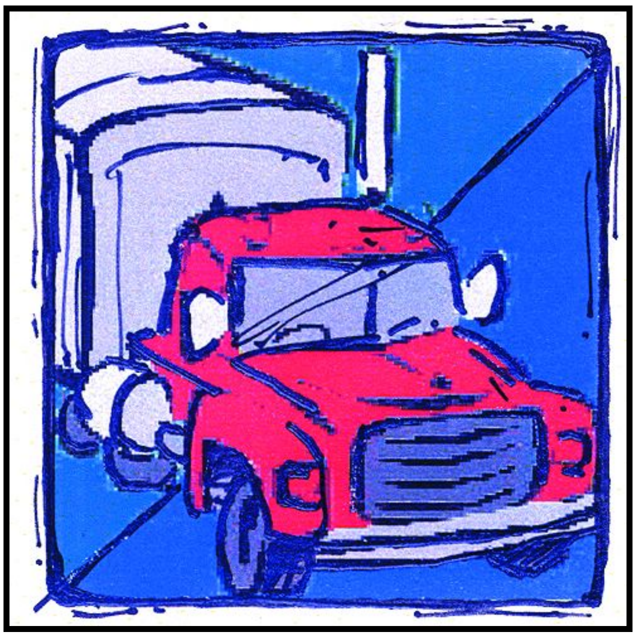
California Environmental Protection Agency

Air Resources Board

Detailed California-GREET Pathway for Biodiesel Produced in California from Used Cooking Oil



Stationary Source Division

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

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SUMMARY

CA-GREET Model Pathway for Biodiesel from UCO

Well-To-Tank (WTT) Life Cycle Analysis of a Biodiesel (BD) fuel pathway (from Used Cooking Oil (UCO) includes steps starting from UCO being transported to a biorefinery and transformation to final finished fuel. Tank-To-Wheel (TTW) analysis includes actual combustion of this fuel in a heavy-duty vehicle for motive power. WTT and TTW analysis are combined to provide a total Well-To-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **Gr**eenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory was modified with assistance from Life Cycle Associates to create a modified GREET model called the CA-GREET model. The methodology inherent in the CA-GREET model was utilized to develop a WTW analysis of the conversion of Used Cooking Oil (UCO) into Biodiesel (BD). The pathway documented here includes UCO transport, BD production, and transport of BD and use in a heavy duty vehicle. The CA-GREET model and pathway documents published by staff are available from www.arb.ca.gov/fuels/lcfs/lcfs.htm.

UCO for this pathway is considered to be waste oil generated in restaurants. All of the steps from feedstock transport to final use of finished fuel is considered to happen within California. Figure 1 provides a step-wise description of the various steps in the UCO to BD pathway. The steps include transport of UCO to a rendering plant, UCO rendering, transport of the rendered UCO to a biodiesel production plant, production of BD via esterification at the plant, and transport of BD to a fuel dispensing facility for final use in a heavy-duty vehicle. For this document, combustion of BD in a heavy-duty vehicle is assumed to generate the same CH_4 and N_2O emissions as Ultra Low Sulfur Diesel (ULSD) (see pathway document for ULSD published on the LCFS website at www.arb.ca.gov/fuels/lcfs/lcfs.htm).

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

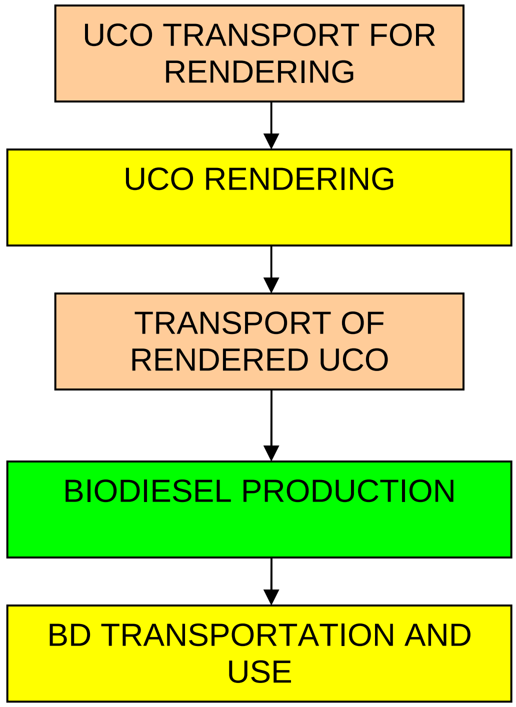


Figure 1. Discrete Components of Used Cooking Oil to Biodiesel

This document provides detailed calculations, assumptions, input values, and other information required to calculate the energy use and GHG emissions for the UCO to BD pathway. The original Argonne GREET model does not include this fuel pathway. The modified CA-GREET model however includes this fuel pathway. A detailed list of all input values used is provided in Appendix B.

Table A provides a summary of the Well-To-Tank (WTT) and Tank-To-Wheel (TTW) energy use and GHG emissions for this pathway. Energy use is presented as Btu/mmBtu and GHG emissions are reported as g CO_2e/MJ, where non-CO_2 gasses (i.e., CH_4 and N_2O) are converted into CO_2 equivalents. Details of converting non-CO_2 gasses to CO_2 equivalents are detailed in Appendix A in this document.

Note: The energy inputs are presented in mmBtu because the calculations in the CA-GREET model use mmBtu.

