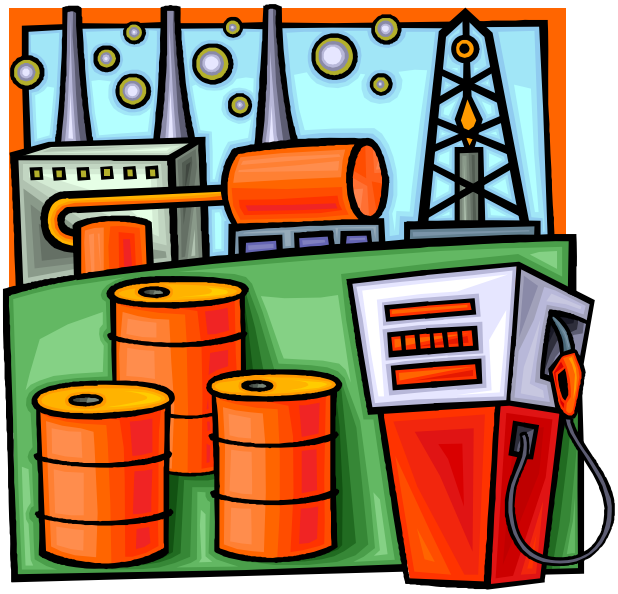
California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for California Reformulated Gasoline – CARBOB Blended with Ethanol



Stationary Source Division

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

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

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SUMMARY

Pathway for California Reformulated Gasoline

A Well-To-Tank (WTT) Life Cycle Analysis of a fuel pathway includes all steps from crude oil recovery to final finished fuel. Tank-To-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. Together, WTT and TTW analysis are combined to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory forms the core basis of the methodology used in this document. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process[2]. This California modified GREET model forms the basis of this document. It has been used to calculate the energy use and greenhouse gas (GHG) emissions associated with the production and use of California Reformulated Gasoline.

California Reformulated Gasoline (CaRFG) is a mixture of California Reformulated Gasoline Blendstock for Oxygenate Blending (CARBOB) and ethanol. Ethanol is added as an oxygenate per regulations of the Air Resources Board (ARB). For CaRFG, the CARBOB blending component is mixed with 5.75% ethanol (by weight) to meet a nominally 2% (by weight) oxygen requirement for gasoline sold and used in California. The corresponding volume of ethanol would be about 5.35%.

In reality, denatured ethanol is blended with CARBOB. Denatured ethanol is pure ethanol mixed with conventional gasoline. The denaturant level is usually between 2 to 4.75% of conventional gasoline but the GREET model assumes 2.5 volume% is used to blend with neat ethanol. The GREET model calculates RFG based on blending with neat ethanol and these calculations are provided in this document (slightly higher levels of denatured ethanol are blended with CARBOB to achieve a 2% oxygen level as required by the ARB).

The WTW analysis for CARBOB and ethanol are provided as separate documents that provide detailed life cycle analysis of these two blending components. The life cycle energy use and GHG emissions for RFG is based on weighted results for CARBOB and ethanol. This document essentially merges the WTW values proportionally and provides an aggregate WTW value for CaRFG. The CARBOB and ethanol pathways are derived from the CA-modified GREET model and are available as separate documents. For detailed explanation, users are referred to the individual pathway documents. Appendix A in this document provides detailed calculations for CaRFG using the pathway information for CARBOB and ethanol.

The pathway for each blending component is shown in Figure 1. The results for each of the blending components are calculated based on each fuel being delivered as a pure

[1] http://www.transportation.anl.gov/software/GREET/
[2] http://www.energy.ca.gov/ab1007/

component through its infrastructure. The CARBOB[3] WTT results are calculated as if pure CARBOB were delivered to the fueling station. Similarly, the WTT results for ethanol are calculated as if this component were delivered to the fueling station. The results for RFG are then calculated based on the energy weighted average. This approach allows the results for RFG to be readily calculated for different ethanol components. For CaRFG, the current pathways in the GREET model are based on blending CARBOB with neat ethanol. In practice, ethanol denatured with conventional gasoline is blended with CARBOB. This is slightly different than the existing GREET pathway. The approach followed here is blending neat ethanol with CARBOB. Detailed calculations are provided in Appendix A. A table listing all input values is provided in Appendix B.

