CA-GREET3.0 Supplemental Document and Tables of Changes

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CA-GREET3.0 Supplemental Document and Tables of Changes

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Summary of major modifications made to the Argonne GREET1_2016 model to create the California-specific CA-GREET3.0 for use in the Low Carbon Fuel Standard Program

The Low Carbon Fuel Standard program uses a "well-to-wheel" life cycle analysis (LCA) to calculate the carbon intensity (CI) of all transportation fuels. To determine each fuel pathway's CI, the greenhouse gas (GHG) emissions from all steps in the fuel's life cycle are summed, adjusted to carbon dioxide equivalent (CO_2e), and divided by the fuel's energy content in megajoules. Carbon intensity is expressed in terms of grams of CO_2 equivalent per megajoule (gCO_2e/MJ).

The CIs are calculated using a modified, California-specific 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 modified Argonne's GREET1_2016 version to create CA-GREET3.0. This document provides details of modifications made to GREET1_2016. 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 and calculations which do not exist in Argonne's model. In addition, information is also included for comparison with the previous version of the California model, CA-GREET2.0.

The following bulleted list highlights critical modifications of GREET1_2016 in creating CA-GREET3.0. Complete details are provided in sections to follow.

- Unlike Tier 1 Calculators of the CA-GREET2.0 model, where user inputs were specified in yellow cells of the T1 Calculator tab, CA-GREET3.0 does not 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.

- Electricity resource mixes for 26 subregions in U.S. are based on the U.S. EPA's 11th edition of the Emissions & Generation Resource Integrated Database with year 2014 data (eGRID2014v2, released 2/27/2017). Staff has incorporated these resource mixes into the CA-GREET3.0 model in addition to a U.S average, User Defined, Brazilian, and a Canadian electricity resource mix.

- 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 and the mobile source emission inventory from

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[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.

EMFAC2011. For natural gas vehicles, tailpipe emission factors are calculated using data from various sources and details are provided in Section 1.

- Staff added used cooking oil (UCO), tallow (animal fat), and distiller's corn/sorghum oil as pathway feedstocks for biodiesel and renewable diesel.

- Staff added cellulosic ethanol from corn or sorghum fiber to the Tier 1 Simplified CI Calculator for Starch and Fiber Ethanol that is based on CA-GREET3.0, though the corn/sorghum fiber pathway is not included in the CA-GREET3.0 model.

- The baseline year of the LCFS program is 2010, as specified in the regulation. In this version of CA-GREET, staff used outputs from the Oil Production Greenhouse Gas Emissions Estimator (OPGEE)[4] Version 2.0b for calculating the carbon intensity (CI) of crude oil used in California refineries in 2010. Refinery efficiencies and carbon intensities for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) and ULSD are calculated from the LP modeling data for California-specific refineries provided by Argonne. The electricity mix and NG production data used in CARBOB and ULSD reflect the 2010 baseline year.

- The regasification-processing step for liquefied natural gas (LNG) to compressed natural gas (CNG) pathway in the previous CA-GREET2.0 model is eliminated for LNG. 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 included in the model.

- Staff used the 2006 IPCC GHG Inventory Guide.[5] Tier 1 default emission factors for N in N_2O as percentage 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 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 percentage of N in N-fertilizer and biomass.

- Changes made to the GREET1_2016 model related to propane and conventional jet fuel are detailed in Section 11. The electricity mix and NG production data used in conventional jet fuel reflect the 2010 baseline year.

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[4] El-Houjeiri, H.M., Vafi, K., Masnadi, M.S., Duffy, J., McNally, S., Sleep, S., Pacheco, D., Dashnadi, Z., Orellana, O., MacLean, H., Englander, J., Bergerson, J and A.R. Brandt. Oil Production Greenhouse Gas Emissions Estimator (OPGEE) Model Version 2.0b, Nov 30th, 2017

[5] Klein C.D., Novoa R.S.A., Ogle S, Smith K.A., Rochette P., Wirth T.C. Chapter 11: N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_N2O&CO2.pdf

- Heating values (HHV and LHV) and densities of gases in CA-GREET3.0 are adjusted to reflect ambient temperature at 60°F and pressure at 1 atm, as it is the standard reference condition used in commercial transactions by the oil and gas industries.

- In consultation with Argonne, staff adjusted (1) fuel economy of the trucks (HHDT and MHDT); (2) cargo payload of the trucks for corn, soybean, and canola; (3) cargo payload of ocean tankers for vegetable oil, biodiesel and renewable diesel; and (4) fuel efficiency and/or energy intensity of trucks and barges. Transportation related parameters for rendered oil, raw tallow and raw UCO were also added.

- Staff corrected the nitrogen content of sugarcane straw to be the average of 4 values, and provided the yeast usage for sugarcane ethanol production. Staff also removed the "VOC from bulk terminal" value in Sugarcane Farming as it is an erroneous entry in GREET1_2016.

The following bulleted list highlights modifications to Tier 1 Simplified CI Calculators since the March 6th posting:

Changes applying to all Simplified CI Calculators:

- Emission factors updated to reflect update to eGRID2014v2 and T&D modifications
- Added field for input of application number

Starch and Fiber Ethanol:

- Biogas and biomass usage and transportation were added as energy inputs to the Starch and Fiber Ethanol Calculator, which also impacted the denaturant calculation
- User-defined option for corn transport removed, and conditional default for corn sourced from corn-growing regions reduced to 40 miles. Rail distance for corn and sorghum shipped to California was updated to 1900 miles.
- Loss factor allocation formula corrected.
- Added application description input field.
- Added user-defined corn transportation option.
- Changed the conditional default truck mileage for ethanol plants in CA to 40 miles.
- Changed corresponding volumes from un-denatured ethanol gallons to denatured ethanol gallons.
- Corrected the calculation for the farm-to-stack transportation.

Biodiesel and Renewable Diesel:

- Clarified that UCO transport field applies to either raw UCO sourced from restaurants or rendered oil from rendering facilities
- Added input for user to declare whether the application is for a provisional pathway
- Added the option to select a User-Defined Ocean Tanker size for BD/RD transport

- Corrected pointing errors in formulas for raw UCO BD transport and raw tallow BD transport (BD)
- Corrected pointing error to formula for RD coproduct credit (RD)
- Corrected pointing errors to formula for RD loss factors (RD)
- Modified emission factor for soy oil transport in RD-Production tab to point to emissions factor table instead of static value. Emission factor unchanged (RD)
- Corrected pointing error for canola oil yield (RD)
- Corrected pointing errors in formulas for canola transport by MDT and HDT and other modes (RD)
- Corrected pointing error in formula for corn oil RD loss factors (RD)
- Corrected operators in formula for raw UCO RD transport and raw tallow RD transport (RD)
- Corrected pointing error in formula pointing to rendered tallow transport by rail rather than by barge (RD)
- Corrected pointing error in formula for displacement credit for light hydrocarbons (RD)
- Deleted the UCO collection energy input as the process would occur in absence of the use of the feedstock for fuel production.

Sugarcane-Derived Ethanol

- Nitrogen to N_2O conversion factor in fertilizer for sugarcane has been equalized with conversion factor for corn (1.325%)
- Cane ethanol T&D in California has been updated to use the CAMX eGRID option
- Changed pointing error in formula for conversion of CO and VOC to GHG emissions by referencing the full CA-GREET conversion factor cell rather than using a static value rounded off to two decimal points.
- Corrected value for GWP of bulk terminal emissions.
- Corrected the nitrogen content of sugarcane straw
- Provided the yeast usage for sugarcane ethanol production.
- Included VOC and CO emissions from sugarcane bagasse combustion.
- Removed the “VOC from bulk terminal” value in Sugarcane Farming as it is an erroneous entry in GREET1_2016.
- Updated nitrogen fertilizer inputs for both 80% and 65% mechanized harvesting scenarios.

Biomethane from Organic Waste

- Replaced the names of categories “food waste” and “green waste” with “Food Scraps” and “Urban Landscaping Waste”, respectively. The characterization and possible sources of these two waste categories have been specified in the calculator and its accompanied instruction manual.
- Provided the degradable organic content (DOC) values of additional common organic waste categories. Staff also provided analytical and mathematical

guidance on determining the DOC and the DOC_f factors for feedstock that cannot be classified into any listed categories.

- Adjusted baseline (avoided) emissions from landfill to include biogenic CO_2.
- Changed the methane and N_2O emission factors for CNG/LNG vehicle (tailpipe emissions) to align with the baseline emissions calculation.

CA Crude Recovery

- Updated the energy efficiency, share of process fuels, and feed loss for the CA Crude Recovery process, based on the latest OPGEE model.

Section 1: Tailpipe Emission Factors

The Argonne version of the model uses federal standard requirements for tailpipe emission factors for transportation vehicles. However, California standards require lower tailpipe emissions compared to federal standards for all vehicles sold in the state. Also, fuel specifications in California are different compared to federal fuel specifications. These lead to different formulations and GHG emissions are therefore different compared to federal GHG emissions included in the Argonne version of the model. To reflect California-specific impacts, the CA-GREET3.0 version uses California-specific GHG emission factors for all fuels for which data are available. If data are unavailable, federal emission standards are used in the model.

a. Tailpipe Emission Factors for combustion of CaRFG, ULSD and conventional jet fuel:

   Tailpipe emission factors for California-specific CaRFG and ULSD are not available in GREET1_2016 and these factors are shown in Table 1. The same table includes emission factors for conventional jet fuel for aircraft refueled in California.

   i. Because 2010 is the baseline of the California LCFS, staff continue to use emission factors from the 2010 data in California's Greenhouse Gas Inventory[6] and the mobile source emission inventory, EMFAC2011[7] to calculate emission factors for CaRFG and ULSD.

   ii. The tailpipe CO_2 emission factor for CaRFG is calculated by converting and allocating the carbon-content of CARBOB to CO_2, and subtracting the carbon emitted as CH_4. This is the same approach used in CA-GREET2.0.

   iii. The tailpipe CO_2 EF for ULSD is calculated by converting the carbon-content of ULSD to CO_2, and subtracting the carbon emitted as CH_4. This is the same approach used in CA-GREET2.0.

   iv. The tailpipe CO_2 EF for conventional jet fuel is calculated by converting the carbon-content of jet fuel to CO_2, and subtracting the carbon emitted as CH_4. CH_4 and N_2O EFs for jet fuel in CA-GREET3.0 represent the average values from six different types of passenger aircraft and four different types of freight aircraft (Table 2).