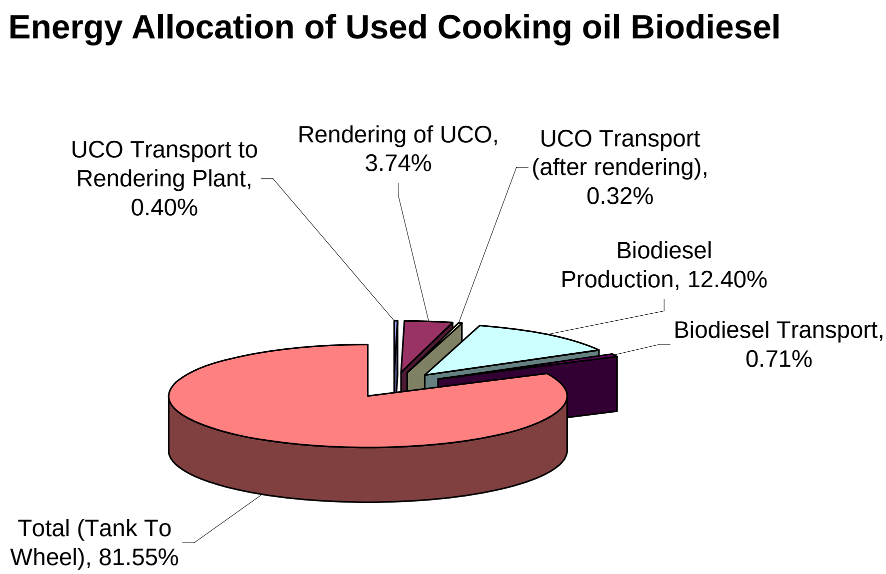
Table A. Summary of Energy Use and GHG Emissions for the Used Cooking Oil (UCO) to Biodiesel Pathway

	Energy Required (Btu/mmBtu)	**% Energy Contribution**	**Emissions (gCO_2e/MJ)**	**% Emissions Contribution**
UCO Transport to Rendering Plant	4,856	0.40%	0.37	2.70%
Rendering of UCO	45,818	3.74%	2.61	19.05%
UCO Transport (after rendering)	3,885	0.32%	0.29	2.12%
Biodiesel Production	152,005	12.40%	5.29	38.61%
Biodiesel Transport	8,662	0.71%	0.66	4.82%
Total (Well To Tank)	**226,282**	**18.45%**	**9.22**	**67.30%**
Total Combustion Emissions	**n/a**	**n/a**	**4.48**	**32.70%**
Total (Tank To Wheel)	**1,000,000**	**81.55%**	**4.48**	**32.70%**
Total (Well To Wheel)	**1,226,282**	**100%**	**13.70**	**100%**

Note: percentages may not add to 100 due to rounding

From Table A, the WTW analysis of BD from UCO indicates that **1,226,282** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy delivered to the vehicle. From a GHG perspective, **13.70** gCO_2e of GHGs are produced during the production and use of 1 (one) MJ of BD.

The values in Table A are illustrated in Figure 2, showing specific energy and GHG contributions of each of the discrete components of the entire fuel pathway. The charts are shown separately for energy use and GHG emissions. From an energy perspective, most of the energy is in the fuel (81.55%). From a GHG perspective, biodiesel production (38.61%), combustion (32.70%), and rendering (19.05%) are the largest contributors to this pathway.



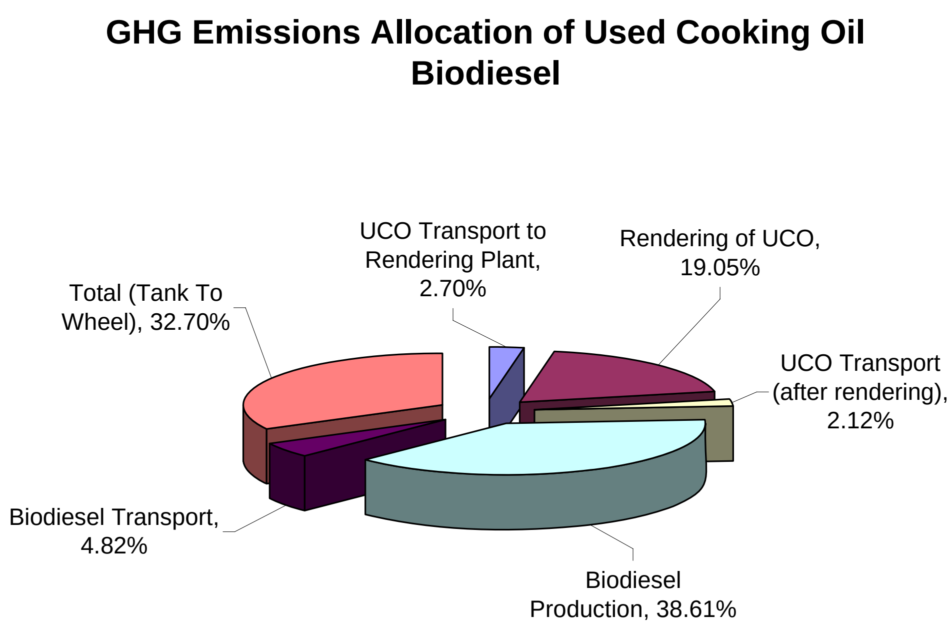


Figure 2. Contributions to Energy Use and GHG Emissions for the Used Cooking Oil to Biodiesel Pathway

WTT Details - Transport of UCO to Rendering Plant

Table B and C provides the energy use and associated GHG emissions related to transport of UCO to a rendering plant in California respectively. Detailed calculations are provided in Appendix A.

Table B. Total Energy Use for UCO Transport to Rendering Plant

Energy Result	Energy
Direct Energy for UCO Transport (Btu/lb UCO)	102,762
Upstream Energy from Transportation Fuel Used (Btu/lb UCO)	22,149
Total Energy (Btu/lb UCO)	**124,911**
Total Energy (Btu/mmBtu)	**4,856**

Table C. Total GHG Emissions from UCO Transport

	GHG Emissions
CO_2 (g/ton UCO)	9,562
CH_4 (g/ton UCO)	11.763
N_2O (g/ton UCO)	0.236
CO (g/ton UCO)	18.354
VOC (g/ton UCO)	4.058
Total GHG emissions (g/tonUCO)	**9,968**
Total GHG emissions (gCO2e/MJ)	**0.37**

WTT Details - Rendering of UCO in CA

Tables D and E provide a summary of the energy use and associated GHG emissions from rendering of UCO in a facility in California respectively. Details are provided in Appendix A.

