CA-GREET4.0 Supplemental Document

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I. Input and Emission Factors in CA-GREET4.0

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 CA-GREET4.0 model is a modified version of the Argonne GREET1 2022 model[1] to reflect California specific fuel pathways. Modifications are based on data sources which include the EPA Emissions & Generation Resource Integrated Database (eGRID)[2], The Oil Production Greenhouse Gas Emissions Estimator (OPGEE3.0b)[3], EMission FACtor (EMFAC2021)[4] and other sources. This document describes modifications made to the GREET1 2022 model to develop the CA-GREET4.0 model.

The CIs can be calculated using the Board approved Tier 1 CI calculators, or using modified Tier 1 calculators or the CA-GREET4.0 model for a Tier 2 pathway. The Tier 1 calculators mostly utilize emission factors and inputs obtained from the CA-GREET4.0 model.

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[1] Wang, M., Elgowainy, A., Uisung, L., Kwang, B., Bafana, A., Benavides, P., Burnham, A., Cai, H., Cappello, V., Chen, P., gan, Y., Gracida-Alvarez, U., Hawkins, T., Iyer, R., Kelly, J., Kim, T., Kumar, S., Kwon, H., Lee, K., Liu, X., Lu, Z., Masum, F., Mg, C., Ou, L., Reddi, K., Siddique, N., Sun, P., Vyawahare, P. Xu, H., & Zaimes, G., *GREET1 2022, October Release*. Center for Transportation Research, Argonne National Laboratory (Accessed on November 11, 2022). *https://greet.anl.gov/greet_excel_model.model*

[2] United States Environmental Protection Agency, *eGRID+Data.xls*. (Updated on January 30, 2023). *https://www.epa.gov/system/files/documents/2023-01/eGRID2021_data.xlsx*

[3] Brandt, A.R., Masnadi, M.S, Rutherford, J.S., El-Houjeiri, Vafi, K., H.M., Langfitt Q., Duffy, J., Sleep, S., Pacheco, D., Dadashi, Z., Orellana, A., MacLean, H., McNally, S., Englander, J., & Bergerson, J., *Oil Production Greenhouse Gas Emissions Estimator OPGEE v.3.0b*. (Updated on May 14, 2022). *https://eao.stanford.edu/research-project/opgee-oil-production-greenhouse-gas-emissions-estimator*

[4] California Air Resources Board, *EMFAC2021. v1.0.2*. (Updated April 2021). *https://arb.ca.gov/emfac/*

II. Modifications Incorporated in CA-GREET4.0

A. Electricity

The Argonne GREET1 2022 model uses 10-region North American Electric Reliability Corporation (NERC) map to develop region-specific GHG emissions for electricity generation. In CA-GREET4.0, CARB uses the U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID) for 2021[2] to determine the impact of stationary electricity use in fuel and feedstock production. This is consistent with the approach deployed in developing the CA-GREET3.0 model[5]. The eGRID contains 27 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 27 subregions include the newly added Puerto Rico Miscellaneous (PRMS) subregion.

The modification used to incorporate 27 e-grid subregions in the CA-GREET4.0 model is the same as in the CA-GREET3.0 model.[6] The conversion to the 27 eGRID subregional mixes in CA-GREET4.0 was accomplished by modifying the electricity resource mixes and subregions in the "Fuel_Prod_TS" worksheet of GREET1 2022 and the associated links to the "Inputs" worksheet. Staff also added U.S Average, User Defined, Brazilian Average and Canadian Average mixes, in addition to the 27 eGRID subregions, for a total of 31 electricity mixes. The 26 eGRID subregions excluding PRMS are mapped to 10 NERC regions for electricity generation efficiency and technology mix in the "Electric" tab. PRMS eGRID, Brazil and Canda are assigned the US average electricity generation efficiency and technology mix (Table 1).

