAMX	18	NEWE
4	NWPP	19	NYUP	4	HICC	4	NWPP	19	NYUP
5	AZNM	20	RFCE	5	MRO	5	AZNM	20	RFCE
6	RMPA	21	NYLI	6	NPCC	6	RMPA	21	NYLI
7	MROW	22	NYCW	7	RFC	7	MROW	22	NYCW
8	SPNO	23	SRVC	8	SERC	8	SPNO	23	SRVC
9	SPSO	24	FRCC	9	SPP	9	SPSO	24	FRCC
10	ERCT	25	AKMS	10	TRE	10	ERCT	25	AKMS
11	MROE	26	AKGD	11	WECC	11	MROE	26	AKGD
12	SRMW	27	HIOA	12	CA	12	SRMW	27	HIOA
13	SRMV	28	HIMS	13	User Defined	13	SRMV	28	HIMS
14	RFCM	29	Brazilian			14	RFCM	29	Brazilian
15	RFCW					15	RFCW	30	Canadian
29 sub-regions				13 NERC regions		30 sub-regions			

iii. eGRID Sub-regions Compared to NERC Regions

Table 16 compares e-grid sub-regions to sub-regions that are part of NERC regions. Most sub-regions are not individual states and most regions are not sub-regions. There are a few exceptions. Alaska and Hawaii are states with their own NERC regions, but are divided by sub-regions. Florida as a state has the same region (FRCC) and sub-region (FRCC). California is part of the WECC NERC region, but is its own sub-region (CAMX).

Table 16. eGRID Sub-regions Grouped by NERC Region

#	Subregion	NERC Region	#	Subregion	NERC Region
1	AKGD	ASCC	14	RFCM	RFC
2	AKMS	ASCC	15	RFCW	RFC
3	ERCT	TRE	16	SRMW	SERC
4	FRCC	FRCC	17	SRMV	SERC
5	HIMS	HICC	18	SRSO	SERC
6	HIOA	HICC	19	SRTV	SERC
7	MROE	MRO	20	SRVC	SERC

#	Subregion	NERC Region	#	Subregion	NERC Region
8	MROW	MRO	21	SPNO	SPP
9	NYLI	NPCC	22	SPSO	SPP
10	NYCW	NPCC	23	CAMX	WECC
11	NEWE	NPCC	24	NWPP	WECC
12	NYUP	NPCC	25	RMPA	WECC
13	RFCE	RFC	26	AZNM	WECC

iv. Modification of eGRID Subregion Data for use in CA-GREET 3.0

Table 17 details how eGRID sub-region resource mixes were modified to create a California resource mix for use in CA-GREET 3.0. Because GREET1 2016 does not have the resource categories used in eGRID for "other fossil" and "other unknown fuel purchased", these percentages were allocated to the percentages of "Residual oil" and "Natural gas", respectively.

Table 17. Modified California Grid-Average Electricity Mix (CAMX)

eGRID 2014 Electricity Generation Sources	**CAMX in CA-GREET 2.0**	**CAMX** eGRID 2014	**Modified CAMX CA-GREET 3.0**
Coal	7.15%	0.43%	0.43%
Oil (Residual oil)	1.38%	0.79%	1.13%
Gas (Natural gas)	50.75%	62.47%	62.81%
Other fossil (N/A)		0.23%	0.0%
Biomass	2.62%	3.43%	3.43%
Nuclear	15.18%	8.98%	8.98%
Hydro	15.19%	8.41%	8.41%
Wind	3.05%	6.54%	6.54%
Solar	0.365	4.28%	4.28%
Geo thermal	4.32%	4.35%	4.35%
other unknown fuel purchased (N/A)	0.00%	0.34%	0.0%
Total	100%	100.00%	100%

In GREET1 2016, electricity resource mixes are further subdivided: GREET segregates hydropower, wind, solar, and geothermal resource mixes in the category of "other" electricity resource mixes. In CA-GREET 3.0 the "other" electricity resources are labeled as, "other renewable resources." Biomass is often considered renewable, but requires combustion; nuclear has no combustion, but is not renewable, so these two resource mixes are not included in the "other" category. In GREET1 2016, wind, solar, geothermal, and hydropower are located in a different set of tables in the Input and Fuel_Prod_TS tabs. In CA GREET 3.0, the same convention regarding renewable resource mixes is followed. An example of how the eGRID data is entered into CA-GREET for the "other" (23.91% in CAMX region in

Table 17) resource mix is shown in Table 18.

Table 18. Other Electricity Resource Mix

Electricity Generation Source	**CAMX "other" Resource Mix**	**CA-GREET 3.0 CAMX "other" Resource Mix**
Wind	6.54%	6.54% / 23.58% = **27.74%**
Solar	4.28%	4.28% / 23.58% = **18.15%**
Geothermal	4.35%	4.35% / 23.58% = **18.45%**
Hydro	8.41%	8.41% / 23.58% = **35.67%**
Total	23.58%	100.00%

v. International Electricity Resource Mixes

The average electricity mix for Brazil and Canada are the only international resource mixes included in CA-GREET 3.0. These electricity mixes are located in the T1 Calculator tab in the column below cell T8 rather than in the Fuel_Prod_TS tab as with the 26 eGRID sub-regions.
Table 19 details the electricity mix calculated from BNEB data obtained from the agency's website from the reports for 2014 for data years 2011-2013. Canadian Electricity Mix was obtained from Statistics Canada 2015. Table 19 details the electricity resource mix for these two regions.

Table 19. 2014 Brazil and Canada Electricity Resource Mix

Resource Mix (GREET1 2016 Category)	**Brazilian** 2014 data **For CA-GREET 3.0**[17]	**Canadian** 2014 data **For CA-GREET 3.0**[18]
Coal and Coal Products (Coal)	11.52%	11.84%

[17] Provided by UNICA on July 13, 2017 via email by Lais Thosmas of UNICA office in Washington D.C
[18] Extracted from Statistics Canada on Jul 31, 2015. Table 127-0007 Electric power generation, by class of electricity producer, annual (megawatt hour).
http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1270007&tabMode=dataTable&srchLan=-1&p1=-1&p2=9

Oil Products (Residual Oil)	0.42%	1.96%
Natural Gas (Natural Gas)	7%	9.9%
Biomass	0%	1.97%
Nuclear	17.71%	0%
Hydro	60.90%	71.69%
Solar	0.6%	0.06
Wind	2%	2.14%
Others	0.39%	0.42%

Section 3: Fuel Specifications

Specifications and properties for some fuels are different in CA-GREET 3.0 compared to GREET 1 2016 and they are detailed in Table 20.