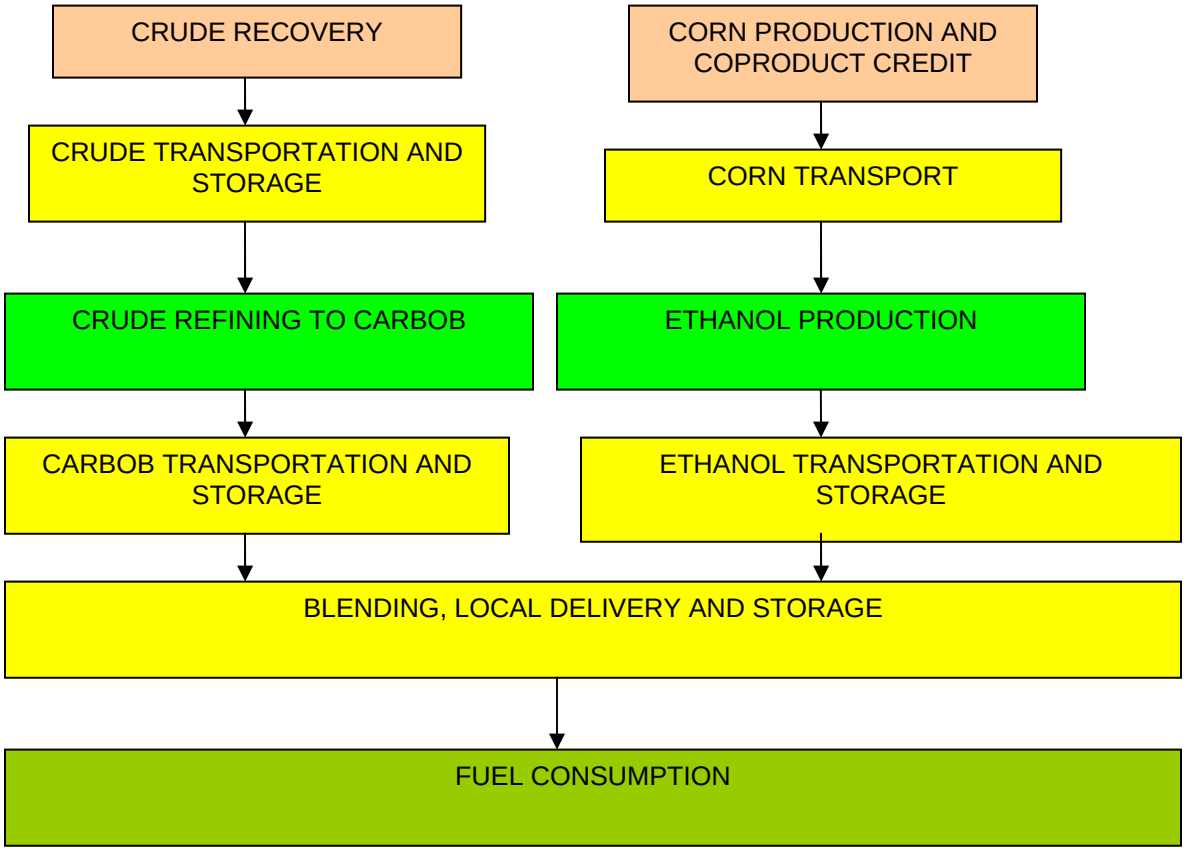

Figure 1. Pathway Components for Ethanol Blended with CARBOB.

Table A below summarizes the energy inputs by stage (Btu/mmBtu) during production and use of CaRFG in a passenger vehicle. Table B summarizes the GHG emissions from the production and use of CaRFG in a passenger vehicle. Figure 2 provides a

[3] Note: CARBOB analysis uses average California crude. Ethanol used here is produced in the mid-western United States using a dry milling process, and transported to California. Complete details of the CARBOB and ethanol pathways are provided in separate documents.

graphical illustration of values in Tables A and B. From a WTW energy use perspective, energy used during combustion (75.3%) and fuel production (16.6%) dominate the energy components of the CaRFG pathway. From a WTW GHG emissions perspective, combustion (75.0%) and fuel production (14.4%) dominate the GHG emissions in this pathway. Detailed calculations are provided in Appendix A. It should be noted that the analysis presented in this document assumes "neat ethanol".