Table D. Total Energy Use for Rendering of UCO

Energy Result	Energy
NG (Btu/lb UCO)	483
Electricity (Btu/lb UCO)	253
Total Energy (Btu/lb UCO)	**736**
Total Energy (Btu/mmBtu)	**45,818**

Table E. Total GHG Emissions from Rendering of UCO

	GHG Emissions
CO_2 (g/lb UCO)	42
CH_4 (g/lb UCO)	0.086
N_2O (g/lb UCO)	0.000
CO (g/lb UCO)	0.023
VOC (g/lb UCO)	0.006
Total emissions (g/lb UCO)	**44**
Total GHG emissions (gCO_2e/MJ)	**2.61**

WTT Details – Biodiesel Production

Pre-Processing of UCO for Converting FFAs

Tables F and G show the energy use and GHG emissions generated from pre-processing of UCO for converting free fatty acids (FFAs) respectively. Complete details are shown in Appendix A.

Table F. Energy Used for Pre-processing UCO for Converting FFAs

	Energy
Natural Gas (Btu/lb BD)	166
Electricity (Btu/lb BD)	32
Total Energy (Btu/lb BD)	**197**
Total Energy (Btu/mmBtu)	**11,056**

Table G. GHG Emissions for Pre-processing of UCO for Converting FFAs

Species	**Direct Emissions (g/lb UCO)**	**Upstream Emissions (g/lb UCO)**	**Total Emissions (g/lb BD)**
CH_4	0.000	0.026	0.024
N_2O	0.000	0.000	0.000
CO_2	10	2.522	11
GHG (gCO_2e/lb UCO)			**12.09**
Total GHGs (gCO_2e/MJ)			**0.64**

Biodiesel Production

Table H shows the energy Btu necessary for producing one million Btu of BD from UCO using esterification.

Table H. Energy Consumed for Biodiesel Production

	Energy
Natural Gas (Btu/lb BD)	950
Electricity (Btu/lb BD)	93
Methanol (Btu/lb BD)	1,354
Sodium Hydroxide (Btu/lb BD)	42
Sodium Methoxide (Btu/lb BD)	209
Hydrochloric Acid	63
Total BD Production Energy (Btu/lb BD)	**2,712**
Total BD Production Energy (Btu/mmBtu)	**152,005**

Table I provides GHG emissions resulting from BD production. The fuel consumption and other specifics necessary for this calculation are detailed in the Appendix A.

Table I. Total GHG Emissions for Biodiesel Production

GHG	GHG Emissions
CO_2 (g/lb of BD)	80
CH_4 (g/lb of BD)	0.292
N_2O (g/lb of BD)	0.001
CO (g/lb of BD)	0.062
VOC (g/lb of BD)	0.030
Total GHG emissions (g/lb of BD)	**5,423**
Total GHG emissions (gCO_2e/MJ)	**4.65**

<u>WTT Details - Biodiesel Transport</u>

Tables J and K provide the energy use and GHG emissions from transporting and distributing BD respectively. Details of all the calculations are presented in Appendix A.

Table J. Energy Use for Transportation and Distribution of BD

Transport mode	Btu/mmBtu
BD transportation by truck to bulk terminal	2,665
BD distribution by HDD truck	5,997
Total	**8,662**

Table K. GHG Emissions from Transporting and Distributing BD

GHGs	Total (gCO_2e/MJ)
CO_2	0.63
CH_4 (converted to CO_2e)	0.02
N_2O (converted to CO_2e)	<0.01
CO (converted to CO_2)	<0.01
VOC (converted to CO_2)	<0.01
Total GHGs	**0.66**

<u>TTW Details - Carbon in Biodiesel</u>

Table L below provides a summary of the combustion emissions from using BD in a heavy-duty vehicle details of which are provided in Appendix A.

Table L. Combustion Emissions for BD

Total GHG Emisisons = **4.48** g CO_2e/MJ

APPENDIX A

Section 1. Energy Consumption and GHG Emissions from Transport of Used Cooking Oil

This document provides details of the pathway from UCO to Biodiesel and final use in a heavy-duty vehicle in California. Complete details of each step are provided in sections below.

1.1 Transport of Used Cooking Oil to Rendering Plant

Used cooking oil (UCO) generated in California is transported by heavy duty diesel truck to a rendering plant in California. The CA-marginal regional parameters are used in CA-GREET for UCO transport; these include California petroleum and electricity parameters. The raw UCO transported is assumed to contain an average moisture content of 20% (for additional details, see Section 1.3). The transport energy and distance parameters used in this analysis are shown below in Table 1.02.

Table 1.01 Used Cooking Oil (UCO) Specifications

Descriptions	Values	
UCO wet ratio	1.25 lb/lb processed UCO	Calculated
UCO/BD ratio	1.11 lb/lb BD	GREET Default
UCO Density	7.5 lb/gallon	
Allocation Factor	90.5%	

Note: To calculate processed UCO yield factor:
(1/(1-20% moisture content)) = 1.25 lbs wet UCO/lb processed UCO.
For Allocation factor details refer to Section 2 of this document.

Table 1.02 Parameters for UCO Transport to Rendering Plant in CA

Mode	Heavy Duty Truck
Mode Share	100%
Fuel	ULSD
Fuel Economy (miles/gallon)	5
Distance (mi)	50
Moisture Content Unprocessed UCO (%)	20%
LHV Ultra Low Sulfur Diesel (Btu/gal) LHV Biodiesel (Btu/gal) LHV Biodiesel (Btu/lb)	128,450 119,550 16,149
Density (g/gal)	3,361
Energy Intensity (Btu/ton-mi)	1,028
Upstream Diesel Energy Factor (Btu/Btu)	0.216

The direct, upstream and total energy requirements based on the inputs shown above are shown in Table 1.03 below. Transportation of UCO for rendering requires **5,366 Btu/mmBtu** of BD produced. This energy is then adjusted using an allocation factor of 90.5% (see Section 2 for details) to provide an adjusted energy requirement of 4,856 Btu/mmBtu of BD produced. The calculations for direct and upstream energy are shown below:

Direct Energy:
1/(119,550 Btu/gal BD)*(3,361 g/gal)/(454 g/lb)*(50 mi)*(1,028 Btu/ton-mi + 1,028 Btu/ton-mi)*(16,149 Btu/lb BD) = **102,762 Btu/ton wet UCO**
(wet UCO here refers to UCO before rendering)

Upstream Energy:
1/(119,550 Btu/gal BD)*(3,361 g/gal)/(454 g/lb)*(50 mi)*(1,028 Btu/ton-mi + 1,028 Btu/ton-mi)*(0.216 Btu/Btu)(16,149 Btu/lb BD) = **22,149 Btu/ton wet UCO**