Table 20. Fuel Properties and Specifications

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
CARBOB	119.54 MJ/gal 113,300 Btu/gal 2,767 g/gal	N/A GREET1 2016 tabulates U.S. gasoline blendstock properties (LHV = 116,090 Btu/gal), but not CARBOB	Same as CA-GREET 2.0
CaRFG	115.82 MJ/gal 109,772 Btu/gal 2,788 g/gal	118.37 MJ/gal 112,194 Btu/gal 2,836 g/gal	Same as CA-GREET 2.0
Ultra-Low Sulfur Diesel	134.48 MJ/gal 127,464 Btu/gal 3,142 g/gal	136.62 MJ/gal 129,488 Btu/gal 3,206 g/gal	Same as CA-GREET 2.0

Section 4: Ethanol

a. Calculation of Carbon Intensity for Denatured Ethanol

The impact of denaturant on carbon intensity was previously estimated as 0.8 gCO_2e/MJ by assuming an “average” anhydrous ethanol CI of approximately 90 gCO_2e/MJ. Given the development of ethanol with a wide range of carbon intensities, staff finds it necessary to account for a representative CI for ethanol which is displaced when denaturant is added. The calculation formula for denaturant CI given below is used to determine CI of denatured ethanol. Unless otherwise indicated, the cells referenced in Table 21 are from the Petroleum tab of the three GREET versions appearing in the column header row.

Table 21. Calculation of Carbon Intensity for Denatured Ethanol

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Denaturant Content of Denatured Ethanol (D-EtOH) (v/v)	2.50% Petroleum tab, Cell B284[6,7]	2.00% Inputs tab, Cell G89	2.50% Petroleum tab, Cell B333[6,7]

b. Starch Ethanol

Table 22 details differences between the three models for corn ethanol. Unless otherwise indicated, the cells referenced in
Table 22 are from the "EtOH" tab of the GREET versions appearing in the column header row.

Table 22. Comparison of Starch Ethanol Parameters in the Three Models

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Corn farming energy	9,608 Btu/bu (cell C18)[19]	6,924 Btu/bu Cell D34	Same as GREET 1 2016
All Fertilizer inputs	N: 423.3 g/bu P: 145.8 K: 151.3 CaCO3: 1,149.9 (cells C20:C23)[20]	N: 382.95 g/bu P: 139.29 K: 146.41 CaCO3: 1,290.21 Herbicide: 5.85 Insecticide: 0.01 (cells D36:I42 – EtOH tab)	Same as GREET 1 2016
Ethanol yield	Applicants must include this information in their application.	2.86 gal/bu Cell C129 – EtOH ta[21]	Applicants must include this information in their application.
Yeast and Enzymes	Applicants must include this information in their application.	Yes	2.02 gCO2e/MJ based on use of yeast, enzymes and

[19] Wang, Michael Q., Jeongwoo Han, Zia Haq, Wallace E. Tyner, May Wu, and Amgad Elgowainy. "Energy and greenhouse gas emission effects of corn and cellulosic ethanol with technology improvements and land use changes." *Biomass and Bioenergy* 35, no. 5 (2011): 1885-1896. http://www.sciencedirect.com/science/article/pii/S0961953411000298

[20] Argonne National Laboratory, GREET 1 2014 spreadsheet, Obtained on 03-OCT-2014 from https://greet.es.anl.gov/greet_1_series

[21] Mueller, Steffen and Kwik, John, "2012 Corn Ethanol: Emerging Plant Energy and Environmental Technologies", UIC Energy Resources Center, (2013) Obtained from: http://ethanolrfa.org/page/-/PDFs/2012%20Corn%20Ethanol%20FINAL.pdf?nocdn=1 Date accessed: 06-AUG-2014

			chemicals and calculated as average CI from operational data from LCFS applications.
Moisture content of DDGS	Changed to 10% in the Inputs tab, cell T381 The change to 10% is based upon staff pathway application experience	12% Citation[22] Cell I532 – Inputs tab	Applicants must include this information in their application.
DGS Yield	Applicants must include this information in their application.	5.63 bone dry lbs/gal Cell C310 – EtOH tab	Applicants must include this information in their application.
DGS Reduced Enteric Emissions CREDIT	No reduced enteric emissions credit. Analysis is explained in the CA-GREET 2.0 Supplemental Document and Tables of Changes[23]	Cell G340 – EtOH tab	No reduced enteric emissions credit.
Drying energy	There is no allocation of energy use to ethanol for producing different moisture content co-products in the Tier 1 Pathways. Applicants may apply and prove associated energy (DGS dryness levels) used for ethanol produced under the Tier 2 application process.	11,141 Btu/gal This value is obtained by subtracting the total energy use when only producing DDGS and that when only producing WDGS in the Inputs Tab, cell L495 – O495.	Applicants must include drying energy data in their application.
N in N_2O as % of N in N fertilizer and biomass	Disaggregated to account for emissions from fertilizer (1.325%) and crop residues (1.225%) separately. Inputs: Cell E330 Tier 1 default EFs from IPCC 2006.[24]	1.225%[24,25,26] Inputs: Cell E443	Same as CA-GREET 2.0

22 Arora, Salil, May Wu, and Michael Wang. "Estimated displaced products and ratios of distillers' co-products from corn ethanol plants and the implications of lifecycle analysis." *Biofuels* 1, no. 6 (2010): 911-922. https://greet.es.anl.gov/publication-corn-ethanol-displaced-products

23 CA-GREET 2.0 Supplemental Document and Tables of Changes, Date June 4, 2015: https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

24 IPCC 2006 N_2O emissions from managed soils, and CO_2 emissions from lime and urea application 2006 IPCC Guidelines for National Greenhouse Gas Inventories vol 4 (Hayama: IGES) chapter 11 http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf

25 IPCC 2010 IPCC Expert Mtg on HWP, Wetlands and Soil N_2O (Geneva, October 2010) (available at www.ipccnggip.iges.or.jp/meeting/pdffiles/1010 GenevaMeetingReport FINAL.pdf accessed September 17, 2014)

26 Frank, Edward D., Jeongwoo Han, Ignasi Palou-Rivera, Amgad Elgowainy, and Michael Q. Wang. "Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels." *Environmental Research Letters* 7, no. 1 (2012): 014030. http://iopscience.iop.org/1748-9326/7/1/014030

	Input	CA-GREET 2.0			
Additional Process Chemical Inputs (User Defined Values)	Sulfuric acid (H_2SO_4, (grams/gal)	User Defined	Sulfuric acid (H_2SO_4, (grams/gal)	4.65	2.02 gCO2e/MJ based on use of yeast, enzymes and chemicals and calculated as average CI from operational data from LCFS applications.
	Ammonia (NH_3, (grams/gal)	User Defined	Ammonia (NH_3, (grams/gal)	17.82	
	NaOH (grams/gal)	User Defined	NaOH (grams/gal)	22.35	
	CaO (grams/gal)	User Defined	CaO (grams/gal)	10.66	
	Urea (grams/gal)	User Defined	Urea (grams/gal)	No Value	

c. Sugarcane Ethanol

Table 23 provides details of parameters in the three models for sugarcane ethanol.