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-GREET4.0 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) for the 2020 data year. The data and methodology used in determining the CI of this pathway are documented in the Lookup Table Pathways Technical Support Documentation.[7]

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[5] California Air Resources Board, *CA-GREET3.0 Model*. (Released August 13, 2018). *https://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet30-corrected.xlsm?_ga=2.110367174.299502000.1698789959-1426221606.1589399602*

[6] California Air Resources Board, *Attachment C CA-GREET3.0 Model Technical Support Documentation*. August 13, 2018. *https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2018/lcfs18/15dayattc2.pdf?_ga=2.54016097.835610192.1686001270-1419472287.1639891760*

[7] California Air Resources Board, *Technical Support Documentation for Lookup Table Pathways*, *Proposed Amendments for the Low Carbon Fuel Standard Regulation*. August 12, 2024. *https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/ca-greet/lut_update_v08122024.pdf*

Table 1: eGRID Subregions Grouped by NERC Region

#	Subregion	NERC Region	#	Subregion	NERC Region
1	CAMX	WECC	16	NEWE	NPCC
2	NWPP	WECC	17	NYUP	NPCC
3	AZNM	WECC	18	RFCE	RFC
4	RMPA	WECC	19	NYLI	NPCC
5	MROW	MRO	20	NYCW	NPCC
6	SPNO	SPP	21	SRVC	SERC
7	SPSO	SPP	22	FRCC	FRCC
8	ERCT	TRE	23	AKMS	ASCC
9	MROE	MRO	24	AKGD	ASCC
10	SRMW	SERC	25	HIOA	HICC
11	SRMV	SERC	26	HIMS	HICC
12	RFCM	RFC	27	PRMS	US average
13	RFCW	RFC	28	Brazil	US average
14	SRTV	SERC	29	Canda	US average
15	SRSO	SERC	30	User defined	

1. Electricity Resource Mixes

The resource mixes for 27 eGRID regions in the USA are shown in Table 2.

Table 2: Electricity Resource Mixes in 27 eGRID subregions in USA[2]

Data Year	eGRID subregion acronym	Coal	Oil	Gas	Nuclear	Hydro	Biomass	Wind	Solar	Geothermal
2021	AKGD	15.3%	9.8%	60.6%	0.0%	11.5%	0.8%	2.1%	0.0%	0.0%
2021	AKMS	0.0%	25.1%	6.1%	0.0%	67.0%	0.0%	1.8%	0.0%	0.0%
2021	AZNM	16.0%	0.1%	46.8%	18.8%	3.4%	0.4%	5.2%	6.0%	3.4%
2021	CAMX	3.8%	0.8%	47.7%	8.1%	6.6%	2.5%	7.7%	18.9%	4.0%
2021	ERCT	17.7%	0.5%	46.6%	9.5%	0.2%	0.2%	21.8%	3.5%	0.0%
2021	FRCC	7.7%	1.2%	74.0%	11.8%	0.1%	1.5%	0.0%	3.6%	0.0%
2021	HIMS	0.0%	64.3%	0.0%	0.0%	4.4%	3.7%	14.8%	5.9%	7.0%
2021	HIOA	16.5%	71.1%	0.0%	0.0%	0.0%	2.8%	4.1%	5.4%	0.0%
2021	MROE	54.4%	1.2%	32.1%	0.0%	4.9%	3.0%	3.1%	1.3%	0.0%
2021	MROW	39.6%	0.3%	10.8%	8.6%	4.4%	0.8%	34.6%	0.9%	0.0%
2021	NEWE	0.6%	1.9%	54.4%	26.3%	5.7%	5.2%	3.7%	2.4%	0.0%
2021	NWPP	19.0%	0.4%	21.2%	3.0%	40.8%	1.1%	11.5%	2.3%	0.7%
2021	NYCW	0.0%	0.7%	90.1%	8.7%	0.0%	0.4%	0.0%	0.0%	0.0%