Total Energy = 102,762 Btu/ton + 22,149 Btu/ton = **124,911 Btu/ton wet UCO**

Table 1.03 Direct, Upstream and Total Energy of Transport of UCO to a Rendering Plant in CA

Energy Result	Heavy Duty Truck (Btu/ton wet UCO)
Direct Energy for UCO Transport	102,762
Upstream Energy from Transportation Fuel Used	22,149
Total Energy (Btu/ton wet UCO)	124,911
Total Energy (Btu/mmBtu BD)	**5,366**
Total Allocated* Energy (Btu/mmBtu BD)	**4,856**

Note: To convert from Btu/ton wet UCO to Btu/mmBtu BD:
(124,911 Btu/lb wet UCO)/(2,000 lbs/ton)*(1.25 lb wet UCO/lb processed UCO)*(1.11 lb UCO/lb BD)/(16,149 Btu/lb BD)*10^6 = 5,366 Btu/mmBtu BD.

*Multiply by 90.5% allocation factor to yield total allocated results for UCO transport.

1.2 GHG Calculations for UCO Transport to a Rendering Plant in California

The analysis assumes a transport distance of 50 miles and assumes heavy duty truck transport from UCO collection sites to the processing facility. Transport emissions were calculated in CA-GREET in g/ton wet UCO, then converted to g/lb BD and g/mmBtu BD. Table 1.04 shows the direct emissions, upstream emissions and total emissions. Sample calculations of the direct and total CO_2 emissions from UCO transport are shown below. The calculations are similar for the other GHG species shown in Table 1.04.

Direct CO_2 Emissions:
(3,361 g/gal)/(119,550 Btu/gal BD)/(454 g/lb)*[(77,809 g/mmBtu)*(1,028 Btu/ton-mi) + (77,912 g/mmBtu)*(1,028 Btu/ton-mi)]*(50 mi)*(16,149 Btu/lb)/10^6 = **8,001 g/ton wet UCO**

where 77,809 and 77,912 g/mmBtu are the heavy duty truck CO_2 emission factors for both ways of travel.

Upstream CO_2 Emissions:
(3,361 g/gal)/(119,550 Btu/gal BD)/(454 g/lb)*[(15,186 g/mmBtu)*(1,028 Btu/ton-mi) + (15,186 g/mmBtu)*(1,028 Btu/ton-mi)]*(50 mi)*(16,149 Btu/lb)/10^6 = **1,561 g/ton wet UCO**

where 15,186 g/mmBtu is the upstream emissions associated with diesel production.

Total CO_2 Emissions = 8,001 g/ton + 1,561 g/ton = **9,562 g/ton wet UCO**

Table 1.04 Greenhouse Gas Emissions for Transport of UCO to a Rendering Plant in California

	Processing to Fuel Plant
Mode	Heavy Duty Truck
Mode Share	100%
Distance, miles	50
Fuel	Diesel
Energy Intensity, Btu/ton-mile	1,028
UCO Moisture Content (%)	20%
Direct Emissions (g/ton wet UCO)	
VOC	3.086
CO	15.730
CH_4	0.157
N_2O	0.216
CO_2	8,001
Upstream Emissions (g/ton wet UCO)	
VOC	0.972
CO	2.624
CH_4	11.606
N_2O	0.020
CO_2	1,561
Total Emissions, (g/ton UCO Transported)	
VOC	4.058
CO	18.354
CH_4	11.763
N_2O	0.236
CO_2	9,562
GHG Emissions (g/ton wet UCO)	9,968
GHGs (g/mmBtu BD)	428
GHGs (g/MJ BD)	**0.41**
Allocated GHGs* (g/MJ BD)	**0.37**

Note: To convert from g/ton wet UCO to g/mmBtu BD:
(9,968 g/ton wet UCO)/(2,000 lbs/ton)*(1.25 lb wet UCO/lb processed UCO)*(1.11 lb UCO/lb BD)/(16,149 Btu/lb BD)*10^6 = 428 g/mmBtu BD.

1.3 Energy for Rendering UCO in California

Depending on the source of the used cooking oil, it may contain varying amounts of water, which must be removed prior to further processing of the oil. At animal by-product rendering plants that also process UCO, cookers are used to evaporate the water from the oil. Because the UCO typically contains much less moisture than animal by-products and requires no crushing, much less thermal and electrical energy are required to process used cooking oil than to render animal by-products.

The range of figures published for the heat energy required to process UCO spans more than an order of magnitude. The reason for the wide range is due primarily to the different approaches used to remove moisture from the UCO. To a lesser extent, it may also be explained by differing assumptions about the moisture content of the raw UCO. The average of the data collected and reported for seven different plants for this study are based on several older rendering plants in the U.S., which process UCO in their cookers. The data reflect information provided by the operators that per pound of product, it takes one-third as much energy to process UCO as it does to render animal by-products.

Table 1.05 presents the range of processing energy inputs based on available literature and survey data. The lowest figure listed in Table 1.05 for thermal energy represents the average of several modern plants in the U.S. that are dedicated to the processing of UCO. In these plants, the UCO is not processed in a cooker, as it is at rendering plants[2]. Instead, the UCO (grease) is heated to liquefy it and break the oil-water emulsion. The liquefied grease is filtered and the water and sediment is allowed to settle from the oil. Because the water is physically separated from the UCO, no energy is required for evaporation, thus resulting in far less energy consumption than for the processing of UCO in a rendering plant cooker.

This analysis assumes a thermal processing input of 3,768 Btu/gallon HHV (3,391 Btu/gallon LHV) as estimated by the Fats Proteins Research Foundation. This value is selected because it lies within the range listed in Table 1.05. It is close to the weighted average of Plants 1-7 in Table 1.05 and the data provided by an industry source. It is estimated that currently 60-80 percent of UCO is processed using the technology employed representative of the data provided from industry source, while the remainder is processed in cookers at rendering plants, such as those represented by Plants 1-7[2]. If 70 percent of the UCO is assumed to be processed in newer plants and 30 percent in older plants, the weighed average energy consumption would be 3,521 Btu/gallon, which is comparable to the Fats Proteins Research Foundation value. For use in the GREET model the energy input (NG) is converted to a Btu/lb UCO basis using a density of 7.5 lb/gal for UCO.