Table 23. Sugarcane Ethanol Parameters

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Agriculture Chemical Inputs	N: 800.0 g/tonne [34] P: 300.0 K: 1,000.0 Lime: 5,200.0 Herbicide: 45.0 Pesticide: 2.50 Inputs P280-286	N: 925.40 g/tonne[34] P: 323.7 K: 1,508.2 Lime: 5,200.0 Herbicide: 45.0 Pesticide: 2.50 EtOH EG412:EL412	Same as GREET 1 2016
Electricity credit: kWh per gallon of ethanol	The electricity mix for all feedstocks and fuel production are controlled through the T1 Calculator tab, linked to the input tab through the Fuel_Prod_TS tab.	-3.505 kWh/gal EtOH, See formula: EtOH C263 Note: This is a GREET calculated value based sugarcane yield.	Applicants must include this information in their application.
Lime use (CaO) to produce $Ca(OH)_2$, for pH adjustment in ethanol processing	Added to CA-GREET 2.0, T1 Calculator as a user input. In Sebra et. al[27], Table 2, page 522 an input of 880 g/MT of cane is used for adjusting the sugar-rich juice pH that is produced from crushing cane	41.1 grams/MT	880 grams/MT[32]

[27] Seabra, Joaquim EA, Isaias C. Macedo, Helena L. Chum, Carlos E. Faroni, and Celso A. Sarto. "Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use." *Biofuels, Bioproducts and Biorefining* 5, no. 5 (2011): 519-532. http://onlinelibrary.wiley.com/doi/10.1002/bbb.289/abstract;jsessionid=345AEC4393BC8CDBE0C72904DFCC76A6.f01t02?deniedAccessCustomisedMessage=&userIsAuthenticated=false

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Added Sugarcane Transportation by HDD	Added HDD to T&D Tab Cells GM103-GM144	12 miles by HDDT in T&D Tab Cells GQ104-GQ144	Same as GREET 1 2016
T&D Ocean Tanker and Truck Transportation Distance	The applicant must include ocean tanker distance for ethanol transport. The following is for reference: Ocean Tanker Transportation to California: 8,758.40 miles T&D_Flowcharts M1510 T&D Tab, cell HJ105 (value in cell: 7,416 miles, from T&D Flowcharts):	Ocean Tanker Transportation to United States: 7,416 miles T&D_Flowcharts M1583 Comment in T&D Tab, cell HH105 (value in cell: 7,416 miles from T&D Flowcharts).	The applicant must include ocean tanker and truck transport distances from a Brazilian port to California.

d. Molasses Ethanol from Cane

The sugarcane molasses to ethanol pathway uses GREET1 2016 upstream agricultural inputs and user inputs reviewed in Table 23. The molasses is a byproduct of the sugar production process. The impacts of the molasses to ethanol pathway are based upon the mass allocation ratio of fermentable sugars in standard molasses to fermentable sugars in cane juice. The mass allocation affects the share of upstream emissions allocated to molasses ethanol. The sugar production share of emissions that are allocated to molasses ethanol is based upon the carbon intensity of sugar production and the share of sugar juice for sugar production. GHG emissions for sugar production used in CA-GREET 3.0 is 3,700 gCO_2e/ton of cane (Gopal and Kammen, 2009)[28] and the share of sugar juice (a percentage) is an input in CA-GREET 3.0.

e. Corn Stover Ethanolodels.

Table 24 provides a comparison of parameters for corn stover between the three GREET models.

Table 24. Corn Stover to Ethanol Parameters

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
N_2O emissions: N in N_2O as % of N in N fertilizer and biomass	1.225% (Inputs J330) Disaggregated to account for emissions from fertilizer (1.325%) and crop residues (1.225%) separately. Tier 1 default EFs from IPCC 2006.[24]	1.525%, Inputs M434	Same as CA-GREET 2.0 (Inputs L443)

[28] Gopal, Anand R.,and Daniel M. Kammen. "Molasses for ethanol: the economic and environmental impacts of a new pathway for the lifecycle greenhouse gas analysis of sugarcane ethanol." Environmental Research Letters 4, no. 4 (2009): 044005.

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Key Assumptions for harvest of corn stover	Harvesting must be conducted appropriately to validate the assumptions of no indirect effects and the sustainable harvest of stover.	Harvest and collection rate[29,30,31] 30% (Inputs H435)	Same as CA-GREET 2.0
Energy Use and Ag Chemical inputs to replace chemicals removed with stover (g/ dry ton)	GREET1 2013[33]	**Farming Energy Use:** 192,500 Btu/d. ton. Note that in the ethanol tab the stover loader (4,200) is included and the ratio of the harvested/collected and transported stover: **223,592** Btu/d. ton collected = (I34 +4200)*E92 = (192,500 Btu/d. ton +4,200)*1.14 Shares of stover harvesting energy use: 100% Diesel Fuel, EtOH DF417 Values for ag. inputs: **N:** 7,957.0 g/ d. ton transported **P:** 2,273.4 g/d. ton **K:** 13,640.6 **Lime** ($CaCO_3$): no input cell Herbicide:0.00 Pesticide: 0.00[32]	Same as GREET 1 2016

[29] Emery, Isaac R. "Direct and Indirect Greenhouse Gas Emissions from Biomass Storage: Implications for Life Cycle Assessment of Biofuels." Order No. 3612988, Purdue University, 2013, http://search.proquest.com/docview/1511453169?accountid=26958 (accessed September 1, 2014).

[30] Kwon, Ho-Young, Steffen Mueller, Jennifer B. Dunn, and Michelle M. Wander. "Modeling state-level soil carbon emission factors under various scenarios for direct land use change associated with United States biofuel feedstock production." *Biomass and Bioenergy* 55 (2013): 299-310.