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[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

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

Parameter	Emission	CA-GREET2.0 (g/MJ)	GREET1_2016 (g/MJ)	CA-GREET3.0 (g/MJ)
CARBOB (or CaRFG)	CH_4	0.14	Not included	0.14[6]
	N_2O	0.91		0.91[6]
	CO_2	72.89		72.89
	CO_2e	73.94		73.94
ULSD[8]	CH_4	0.03	Not included	0.03[6]
	N_2O	0.72		0.72[6]
	CO_2	74.10		74.10
	CO_2e	74.86		74.86
Jet Fuel	CH_4	Not included	$8.45*10^{-5}$	$8.45*10^{-5}$
	N_2O		$1.65*10^{-4}$	$1.65*10^{-4}$
	CO_2		72.92	73.16
	CO_2e		72.97	73.21

Table 2. Tailpipe CH_4 and N_2O Emissions for different Aircraft

	CH_4 (g/mmBtu)	**N_2O (g/mmBtu)**
Passenger Aircraft, Single Aisle (SA)	0.112	0.220
Passenger Aircraft, Small Twin Aisle (STA)	0.067	0.130
Passenger Aircraft, Large Twin Aisle (LTA)	0.029	0.056
Passenger Aircraft, Large Quad (LQ)	0.027	0.053
Passenger Aircraft, Regional Jet (RJ)	0.147	0.288
Passenger Aircraft, Business Jet (BJ)	0.156	0.306
Freight Aircraft, Single Aisle (SA-F)	0.174	0.342
Freight Aircraft, Small Twin Aisle (STA-F)	0.096	0.188
Freight Aircraft, Large Twin Aisle (LTA-F)	0.047	0.092
Freight Aircraft, Large Quad (LQ-F)	0.037	0.072
Average	**0.089**	**0.175**

[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

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-GREET3.0 uses the same calculation methodology as used in CA-GREET2.0. The CO_2 emissions for CNG and LNG presented in Table 3 from combustion are calculated based on the carbon content of the fuel (assuming complete oxidation of VOC and CO to CO_2). Carbon emitted as CH_4 is subtracted from this calculation.

Table 3. Tailpipe Carbon Dioxide Emissions for CNG and LNG Vehicles

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
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**	57.23 gCO_2/MJ	72.4% gC/gNG * 22.0 gNG/ft^3 * 44/12 gCO_2/gC/ 983 Btu/ft^3 * 10^6 Btu/MMBtu = 58,853.65 gCO_2/MMBtu Correction for C as CH_4: (58,853.65 – 203.31*44/16)/1055.06 = **55.78 gCO_2/MJ**
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**	57.46 gCO_2/MJ	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**

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 Laboratory, U.S. EPA[9] and Lipman and Delucchi (2002).[10] The general formula used is given in Equation 1: factors **A** through **D** in bold denote variables referred to in subsequent tables.

[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. General Formula for Tailpipe Emission Factor Calculation

$$\left(\boldsymbol{A}\ Species\ Emission\ Factor\ \frac{\text{g species}}{\text{mi}} \times \mathbf{B}\ NG\ Vehicle\ Scale\ Factor\ \%\right) \times \left(\boldsymbol{C}\ Baseline\ Fuel\ Economy\ \frac{\text{mi}}{\text{gal}} \times \mathbf{D}\ NG\ Vehicle\ Scale\ Factor\ \%\right) \div GGE\ (or\ DGE) \frac{\text{Btu}}{gal} \times 10^6\ \frac{\text{Btu}}{\text{MMBtu}} = Species\ Emission\ Factor\ \frac{\text{g Species}}{\text{MMBtu}}$$

Scale factors for fuel economy are provided relative to gasoline for all light and medium duty vehicles in Table 4, Table 5, and Table 6 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 4. 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 Factor C	Fuel Economy Scale Factor[11] Equation 1 Factor D	Source
Class 2b Heavy-duty pickup trucks and vans	17.20	Same as gasoline	ANL HDV, 2015.
Class 2a Light Duty Trucks (LDT2)	16.43	Same as gasoline	LDT2_TS tab
Light Duty Trucks (LDT1)	20.06	Same as gasoline	LDT1_TS tab
Gasoline Cars	26.08	Same as gasoline	Cars_TS tab

[11] 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

Table 5. 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 Factor A	NGV CH_4 Scale Factor Equation 1 Factor B	Source	Baseline Vehicle N_2O (g/mi) Equation 1 Factor A	NGV N_2O Scale Factor Equation 1 Factor 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	0.041	100	LDT2_TS tab
Light Duty Trucks (LDT1)	0.0126	1000	LDT1_TS tab	0.010	100	LDT1_TS tab
Cars	0.0106	1000	Cars_TS tab	0.008	100	Cars_TS tab

Table 6. 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
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[12] includes methane emission factors on a fuel throughput basis, rather than per mile, for ten representative HDVs. Therefore, a scale factor approach is used only for N_2O emissions from HDVs in CA-GREET3.0. NG vehicle fuel economy is provided in Btu/mile for these vehicles, eliminating the need for a scale factor adjustment to this 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

$$\text{(Tailpipe + Crankcase) CH}_4\text{ Emission Factor } \frac{\text{g CH}_4}{\text{MMBtu NG}} = \text{Vehicle CH}_4\text{ Emission Factor} \frac{\text{g CH}_4}{\text{MMBtu NG}}$$

Equation 3. Heavy Duty Vehicles Nitrous Oxide Emission Factor Calculation

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

Table 7, Table 8, and Table 9 provide details of fuel economy, methane emissions, and nitrous oxide emissions respectively for NG use in HDVs. Table 10 summarizes calculated emissions factors for HD vehicles which use CNG as a fuel.

Table 7. 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

[12] 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

Table 8. 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 9. 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 10. Calculated Emission Factors for Heavy Duty NG Vehicles*

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 11 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.[13] 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) (lbs.), and do not align well with the ANL HDV Classes. These two sources were combined in order to estimate the proportion of fuel consumed by each vehicle type, as described below and in Table 12 and Table 13.

Vehicle Class 4 to 8 all fall within the broad weight range defined as heavy-duty in the LRT. These classes include not only a wide range of body types, engines, and pay loads,

[13] 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

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 11. Alignment of Vehicle Categories in GREET (source of emission factors) and EIA AFV User Database and LCFS Reporting Tool Database (source of fuel consumption shares)

<table>
<tr><th>MOVES 2014 Vehicle Categories</th><th>GREET Vehicle Categories</th><th>EPA GVWR Rating</th><th>EPA GVWR (lbs)</th><th>LCFS Reporting Tool Vehicle Categories</th><th>EIA Vehicle Categories</th><th>EIA Vehicle Types</th></tr>
<tr><td></td><td>Cars</td><td>N/A</td><td></td><td rowspan="4">Light & Medium Duty, GVWR ≤ 14,000 lbs</td><td rowspan="3">Light Duty, GVWR ≤ 8,500 lbs</td><td rowspan="3">Automobiles, Other</td></tr>
<tr><td>Light Duty Trucks</td><td>LDT 1</td><td>LDT 1 & 2</td><td>Up to 6,000</td></tr>
<tr><td>Light Duty Trucks</td><td>LDT 2</td><td>LDT 3 & 4</td><td>6,000-8,500</td></tr>
<tr><td>Class 2b passenger trucks or light commercial trucks</td><td>Heavy-duty pickup trucks and vans</td><td>HDV Class 2b</td><td>8,500-10,000</td><td rowspan="4">Medium Duty, 8,501 < GVWR ≤ 26,000 lbs</td><td rowspan="4">Trucks, Vans, Pickups</td></tr>
<tr><td>Class 4 and 5 light heavy duty single unit short- or long-haul trucks</td><td>Light heavy-duty vocational vehicles</td><td>HDV Class 4</td><td>14,000-16,000</td><td rowspan="9">Heavy Duty, GVWR > 14,001 lbs</td></tr>
<tr><td>Class 6 and 7 medium heavy duty single unit short- or long-haul trucks</td><td>Medium heavy-duty vocational vehicles</td><td>HDV Class 6</td><td>19,500-26,000</td></tr>
<tr><td>Class 6 and 7 school buses</td><td>School buses</td><td>HDV Class 6 or 7</td><td>19,500-33,000</td></tr>
<tr><td>Class 8 heavy heavy duty single unit short- or long-haul trucks</td><td>Heavy heavy-duty vocational vehicles</td><td>HDV Class 8b</td><td>>60,000</td><td rowspan="6">Heavy Duty, GVWR > 26,000 lbs</td><td rowspan="6">Trucks, Transit buses, School buses, Intercity buses</td></tr>
<tr><td>Class 8 refuse trucks</td><td>Refuse trucks</td><td>HDV Class 8a</td><td>33,000-60,000</td></tr>
<tr><td>Class 8 combination long-haul trucks</td><td>Combination long-haul trucks</td><td>HDV Class 8b</td><td>>60,000</td></tr>
<tr><td>Class 8 combination short-haul trucks</td><td>Combination short-haul trucks</td><td>HDV Class 8b</td><td>>60,000</td></tr>
<tr><td>Class 8 transit buses</td><td>Transit buses</td><td>HDV Class 8a</td><td>33,000-60,000</td></tr>
<tr><td>Class 8 intercity buses</td><td>Intercity buses</td><td>HDV Class 8a</td><td>33,000-60,000</td></tr>
</table>