Data Year	eGRID subregion acronym	Coal	Oil	Gas	Nuclear	Hydro	Biomass	Wind	Solar	Geothermal
2021	NYLI	0.0%	9.4%	85.4%	0.0%	0.0%	3.5%	0.0%	1.8%	0.0%
2021	NYUP	0.0%	0.4%	25.9%	33.2%	33.2%	1.6%	4.9%	0.9%	0.0%
2021	PRMS	17.5%	37.2%	42.8%	0.0%	0.0%	0.0%	0.9%	1.6%	0.0%
2021	RFCE	10.3%	0.8%	48.7%	36.0%	1.4%	1.0%	1.0%	0.8%	0.0%
2021	RFCM	39.1%	2.6%	31.0%	17.3%	0.0%	1.5%	8.1%	0.4%	0.0%
2021	RFCW	35.6%	1.0%	27.8%	28.5%	1.1%	0.5%	5.2%	0.3%	0.0%
2021	RMPA	39.7%	0.1%	23.0%	0.0%	9.4%	0.3%	25.0%	2.6%	0.0%
2021	SPNO	40.6%	0.4%	9.5%	11.7%	0.2%	0.1%	37.3%	0.1%	0.0%
2021	SPSO	26.8%	1.9%	36.2%	0.0%	4.1%	1.2%	29.4%	0.4%	0.0%
2021	SRMV	11.1%	2.0%	59.0%	24.9%	1.6%	1.0%	0.0%	0.3%	0.0%
2021	SRMW	67.4%	0.1%	11.2%	11.1%	1.7%	0.1%	7.9%	0.4%	0.0%
2021	SRSO	19.2%	0.1%	51.5%	19.3%	3.4%	4.1%	0.0%	2.3%	0.0%
2021	SRTV	31.6%	0.1%	26.2%	30.9%	10.1%	0.8%	0.0%	0.3%	0.0%
2021	SRVC	13.4%	0.4%	38.1%	38.8%	1.9%	2.3%	0.4%	4.7%	0.0%

The average electricity mix for Brazil and Canada are the only international resource mixes included in CA-GREET4.0. The recent electricity resource mix data for these countries are obtained from EIA.[8] These electricity mixes are incorporated in the "Fuel_Prod_TS" worksheet in addition to the 27 eGRID subregions. Table 3 details the electricity mixes in Brazil and Canada.

Table 3: Electricity Resource Mixes in Brazil and Canada

Data Year	Country	Coal	Oil	Gas	Nuclear	Hydro	Biomass	Wind	Solar
2020	Brazil	3.19%	1.77%	8.61%	2.26%	63.80%	9.46%	9.18%	1.73%
2021	Canada	5.77%	0.78%	11.89%	14.40%	59.24%	1.59%	5.53%	0.80%

B. California Crude Oil Extraction and Transport

The emission factors associated with crude oil extraction and transport used in modeling well-to-wheel GHG emissions of California-specific petroleum products (ULSD, CARBOB, CaRFG, jet fuel, and propane) are derived from the OPGEE3.0b model and are incorporated into the CA-GREET4.0 model. Details are available in the Technical Support Documentation for Lookup Table Pathways.[7]

C. Ocean Tanker and Truck Transport

A backhaul energy intensity of 85.7 btu/ton-mile corresponding to the payload of 35,000 DWT is added to ocean tanker transport for Brazilian sugarcane ethanol based on the data provided by fuel suppliers. The ocean tanker transport emission factors for other alternative fuels and feedstocks used in the Tier 1 calculators are derived from the ocean tanker with three payload (DWT) sizes: 12,500 DWT, 22,500 DWT and 35,000 DWT.

The fuel economy (miles per gallon) of medium heavy-duty truck (MHDT) and heavy heavy-duty truck (HHDT) are updated with fuel economy data obtained from EMFAC2021 (v1.0.2).[4] The EMFAC model is used to develop GHG inventory for California's transport sector to support regulatory and air quality planning efforts and provides representative fuel economy and emissions data. The fuel economy values of 8.61 and 5.57 miles/gallon for MDHT and HHDT, respectively are based on the fleet-wide weighted averages for various model year trucks that operated in 2021 in California.