Table A. Well to Tank Analysis for CaRFG and Blending Components

Components	**Energy (Btu/mmBtu)**		**CaRFG**	
	Corn Dry Mill Neat Ethanol	CARBOB	Energy (Btu/mmBtu)	% Energy Contribution
Feedstock Production	296,613	86,477	94,182	7.1%
Feedstock Transportation	28,001	10,076	10,733	0.8%
Fuel Production	543,785	208,621	220,910	16.6%
Fuel T&D	34,531	4,309	5,417	0.4%
Denaturant	11,484	0	421	0%
Co-products	-97,301	0	-3,568	-0.3%
Storage	0	0	0	0.0%
Total Well-To-Tank	**817,113**	**309,483**	**328,096**	**24.7%**
Neat Ethanol	975,000	0	35,749	2.7%
Denaturant/CARBOB	25,000	1,000,000	964,251	72.6%
Total Tank-to-Wheel	**1,000,000**	**1,000,000**	**1,000,000**	**75.3%**
Total Well-to-Wheel	**1,817,113**	**1,309,483**	**1,328,096**	**100%**

Note: Assumes 100% dry mill ethanol and some numbers may not add to 100% due to rounding. Calculations are for neat ethanol based on equations in GREET. Example calculation for feedstock production is (305,318*0.0367)+(86,477*0.9627). The 0.0367 is derived from 3.67% energy attributable to 5.35 vol% neat ethanol and the balance to CARBOB. Details of this are shown in Tables 1.01 and 1.02 in Appendix A.

Table B. GHG Emission Summary for CaRFG.

Corn Ethanol Fuel Cycle Components	**GHG Emissions (gCO_2e/MJ)**		**RFG**	
	Corn Dry Mill Neat Ethanol	CARBOB	GHG (gCO_2e/MJ)	% Emission Contribution
Feedstock Production	42	6.6	7.9	8.2%
Land Use Change	0.9	0	0	0%
Feedstock Transportation	2.1	2.2	2.2	2.3%
Fuel Production	35.7	13.1	13.9	14.4%
Fuel T&D	2.6	0.3	0.4	0.4%
Denaturant (well-to-tank)	0.8	0	0	0%
Co-Products	-10.4	0	-0.4	-0.4%
Storage	0	0	0	0%
Total Well-to-Tank	**73.8**	**22.3**	**24.2**	**25%**
Denaturant/CARBOB (carbon in fuel)	0	72.9	70.2	72.7%
Vehicle CH_4 and N_2O	--	--	2.2	2.3%
Total Tank-to-Wheel	**0**	**72.9**	**72.4**	**75%**
Total Well-to-Wheel	**76.5**	**95.2**	**96.6**	**100%**

Note: The tank-to-wheels emissions include only fossil carbon in fuel; biogenic carbon is excluded from the well-to-wheels analysis. Vehicle CH_4 and N_2O emissions are 2.18 g CO_2e/MJ for gasoline and these would presumably be comparable for other ethanol blends in flexible fueled vehicles. Example calculation for feedstock production is (42*0.0367)+(6.6*0.9627) =7.9. The 0.0367 is derived from 3.67% energy attributable to 5.35 vol% neat ethanol and the balance to CARBOB. Details of this are shown in Tables 1.01 and 1.02 in the Appendix A.