Figure 1. Comparison of Vehicle Categorization among Data Sources

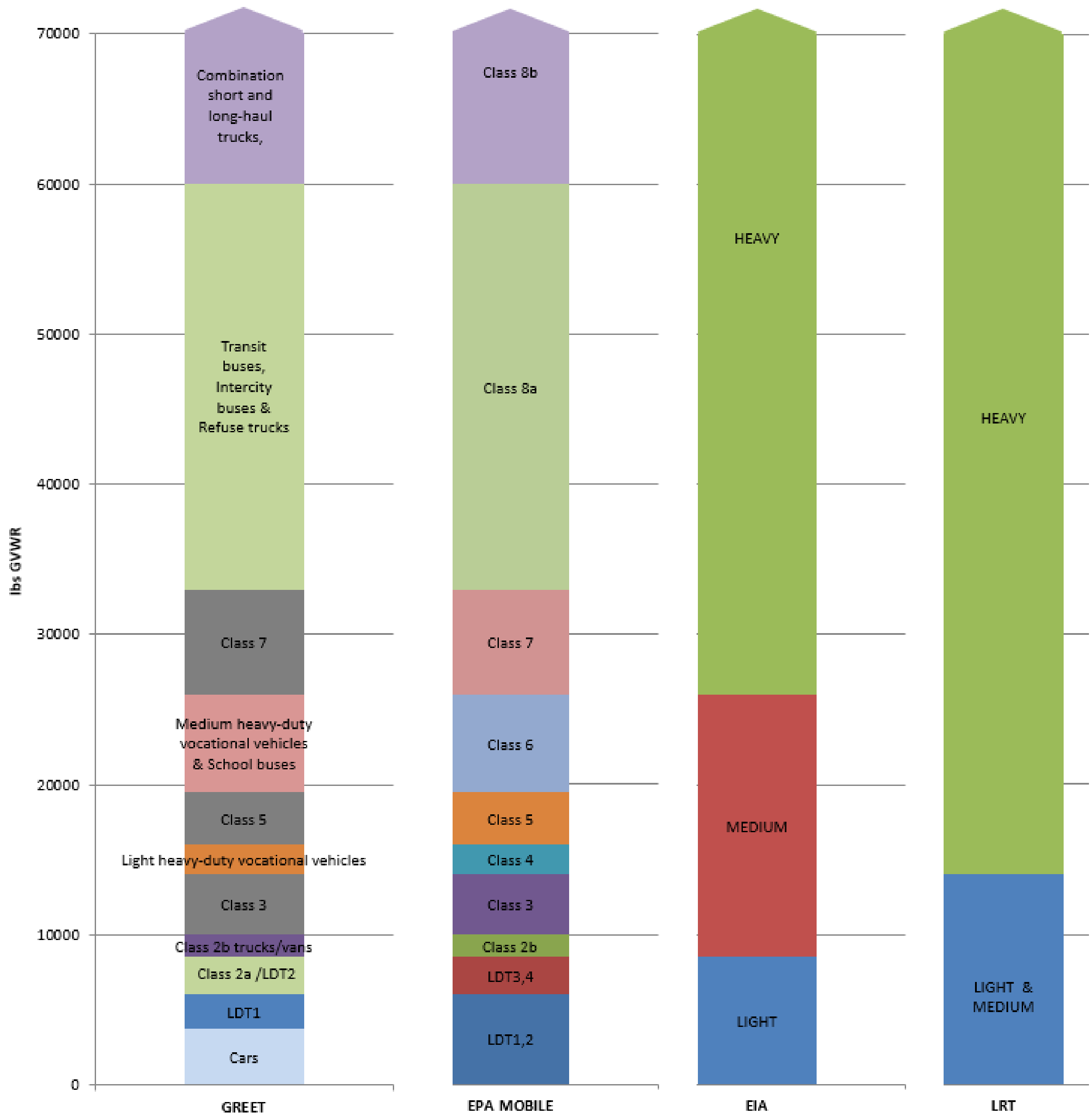

Table 12. Adjustment of 2011 EIA Fuel Shares as a Proportion of LRT 2014 Fuel Consumption by CNG heavy and Light-to-Medium Duty Vehicles

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 13. 2011 EIA Fuel Consumption Shares of 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 lbs.)	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 14 details matching ANL emission factors 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[14] to quantify fuel consumption in school, transit and intercity buses.

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

Table 14. 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 was used to calculate a consumption-weighted average emission factor.

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

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

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 15 details the results from fuel consumption weighted emission factors for CNG and LNG vehicles in CA-GREET3.0.

Table 15. 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	gCH_4/MMBtu		gN_2O/MMBtu		gCO_2e/MJ		Note
	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	203.31	0.02	0.307	5.693	**4.90**	Based on EIA's Alternative Fuel Vehicle Data 2011. Same as CA-GREET2.0. Not available in GREET1_2016
Light & Med Duty CNG	20.980		1.744		0.990		
Heavy Duty LNG		207.23		0.003		**4.91**	

Section 2: Electricity

The Argonne version of the model uses the 10-region North American Electric Reliability Corporation (NERC) to develop region-specific GHG emissions for electricity generation. In developing CA-GREET, however, CARB uses the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID)[15] to determine the impact of stationary electricity use in fuel and feedstock production. The eGRID contains 26 subregions to capture subregional variabilities in GHG emissions for electricity generation, and is used in fuel pathway CIs to ensure consistency across all subregions, in and outside of the state.

The conversion to the 26 eGRID subregional mixes in CA-GREET3.0 was accomplished by modifying the electricity resource mixes and subregions in the Fuel_Prod_TS tab of CA-GREET3.0 and the associated links to the Inputs tab. Staff also added U.S Average, User Defined, Brazilian Average and Canadian Average mixes, in addition to the 26 eGRID subregions, for a total of 30 subregional electricity mixes. Note that the electricity transmission and distribution loss factor for all North America regions (including all subregions in the U.S. and Canada) in CA-GREET3.0 is assumed to be 6.5%, while the same loss factor for Brazilian electricity is 8.1%.

To determine the CI of California average grid electricity used directly as a transportation fuel (e.g., electricity used for EV charging or fixed guideway transit), the electricity resource mix is based on the California Energy Commission (CEC) 2016 QFER data[16] (Table 19, also available in the Inputs tab of the model). The data and methodology used

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[15] United States Environmental Protection Agency, 11th edition of the Emissions & Generation Resource Integrated Database with year 2014 data (eGRID2014v2, released February 27, 2017): https://www.epa.gov/sites/production/files/2017-02/documents/egrid2014_summarytables_v2.pdf

[16] 2016 California Total System Electric Generation data from California Energy Commission (CEC) website, accessed 11/2017: http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html

in determining the CI of this pathway is documented in the Lookup Table Pathways Technical Support Documentation.

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 in the EF tab. The second set is taken from the U.S. EPA and EIA emission factor database. For the LCFS fuel pathways, only stationary electricity resource mixes in CA-GREET3.0 are considered. Details of electricity emission factors incorporated in CA-GREEET3.0 are discussed below. Staff restructured the available GREET1_2016 regional electricity resource mixes to allow fuel producers to use more representative subregional electricity resource mixes to obtain a more representative CI for the subregion. 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 the 26 subregions.

ii. Table 16 compares the subregion categories used in CA-GREET3.0 to the NERC region categories used in GREET1_2016.

Table 16. Comparison of Electricity Resource Mix Selections Available in the Three Models

CA-GREET2.0				**GREET1_2016**		**CA-GREET3.0**			
Electricity Mix Stationary Use				**Electricity Mix Stationary Use**		**Electricity Mix Stationary Use**			
1	US Ave	16	SRTV	1	U.S.	1	US Ave	16	SRTV
2	User Defined	17	SRSO	2	ASCC	2	User Defined	17	SRSO
				3	FRCC				
3	CAMX	18	NEWE	4	HICC	3	CAMX	18	NEWE
4	NWPP	19	NYUP	5	MRO	4	NWPP	19	NYUP
5	AZNM	20	RFCE	6	NPCC	5	AZNM	20	RFCE
6	RMPA	21	NYLI	7	RFC	6	RMPA	21	NYLI
7	MROW	22	NYCW	8	SERC	7	MROW	22	NYCW
8	SPNO	23	SRVC	9	SPP	8	SPNO	23	SRVC
9	SPSO	24	FRCC	10	TRE	9	SPSO	24	FRCC
10	ERCT	25	AKMS	11	WECC	10	ERCT	25	AKMS
11	MROE	26	AKGD	12	CA	11	MROE	26	AKGD
12	SRMW	27	HIOA	13	User Defined	12	SRMW	27	HIOA
13	SRMV	28	HIMS	**13 NERC regions**		13	SRMV	28	HIMS
14	RFCM	29	Brazilian			14	RFCM	29	Brazilian
15	RFCW					15	RFCW	30	Canadian
29 subregions						**30 subregions**			

iii. eGRID Subregions Compared to NERC Regions

Table 17 compares eGRID subregions to subregions that are part of NERC regions. Most subregions are not individual states and most regions are not subregions. There are a few exceptions. Alaska and Hawaii are states with their own NERC regions, but are divided by subregions. Florida as a state has the same region (FRCC) and subregion

(FRCC). California is part of the WECC NERC region, but is its own subregion (CAMX). The electricity resources mixes of U.S. average and 26 subregions are included in Table 18.

Table 17. eGRID Subregions 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
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

Table 18. Electricity Resources Mix of U.S. average and 26 eGRID Subregions (unit: %)

Region	Coal	Residual Oil	NG	Nuclear	Hydro	Biomass	Wind	Solar	Geo-thermal	Others
US	38.67	1.22	27.47	19.50	6.19	1.56	4.43	0.43	0.39	0.13
AKGD	11.68	7.02	66.07	0.00	11.46	1.18	2.60	0.00	0.00	0.00
AKMS	0.00	8.69	10.31	0.00	78.29	0.50	2.20	0.00	0.00	0.00
AZNM	21.25	0.04	39.07	23.56	6.44	0.42	1.79	4.59	2.83	0.01
CAMX	0.43	0.79	62.47	8.98	8.41	3.43	6.54	4.28	4.35	0.34
ERCT	33.21	0.48	45.30	10.62	0.08	0.33	9.81	0.08	0.00	0.10
FRCC	21.65	1.42	61.42	12.67	0.10	1.91	0.00	0.10	0.00	0.73
HIMS	1.59	60.79	0.00	0.00	3.30	3.63	13.85	0.53	8.91	7.40
HIOA	19.93	74.10	0.00	0.00	0.00	3.14	2.51	0.33	0.00	0.00
MROE	71.28	1.39	10.47	0.00	5.04	4.71	6.91	0.00	0.00	0.21
MROW	58.38	0.31	3.16	12.99	5.68	1.30	17.98	0.00	0.00	0.20
NEWE	4.52	3.60	43.19	33.27	6.38	6.81	1.84	0.30	0.00	0.09
NWPP	36.21	0.40	11.93	2.78	39.72	1.09	6.73	0.02	1.03	0.10
NYCW	0.00	2.48	55.18	41.85	0.00	0.48	0.00	0.00	0.00	0.00
NYLI	0.00	11.23	84.00	0.00	0.00	4.18	0.00	0.59	0.00	0.00
NYUP	5.46	0.88	25.91	30.57	30.40	2.06	4.71	0.00	0.00	0.00
RFCE	23.34	1.42	30.68	40.53	1.16	1.31	1.28	0.24	0.00	0.04
RFCM	59.64	2.96	14.61	16.06	0.00	2.28	4.45	0.00	0.00	0.00
RFCW	60.03	1.21	9.29	25.75	0.65	0.60	2.36	0.05	0.00	0.07
RMPA	68.26	0.04	16.00	0.00	2.86	0.17	12.26	0.34	0.00	0.06