[31] Emery, Isaac R., and Nathan S. Mosier. "The impact of dry matter loss during herbaceous biomass storage on net greenhouse gas emissions from biofuels production." *biomass and bioenergy* 39 (2012): 237-246. http://www.sciencedirect.com/science/article/pii/S0961953413000950

[32] Zhichao Wang, Jennifer B. Dunn, Jeongwoo Han, and Michael Wang, Material and Energy Flows in the Production of Cellulosic Feedstocks for Biofuels in the GREET Model, Argonne National Laboratory, 2013. https://greet.es.anl.gov/publication-feedstocks-13

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Ethanol Yield and Energy use for ethanol production	Applicants must include this information in their application	205kWh/dry ton, Fuel_Prod_TS BW284, Citation[33] *With the assumed yield (85 gal/ton) this is equivalent to:* 2.412 *kWh/gal of EtOH* 85.0 gallons/dry ton, Inputs F568 Citation[34]	Applicants must include this information in their application

f. Grain Sorghum to Ethanol

All farming inputs for sorghum in CA-GREET 3.0 are the same as in GREET 1 2016. Table 24 includes production parameters which are different in CA-GREET 3.0 compared to GREET 1 2016 for sorghum ethanol production.

Table 24: Grain Sorghum Ethanol Parameters

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Process Energy use for ethanol production: Btu/gallon of ethanol	Applicants must report all energy use for ethanol production	18,328 Btu/gal • 15,827 Btu/gal Natural Gas, (86.4%) • 2,501 Btu/gal Electricity, (13.6%)	Applicants must report all energy use for ethanol production.
Ethanol yield	Applicants must report ethanol production in their application.	2.81 gal/bu Cell C160 EtOH tab	Applicant must report ethanol production in their applications.

g. Corn Fiber to Ethanol

Edeniq Corporation has developed a proprietary process for the conversion of fiber in corn grain to ethanol. This process has an approved pathway registration from the EPA under the RFS program. In CA-GREET 3.0, to facilitate the use of this pathway, GHG emissions from the use of cellulase enzyme is included from the GREET 1 2016 model.

33 Tao, L., D. Schell, R. Davis, E. Tan, R. Elander, and A. Bratis. *NREL 2012 Achievement of Ethanol Cost Targets: Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover*. No. NREL/TP-5100-61563. National Renewable Energy Laboratory (NREL), Golden, CO., 2014. http://www.nrel.gov/docs/fy14osti/61563.pdf

34 Humbird, D., R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, P. Schoen et al. *Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol. National Renewable Energy Laboratory Technical Report NREL*. TP-5100-47764, 2011. http://www.nrel.gov/docs/fy11osti/47764.pdf

Production of cellulosic ethanol volumes from corn fiber by facilities must conform to verification guidelines required by the EPA.[35]

Section 5: Biodiesel and Renewable Diesel

a. Soyoil to Biodiesel (BD) or Renewable Diesel (RDII)

Table 25 includes a comparison of changes between the three models for soybean biodiesel and renewable diesel pathways.

Table 25. Soybean Biodiesel and Renewable Diesel Parameters

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Mass of soy bean to Mass of Soy Oil Ration	5.00 lb soy /lb soyoil (this is fixed, BioOil Tab, cell B29) Note that there is no loss assumed for extraction in CA-GREET 2.0. This value was changed to be consistent with the mass allocation of soybeans and soy oil.[36,37]	21.3% soyoil (this is a formula, BioOil Tab, cell B235) Note there is no loss assumed for extraction in GREET1 2016	Same as CA-GREET 2.0
Soy oil Transesterification	Applicants must provide this information as part of their application.	Total energy: 1,213 Btu/lb BD) BioOil BI262 BioOil BI261-272: • Natural gas (30.7 %) • Electricity (4.6%) • 785 Btu/lb Methanol (64.7%) • Sodium Hydroxide 0.44 g/lb BD	Applicants must provide this information as part of their application.

35 U.S EPA guideline for corn fiber ethanol to earn D3 RIN: https://www.gpo.gov/fdsys/pkg/CFR-2011-title40-vol16/pdf/CFR-2011-title40-vol16-sec80-1426.pdf

36 Due to soy oil composing approximately 20% of the soybean, 20% of the GHG emissions from farming soybeans through extraction of the soy oil are applied to the biodiesel product. Due to glycerin being a co-product of biodiesel production, 4.93% of the total energy from farming through biodiesel production (transesterification and purification) is allocated to glycerin. The allocation of soy oil does not apply to transportation of soy oil; however, transportation of soy oil is allocated 95.07% to the biodiesel product (due to the glycerin allocation). The allocation of soy oil and glycerin do not apply to the transportation of finished soy oil biodiesel, which is 100% allocated to the biodiesel product.

37 Due to soy oil composing approximately 20% of the soybean, 20% of the GHG emissions from farming soybeans through extraction of the soy oil are applied to the renewable diesel product. Due to propane (and other gas-phase hydrocarbons) being a co-product of renewable diesel production, 4.90% of the total energy from farming through renewable diesel production (transesterification and purification) is allocated to the by-product hydrocarbon gas. The allocation of soy oil does not apply to transportation of soy oil; however, transportation of soy oil is allocated 95.07% to the biodiesel product (due to the glycerin allocation). The allocation of soy oil and by-product hydrocarbon gas does not apply to the transportation of finished soy oil renewable diesel, which is 100% allocated to the renewable diesel product.

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
		• Sodium Methoxide 10 g/lb BD • Hydrochloric acid 7 g/lb BD footnote[38]	
Glycerin Yield	Using the same value as CA-GREET1.8b, BioOil Tab, Cell C51	0.11 lb glycerin / lb BD, BioOil Tab, Cell C52	Applicants must provide this information as part of their application.
RD Production	Applicants must provide this information as part of their application.	1,851 (Btu/lb of renewable diesel) BioOil C57 • 83 Btu/lb Natural gas (4.5%) • 95 Btu/lb of renewable diesel, Electricity (5.1%) • 1,673 Btu/lb of renewable diesel, Hydrogen (90.4%)	Applicants must provide this information as part of their application.
Soy Oil Biodiesel: Soymeal and Soy Oil Allocation	Staff used the same allocation method used in CA-GREET 1.8b. Soy oil at 20% by mass allocation and glycerine/(glycerine+BD energy) at 4.93% by energy allocation.[39]	Hybrid Allocation (mass and energy) is used for soybean Biodiesel pathway based on energy of glycerin, not glycerin and soybean meal	Same as CA-GREET 2.0
Soy Oil Renewable Diesel: Soymeal and Soy Oil Allocation	Staff used the same allocation method used in CA-GREET 1.8b. The allocation is: 20% soy oil (mass allocation). Propane allocation is 4.90% on an energy basis.	Hybrid Allocation (mass and energy) is used for the soybean renewable diesel pathway based on energy of propane, not propane and soybean meal.	Same as CA-GREET 2.0

b. Tallow to Biodiesel (BD) or Renewable Diesel

Table 26 compares the three models for parameters related to tallow conversion to biodiesel and renewable diesel.