The payload of HHDT for corn transport is revised from 15 tons to 25 tons. This revision is based on the personal communication with the Argonne National Lab and other available

[8] IEA, *Countries & Regions.* (Accessed on October 8, 2023). *https://www.iea.org/countries*

evidence[9]. This is supported by the fact that the payload of HHDT for sorghum transport is also 25 tons in the GREET1 2022 model.

D. Tailpipe Emission Factors

The tailpipe emission factors for natural gas, ULSD, CARBOB, and CaRFG are derived from EMFAC2021 (v1.0.2) model[4] and carbon content of fuels. Details are provided in the Technical Support Documentation for Lookup Table Pathways [7].

The tailpipe CH_4 and N_2O emissions from the use of propane in light duty propane vehicles are calculated using the values from the Argonne GREET1 2022 model[1]. CO_2 emissions are calculated based on carbon content in propane as described in the Technical Support Documentation for Lookup Table Pathways [7].

The tailpipe emissions of conventional jet fuel are provided in the "JetFuel_WTP" worksheet which are obtained from CA-GREET3.0 for CH_4 and N_2O.[6] CO_2 emissions are calculated based on the carbon content of conventional jet fuel provided in CA-GREET4.0.

The tailpipe emission factors for biodiesel, renewable diesel, and alternative jet fuel are derived from CA-GREET3.0. For details, see CA-GREET3.0 Technical Support Documentation published as part of the 2018 LCFS regulatory amendments[6].

E. Tallow and UCO Rendering Emissions

The energy inputs for tallow and UCO rendering used in the GREET1 2022 have been modified to remain consistent with CA-GREET3.0[5]. The allocated rendering energy for tallow and UCO is 3,944 btu/lb and 1,073 btu/lb, respectively. The data provided by rendering facilities suggest that rendering energy data in the CA-GREET3.0 model are accurate and conservative.

F. Fuel Specifications

The energy density values of various fuels are updated in CA-GREET4.0 as shown in Table 4. These values are obtained from Table 5 of the LCFS regulation document[10] to be consistent with energy density values used in reporting fuels in the LRT-CBTS system.

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[9] Blaze, J., *Commentary: Moving grain is a major market for U.S. and Canadian railroads* (Accessed on November 16, 2023). *https://www.freightwaves.com/news/commentary-moving-grain-is-a-major-market-for-u-s-and-canadian-railroads*

[10] California Air Resources Board, *Unofficial electronic version of the Low Carbon Fuel Standard Regulation*. July 2025. *https://ww2.arb.ca.gov/sites/default/files/2025-07/2025_lcfs_fro_oal-approved_unofficial_07012025.pdf*

Table 4: Updated Energy Density of Liquid Fuels (LHV)

Parameter	MJ/gal	Btu/gal	Source
CARBOB	119.53 MJ/gal	113,293 Btu/gal	LCFS Regulation[10]
CARFG	115.83 MJ/gal	109,786 Btu/gal	
ULSD	134.47 MJ/gal	127,453 Btu/gal	
Propane	89.63 MJ/gal	84,953 Btu/gal	
Ethanol	80.53 MJ/gal	76,330 Btu/gal	
Biodiesel	126.13 MJ/gal	119,548 Btu/gal	

Fuel specifications, especially heating values (HHV and LHV) and densities of gases in CA-GREET4.0 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 5. These values are the same as in CA-GREET3.0.

Table 5: Updated Specifications of Various Gases at 60°F and 1 atm

Parameter	CA-GREET4.0	CA-GREET4.0	CA-GREET4.0
Specification	LHV, Btu/CF	HHV, Btu/CF	Density, g/CF
Natural Gas	930	1,030	20.8
Pure Methane	910	1,010	19.2
Gaseous hydrogen	274	325	2.41
Carbon Dioxide			53.0
Still gas (in refineries)	929	987	19.2

In addition, the temperature correction factors for ethanol and biodiesel volume at 60°F (commercial transactions are reported at 60°F) are included in the "Fuel_Specs" worksheet of CA-GREET4.0.