SPNO	66.21	0.19	6.47	12.08	0.02	0.10	14.93	0.00	0.00	0.00
SPSO	48.41	2.40	34.51	0.00	2.20	1.57	10.81	0.06	0.00	0.03
SRMV	25.76	2.67	48.97	19.23	1.39	1.73	0.00	0.00	0.00	0.26
SRMW	82.40	0.17	1.18	12.24	0.78	0.12	2.92	0.01	0.00	0.19
SRSO	36.23	0.20	36.51	21.49	2.57	2.96	0.00	0.04	0.00	0.00
SRTV	52.43	0.70	14.79	23.03	7.92	1.09	0.02	0.01	0.00	0.00
SRVC	31.67	0.86	20.76	42.16	1.27	2.92	0.00	0.25	0.00	0.11

iv. Modification of eGRID Subregion Data for California in CA-GREET3.0

Table 19 details how an eGRID subregion resource mix was modified to create a California resource mix for use in CA-GREET3.0. 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 19. Modified California Average Grid Electricity Mix

Electricity Generation	**CA-GREET2.0**	**CA-GREET3.0**			
Region (Data source)	**Modified CAMX**	**CAMX** eGRID2014v2	**Modified CAMX**	**CA Average** CEC 2016	**Modified CA Average ***
Coal	7.15%	0.43%	0.43%	4.13%	4.13%
Oil (Residual oil)	1.38%	0.79%	0.79%	0.01%	0.15%
Gas (Natural gas)	50.75%	62.47%	62.80%	36.48%	50.87%
Other fossil	-	-	-	0.14%	-
Biomass	2.62%	3.43%	3.43%	2.25%	2.25%
Nuclear	15.18%	8.98%	8.98%	9.18%	9.18%
Wind	3.05%	6.54%	6.54%	9.06%	9.06%
Solar	0.36%	4.28%	4.28%	8.11%	8.11%
Geo thermal	4.32%	4.35%	4.35%	4.38%	4.38%
Hydro	15.19%	8.41%	8.41%	11.87%	11.87%
other unknown fuel purchased	-	0.33%	-	14.39%	-
Total	**100%**	**100%**	**100%**	**100%**	**100%**
Application:	Stationary & Transportation uses		Stationary use		Transportation use

* This mix was used to determine the CI of the CA-GREET3.0 Lookup Table Pathway for California Average Grid Electricity supplied to electric vehicles.

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-GREET3.0 the "other" electricity resources are labeled as "other renewable resources." Biomass is often considered renewable, but requires combustion; nuclear involves 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 Inputs 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 integrated into CA-GREET3.0 for the renewable resource mix is shown in Table 20.

Table 20. Other Resource Mixes Integrated into CA-GREET3.0

Electricity Generation Source	CAMX “other” Resource Mix	CA-GREET3.0 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-GREET3.0. These electricity mixes are incorporated in the Fuel_Prod_TS tab in addition to the 26 eGRID subregions.

Table 21 details the electricity mixes in Brazil and Canada. Brazilian Electricity Mix was originally obtained from Empresa de Pesquisa Energética[17] (Energy Research Company). Canadian Electricity Mix was obtained from Statistics Canada 2015.[18]

Table 21. 2014 Brazil and Canada Electricity Resource Mix

Resource Mix (GREET1_2016 Category)	**Brazilian** 2014 data **For CA-GREET3.0**[17]	**Canadian** 2014 data **For CA-GREET3.0**[18]
Coal and Coal Products (Coal)	4.3%	11.5%
Oil Products (Residual Oil)	5.7%	0.4%
Natural Gas	13.0%	7.0%
Biomass	7.4%	0%
Nuclear	2.5%	17.7%
Hydro	65.2%	60.7%
Solar	0%	0.06%
Wind	2.0%	2.2%
Others	0%	0.39%

[17] The Empresa de Pesquisa Energética data was 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 127-0006 Electricity generated from fuels, by electric utility thermal plants, annual (megawatt hour) http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1270006&tabMode=dataTable&p1=-1&p2=9&srchLan=-1.

Also, 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. Verified by (S&T)[2] Consultants Inc.

Section 3: Fuel Specifications

Specifications (e.g., aromatics in diesel) for transportation fuels in California are different compared to federal specifications. The CA-GREET3.0 model uses California fuel specifications and changes made to the Argonne version of the model are detailed in Table 22.

Table 22. Comparison of Fuel Properties and Specifications

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
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-GREET2.0
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-GREET2.0
Ultra-Low Sulfur Diesel	134.47 MJ/gal 127,460 Btu/gal 3,142 g/gal	136.62 MJ/gal 129,488 Btu/gal 3,206 g/gal	Same as CA-GREET2.0

Specifications, especially heating values (HHV and LHV) and densities of gases in CA-GREET3.0 are adjusted to reflect ambient temperature at 60°F and pressure at 1 atm, as it is the standard reference condition used in commercial transactions by the oil and gas industries; details are summarized in Table 23.

Table 23. Comparison of Specifications of Various Gases

Parameter	CA-GREET2.0			GREET1_2016			CA-GREET3.0		
Temperature & Pressure	32°F, 1 atm			32°F, 1 atm			60°F, 1 atm		
Specification	HHV, Btu/CF	LHV, Btu/CF	Density, g/CF	HHV, Btu/CF	LHV, Btu/CF	Density, g/CF	HHV, Btu/CF	LHV, Btu/CF	Density, g/CF
NG	983	1089	22.0	983	1089	22.0	930	1030	20.8
Pure Methane	962	1068	20.3	962	1068	20.3	910	1010	19.2
Gaseous hydrogen	290	343	2.55	290	343	2.55	274	325	2.41
Carbon Dioxide			56.0			56.0			53.0
Still gas (in refineries)	982	1044	20.3	982	1044	20.3	929	987	19.2

Additionally, temperature correction factors for ethanol and biodiesel volume at 60°F (commercial transactions are reported at 60°F) are included in the Fuel_Specs tab of CA-GREET3.0.

Specifically, for ethanol:
$V_{@60°F} = V_{@\,T_{actual}} \times (-0.0006301 \times T_{actual} + 1.0378)$

For biodiesel:
$V_{@60°F} = V_{@\,T_{actual}} \times (-0.00045767 \times T_{actual} + 1.02746025)$

where *V* is volume in gallons and *T* is for temperature in °F.

Section 4: Ethanol

CA-GREET3.0 uses most of the crop farming data from GREET1_2016; however, parameters regarding ethanol production, co-production handling methods, N_2O emissions from biomass and fertilizer, transportation, etc. in CA-GREET3.0 are different. For the LCFS, denaturant used is considered to be CARBOB which is the fossil blendstock in finished gasoline. This section details changes to ethanol parameters in CA-GREET3.0 compared to the Argonne model.

a. Calculation of Carbon Intensity for Denatured Ethanol

Given the supply of ethanol to the California market with a wide range of carbon intensities, staff finds it appropriate to account for a representative CI for ethanol when denaturant is blended with anhydrous ethanol. The calculation for denaturant CI given below is used to determine CI of denatured ethanol (Table 24). The 2.5% denaturant blending is used as a 'standard value' in CA-GREET3.0.

Table 24. Comparison of Calculation of Carbon Intensity for Denatured Ethanol

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Denaturant Content of Denatured Ethanol (D-EtOH) (v/v)	2.50% Petroleum tab[6,7]	2.00% Inputs tab	2.50% Petroleum tab[6,7]
Net Denaturant Contribution to CI (gCO2e/MJ)	0.77	Not available	0.85

b. Corn Ethanol

Table 25 details differences between the three models for corn ethanol. The LCFS program requires facility-specific inputs for energy, co-product and ethanol yields and does not use industry-average values for these inputs. For chemical and enzymes, the CA-GREET3.0 uses a weighted-average carbon intensity calculated from pathway applications certified using CA-GREET2.0 from 2016-2017. N_2O emissions in CA-GREET3.0 use IPCC (2006)[5~~19~~] default values and are different from the Argonne model. Enteric emissions credits are not considered and is the same approach used in CA-GREET2.0.[23]

Table 25. Comparison of Parameters between the Three Models for Corn Ethanol

Parameter	CA-GREET2.0	GREET1_2016[19]	CA-GREET3.0
Farming energy	9,608 Btu/bu [20]	6,924 Btu/bu	Same as GREET1_2016
Fertilizer inputs	Inputs in g/bu N: 423.3 P: 145.8 K: 151.3 $CaCO_3$: 1,149.9	Inputs in g/bu N: 382.95 P: 139.29 K: 146.41 $CaCO_3$: 1,290.21 Herbicide: 5.85 Insecticide: 0.01	Same as GREET1_2016
Ethanol yield	Required to be input by applicants as part of pathway CI certification.	2.86 gal/bu [21]	Required to be input by applicants as part of pathway CI certification.
Yeast and Enzymes	Required to be input by applicants as part of pathway CI certification.	Included	2.02 gCO_2e/MJ based on use of yeast, enzymes and chemicals and calculated as average CI from operational data from LCFS applications (2016-2017).
Moisture content of DDGS	10% is based upon staff pathway application experience	12% [22]	Required to be input by applicants as part of pathway CI certification.
DGS Yield	Required to be input by applicants as part of pathway CI certification.	5.63 bone dry lbs/gal	Required to be input by applicants as part of pathway CI certification.
DGS Reduced Enteric Emissions CREDIT	No reduced enteric emissions credit.[23]	-2,260 gCO2e/MMBtu	No reduced enteric emissions credit.
Drying energy	For applicants who desire a separate pathway to account for separate DGS streams (differentiated by moisture content), meters	11,141 Btu/gal This value is obtained by subtracting NG energy used when a facility is producing	Required to be input by applicants as part of pathway CI certification using dedicated meters for NG used for drying.