2 Wellons, Fred, Tellurian Biodiesel, Personal Communication, June 25, 2009.

Table 1.05 Energy for Processing Used Cooking Oil

Processing Energy Data Source	Thermal Energy	Electrical Energy	Notes
	Btu/gal	kWh/gal	
Survey of U.S. Rendering Plants for ARB, 2009[3]			
Plant 1	7,250	0.259	
Plant 2	8,213	0.112	
Plant 3	7,383	0.309	
Plant 4	9,259	0.284	
Plant 5	7,648	0.295	
Plant 6	13,602	0.478	
Plant 7	13,485	0.418	
Average Plants 1-7	9,549	0.308	
Natural Resources Canada, 2005[4]	2,440	0.337	Based on 40% water in UCO, reduced mechanically to 14.3% before rendering
Fats Proteins Research Foundation, 2005[5]	3,768	0.278	Electricity based on soybean processing; thermal energy based on evaporation of 20% moisture in of raw material (0.53 MJ/lb oil produced)
CSIRO, 2007[6]	1103	0.012	Basis for figures not specified
Industry Sourced Data, 2009[7]	938	0.060	Water removed by heating used oil and allowing water to settle; not processed in a cooker.

Electricity consumption for UCO processing is also much less than for rendering animal by-products. Data for the seven rendering plants surveyed for this study indicate that on average, the plants consume 0.308 kWh per gallon of UCO produced. This analysis uses the estimate of the Fats Proteins Research Foundation, 0.278 kWh/gallon. This figure is intermediate among the range of surveyed values. It is equivalent to 0.037 kWh per pound of product (based on a density of 7.5 lbs per gallon for UCO).

The direct energy and upstream energy consumption of the processing process is calculated as shown in Table 1.06. Details of the calculations for direct and upstream energy are presented below:

[3] Wellons, Fred, Tellurian Biodiesel, Personal Communication, June 2, 2009.
[4] Natural Resources Canada, 2005.
[5] Fats Proteins Research Foundation, 2005.
[6] CSIRO, The Greenhouse and Air Quality Emissions of Biodiesel Blends in Australia. Vitoria, Australia. August, 2007.
[7] Industry Representative, Personal Communication, June 23, 2009.

Upstream NG Energy:
(452 Btu/lb UCO)*(68,865 Btu/mmBtu NG)/10^6 = **31 Btu/lb UCO**

Upstream Electricity Energy:
(452 Btu/lb UCO)*((111,573 Btu/mmBtu Feedstock) + (1,884,989 Btu/mmBtu Electricity))/10^6 – (126 Btu/mmBtu direct energy) = **126 Btu/lb UCO**

Table 1.06 Direct and Upstream Energy Use for Rendering UCO in CA

Inputs	Direct	Upstream Energy	Total Energy
NG (heat) (Btu/lb UCO)	((3,391 Btu/gal LHV) / (7.5 lbs/gal)) = 452	31	483
Electricity (CA marginal) (Btu/lb UCO)	(0.278 kWh/gal) *(3,412 Btu/kWh) /(7.5 gal/lb) = 126	126	253
Total Energy Input	**579**	**157**	**736**
Convert to Btu/mmBtu BD			**50,627**
Convert to Allocated Btu/mmBtu BD*			**45,818**

Note: Upstream energy is from WTT energy of NG and electricity documents[8]. Converting from Btu/lb UCO to Btu/mmBtu requires the ratio of the UCO to BD (1.11 lb UCO/lb BD) and the LHV for BD (16,149 Btu/lb BD). *Calculate allocated energy input using 90.5% energy allocation factor (see section 2)

[8] See Natural Gas and Electricity pathway documents published by ARB February 2009

1.4 Greenhouse Gas Emissions from Rendering of UCO in California

Details of GHG emissions from the rendering process are shown in Table 1.07.

Table 1.07 GHG Emissions from Direct and Upstream Energy Used in Rendering of UCO in California

Emission Species	Direct Emissions (g/lb UCO)	Upstream Emissions (g/lb UCO)	Total Emissions (g/lb UCO)
VOC	0.001	0.005	0.006
CO	0.010	0.013	0.023
CH_4	0.000	0.086	0.086
N_2O	0.000	0.000	0.000
CO_2	**26**	**16**	42
Total Emissions	26	18	44
Total Emissions (gCO_2e/mmBtu BD)			**3,040**
Total Emissions (gCO_2e/mmBtu BD)			**2.88**
Total Allocated Emissions* (gCO_2e/MJ)			**2.61**

Note: Upstream energy is from WTT energy of NG and electricity documents. Converting from Btu/lb UCO to Btu/mmBtu requires the ratio of the UCO to BD (1.11 lb UCO/lb BD) and the LHV for BD (16,149 Btu/lb BD). *Calculate allocated energy input using 90.5% energy allocation factor (see section 2).

Example Calculations of CO_2 emissions[9]

Direct CO_2:
((452 Btu NG/lb UCO)[50%*(58,198 g/mmBtu utility boiler CO_2 EF) + 50%*(58,176 g/mmBtu utility boiler CO_2 EF)])/10^6 = **26 g/lb UCO**

The upstream CO_2 emissions of the NG and electricity used

Upstream CO_2:
((452 Btu NG/lb UCO)*(5,050 NG WTT CO_2 Emissions)+(423 Btu/lb UCO)*((8,277 g/mmBtu feedstock) + (96,250 g/mmBtu)))/10^6 = **16 g/lb UCO**

1.5 Energy Use for Transport of Rendered UCO to a BD Production Plant

Processed UCO is transported by heavy duty truck to a fuel plant in California. The CA-marginal regional parameters are used in CA-GREET for UCO transport; these include California petroleum and electricity parameters. UCO transport is modeled in CA-GREET using the BD heavy duty truck transport calculations in Btu/ton of product transported. The key transport energy and distance parameters are shown in Table 1.08.

[9] Emission Factors of boilers and feedstock of electricity used are from CA-GREET Model and is available in the BD from soybean pathway document published in 02/2009.