Table 26: Tallow to Biodiesel and Renewable Diesel

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Collection and Transportation of	Tallow collection and transport included in T1	Not Included	Tallow collection and transport is a

[38] The United Soybean Board (2010), "*Life Cycle Impact of Soybean Production and Soy Industrial Products*", Industry Publication, http://www.biodiesel.org/reports/20100201_gen-422.pdf

[39] Due to soy oil composing approximately 20% of the soybean, 20% of the GHG emissions from farming soybeans through extraction of the soy oil are applied to the biodiesel product. Due to glycerin being a co-product of biodiesel production, 4.93% of the total energy from farming through biodiesel production (transesterification and purification) is allocated to glycerin. The allocation of soy oil does not apply to transportation of soy oil; however, transportation of soy oil is allocated 95.07% to the biodiesel product (due to the glycerin allocation). The allocation of soy oil and glycerin do not apply to the transportation of finished soy oil biodiesel, which is 100% allocated to the biodiesel product.

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Unrendered Tallow for BD/RD pathways	Calculator tab as part of the tallow BD/RD pathways. In the BioOil tab the cells DK243 to DL302 detail the energy and emissions from collection and transportation of tallow. T&D and T&D Flowcharts also updated accordingly.		pathway specific input.
Tallow use/BD Yield: (lbs. tallow/lb. biodiesel)	Applicants must provide this information as part of their applications.	Biodiesel: 1.01 lb of tallow / lb BD, BioOil C40. Note that after allocation, the value is 1.044 lb of tallow / lb BD, Bio Oil Tab, Cell C50	Applicants must provide this information as part of their applications.
Tallow Transesterification Energy Use (Btu/lb. of biodiesel)	Applicants must provide this information as part of their applications.	Energy use for BD Production from tallow as a feedstock is as follows: Feedstock use: 1.01 lb tallow/lb BD, BioOil C40, NOTE: After allocation the yield is 1.044 lb of tallow / lb BD, Bio Oil Tab, Cell C50 1,213 Btu/lb BD (Bio Oil Tab Cell BI262)[40] • 372 Btu/lb Natural gas (30.7%) • 56 Btu/lb Electricity (4.6%) • 785 Btu/lb Methanol (64.7%)	Applicants must provide this information as part of their application.
Renewable Diesel Tallow use/yield: (lbs. tallow/lb RD)	Applicants must provide this information as part of their applications.	Not Specifically stated for Tallow in GREET1 2016, Vegetable oil in general is used. For all Bio Oil Based Fuel Production the following for RD2: 1.17 lb bio oil/lb RD, BioOil B57.	Applicants must provide this information as part of their applications.
Renewable Diesel Production (Btu/lb of renewable diesel)	Applicants must provide this information as part of their applications.	For all Bio Oil Based Fuel Production the following for RD: Energy Use: 1,851 Btu/lb RD2 BioOil Tab Cell CM262. 1,851 Btu/lb RD • 83 Btu/lb of renewable diesel, Natural gas (4.5%) • 95 Btu/lb of renewable diesel, Electricity (5.1%) • 1,673 Btu/lb of renewable diesel, Hydrogen (90.4%)	Applicants must provide this information as part of their applications.
Tallow RD Propane Fuel Mix co-product	GREET1 2013/CA-GREET 1.8b Default	Not Specifically listed for Tallow. 0.059 lb of propane fuel mix / lb of RD, BioOil C94 1,096 Btu of propane fuel mix / lb of RD, BioOil D94	Applicants must provide this information as part of their applications.

[40] López, Dora E., Joseph C. Mullins, and David A. Bruce. "Energy life cycle assessment for the production of biodiesel from rendered lipids in the United States." *Industrial & Engineering Chemistry Research* 49, no. 5 (2010): 2419-2432. http://pubs.acs.org/doi/abs/10.1021/ie900884x

c. Used Cooking Oil to Biodiesel or Renewable Diesel

Used Cooking Oil (UCO) is not included in GREET 1 2016. CARB staff added UCO as a feedstock for the production of biodiesel and renewable diesel. Table 27 provides details of the inclusion of UCO in CA-GREET 3.0 in the production of biodiesel and renewable diesel.

Table 27. Used Cooking Oil Biodiesel and Renewable Diesel

Parameter	**CA-GREET 2.0** Except as noted[41]	**GREET1 2016**	**CA-GREET 3.0** Except as noted[41]
UCO to BD Aggregated Pathway in BioOil Tab	1. UCO collection and transport added to the aggregated BioOil tab in cells DW244-DX305 2. UCO Rendering for BD added to the aggregated BioOil tab in cells DY244-EA305. This is a standard value of 1,018 Btu/lb from CA-GREET 1.8b 3. UCO to BD added to the aggregated BioOil tab in cells EB244-EE305	Not available in GREET1 2016	1. UCO collection and transport added to the aggregated BioOil tab in cells EB260-EE318 2. UCO Rendering for BD added to the aggregated BioOil tab in cells EF260-EH318. This is a standard value of 1,018 Btu/lb from CA-GREET 1.8b 3. UCO to BD added to the aggregated BioOil tab in cells EI260-EL318
UCO to RD Aggregated Pathway in BioOil Tab	1. UCO collection and transport added to the aggregated BioOil tab in cells DW243-DX302 2. UCO to RD added to the aggregated BioOil tab in cells EH244-EI305	Not available in GREET1 2016	1. UCO collection and transport added to the aggregated BioOil tab in cells DW243-DX302 2. UCO to RD added to the aggregated BioOil tab in cells EM260-EH318
Energy content (LHV) of UCO	9,214 Btu/lb BioOil Tab B199, Staff Calculation	Not available in GREET1 2016	Same as CA-GREET 2.0
Energy-based allocation	Added to BioOil Tab, Cell range: Z206:AC227	Not available in GREET1 2016	Same as CA-GREET 2.0
UCO Yield for BD and RD	Added to BioOil Tab G40=1.11 lb/lb BD	Not available in GREET1 2016	This is calculated from fuel produced and input feedstock

41 California Air Resources Board, "Detailed California-Modified GREET Pathway for Biodiesel Produced in the Midwest from Used Cooking Oil and Used in California", June 30, 2011, Version 2.0. http://www.arb.ca.gov/fuels/lcfs/2a2b/internal/15day-mw-uco-bd-rpt-022112.pdf

Parameter	**CA-GREET 2.0** Except as noted[41]	**GREET1 2016**	**CA-GREET 3.0** Except as noted[41]
	H40 = 1.17 lb/lb RDII		quantity. G43 in unit of lb rendered oil/lb BD. H43 in unit of lb rendered oil/lb RD

d. Corn Oil to Biodiesel or Renewable Diesel

Table 28 compares inputs which have been changed between the three models for corn oil used in the production of biodiesel and renewable diesel.