[19] Summary of Expansions, Updates, and Results in GREET® 2016 Suite of Models. Systems Assessment Group, Energy Systems Division, Argonne National Laboratory. ANL/ESD-16/21. https://greet.es.anl.gov/files/summary-updates-2016

[20] 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

[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

[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-GREET2.0 Supplemental Document and Tables of Changes, Date June 4, 2015: https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm

	need to be installed to account for drying energy.	dedicated dry and wet DGS streams.	
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 tab. Tier 1 default EFs from IPCC 2006.[5]	1.225%[24,25] Inputs tab	Same as CA-GREET2.0
Additional Process Chemical Inputs (User Defined Values)	H_2SO_4, grams/gal: User Defined NH_3, grams/gal: User Defined NaOH grams/gal: User Defined CaO grams/gal: User Defined Urea grams/gal: User Defined	H_2SO_4, grams/gal: 4.65 NH_3, grams/gal: 17.82 NaOH grams/gal: 22.35 CaO grams/gal: 10.66 Urea grams/gal: No Value	2.02 gCO2e/MJ based on use of yeast, enzymes and chemicals and calculated as average CI from operational data from LCFS applications (as of 12/11/2017).

c. Sugarcane Juice-to-Ethanol

The Argonne version of the model only includes sugarcane juice to ethanol and does not model the conversion of molasses (mostly uncrystallizable sucrose) to ethanol. CA-GREET3.0 accounts for ethanol produced from both these feedstocks. All of the agricultural inputs in CA-GREET3.0 are from the Argonne model. Ethanol production inputs, transport, percentage of sucrose, molasses-related inputs are facility-specific and are different compared to the Argonne model values. This section includes differences between the three models and provides details of molasses modeling in CA-GREET3.0. Electricity co-product credit and Table 26 provides details of parameters in the three models for sugarcane ethanol.

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

[25] 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

Table 26. Comparison of Parameters for Sugarcane Ethanol

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0	
Fertilizer Inputs	N: 800.0 g/MT P: 300.0 K: 1,000.0 Lime: 5,200.0 Herbicide: 45.0 Pesticide: 2.50	N: 925.40 g/MT P: 323.7 K: 1,508.2 Lime: 5,200.0 Herbicide: 45.0 Pesticide: 2.50	**For 80% mechanized harvesting**: N: 995.8 g/MT [26] P: 317.3 K: 1,371.3 Lime: 5,200.0 Herbicide: 45.0 Pesticide: 2.50	**For 65% mechanized harvesting**: N: 1118.8 g/MT P: 311.1 K: 1,237.4 Lime: 5,200.0 Herbicide: 45.0 Pesticide: 2.50
VOC from bulk terminal in sugarcane farming	Not applicable	21.485 g/MT (later deemed as an error by Argonne)	Not applicable	
Yield of sugarcane straw	0.238 dry MT/MT sugarcane	0.14 dry MT/MT sugarcane	Same as CA-GREET2.0	
Amount of sugarcane straw burned in the field	0.214 dry MT/MT sugarcane. LCFS assumes emissions from 100% straw burning in the default CI calculation unless applicant provides proof of the burning ratio, which will be credited back to the pathway.	0.019 dry MT/MT sugarcane, proportioned based on the percentage of manual cutting field	Same as CA-GREET2.0	
Nitrogen content of sugarcane straw	0.37%	Same as CA-GREET2.0	0.53%	
Electricity credit: kWh/gal EtOH	Required to be input by applicants as part of pathway CI certification.	-3.505 kWh/gal EtOH, This is a GREET calculated value.	Required to be input by applicants as part of pathway CI certification.	
Lime (CaO) use to produce $Ca(OH)_2$, for pH adjustment in ethanol processing	Added to CA-GREET2.0, T1 Calculator as a user input. In Seabra et al.[27] an input of 880 g/MT of cane is used for adjusting the sugar-rich juice pH that is produced from crushing cane.	880 g/MT	880 g/MT [29]	
Yeast	0	Same as CA-GREET2.0	3.34 g/gal EtOH	

[26] Values presented here include both baseline and supplemental fertilizer inputs. The baseline fertilizer inputs are identical to CA-GREET2.0; the supplemental N input is based on the amount of collected and burned straw; the supplemental P_2O_5 and K_2O inputs are based on the amount of collected straw.

[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.

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Sugarcane Transportation by HDD	Added HDD to T&D Tab	2 miles by MDT, 10 miles (User Input) by HDT in T&D Tab	Same as GREET1_2016, with truck transport to mill distance to be input by applicants as part of CI certification.
T&D Ocean Tanker and Truck Transportation Distance	The applicant must include transport distance for ethanol transport from Brazil to California.	Ocean Tanker Transportation to United States: 7,416 miles	The applicant must include truck transport distances from the mill to the port, and ocean tanker transport distances from the Brazilian port to a California port. The formula which assesses a back-haul energy charge and emissions impact to ocean transport of ethanol from Port in Brazil to a California Port was added in the T&D tab.

d. Sugarcane Molasses-to-Ethanol

Sugarcane molasses is a byproduct of the finished or table sugar production process, and is commonly used as a feedstock for ethanol production at most sugarcane-based sugar and ethanol mills in Brazil. The sugarcane molasses-to-ethanol pathway parameters are identical to the CA-GREET2.0 parameters in which upstream GHG impacts associated with sugarcane farming, fertilizer and other agricultural inputs, straw burning, sugarcane transport to the mill, and sugar production are apportioned by a calculated mass allocation ratio. This ratio is determined from user inputs based upon allocation of crystallizable and fermentable sugars in cane juice obtained from the sugarcane crush, and made available for the production of finished or table sugar, production of standard molasses, or made available for direct fermentation for the production of ethanol. The mass allocation ratio represents the fraction of unconverted sugars in sugarcane juice sent to sugar production that are made available for fermentation into ethanol. Hence, only that fraction of upstream impacts associated with sugar production can be attributed to sugarcane molasses-based ethanol production. Some GHG emissions associated with raw sugar production are also attributed to the sugarcane molasses-based ethanol pathway. This value in CA-GREET3.0 is 3,700 gCO_2e/ton of cane.[28]

e. Corn Stover Feedstock

To account for the removal of stover, the LCFS analysis attributes emissions from farming energy and chemical inputs required to replace 'harvested' stover to the cellulosic pathway and is the same approach used in CA-GREET2.0.[23] Pathway applicants are also required to limit indirect effects by demonstrating sustainable harvesting of stover used in fuel production. N_2O emissions rate from nitrogenous fertilizer is different in CA-

[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.

GREET models and this has been detailed in the corn ethanol section. For the LCFS, all fuel producers are required to provide facility specific ethanol production and does not consider the use of a default value for ethanol yield as is exists in the Argonne version of the model. Ethanol production Table 27 provides a comparison of parameters for corn stover used as feedstock for cellulosic ethanol between the three GREET models.

Table 27. Comparison of Parameters for Corn Stover to Ethanol

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
N_2O emissions: 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. Tier 1 default EFs from IPCC 2006.[5]	1.525%	Same as CA-GREET2.0
Key Assumptions for harvest of corn stover	Harvesting must be conducted appropriately to limit indirect effects and sustainable harvesting of stover needs to be demonstrated.	Harvest and collection rate [29,30,31] 30%	Same as CA-GREET2.0
Energy Use and Ag Chemical inputs to replace chemicals removed with stover (Btu or g/dry ton)	233,592 Btu Diesel/dry ton transported, N: 7,957 g/dry ton transported, P_2O_5: 2,273.4 g/dry ton transported, K_2O: 13,640.6 g/dry ton transported.	**Farming Energy Use:** 192,500 Btu/ton collected (100% Diesel Fuel). Note that in the ethanol tab, the stover loader (4,200) is included and the ratio of stover harvested to stover collected and transported is **223,592** Btu/dt transported. **Chemical Inputs (per ton transported):** **N:** 7,957.0 g/ton **P:** 2,273.4 g/ton **K:** 13,640.6 g/ton[32]	Same as GREET1_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-GREET2.0	GREET1_2016	CA-GREET3.0
Ethanol Yield and Energy use for Ethanol Production	Required to be input by applicants as part of pathway CI certification.	205kWh/dry ton, Fuel_Prod_TS,[33] With the assumed yield (85 gal/ton) this is equivalent to: 2.412 kWh/gal of ethanol. 85.0 gallons/dry ton [34]	Required to be input by applicants as part of pathway CI certification.

f. Grain Sorghum to Ethanol

Due to the lack of representative and periodic updates to sorghum farming data compared to corn farming from the United States Department of Agriculture, the National Sorghum Producers Association provided the aggregated databased on their 2012 survey of grain sorghum producers.[35] Argonne National Laboratory reviewed the updated grain sorghum data and deemed the data appropriate for use in CA-GREET3.0. Table 28 includes grain sorghum farming and sorghum ethanol production parameters compared among three models.

[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

[35] National Sorghum Producers Carbon Intensity Calculations Based on 2015 SGS North America Report and Supporting Documentation. March 30, 2017

Table 28: Comparison of Parameters for Grain Sorghum to Ethanol

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Farming energy	16,741 Btu/bu includes: Diesel fuel: 35.7% Gasoline: 18.5% NG: 45.7% and Electricity: 0.1%	Same as CA-GREET2.0	10,302 Btu/bu includes: Diesel fuel: 92.8% (including 92.2% diesel and 0.54% jet fuel) Gasoline: 4.8% NG: 1.6% Electricity: 0.8%
Fertilizer inputs	All inputs in g/bu N: 522.0 P: 123.2 K: 19.0 Herbicide: 28.67	All inputs in g/bu N: 522.4 P: 123.5 K: 19.4 Herbicide: 28.67	All inputs in g/bu N: 419.7 P: 101.8 K: 20.2 Herbicide: 28.02
Process Energy use for ethanol production: Btu/gallon of ethanol	Required to be input by applicants as part of pathway CI certification.	18,328 Btu/gal Includes: 15,827 Btu/gal Natural Gas, (86.4%) and 2,501 Btu/gal Electricity, (13.6%)	Required to be input by applicants as part of pathway CI certification.
Ethanol yield	Required to be input by applicants as part of pathway CI certification.	2.81 gal/bu EtOH tab	Required to be input by applicants as part of pathway CI certification.

g. Corn/Sorghum Fiber to Ethanol

Staff added cellulosic ethanol from corn/sorghum fiber process to the Tier 1 Simplified CI Calculator for Starch and Fiber Ethanol that is based on CA-GREET3.0, though the corn/sorghum fiber pathway is not included in the CA-GREET3.0 model. Please see “Tier 1 Simplified CI Calculator Instruction Manual Starch and Fiber Ethanol” for detail. Note that all references to sorghum in this section refer to grain sorghum.