Table 1.08 Transport Parameters for Rendered UCO

Mode	**Heavy Duty Truck**
Mode Share	100%
Fuel	Diesel
Fuel Economy (mpg)	5
Distance (mi)	50

The direct, upstream, and total energy requirements based on the inputs above are shown in Table 1.08. Transportation of UCO for BD production requires **4,293 Btu/mmBtu** BD produced. An energy-based allocation factor (90.5%) is used to calculate the total energy for UCO transport allocated to biodiesel production. See section 2 for the explanation and derivation of the allocation factor.

Table 1.09 Direct, Upstream and Total Energy for Transport of Rendered UCO to a BD Production Plant

Energy Result	**Heavy Duty Truck (Btu/ton processed UCO)**
Direct Energy for UCO Transport	102,762
Upstream Energy from Transportation Fuel Used	22,149
Total Energy (Btu/lb processed UCO)	124,911
Total Energy (Btu/mmBtu BD)	**4,293**
Total Allocated* Energy (Btu/mmBtu BD)	**3,885**

Note: To convert from Btu/lb wet UCO to Btu/mmBtu BD:
(124,911 Btu/ton processed UCO)/(2,000 lbs/ton)*(1.11 lb UCO/lb BD)/(16,149 Btu/lb BD) = 4,293 Btu/mmBtu BD. *Calculate allocated energy input using 90.5% energy allocation factor (see section 2).

1.6 GHG Calculations for Transport of Rendered UCO to a Biodiesel Production Plant

The analysis assumes 50 miles heavy duty transport from UCO processing plant to the fuel plant. Transport emissions were calculated in GREET in g/ton processed UCO, then converted to g/lb BD and g/mmBtu BD. Table 1.09 below shows the direct emissions, upstream emissions and total emissions.

Table 1.10 Greenhouse Gas Emission Results for Transport of Rendered UCO

	Processing to Fuel Plant
Mode	Heavy Duty Truck
Mode Share	100%
Distance, miles	50
Fuel	Diesel
Energy Intensity, Btu/ton-mile	1,028
Direct Emissions (g/ton Processed UCO)	
VOC	3.086
CO	15.730
CH_4	0.157
N_2O	0.216
CO_2	8,001
Upstream Emissions (g/ton Processed UCO)	
VOC	0.972
CO	2.624
CH_4	11.606
N_2O	0.020
CO_2	1,561
Total Emissions, (g/ton Processed UCO)	
VOC	4.058
CO	18.354
CH_4	11.763
N_2O	0.236
CO_2	9,562
GHG Emissions (g/ton processed UCO)	9,968
GHGs (g/mmBtu BD)	342
GHGs (g/MJ BD)	**0.32**
Allocated GHGs* (g/MJ BD)	**0.29**

Note: To convert from g/ton processed UCO to g/mmBtu BD:
(9,968 Btu/ton processed UCO)/(2,000 lbs/ton)*(1.11 lb UCO/lb BD)/(16,149 Btu/lb BD) = 342 g/mmBtu BD.

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Section 2. Biodiesel Production

2.1 Energy for Pre-Processing of UCO (Free Fatty Acid Conversion)

When processing biodiesel feedstocks that have a high free fatty acid (FFA) content, such as UCO, a pre-processing step is necessary to reduce the FFA content before it is esterified to biodiesel. It is estimated that roughly half the UCO in the US is processed via acid esterification using sodium hydroxide to neutralize sulfuric acid, and the other half processed with continuous, non-acid esterification[10]. The acid esterification process consumes on average 1,862 Btu's of thermal energy and 0.04375 kWh of electricity per gallon of biodiesel produced, while the non-acid esterification process consumes 722 Btus of thermal energy and 0.02575 kWh of electricity per gallon of biodiesel produced[11]. Since roughly equal quantities of UCO are processed using each method, this analysis uses the average energy consumption of these two be used to represent this processing step in the CA-GREET model. The average values for thermal energy and electricity per gallon of biodiesel produced are 1,292 Btu (HHV) and 0.03475 kWh. These values are based on a 90 percent yield of biodiesel upon distillation. Figure 2.1 below shows the fuel production configuration.

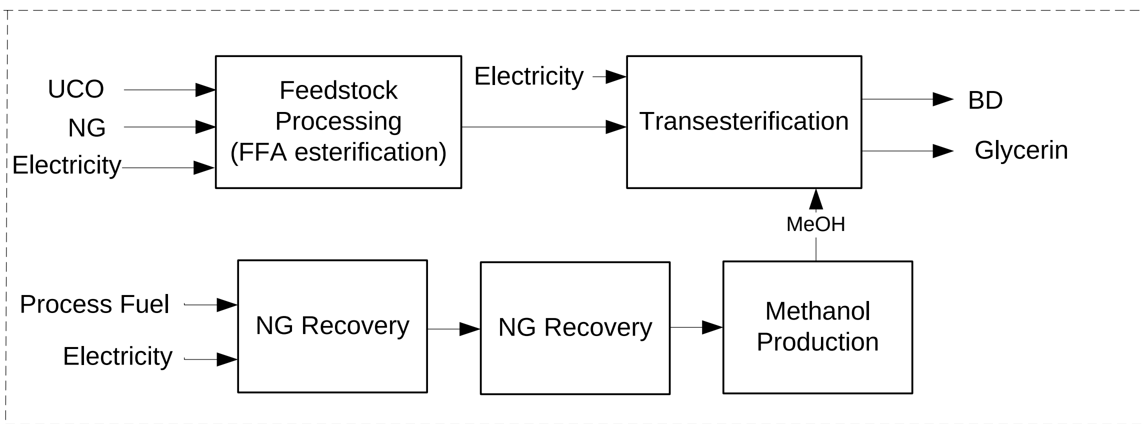

Figure 3. Configuration for UCO Conversion to Biodiesel.

The process inputs for FFA pre-processing are presented in Table 2.01, converted to Btu/lb BD (LHV). The CA marginal electricity mix was used for this analysis.

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[10] Wellons, Fred, Tellurian Biodiesel, Personal Communication, June 23, 2009.
[11] Ibid.