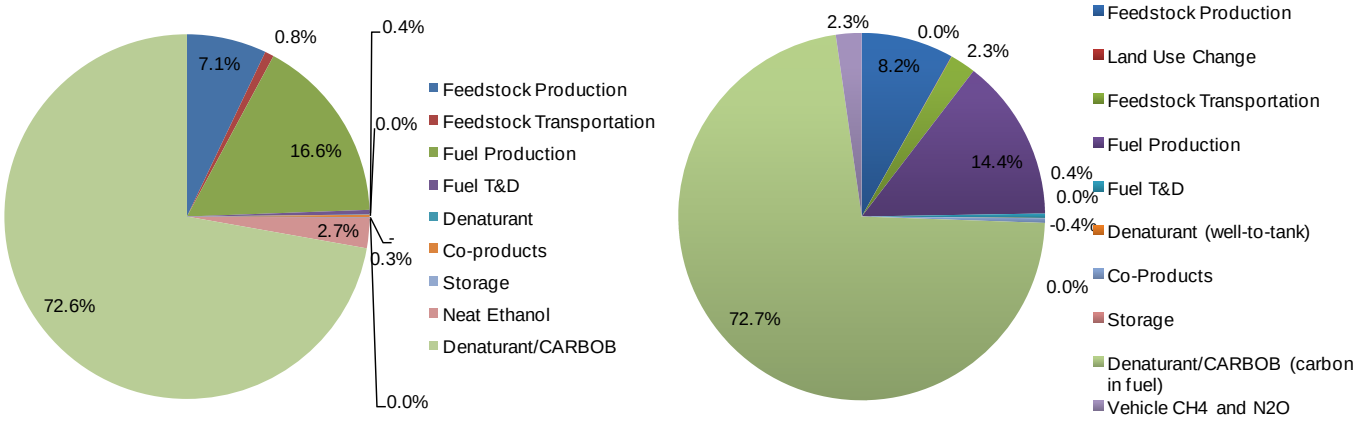

Figure 2. Energy Use and GHG Emission Contributions of CaRFG

APPENDIX A

1.1 Energy Use and GHG Emissions for CaRFG Pathway

This section provides details on combining the energy and GHG emission components of CARBOB and dry mill ethanol. The energy fraction of each component is shown in Table 1.01. The calculations shown here are for RFG blended with 5.35 volume % neat ethanol and 94.65% CARBOB. The 2% oxygen content of CaRFG is used to calculate the energy contribution of neat ethanol to CaRFG. This is detailed in Table 1.02 which shows that ethanol contributes 3.67% on an energy basis to the total LHV of CaRFG. The lower heating value and carbon content of RFG is based on the volumetric fraction and heating value of its blending components. Vehicle related N_2O and CH_4 emissions are detailed in Table 1.03.

Table 1.01 Energy and Carbon Content of CaRFG Blending Components

Fuel Components	Denatured Ethanol	CARBOB	Neat Ethanol	CaRFG
Lower Heating Value (Btu/gal)	77,254	113,300	76,330	111,323
Ethanol Fraction (vol%)	97.5%	0%	100%	5.35%
Energy Fraction in Blend	100%	96.3% of RFG	3.67% of RFG	100%
Fossil Carbon in Fuel as CO_2 (g/MMBtu)	2,815	76,921	0	74,101
Biogenic Carbon in Fuel as CO_2 (g/mmBtu)	72,177	0	74,925	2,747
Non Biogenic Carbon in Fuel as CO_2 (g/MJ)	2.67	72.91	0	70.2
Reference	Calculation	AB1007	Calculation	Calculation

Note: All values indicated here are either GREET default values or provided in the accompanying CARBOB and ethanol WTW analysis.

Table 1.02 Calculation of Energy Content of Ethanol in CaRFG

Component	**Oxygen content (wt%)**	**Ethanol content**		
		Wt %	Vol %	Energy %, LHV
Ethanol	16/(46)= 34.8%			
CARBOB	2%	(2% * 46/16) = 5.75%	(5.75%/2988)/ ((1-5.75%)/2767)+ 5.75%/2988)= 5.35%	(5.35%*76330)/ (((1-5.35%) * 113,300)+ (5.35%*76,330))=3.67%

Note: CARBOB density = 2767g/gal, Neat ethanol density = 2,988 g/gal (both GREET default values)
Molecular weight of ethanol= 46 g/mole, molecular weight of oxygen =16 g/mole.