Note that the system boundary of this pathway does not include the upstream corn production process nor land use change (LUC) associated with corn ethanol; however, it takes into account the enzyme (cellulose) use and the reduction in mass of co-produced DGS. Other inputs of this pathway are assumed to be same as the corn starch ethanol pathway.

Section 5: Biodiesel and Renewable Diesel

CA-GREET3.0 uses most of the crop farming data from GREET1_2016; however, parameters regarding biodiesel and renewable diesel production, co-production handling methods, N_2O emission from biomass and fertilizer, and transportation in CA-GREET3.0 were modified to reflect California-specific cases including some parameters which require inputs from production facility as part of pathway CI certification. CA-GREET3.0 also includes used cooking oil (UCO) to biodiesel and renewable diesel pathways which are not available in the Argonne version of the model. For biodiesel and renewable diesel transported from overseas to California, an ocean tanker (37,000 ton cargo payload) is included for transportation of these fuels in CA-GREET3.0.

a. Soy Oil to Biodiesel (BD) or Renewable Diesel (RD)

Table 29 provides a comparison of changes between the three models for soybean biodiesel and renewable diesel pathways.

Table 29. Comparison of Parameters for Soybean Oil to Biodiesel and Renewable Diesel

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Mass of Soy Bean to Mass of Soy Oil Ratio	5.00 lbs. soy/lb. soy oil. This value was changed to be consistent with the mass allocation of soybeans and soy oil.[36,37]	21.3% soy oil. Note there is no loss assumed for extraction in GREET1_2016	Same as CA-GREET2.0
Soy Oil Extraction Energy	Total energy: 3,687 Btu/lb. soy oil	Total energy: 3,687 Btu/lb. soy oil. Original data from National Oilseed Processors Association[38] was subsequently corrected due to errors in the interpretation of the original data.[39]	Total energy: 3,073 Btu/lb. soy oil.[42]
Soy Oil Transesterific-ation Energy	Required to be input by applicants as part of pathway CI certification.	Total energy: 1,213 Btu/lb, which includes: - Natural gas (30.7%), - Electricity (4.6%), - Methanol (64.7%).	Required to be input by applicants as part of pathway CI certification.
Soy Oil Transesterific-ation Chemicals	Required to be input by applicants as part of pathway CI certification.	Chemical input data[40] Sodium Hydroxide 0.44 g/lb. BD Sodium Methoxide 10.48 g/lb.	**For Tier 1 applications:** Sodium hydroxide: 2.42 g/lb. BD Sodium Methoxide: 4.16 g/lb. Hydrochloric acid: 1.05 g/lb. Phosphoric acid: 0.14 g/lb.

[36] CA-GREET 2.0 assumed an average value of 20% oil in soybean and therefore, 20% of the GHG emissions from soybean farming through extraction of soy oil are allocated to biodiesel.

[37] CA-GREET 2.0 assumed an average value of 20% oil in soybean and therefore, 20% of the GHG emissions from soybean farming through extraction of soy oil are allocated to renewable diesel.

[38] Omni Tech International, 2010. Life Cycle Impact of Soybean Production and Soy Industrial Products. Prepared for the United Soybean Board. http://biodiesel.org/reports/20100201_gen-422.pdf (Accessed on 01/02/2018)

[39] Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., O'Connor, D., Duffield, J. 2018. Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. Bioresource Technology. 251:249-258. https://doi.org/10.1016/j.biortech.2017.12.031

[40] 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

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
		Hydrochloric acid 7.28 g/lb Phosphoric acid: 0.29 g/lb Citric acid: 0.33 g/lb.	Citric acid: 0.0 g/lb. Sulfuric acid: 1.89 g/lb. [All based on LCFS certified biodiesel pathways as of December 2017] **For Tier 2 applications:** Required to be input by applicants as part of pathway CI certification.
Glycerin Yield	0.105 lb. glycerin/lb. BD	0.11 lb. glycerin/lb. BD	Required to be input by applicants as part of pathway CI certification.
RD Production Energy	Required to be input by applicants as part of pathway CI certification.	1,851 Btu/lb. RD which includes: - Natural gas (4.5%) - Electricity (5.1%) - Hydrogen (90.4%)	Required to be input by applicants as part of pathway CI certification.
Soy Oil Biodiesel: Soymeal and Soy Oil Allocation	Same allocation method used in CA-GREET1.8b: Soy oil at 20% by mass allocation.[41] Glycerin at 4.93% by energy allocation [Glycerin]:[Glycerin+BD]	Hybrid Allocation (mass and energy) is used for soybean Biodiesel pathway based on energy of glycerin, not glycerin and soybean meal	The same allocation method used in CA-GREET2.0. Co-product quantities (glycerin, free fatty acids, and bottom distillates) must be entered by applicant. The current 4.93% allocation factor for glycerin in the model is a place holder value only.
Soy Oil Renewable Diesel: **Soymeal and Soy Oil Allocation**	Staff used the same allocation method used in CA-GREET1.8b. 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 allocation method used in CA-GREET2.0. Co-products (propane, naphtha, and other distillates) must be entered by applicant. The current 4.90% allocation factor in the model is a place holder value only.

[41] CA-GREET 2.0 assumed an average value of 20% oil in soybean and therefore 20% of the GHG emissions from soybean farming through extraction of soy oil are allocated to renewable diesel.

b. Tallow to Biodiesel (BD) or Renewable Diesel

Most of the inputs to this pathway are facility-specific and require data related to biodiesel or renewable diesel production. Table 30 compares the three models for parameters related to tallow conversion to biodiesel or renewable diesel.

Table 30. Comparison of Tallow to Biodiesel and Renewable Diesel Parameters

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Collection and Transportation of Unrendered Tallow for BD/RD pathways	Tallow collection and transport included in T1 Calculator tab as part of the tallow BD/RD pathways. The BioOil tab details the energy and emissions from collection and transportation of tallow. T&D and T&D Flowcharts also updated accordingly.	Not Included	Required to be input by applicants as part of pathway CI certification.
Tallow to BD Yield: (lbs. tallow/lb. BD)	Required to be input by applicants as part of pathway CI certification.	Production from tallow as a feedstock: Feedstock use: 1.01 lbs. tallow/lb. BD. After allocation, the yield is 1.044 lbs. tallow/lb. BD	Required to be input by applicants as part of pathway CI certification.
Tallow Transesterification Energy Use (Btu/lb. BD)	Required to be input by applicants as part of pathway CI certification.	Energy use for Biodiesel: 1,213 Btu/lb.:[42] - Natural gas (30.7%) - Electricity (4.6%) - Methanol (64.7%)	Required to be input by applicants as part of pathway CI certification.
Renewable Diesel Yield per lb. of Tallow (lbs. tallow/lb. RD)	Required to be input by applicants as part of pathway CI certification.	Not specifically stated for Tallow. All BioOil-based RD Production: 1.17 lb. oil/lb. RD	Required to be input by applicants as part of pathway CI certification.
Renewable Diesel Production (Btu/lb. RD)	Required to be input by applicants as part of pathway CI certification.	For all BioOil-based RD Production energy use is 1,851 Btu/lb.: - Natural gas (4.5%) - Electricity (5.1%) - Hydrogen (90.4%)	Required to be input by applicants as part of pathway CI certification.
Tallow RD Propane co-product yield	0.059 lbs. propane/lb. RD (same as CA-GREET1.8b)	Not specifically stated for Tallow. 0.059 lbs. propane/lb. RD 1,096 Btu propane/lb. RD	Required to be input by applicants as part of pathway CI certification.

[42] 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) to biodiesel or renewable diesel pathways are not available in GREET1_2016. CARB staff added UCO to CA-GREET as a feedstock for the production of biodiesel and renewable diesel. Table 31 provides details of the inclusion of UCO in CA-GREET3.0 for the production of biodiesel and renewable diesel.

Table 31. Comparison of Parameters for Used Cooking Oil used in Biodiesel and Renewable Diesel

Parameter	**CA-GREET2.0** Data from CARB (2011)[43] unless otherwise noted	GREET1_2016	CA-GREET3.0
UCO to BD Aggregated Pathway in BioOil Tab	1. UCO collection and transport 2. UCO Rendering for BD. This is a standard value of 1,018 Btu/lb. from CA-GREET1.8b 3. UCO to BD	Not available in GREET1_2016	Removed energy input for the UCO collection; the UCO transportation only applies to self-rendering fuel producers, not for the oil that is sourced from distributor. Other parameters are the same as CA-GREET2.0
UCO to RD Aggregated Pathway in BioOil Tab	1. UCO collection and transport. 2. UCO to RD	Not available in GREET1_2016	Removed energy input for the UCO collection; the UCO transportation only applies to self-rendering fuel producers, not for the oil that is sourced from distributor. Other parameters are the same as CA-GREET2.0
Energy content (LHV) of UCO	9,214 Btu/lb. BioOil Tab, Staff Calculation	Not available in GREET1_2016	Same as CA-GREET2.0
Energy-based allocation	Added to BioOil Tab	Not available in GREET1_2016	Same as CA-GREET2.0
UCO used in BD or RD production	Added to BioOil Tab G40=1.11 lb./lb. BD H40 = 1.17 lb./lb. RD	Not available in GREET1_2016	Required to be input by applicants as part of pathway CI certification (composite yield based on all feedstocks used in a facility).

[43] 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

d. Distiller's Corn/Sorghum Oil to Biodiesel or Renewable Diesel

Table 32 compares inputs that have been changed between the three models for distiller's corn/sorghum oil used in the production of biodiesel and renewable diesel.

Table 32. Comparison of Distiller's Corn/Sorghum Oil Parameters for Biodiesel and Renewable Diesel

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Co-product Allocation method	Displacement	Marginal allocation	Same as CA-GREET2.0
Oil Production	Total Energy used is 924.29 Btu/lb. oil: - NG: 767 Btu/lb oil - Electricity: 157 Btu/lb oil	266 Btu/lb. oil using electricity[44]	Same as CA-GREET2.0
Oil Yield	0.03 gal oil/ gal ethanol	0.19 lb/ gal ethanol or 0.0247 gal/gal ethanol (ethanol density is 7.7 lb/gal)	**For Tier 1 applications:** 0.03 gal oil/gal ethanol **For Tier 2 applications:** Required to be input by applicants as part of pathway CI certification.