Table 2.01 Calculation of Direct Energy Consumption (Btu/lb BD) for Pre-processing of UCO to Convert FFAs

Process Fuel Type	Direct Energy Calculation (Btu/lb BD)	Direct Energy Consumption, (Btu/lb BD)
Natural Gas	((1,163 Btu/gal LHV) / (7.5 lbs/gal)) = 155	155
Electricity	(0.03475 kWh/gal) *(3,412 Btu/kWh) /(7.5 gal/lb) = 16	16
Direct Energy Consumption		**171**

The values provided in Table 2.01 are direct energy consumption per lb of BD produced. The natural gas input is based on 1,292 Btu/gal BD HHV (1,973 Btu/gal LHV) The total energy includes the direct and upstream energy components, and the total energy requirement is then allocated among the BD fuel and co-product glycerin based on energy content of each and glycerin yield (see allocation factor calculation below)[12]. Table 2.02 below shows the total energy consumption (in Btu/lb) and allocated energy consumption (in Btu/lb BD and Btu/mmBtu BD).

$$\text{BD Allocation Factor} = \frac{16{,}149 \text{ Btu/lb BD}}{(16{,}149 \text{ Btu/lb BD} + (7{,}979 \text{ Btu/lb glycerin})*(0.213 \text{ lb propane/lb BD})} = 90.5\%$$

Table 2.02 expresses the contribution energy with direct and upstream energy for each fuel. Table 2.03 presents the total energy for pre-processing to convert FFAs prior to esterification.

Table 2.02 Calculation of Direct and Upstream Energy Consumption (Btu/lb BD) for Pre-processing of UCO to Convert FFAs

Process Fuel Type	Direct Energy (Btu/lb)	Upstream Energy (Btu/lb)	Total Energy Consumption, Btu/lb BD
Natural Gas	155	$155*(1+68{,}865/10^6)$	166
Electricity	16	$16*(111{,}573+1{,}884{,}989)/10^6$	32
Direct and Upstream Energy Input (Btu/lb BD)			**197**

Where:
Energy of NG as fuel: 68,865 Btu/mmBtu
Energy of Electricity as feedstock: 111,573 Btu/mmBtu
Energy of Electricity as fuel: 1,884,989 Btu/mmBtu

[12] This allocation factor is assumed the same as soy bean BD. Please refer to this document for complete details. It is available on the Low Carbon Fuel Standard website.

Table 2.03 Total and Allocated Energy Consumption for Pre-Processing of UCO to Convert FFAs

Energy Consumption	Value
Total Energy (Btu/lb BD)	197
Total Energy (Btu/mmBtu BD)	12,216
Total Adjusted Energy* (Btu/mmBtu BD)	**11,056**

Note:
Total adjusted energy includes allocation (90.5%) and downstream loss factor (1.000)
To convert Btu/lb BD to Btu/mmBtu BD:
(197 Btu/lb UCO)/(16,149 Btu/lb BD)*10^6 = 12,216 Btu/mmBtu BD
To convert Btu/mmBtu BD to energy-allocated Btu/mmBtu:
(12,216 Btu/mmBtu BD)*(90.5%) = 11,056 Btu/mmBtu

After FFA conversion, the intermediate UCO product is esterified like soybean oil. The analysis assumes the same esterification input parameters used for soybean oil esterification to biodiesel[13]. Table 2.04 below presents the direct, and upstream energy for BD production (UCO esterification). Table 2.05 provides the total energy use for BD production.

Table 2.04 Calculation of Direct and Upstream Energy Consumption (Btu/lb BD) for BD Production

Process Fuel Type	**Fuel Shares**	**Direct Energy (Btu/lb)**	**Upstream Energy (Btu/lb)**	**Total Energy Consumption (Btu/lb BD)**
Natural Gas	42.0%	(42.0%)*(2,116) = 889	889*(1+68,865/10^6)	950
Electricity	2.2%	(2.2%)*(2,116) = 47	47*(111,573+1,884,989)/10^6	93
Methanol	40.9%	(40.9%)*(2,116) = 865	865*(31,792*1.000+532,954)/10^6	1,354
Sodium Hydroxide	2.0%	(2.0%)*(2,116) = 42	-	42
Sodium Methoxide	9.9%	(9.9%)*(2,116) = 209	-	209
Hydrochloric Acid	3.0%	(3.0%)*(2,116) = 63	-	63
Direct Energy Input (Btu/lb BD)				**2,712**

[13] See Soybean Biodiesel Pathway Document published by ARB February 2009, www.arb.ca.gov/fuels/lcfs/lcfs.htm

Table 2.05 Total Energy Consumption for BD Production

Energy Consumption	Value
Total Energy (Btu/lb BD)	2,712
Total Energy (Btu/mmBtu BD)	167,961
Total Adjusted Energy* (Btu/mmBtu BD)	**152,005**

Note:
Total adjusted energy includes allocation (90.5%) and downstream loss factor (1.000)
To convert Btu/lb BD to Btu/mmBtu BD:
(2,712 Btu/lb BD)/(16,149 Btu/lb BD)*10^6 = 167,961 Btu/mmBtu BD
Btu/mmBtu BD (where 16,194 Btu/lb is assumed LHV of BD)
To convert Btu/mmBtu BD to energy-allocated Btu/mmBtu:
(167,961 Btu/mmBtu)*(90.5%) = 152,005 Btu/mmBtu

2.2 Greenhouse Gas Emissions from Biodiesel Production

Direct, upstream and total greenhouse gas emissions for FFA conversion in UCO are shown below in Table 2.06. The California marginal electricity mix is used to calculate emissions from electricity generation. The calculations for direct and upstream CO_2 emissions are shown below.

Direct CO_2 Emissions:
(155 Btu NG/lb BD)*(50%*(58,198 g/mmBtu NG) + 50%*(58,176 g/mmBtu NG))/10^6 = **9 g/lb BD**

where 58,198 g/mmBtu and 58,176 g/mmBtu are the emission factors for NG utility and small boilers, respectively (no direct electricity emissions).