1.2 Vehicle CH_4 and N_2O emissions

The California Climate Action Registry (CCAR) estimates g/mile values for CH_4 and N_2O. To convert to g/MJ, the emissions per mile are divided by the vehicle energy consumption in MJ/mi. The AB1007 analysis summarizes both the CCAR emission factors and estimates vehicle energy consumption (4.6 MJ/mile). The Global Warming Potentials for CH_4 and N_2O are from IPCC guidelines and are GREET default values. The calculations are shown in Table 1.03.

Table 1.03 Vehicle CH_4 and N_2O Emissions (per MJ fuel).

Parameter	**Emissions factor (g/mi)**	**GWP**	**Calculation**	**GHG (gCO_2e/MJ)**
N_2O	0.03	296	0.03 * 296/4.6	1.93
CH_4	0.05	23	0.05 * 23/4.6	0.25
Vehicle Energy Consumption	4.6 MJ/mi		**Total**	**2.18**

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APPENDIX B

CALIFORNIA REFORMULATED GASOLINE PATHWAY INPUT VALUES

Average Crude Oil to CA refineries to make CARBOB, blended with Midwest Corn, Dry Milling Ethanol for CaRFG

1) CARBOB Production

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		23	
N_2O		296	
VOC		3.1	
CO		1.6	
Crude Recovery			
Efficiency		93.9%	Crude Recovery for 2010 - user input
Process Shares			
Crude		1%	
Residual Oil		1%	
Conventional Diesel		15%	
Conventional Gasoline		2%	
Natural Gas		61.9%	
Electricity		19%	
Feed Loss crude recovery		0.04%	
Equipment Shares			
Commercial Boiler - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,167	
Stationary Reciprocating Eng. - Diesel		50%	
CO_2 Emission Factor	gCO_2/mmBtu	77,349	
Turbine - Diesel		25%	
CO_2 Emission Factor	gCO_2/mmBtu	78,179	
Stationary Reciprocating Eng. - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	56,551	
Small Industrial Boiler - NG		50%	
CO_2 Emission Factor	gCO_2/mmBtu	58,176	
Transportation to CA refineries			
Pipeline shares		42%	by pipeline to CA
Pipeline distance	miles	150	One way
Pipeline Energy Intensity	Btu/mile-ton	253	
Ocean Tanker shsres		58%	from Alaska
Average distance traveled	miles	3,300	Energy Intensity 27Btu/mile-ton, 24 for return trip
Transportation to US refineries			
Pipeline distance	miles	266	One way from 48 states, import
Pipeline Energy Intensity	Btu/mile-ton	253	
Ocean Tanker distance traveled	miles	2,100	One way from Alaska
Ocean Tanker Energy Intensity	Btu/mile-ton	27	24 Btu/mile-ton for return trip
Loss Factor in Crude T&D		1.000062	
CARBOB Refining			
Efficiency		84.5%	CARBOB Refining for year 2010 - user input
Process Shares			
Residual Oil		6%	
Natural Gas		40%	

Electricity		4%	
Still Gas		50%	
Equipment shares			
Large Turbine - Natural Gas		25%	
Parameters	**Units**	**Values**	**Note**
CO_2 Emission Factor	gCO_2/mmBtu	58,179	
Large Industrial Boiler - Natural Gas		60%	
CO_2 Emission Factor	gCO_2/mmBtu	58,198	
Small Industrial Boiler - Natural Gas		15%	
CO_2 Emission Factor	gCO_2/mmBtu	58,176	
Industrial Boiler - Residual Oil		100%	
CO_2 Emission Factor	gCO_2/mmBtu	85,045	
Transportation			
Transportation by pipeline		80%	20% directly from refinery terminal rack
Distance	miles	50	
Energy Intensity	Btu/ton-mile	253	
Distribution by truck		99.4%	0.6% directly supplied by pipeline
Distance	miles	50	
Energy Intensity	Btu/ton-mile	1,028	
Loss Factor in CARBOB T&D		1.000201	
Fuel Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	
Residual Oil	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,686	2,651	NG Liquids
Ethanol	76,330	2,988	
Still Gas	128,590		
Transportation Modes			
Ocean Tanker	tons	250,000	Crude Oil
	tons	150,000	Gasoline
Heavy Duty Truck	tons	25	Crude Oil
	tons	25	Gasoline