In the LCA of the ethanol pathway, DGS is considered a co-product and is modeled as a credit using the displacement method in CA-GREET3.0. The DGS includes solids and oil as a composite mixture; thus, when oil is extracted from DGS and used as a feedstock in the production of biodiesel/renewable diesel, a debit is assessed in the distiller's corn/sorghum oil pathway, which is a portion of the DGS co-product credit determined in the ethanol pathway.

Conversion of DGS Credit (from ethanol pathway) to Debit in the Distiller's Corn/Sorghum Oil Pathway:

- Staff used the average DGS displacement credit (12.31 gCO2e/MJ ethanol) and average oil yield (0.236 lb. oil/gal ethanol or 0.03 gal/gal) and the oil content of DGS (4.2 percent by mass of composite DGS) from starch ethanol pathways certified in 2016-17. Tier 1 applications will utilize this historical average data; Tier 2 applications must supply the site-specific information.

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

Table 33 compares production inputs between the three models for Canola Oil used in the production of biodiesel and renewable diesel. Noting that the calculation of canola transportation in GREET1_2016 is missing a unit conversion from short ton to metric ton; this issue has been corrected in CA-GREET3.0.

[44] 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.

Table 33. Comparison of Inputs for Canola Oil to Biodiesel and Renewable Diesel Pathways

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Agricultural Chemical Inputs	Inputs in g/dry MT N: 54,698.90 P: 15,298.90 K: 2,946.15 Herbicide: 300.0 Pesticide: 42.86[45]	Same as CA-GREET2.0	Same as CA-GREET2.0
Energy and fuel shares	1,238 Btu/lb. canola Fuel Shares: - 81.2% NG - 14.4% Electricity - 4.4% N-hexane[45]	1,316 Btu/lb. canola Fuel Shares: - 79.3% NG - 13.4% Electricity, - 7.3% N-hexane[46]	Same as GREET1_2016
Canola oil mass allocation	42.8%	47.3%	Same as GREET1_2016. The 42.8% value in CA-GREET2.0 does not specify if it was dry or wet weight based. Argonne's calculation includes 9% moisture.

Section 6: Hydrogen

The hydrogen pathways using steam methane reforming in CA-GREET3.0 assume that feedstocks (fossil NG and biomethane) are transported from out-of-state to California while the SMR hydrogen production occurs in California. The hydrogen pathways using electrolysis method use the California eGRID mix while Argonne's GREET1_2016 uses U.S. average electricity. Detailed explanation and calculations are provided in the Hydrogen section in the "CA-GREET3.0 Lookup Table Pathways – Technical Support Documentation" included as part of the 2018 LCFS regulatory amendments.

Table 34 compares inputs in the three models for hydrogen produced in central steam methane reforming plants.

[45] 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.

[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

Table 34. Central Hydrogen Plant Parameters (North American NG to Hydrogen)

Parameter	CA-GREET2.0	GREET1_2016 [47]	CA-GREET3.0
NG Transportation to Hydrogen Plant	Pipeline 100% - 750 mi	Pipeline 100% - 680 mi	Pipeline 100% - 1,000 mi
H_2 Compression Energy Efficiency	93.9%	90.7%	Same as GREET1_2016

Section 7: Petroleum Products

California's stringent fuel specifications require additional processing of crude to produce finished fuels or fuel blendstocks compared to fuels produced from refineries which meet federal fuel specifications. Accordingly, for California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) and Ultra-Low Sulfur Diesel (ULSD), CA-GREET3.0 uses California-specific refinery modeling to calculate refining emissions for the production of these fuels. The OPGEE 2.0b model is used to calculate crude oil recovery and transport emissions in CA-GREET3.0.

[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

a. Upstream crude extraction carbon intensity

Table 35 details compares input values for California crude in the three models.

Table 35. Comparison of California Crude Oil Properties

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
CI of Recovery Energy Efficiency, Total Energy, and Shares of Processing Fuels	Using OPGEE 1.0 Crude Oil CI of 11.98 gCO_2e/MJ. Efficiency: 92.58% NG: 99.60% Diesel: 0.04% Electricity: 0.26% Feed loss: 0.10%	N/A	Using OPGEE 2.0b Crude Oil CI of 11.78 gCO_2e/MJ. Efficiency: 90.98% NG: 98.99% Diesel: 0.20% Electricity: 0.78% Feed loss: 0.03%
API gravity Average of Crude to Refineries	25.16	Not included for CA	Same as CA-GREET2.0
Sulfur Content of Average Crude to Refineries (wt %)	1.36 wt.%	Not Included for CA	Same as CA-GREET2.0
Refinery Heavy Product Yield (MMBtu of MMBtu of total refinery products)	11%	Not Included for CA	Same as CA-GREET2.0
Added Complexity Index	13.83	Not Included for CA	Same as CA-GREET2.0
Added California Crude Oil Sources	Added California crude oil sources to Inputs tab. (OPGEE 1.0)	Not Included for CA	Added California crude oil sources to Inputs tab. (OPGEE 2.0b)
Modified T&D Flowchart for Conventional Crude Oil for Use in California Refinery	Modified T&D Flowcharts (OPGEE 1.0)	Not Included for CA	Modified T&D Flowcharts (OPGEE 2.0b)

Note that the OPGEE model defaults to most equipment used in CA crude recovery being powered by natural gas, due to the lack of real-world data. The fuel shares of the CA crude recovery are weighted averages of the top 16 crude sources, which represent 76.6% of the total crude volume in CA.

b. Transportation of Conventional Crude for Use in CA Refineries

Transportation of crude to California refineries is from the OPGEE 2.0b model and is different compared to the Argonne model which uses U. S. average data. Table 36 compares parameters for transportation of conventional crude among three models.

Table 36. Parameters for Transportation of Conventional Crude for use in CA Refineries

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0[48]
Domestic, Alaska	10.99% of the total conventional crude used in CA refineries is transported by ocean tanker for 2,364 mi and pipeline (3.72%) 800 mi	Ocean Tanker, 28.8%, 3,900mi	Same as CA-GREET2.0
Domestic, Contiguous 48 States	Pipeline: 37.73%, 100 mi Rail: 0.08%, 2,000 mi	28.9% DIRECT Transportation (i.e. produced and sent directly for distribution from refineries)	Same as CA-GREET2.0
Imported from Non-North America Countries	Ocean Tanker: 40.4%, 3,709 mi Pipeline: 3.2%, 38 mi	Ocean Tanker: 40.2%, 10,762mi	Same as CA-GREET2.0
Imported from Canada and Mexico	Pipeline: 1.6%, 900 mi Rail: 5.5%, 800 mi	2.1% Pipeline, 885 mi	Same as CA-GREET2.0

c. California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) Refining/Processing

Table 37 compares refining parameters for gasoline blendstock between the three models. Parameters such as energy inputs, refining efficiency and refinery operational details for the production of CARBOB have been updated based on aggregated linear programming (LP) modeling results for California-specific refineries. For detailed explanation and calculation, refer to the CARBOB section in the “CA-GREET3.0 Lookup Table Pathways – Technical Support Documentation” included as part of the 2018 LCFS regulatory amendments.

Table 37. Comparison of CARBOB Refining/Processing Parameters

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
CARBOB Energy Efficiency	89.0%	88.74% [49]	88.64%
Total Energy Input for CARBOB Production	1,123,630 Btu/MMBtu	1,126,838 Btu/MMBtu	1,128,160 Btu/MMBtu

48 Crude transport to CA is the same as in CA-GREET2.0, which is estimated by OPGEE

49 Amgad Elgowainy, Jeongwoo Han, Hao Cai, Michael Wang, Grant S. Forman , Vincent B. Divita, and. "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries” May 2014. https://greet.es.anl.gov/publication-energy-efficiency-refineries.

d. Calculation of Carbon Intensity for California Reformulated Gasoline (CaRFG)

The Argonne GREET1_2016 model does not include CaRFG as a finished fuel which is included in CA-GREET3.0. Table 38 provides details of inputs used to calculate CI for CaRFG.

Table 38. Comparison of Calculation of Carbon Intensity for CaRFG

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Ethanol Content of CaRFG (v/v)	9.50%[6]	9.80%	Same as CA-GREET2.0
Ethanol Content of CaRFG (MJ/MJ)	6.82%	N/A	Same as CA-GREET2.0
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) =77.81 g CO_2e/MJ	N/A	Same as CA-GREET2.0
2010 Baseline CARBOB CI	99.78 gCO_2e/MJ	N/A	100.82 gCO_2e/MJ
Tailpipe CH_4	CaRFG Tailpipe CH_4 Emission: 0.0004 (Ethanol) + 0.0056 (CARBOB) = 0.006 gCH_4/MJ[6]	CA Gasoline: 0.0019 gCH_4/MJ	Same as CA-GREET2.0
Tailpipe N_2O	CaRFG Tailpipe N_2O Emissions: 0.0002 (Ethanol) + 0.0031 = 0.0033 gN_2O/MJ [6]	CA Gasoline: 0.0017 gN_2O/MJ	Same as CA-GREET2.0

Table 39 compares transport and distribution parameters for CARFG between the three models.

Table 39. Comparison of T&D of CA Reformulated Gasoline

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
CA-RFG Transportation	80% of the total CA-RFG is transported by pipeline for 50 miles to blending terminal and 20% by HDD truck direct from the refinery gate to fueling stations	Does not include CA-RFG	Same as CA-GREET2.0
CA-RFG Distribution	HDD Truck for 50 miles	Does not include CA-RFG	Same as CA-GREET2.0

e. California Ultra-Low Sulfur Diesel (ULSD) Refining/Processing, Transportation and Distribution

Table 40 compares refining parameters for ULSD between the three models. For detailed explanation, refer to the ULSD section in the "CA-GREET3.0 Lookup Table Pathways – Technical Support Documentation" included as part of the 2018 LCFS regulatory amendments.

Table 40. Comparison of ULSD Refining Parameters

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
ULSD Refining Energy Efficiency (weighted average)	88.0%	90.91%	85.87%
Total Energy Input for ULSD Production	1,136,398 Btu/MMBtu fuel throughput	1,099,962 Btu/MMBtu fuel throughput	1,164,551 Btu/MMBtu fuel throughput

Table 41 compares transport and distribution parameters and values for ULSD among three models.