Table 28. Corn Oil Biodiesel or Renewable Diesel

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Corn Oil Production	Total Energy: 924.29 Btu/lb oil NG: 767 Btu/lb oil Electricity: 157 Btu/lb oil (EtOH – EJ265:275)	266 Btu/lb oil using electricity (EtOH-AF412)[42]	Same as GREET1 2016.
Corn Oil Yield	0.3 gal oil/ gal EtOH	0.54 lbs/bu of corn (EtOH – F129)	0.414 lbs oil/bushel of corn (EtOH – H130)[43]

e. Canola (Rapeseed) Oil to Biodiesel or Renewable Diesel

Table 29 compares inputs which have been changed between the three models for Canola Oil used in the production of biodiesel and renewable diesel.

Table 29. Canola Oil to Biodiesel or Renewable Diesel

Parameter	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Agricultural Chemical Inputs	N: 54,698.90 g/dry MT P: 15,298.90 K: 2,946.15 Lime ($CaCO_3$): 0.00 Herbicide: 300.0 Pesticide: 42.86 (BioOil Tab AC-AH 247)[44]	N: 53,796.9 g/dry MT P: 15,417.4 K: 14,105.3 Lime ($CaCO_3$): 0.0 Herbicide: 754.5 Pesticide: 0.0 BioOil Tab AC-AH 242[45]	Same as CA-GREET 2.0
Energy and fuel shares	Fuel Shares: 81.2% NG 14.4% Electricity 4.4% N-hexane[44]	1,316 Btu/lb rapeseed (BioOil Tab AJ262:AJ278) Fuel Shares: 79.3% NG, 13.4% Electricity, 7.3% N-hexane[46]	Same as GREET 1 2016

42 Z. Wang, J. B. Dunn, J. Han, M. Q. Wang: Influence of corn oil recovery on life-cycle greenhouse gas emissions of corn ethanol and corn oil biodiesel

43 From LCFS application, Corn Oil Yield average based LCFS applications are 2 gal/100 gal Ethanol = 0.414 lbs oil/gal

44 Hao Cai, Jeongwoo Han, Amgad Elgowainy, and Michael Wang, "Draft Argonne National Laboratory Research Note: Updated Parameters of Canola Biofuel Production Pathways in GREET" Canola Council of Canada (CCC), 2013. Development of Aggregated Regional GHG Emission Values for Canola Production in Canada. Final Report.

45 US EPA, Air and Radiation Docket EPA-HQ-OAR-2010-0133-0049, "Memorandum- Summary of Modeling Input Assumptions for Canola Oil Biodiesel", July 16, 2010. http://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2010-0133-0049

46 Hao Cai, Jeongwoo Han, Amgad Elgowainy, and Michael Wang, "Parameters of Canola Biofuel Production Pathways in GREET", September 2015. https://greet.es.anl.gov/publication-canadian-canola

Section 6: Hydrogen

Table 30 compares inputs which have been changed between the two models for hydrogen produced in central reforming plants.

Table 30. Central Hydrogen Plants Parameters (North American NG to Hydrogen)

Parameter	CA-GREET 2.0	GREET1 2016 Primary Citation[47]	CA-GREET 3.0 Primary Citation[47]
H2 Compression Energy Efficiency	93.9%	90.7% (Hydrogen - Cell H100)	Same as GREET 1 2016

Section 7: Petroleum Products

a. Upstream crude extraction carbon intensity

Table 31 details values derived from OPGEE 2.0. This is not available in GREET 1 2016 for California crude. The Table compares the parameter values for the three models.

Table 31. California Crude Oil Properties

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Recovery Energy Efficiency, Total Energy, and Shares of Processing Fuels	Using OPGEE 1.0 Crude Oil CI of 11.98 gCO_2e/MJ[48]	N/A	Using OPGEE 2.0 Crude Oil CI of 12.31 gCO_2e/MJ Citation[47] For Crude Recovery and Transportation Petroleum Tab, Cell F253
API gravity Average of Crude to Refineries	25.16 (Inputs Tab, cell O63)	Not included for CA	Same as CA-GREET 2.0. (Inputs Tab, cell O69)
Sulfur Content of Average Crude to Refineries (wt %)	1.36 wt.% (Petroleum O64)	Not Included for CA	Same as GREET 2.0. (Inputs Tab, cell O64)

47 Amgad Elgowainy, Jeongwoo Han, and Hao Zhu, “Updates to Parameters of Hydrogen Production Pathways in GREET”, October 7, 2013, Argonne National Laboratory https://greet.es.anl.gov/publication-h2-13

48 OPGEE Version 2.0 (August 7, 2017); The following web page should be updated with this version of the OPGEE model that shows the estimated CA crude CI reported in this document. http://www.arb.ca.gov/fuels/lcfs/crude-oil/crude-oil.htm

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Refinery Heavy Product Yield (mmBtu of mmBtu of total refinery products)	11% Inputs Tab, cell O65	Not Included for CA	Same as GREET 2.0. Inputs Tab, cell O71
Added Complexity Index	13.83 Inputs Tab, cell O66	Not Included for CA	Same as CA-GREET 2.0. Inputs Tab, cell O72
Added California Crude Oil Sources	Added California crude oil sources to Inputs tab to row 25 labeled in cell E25. Source: OPGEE[48]	Not Included for CA	Added California crude oil sources to Inputs tab to row 25 labeled in cell E26. Source: OPGEE 2.0[48]
Modified T&D Flowchart for Conventional Crude Oil for Use in California Refinery	Modified T&D Flowcharts starting from B48-M73 Source: OPGEE 1.0[48]	Not Included for CA	Modified T&D Flowcharts starting from (T&D_Flowcharts B77-M100) Source: OPGEE 2.0[48]

b. Transportation of Conventional Crude for Use in CA Refineries

Table 32 compares parameters for transportation of conventional crude n the three models.