2) Ethanol Production

Parameters	**Units**	**Values**	**Note**
GHG Equivalent			
CO_2		1	
CH_4		23	
N_2O		296	
VOC		3.1	
CO		1.6	
Corn Farming			
Fuel Use Shares			
Diesel		38.3%	
Gasoline		12.3%	
Natural Gas		21.5%	

LPG		18.8%	
Electricity		9%	
Cultivation Equipment Shares			
Parameters	**Units**	**Values**	**Note**
Diesel Farming Tractor		80%	
CO_2 Emission Factor	g/mmBtu	77,204	
Diesel Engine		20%	
CO_2 Emission Factor	g/mmBtu	77,349	
Gasoline Farming Tractor		80%	
CO_2 Emission Factor	g/mmBtu	49,494	
NG Engine		100%	
CO_2 Emission Factor	g/mmBtu	56,551	
LPG Commercial Boiler		100%	
CO_2 Emission Factor	g/mmBtu	68,036	
Corn Farming			
Corn energy use	Btu/bu	22,500	
Corn harvest	lbs/bu	56	Shelled Corn
	bu/acre	158	
Land Use from Corn farming	g/bu	195	
Corn T&D			
Transported from Corn Field to Stack			
by medium truck	miles	10	2,199 Btu/mile-ton Energy Intensity
fuel consumption	mi/gal	7.3	capacity 8 tons/trip
CO_2 emission factor	g/mi	1,369	
Transported from Stack to EtOH Plant			
by heavy duty diesel truck	miles	40	1,713 Btu/mile-ton Energy Intensity
fuel consumption	mi/gal	5	capacity 15 tons/trip
CO_2 emission factor	g/mi	1,999	
Chemicals Inputs			
Nitrogen	g/bu	420	
NH3			
Production Efficiency		82.4%	
Shares in Nitrogen Production		70.7%	
CO_2 Emission Factor	g/g	2.475	
Urea			
Production Efficiency		46.7%	
Shares in Nitrogen Production		21.1%	
Ammonium Nitrate			
Production Efficiency		35%	
Shares in Nitrogen Production		8%	
P_2O_5	g/bu	149	
H_3PO_4			
Feedstock input	tons	n/a	
H_2SO_4			
Feedstock input	tons	2.674	
Phosphor Rock			
Feedstock input	tons	3.525	
K_2O	g/bu	174	
$CaCO_3$	g/bu	1,202	
Herbicide	g/bu	8.1	
Pesticide	g/bu	0.68	

Land Use	g/bu	529	CO_2 from $CaCO_3$ use
Co-Product Credit			
Corn Gluten Meal Yield	gal/bu	2.6	
Parameters	**Units**	**Values**	**Note**
Corn Gluten Feed Yield	lb/bu	11.2	
Soy Oil Yield	lb/bu	2.08	
EtOH Production			
Dry mill (shares of total)		80%	
Dry EtOH Yield	gal/bu	2.8	
Energy use for Dry Mill EtOH	Btu/gal	36,000	
NG used for dry mill		92.7%	
Large NG Boiler	g/mmBtu	58,198	50% usage
Small NG Boiler	g/mmBtu	58,176	50% usage
Electricity used for dry mill		7.3%	
Wet mill (shares of total)		20%	
Wet EtOH Yield	gal/bu	2.62	
Energy use for Wet Mill EtOH		45,970	
NG used for wet mill		60%	
Large NG Boiler	g/mmBtu	58,198	50% usage
Small NG Boiler	g/mmBtu	58,176	50% usage
Coal used for wet mill		40%	
Coal Boiler	g/mmBtu	137,383	
EtOH T&D			
Transported by rail	miles	1,400	370 Btu/mile-ton Energy Intensity
Transported by HHD truck	miles	40	1,028 Btu/mile-ton Energy Intensity both ways
Distributed by HHD truck	miles	50	1,028 Btu/mile-ton Energy Intensity both ways
Fuels Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	
Residual Oil	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,868	2,651	As liquid
EtOH	76,330	2,988	Anhydrous ethanol (neat)
EtOH	77,254	2,983	Denatured ethanol
Still Gas	128,590		