Table 41. Comparison of T&D Parameters for ULSD

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
ULSD Transportation	80% of the total ULSD is transported by pipeline for 50 miles to blending terminal and 20% by HDD truck direct from the refinery gate to fueling stations	95% by pipeline, 150 mi 5% by rail, 250 mi	Same as CA-GREET2.0
ULSD Distribution	HDD Truck for 50 miles	100% by HDDT, 30 mi	Same as CA-GREET2.0

Section 8: Renewable Natural Gas

Argonne's GREET1_2016 includes a CO_2 credit to the RNG pathway for avoided flaring and subsequently debits the pathway for combustion of RNG in an internal combustion engine. The LCFS however, uses a different approach. For the life cycle analysis, flaring of RNG is considered as the baseline and no credits or debits accrue to the pathway for CO_2 attributable to RNG. Only GHG emissions from processing, transport and final compression before delivery to the CNG vehicle are considered in the life cycle of RNG from landfills. Table 42 compares differences between the three models for renewable natural gas.

Table 42. Comparison of Renewable Natural Gas Parameters

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
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.	Extraction and Processing are combined in a single "Production" stage.	A column was added to distinguish Extraction (recovery) energy and emissions for landfill gas to LNG.
Transmission from RNG site to LNG Plant or CNG delivery site	A column was added to allow for transportation of RNG by pipeline. Distance in miles must be input by applicant requesting pathway certification.	Not Included	A column was added to allow for transportation of RNG by pipeline. Distance in miles must be input by applicant requesting pathway certification.
Landfill Gas CH_4 Leakage during Processing	1% of feed	2% of feed [25]	Same as CA-GREET2.0.

Section 9: Fossil Natural Gas

Methane leakage factors for fossil natural gas in CA-GREET3.0 reflect values in GREET1_2016. An error in CH_4 Venting and Leakage value of 74.6 g CH_4/mmBtu NG in GREET1_2016 is corrected in CA-GREET3.0 to reflect the correct value of 46.7 g CH_4/mmBtu NG. Natural gas transmission and distribution emission factors in CA-GREET3.0 are different compared to the Argonne model since the CA-GREET3.0 model uses California specific values for natural gas transmission and distribution. Details are provided in the natural gas section in "CA-GREET3.0 Lookup Table Pathways – Technical Support Documentation" included as part of the 2018 LCFS regulatory amendments. Table 43 compares processing parameters for shale-derived natural gas between the three models.

Table 43. Comparison of Methane Leakage for Shale-Derived Natural Gas

Para-meter	CA-GREET2.0		GREET1_2016[50]		CA-GREET3.0[51,52]	
NA-NG Process	Processing CH_4 Venting & Leakage: **26.71** $gCH_4/MMBtu$		Processing CH_4 Venting & Leakage: **26.24** $gCH_4/MMBtu$		Same as GREET1_2016	
NA-NG T&D	Stage	gCH_4 per MMBtu NG	Stage	gCH_4 per MMBtu NG	Stage	gCH_4 per MMBtu NG
	Transmission & Storage Venting & Leakage	81.189	Transmission & Storage Venting & Leakage	74.55	Transmission & Storage Venting & Leakage	46.7
	Distribution Venting and Leakage	63.635	Distribution Venting and Leakage	17.699	Distribution Venting and Leakage	17.699
	Total	**144.82**	**Total**	**118.49**	**Total**	**90.64**

Table 44 compares the transportation assumptions for fossil natural gas among the three models.

Table 44.Comparison of NG Pipeline Transportation Energy Intensity and Transport Distances

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Pipeline Distance from NG Fields to end use	Pipeline distance to stationary combustion sources is 680 miles.	375 miles	Same as CA-GREET2.0
Pipeline Distance to California CNG Stations	Pipeline distance to CNG stations is 1,000 miles	750 miles	Same as CA-GREET2.0
Pipeline Distance to LNG Plants	Applicant must report transport distance	To U.S LNG Plant: 50 miles	Input pipeline transport distance as part of pathway application

[50] 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

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

[52] 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-GREET3.0.

For NG liquefaction, based on applicant information, CA-GREET3.0 considers NG used in processing is combusted in an internal combustion engine. The Argonne GREET model assumes NG combustion in a large turbine.

For the Transportation and Distribution of LNG, CA-GREET3.0 considers transport using HDD truck and requires user specific input of transport distance from liquefaction facility to LNG dispensing station in CA. GREET1_2016 considers it is transported 50% by barge (520 miles) and 50% by rail (800 miles) to the bulk terminal, and distributed 100% by HDD truck (30 miles) to the refueling station.

Section 10: Propane

Table 45 below compares changes in CA-GREET3.0 with GREET1_2016 for LPG sources and transport. For detailed explanation of the Propane pathway analysis, refer to the Fossil Propane section in the "CA-GREET3.0 Lookup Table Pathways – Technical Support Documentation" included as part of the 2018 LCFS regulatory amendments.

Table 45. Comparison of Parameters for Propane

Parameters	CA-GREET2.0	GREET1_2016	CA-GREET3.0
LPG Sources	Propane exempt from the regulation.	For model year 2014, **US average**: 65% from natural gas, 35% from crude	For model year 2014, **California average**: 25% from natural gas, 75% from crude
LPG Transport	Propane exempt from the regulation.	LPG Transport from LPG plant to bulk terminal • Barge 6% - 520 mi • Pipeline 60% - 400 mi • Rail 34% - 800 mi LPG Distribution from bulk terminal to stations • Truck 100% - 30 mi	LPG Transport from LPG plant to bulk terminal: N/A. It is assumed LPG is distributed from LPG plant directly to stations in CA. LPG T&D to stations in CA • Truck 100% - 200 mi

Section 11: Conventional Jet Fuel

The conventional jet fuel pathway in GREET1_2016 reflects the U.S. average jet fuel production. The CA-GREET3.0 model however, includes parameters to reflect conventional jet fuel produced in CA refineries.

a. Feedstock recovery

Table 46 compares the subtotal CIs of the feedstock recovery process for the conventional jet fuel in two models: GREET1_2016 uses U.S. average crude recovery, whereas CA-GREET3.0 uses the OPGEE 2.0b Crude Oil CI.

Table 46. Comparison of Emissions from Crude Oil Recovery used in Conventional Jet Fuel Production

	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Feedstock (crude oil) recovery, gCO2e/MJ	Did not consider jet fuel in the regulation.	10.26	11.78

b. Jet fuel refining

Table 47 compares the energy efficiency, loss factor, energy inputs, intermediate energy use, and emissions from on-site hydrogen production using steam methane reforming. Both GREET1_2016 and CA-GREET3.0 use Linear Programming (LP) results provided by Argonne; however, GREET1_2016 data represent the U.S. average scenario, whereas CA-GREET3.0 data represent CA refineries producing conventional jet fuel (based on aggregated LP modeling results for California-specific refineries). The carbon intensity for Conventional Jet Fuel was evaluated for the baseline year of 2010, the same as for CARBOB and ULSD.

Table 47. Comparison of Jet Fuel Production Inputs

	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Energy efficiency	Did not consider jet fuel in the regulation.	95.3%	94.9%
External Energy Input (Btu/MMBtu of conventional jet fuel)			
Crude	N/A	1,008,900	999,147
Residual oil		10,036	12,009
Natural gas		24,061	39,145
Electricity		1,598	2,251
Hydrogen		4,285	910
N-butane		56	147
GTL		0	49
Intermediate products combustion (Btu/MMBtu of conventional jet fuel)			
Pet coke	N/A	2,683	2,645
Refinery still gas		31,292	40,885
Non-combustion emissions from on-site H_2 SMR (gCO_2e/MMBtu of conventional jet fuel)			
	N/A	288	584

c. Jet fuel transportation and distribution

Table 48 compares mode, share, and distance of the jet fuel transportation and distribution. In CA-GREET3.0, jet fuel is distributed directly from the refinery in CA to the airports instead of being transported to the blending terminal.

Table 48. Comparison of Jet Fuel Transportation and Distribution

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Transportation to Blending Terminal	Did not consider jet fuel in the regulation.	Mode / Share / Distance (miles): Tanker, 4%, 1,300 Barge, 48.5%, 200 Pipeline, 46.4%, 110 Rail, 5.1%, 490	Assuming pipeline transportation to large airports/fuel terminal: Pipeline (100%) - 110 miles
Distribution to Airport	Did not consider jet fuel in the regulation.	Truck 100% - 30 miles	Assuming truck transportation from fuel terminal to small airports: Truck 20% - 200 miles

Section 12: Transportation Modes

In consultant with the GREET development team at the Argonne National Laboratory, staff updated the following parameters of various transportation modes:

a. Table 49 compares the cargo payloads of HHDT and MHDT for corn, soybean and canola among three models.

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Heavy Heavy-Duty Truck (Class 8b)	Corn: 15 tons Soybean: 15 tons Canola: 15 tons	Same as CA-GREET2.0	Corn: 20.4 tons Soybean: 20.4 tons Canola: 20.4 tons
Medium Heavy-Duty Truck (Class 6)	Corn: 8 tons Soybean: 8 tons Canola: 8 tons	Same as CA-GREET2.0	Corn: 4.8 tons Soybean: 4.8 tons Canola: 4.8 tons

Table 49. Comparison of Cargo Payloads for Corn, Soybean and Canola

b. Table 50 compares the fuel economy of both forward (origin → destination) and back-haul (destination → origin) trips for HHDT and MHDT among three models.

Parameter	CA-GREET2.0	GREET1_2016	CA-GREET3.0
Heavy Heavy-Duty Truck (Class 8b)	Origin → Destination: 5.3 miles/diesel gallon Destination → Origin: 5.3 miles/diesel gallon	Same as CA-GREET2.0	Origin → Destination: 7.3 miles/diesel gallon Destination → Origin: 9.2 miles/diesel gallon
Medium Heavy-Duty Truck (Class 6)	Origin → Destination: 10.4 miles/diesel gallon Destination → Origin: 10.4 miles/diesel gallon	Same as CA-GREET2.0	Origin → Destination: 8.3 miles/diesel gallon Destination → Origin: 8.9 miles/diesel gallon

Table 50. Comparison of Fuel Economy of HHDT and MHDT

c. The energy intensity of barge transportation mode in CA-GREET3.0 is set at 223 Btu/ton-mile, which represents the average energy intensity of a round trip.

d. Similarly, the energy intensity of rail transportation mode in CA-GREET3.0 is set at 274 Btu/ton-mile, which represents the average energy intensity of a round trip.