Table 32. Parameters for Transportation of Conventional Crude for use in CA Refineries

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0[49]
Domestic, Alaska	Ocean Tanker: 10.99%, 2,364 mi Pipeline: 3.72%, 800 mi	Ocean Tanker, 28.8%, 3,900mi (F80)	Same as CA-GREET 2.0
Domestic 48 States	Pipeline: 37.73%, 100 mi Rail: 0.08%, 2,000 mi	28.9% (C58) DIRECT Transportation (i.e. produced at a refineries and sent for distribution from refineries)	Same as CA-GREET 2.0
Imported Offshore Countries	Ocean Tanker: 40.4%, 3,709 mi Pipeline: 3.2%, 38 mi	Ocean Tanker: 40.2%, 10,762mi (F92)	Same as CA-GREET 2.0
Imported from Canada and Mexico	Pipeline: 1.6%, 900 mi Rail: 5.5%, 800 mi	2.1% (F68), Pipeline, 885mi (F96)	Same as CA-GREET 2.0

49 Crude transport to CA is the same as in CA-GREET 2.0 which is from OPGEE

c. CA Gasoline Blendstock (CARBOB) Refining/Processing

Table 33 compares refining parameters for gasoline blendstock in the three models.

Table 33. Comparison of CARBOB) Refining/Processing Parameters

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
CARBOB Energy Efficiency	89% (Petroleum - Cell AT82)	88.7% (Petroleum - Cell AT82) [50],	88.64% (Petroleum Tab Cell AU82)[51]
Total Energy for Refining/Processing to Produce CARBOB	110,000 Btu/mmBtu fuel throughput	113,000 Btu/mmBtu fuel throughput	128,160 Btu/mmBtu fuel throughput

d. Calculation of Carbon Intensity for CaRFG

The Argonne GREET1 2016 does not list CaRFG as a fuel. Table 34 provides details of inputs used to calculate CI for CaRFG.

Table 34. Calculation of Carbon Intensity for CaRFG

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Ethanol Content of CaRFG (v/v)	9.50%[6] (Petroleum - Cell H127)	9.80% (Petroleum - Cell H161)	Same as CA-GREET 2.0 (Petroleum - Cell H161)
Ethanol Content of CaRFG (MJ/MJ)	6.82% (Petroleum - Cell B266)	N/A	Same as CA-GREET 2.0 (Petroleum - Cell B315)
2010 Average Ethanol CI + ILUC	In 2010, 95% non-CA corn ethanol (58.62 g CO_2e/MJ) and 5% CA corn ethanol (46.41 g CO_2e/MJ) + 2014 ILUC value (19.8 g CO_2/MJ (EtOH tab, cell L435) =77.81 g CO_2e/MJ Cell B267 (calculation shown in Cell B267)	N/A	Same as CA-GREET 2.0

50 Forman, Grant Stephen, Vincent B. Divita, Jeongwoo Han, Hao Cai, Amgad Elgowainy, and Michael Q. Wang. "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries" https://greet.es.anl.gov/publication-energy-efficiency-refineries

51 Personal Communication with Argonne Staff for California refinery efficiency on 7/2017. The data was based on Jacob Consultancy contracted with Argonne.

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
2010 Baseline CARBOB CI	99.78 gCO_2e/MJ Cell B274 (calculation) or in cell I274 as a value	N/A	101.69 gCO_2e/MJ Cell B323 (calculation) or in cell I323 as a value
Tailpipe CH_4	CaRFG Tailpipe Emissions allocated to Ethanol: 0.0004 gCH_4/MJ cell B268 CaRFG Tailpipe Emissions allocated to CARBOB: 0.0056 gCH_4/MJ cell B272[6]	2.899 $gCH_4/MMBtu$ 0.0027 gCH_4/MJ 0.069 gCO_2e/MJ Results tab, Cells H73	Same as CA-GREET 2.0
Tailpipe N_2O	CaRFG Tailpipe Emissions allocated to Ethanol: 0.0002 gN_2O/MJ cell B269 CaRFG Tailpipe Emissions allocated to CARBOB: 0.0031 gN_2O/MJ cell B273[6]	1.418 $gN_2O/MMBtu$ 0.0013 gN_2O/MJ 0.401 gCO_2e/MJ Results tab, Cells H74	Same as CA-GREET 2.0

Table 35 compares transport and distribution parameters and values for CARFG between the two models.

Table 35. Comparison of T&D of CA Reformulated Gasoline

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
CA-RFG Transportation	80% by pipeline for 50 miles to blending terminal and 20% of the transportation is direct from the refinery gate by HDDT to fueling stations	95% by pipeline, 150 miles 5% by rail, 250 mi	Same as CA-GREET 2.0
CA-RFG Distribution	Truck HDDT, for 50 miles	100% by HDDT, 30 miles	Same as CA-GREET 2.0

Table 36 compares refining parameters for ULSD between the three models.

Table 36. Comparison of ULSD Refining Parameters

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Low Sulfur Diesel Refining Energy Efficiency	88% (Petroleum - Cell AQ62)	90.9% (Petroleum - Cell BO82)	85.87% (Petroleum - Cell BO82)
Total Energy for Refining/Processing to Produce Low Sulfur Diesel	120,000 Btu/mmBtu fuel throughput (Petroleum Tab - Cell AV81:AV89)	91,000 Btu/mmBtu fuel throughput (Petroleum Tab – Cells BO86:99)	141,300 Btu/mmBtu fuel throughput (Petroleum Tab - Cells BO107:BO117)

Table 37 compares transport and distribution parameters and values for ULSD between the three models.

Table 37. Comparison of T&D Parameters for ULSD

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
ULSD Transportation **ULSD Distribution**	Pipeline: 80.0% for 50 miles by pipeline to rack and 20% direct from the refinery gate by HDDT to fueling stations Distribution: From Bulk terminal to refueling station for 50 miles by HDDT.	After selection diesel for CA use in Inputs Tab – F102 Pipeline: 95.0%, 150miles Rail: 5.0%, 250 miles From Bulk terminal to refueling station: 100% HDDT, 30 miles.	Same as CA-GREET 2.0

Section 8: Renewable Natural Gas

Table 38 compares differences between the three models in the lifecycle analysis of renewable natural gas.

Table 38. Comparison of Renewable Natural Gas Parameters

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Landfill Gas to LNG: Extraction and Processing	A column was added to distinguish Extraction (recovery) and Processing energy and emissions for landfill gas to LNG. (RNG Tab Cells O351-P390)	Extraction and Processing are combined in a single “Production” stage. RNG Tab Cells N351:N390	A column was added to distinguish Extraction (recovery) energy and emissions for landfill gas to LNG. (RNG Tab Cells E558-E605) Note: In CA-GREET 3.0, flaring of biogas in landfills is considered baseline operation and no credits are provided for ‘no flaring’ at upgrading plants with no attendant tailpipe CO emissions from combustion of RNG in vehicles,
Transmission of RNG site to LNG Plant	A column was added to allow for transportation of RNG by pipeline. Distance in miles must be supplied by applicant in the T1 Calculator tab. (RNG Tab Cells Q351-Q390)	Not Included	A column was added to allow for transportation of RNG by pipeline. (RNG Tab Cells L558:L605)
Landfill Gas CH_4 Leakage during Processing	1% of feed used in regulation. (RNG Tab cell B173) Biogas processing leakage is based on studies of Anaerobic Digester (AD) systems. Four sources are cited[26], in support of 2% methane leakage in biogas processing from AD systems. 1.0% leakage is allocated to 1st cleanup and 1.0% of feed to 2nd cleanup. (RNG Tab, Cells B177 and C177 respectively)	2% of feed (RNG Tab cell E323)[26]	Same as CA-GREET 2.0. (RNG Tab cell E323)

Section 9: Fossil Natural Gas

CA-GREET 3.0 updated natural gas to reflect values in GREET 1 2016 with ratio 49.78% conventional NG and 50.22% shale NG.[52] Table 39 compares methane leakage for shale derived natural gas between the three models.

Table 39. Methane Leakage Share for Shale Derived Natural Gas

<table>
<tr><th>Parameter</th><th>CA-GREET 2.0</th><th>GREET1 2016[53]</th><th>CA-GREET 3.0[54,55]</th></tr>
<tr><td>NA-NG Process</td><td>Processing CH_4 Venting & Leakage: 26.71 gCH_4/mmBtu (Inputs G116)</td><td>Processing CH_4 Venting & Leakage: 26.24 gCH_4/mmBtu (Inputs G126)</td><td>Same as GREET 1 2016</td></tr>
<tr><td>NA-NG T&D</td><td>Inputs Tab, Cells G117-G118
<table>
<tr><th>Stage</th><th>gCH_4/ mmBtu of NG throughput</th></tr>
<tr><td>Transmission and Storage Venting and Leakage</td><td>81.189</td></tr>
<tr><td>Distribution Venting and Leakage</td><td>63.635</td></tr>
<tr><td>Sum</td><td>144.82</td></tr>
</table></td><td>Inputs Tab, Cells G127-G128
<table>
<tr><th>Stage</th><th>gCH_4/mmBtu of NG throughput</th></tr>
<tr><td>Transmission & Storage Venting & Leakage</td><td>74.55</td></tr>
<tr><td>Distribution Venting and Leakage</td><td>17.699</td></tr>
<tr><td>Sum</td><td>92.25</td></tr>
</table></td><td>Inputs Tab, Cells G127-G128
<table>
<tr><th>Stage</th><th>gCH_4/mmBtu of NG throughput</th></tr>
<tr><td>Transmission & Storage Venting & Leakage</td><td>74.55</td></tr>
<tr><td>Distribution Venting and Leakage</td><td>17.699</td></tr>
<tr><td>Sum</td><td>92.25</td></tr>
</table></td></tr>
</table>

52 Energy Outlook 2015 - EIA - DOE. http://www.eia.gov/beta/aeo/#/?id=14-AEO2015&cases=ref2015

53 Andrew Burnham, Jeongwoo Han, Amgad Elgowainy, and Michael Wang. "*Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET™ Model*", Argonne National Laboratory, October 2013. https://greet.es.anl.gov/publication-ch4-updates-13

54 A. Burnham, J. Han, A. Elgowainy, M. Wang, "Updated Fugitive Grenhouse Gas Emissions for Natural Gas Pathways in the GREET1_2014 Model", (October 3, 2014) https://greet.es.anl.gov/publication-emissions-ng-2014

55 Staff notes that natural gas throughput is affected by LHV of NG. As a result, these parameters are slightly different than the reference due to different natural gas LHVs and densities used between GREET1 2013 and GREET1 2014 compared to CA-GREET 3.0.

Table 40 compares transportation energy intensity and transport distances for fossil natural gas between the three models.

Table 40. Natural Gas Pipeline Transportation Energy Intensity and Transport Distances

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
Pipeline Distance from NG Fields to end use	The distance for NG to stationary combustion sources is 680 miles. (T&D_Flowcharts tab, Cell F475)	375 miles (T&D Flowcharts tab, Cell F502)	Same as CA-GREET 2.0 (T&D_Flowcharts tab, Cell F502)
Pipeline Distance to California CNG Stations	1,000 miles (T&D_Flowcharts tab, Cell F485)	750 miles (T&D_Flowcharts tab, Cell F522)	Same as CA-GREET 2.0 (T&D_Flowcharts tab, Cell F522)
Pipeline Distance to California LNG Plants	Applicant must report transport distance (T&D_Flowcharts tab, Cell F375)	To U.S LNG Plant: 50 miles (T&D_Flowcharts tab, Cell F402)	Applicant must report transport distance (T&D_Flowcharts tab, Cell F402)

Section 10: Propane

Table 41 below compares changes in CA-GREET 3.0 with factors in GREET 1 2016 for LPG transport.

Table 41. Comparison of Propane Parameters

Parameters	CA-GREET 2.0	GREET1 2016	CA-GREET 3.0
LPG Transport	Propane exempt from the regulation.	T&D Tab, Cells O206-O210 (from GREET default)LPG Transport to LPG plant • Ocean Tanker 7% for 5200 miles • Barge 6% - 520 miles • Pipeline 60% - 400 miles • Rail 34% - 800 miles LPG Distribution to stations • Truck 30 miles	T&D Tab, Cells O206-O210 (from GREET default) LPG Transport to LPG plant in US • Ocean Tanker 7% for 5200 miles • Barge 6% - 520 miles • Pipeline 60% - 400 miles • Rail 34% - 800 miles LPG Distribution to stations in CA (assumed to be similar to NG) • Rail 1000 miles • Truck 90 miles (to be the same as other fuels)