Upstream CO_2 Emissions:
[(155 Btu NG/lb BD)*(5,050 g/mmBtu)+(16 Btu electricity/lb BD)*((8,277 g/mmBtu Feedstock)+(96,250 g/mmBtu Electricity))]/10^6 = **2 g/lb BD**

where 5,050 g/mmBtu is the upstream emissions for NG production. 8,277 g/mmBtu and 96,250 g/mmBtu are the upstream emissions associated with electricity feedstock and generation, respectively.

Table 2.06 Direct, Upstream and Total Greenhouse Gas Emissions for Pre-processing of UCO to Convert FFAs

Species	Direct Emissions (g/lb BD)	Upstream Emissions (g/lb BD)	Total Emissions (g/lb BD)
VOC	0.000	0.001	0.002
CO	0.004	0.003	0.006
CH_4	0.000	0.023	0.024
N_2O	0.000	0.000	0.000
CO_2	9	2	11
GHG (gCO_2e/lb BD)[1]			**12.09**
GHG (gCO_2e/mmBtu)[1]			**748**
Total GHG (g/MJ)			**0.71**
Total Adjusted[2] GHG (g/MJ)			**0.64**

Note:
1. Adjusted to Global Warming Potential: CH_4: 25, N_2O: 298, CO_2: 1
2. Total adjusted energy includes allocation (90.5%) and downstream loss factor (1.000)
To convert from g/lb BD to g/mmBtu BD:
(12.09 g/lb BD)/(16,149 Btu/lb BD)*10^6 = 748 Btu/mmBtu BD

Direct, upstream and total greenhouse gas emissions for UCO esterification (BD production) are shown below in Table 2.07. The California marginal electricity mix is used to calculate emissions from electricity generation.

Table 2.07 Direct, Upstream and Total Greenhouse Gas Emissions for BD Production

Species	Direct Emissions (g/lb BD)	Upstream Emissions (g/lb BD)	Total Emissions (g/lb BD)
VOC	0.002	0.029	0.030
CO	0.020	0.0419	0.062
CH_4	0.001	0.291	0.292
N_2O	0.000	0.000	0.001
CO_2	52	28	80
GHG (gCO_2e/lb BD)			**87.6**
GHG (gCO_2e/mmBtu)			**5,423**
Total GHG (g/MJ)			**5.14**
Total Adjusted[2] GHG (g/MJ)			**4.65**

Note:
Adjusted to Global Warming Potential: CH_4: 25, N_2O: 298, CO_2: 1
To convert from g/lb BD to g/mmBtu BD:
(87.6 g/lb BD)/(16,149 Btu/lb BD)*10^6 = 5,423 Btu/mmBtu BD (where 16,194 Btu/lb is the assumed LHV of BD)

Section 3. Biodiesel Transport and Distribution

3.1 Energy Calculations for Biodiesel Transport to Retail Stations

The next step in the Biodiesel pathway is transport from the production plant in California to a retail station. Table 3.01 provides the transport assumptions and calculations for this final step.

80% of the Biodiesel is transported by heavy duty truck 50 miles from the plant to bulk terminal; the remaining 20% is distributed directly from the plant. All BD is then transported 90 miles by heavy duty truck from the bulk terminal to refueling stations. The energy values are converted from Btu/ton-mile to total energy as follows: The energy and emissions are calculated the same here as for BD from soyoil pathway document (see document on LCFS website at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). Btu/ton-mile factors are converted to Btu/ton, which is converted to Btu/mmBtu fuel for both legs of the trip. The energy for each mode is multiplied by the mode share shown in Table 3.01 to yield the total energy. No allocation factor adjustment is made for BD transport.

Table 3.01 Biodiesel Transport Parameters and Results

Parameter	Units	Plant to Bulk Terminal	Distribution	Total
Mode	-	Heavy Duty Truck	Heavy Duty Truck	
Shares	%	80%	100%	
Distance	Miles	50	90	
Payload	Tons	25	25	
Fuel Economy	mi/gal	5	5	
Fuel	-	Diesel	Diesel	
Fuel LHV	Btu/gal	128,450	128,450	
Energy Intensity	Btu/ton-mile	1,028	1,028	
Direct Energy (Btu/mmBtu)[1]		2,741	4,934	
Upstream Energy (Btu/mmBtu)[1]		591	1,063	
Total Energy (Btu/mmBtu)[1]		3,332	5,997	
Total BD T&D Energy (Btu/mmBtu)		**2,665**	**5,997**	**8,662**

[1]Excludes mode share, which is accounted for in the total energy
Note: Energy Intensity = LHV / fuel economy / payload = 1,028 Btu/mile-ton
Direct truck energy doubles the miles to take into account round trip energy.

3.2 GHG Calculations for Biodiesel Transport to Retail Stations

Biodiesel is assumed to be transported as follows in CA-GREET:

- 80% transported 50 miles by heavy duty diesel truck (HDD) from plants in CA to bulk terminal
- 100% distributed 90 miles by heavy duty truck.

Table 3.02 below shows the direct emissions, upstream emissions (without accounting for mode share) and total emissions, accounting for mode share.

Table 3.02 Biodiesel Greenhouse Gas Emissions

	Plant to Bulk Terminal	**Fuel Distribution**	**Total Transport**
Mode	HDD Truck	HDD Truck	
Mode Share	80%	100%	
Distance, miles	50	90	
Fuel	Diesel	Diesel	
Energy Intensity, Btu/ton-mile	1,028	1,028	
Direct Emissions (g/mmBtu)			
VOC	0.082	0.148	
CO	0.420	0.755	
CH_4	0.004	0.008	
N_2O	0.006	0.010	
CO_2	213	384	
Upstream Emissions (g/mmBtu)			
VOC	0.0296	0.047	
CO	0.07	0.126	
CH_4	0.310	0.557	
N_2O	0.001	0.001	
CO_2	42	75	
Total Emissions, (g/mmBtu)			
VOC	0.086	0.047	0.281
CO	0.392	0.126	1.273
CH_4	0.251	0.557	0.816
N_2O	0.005	0.001	0.016
CO_2	204	462	663
GHGs (g/mmBtu)	212.7	478.5	691.2
GHGs (g/MJ)	**0.20**	**0.46**	**0.66**

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Section 4. GHG Emissions from a Biodiesel-Fueled Vehicle

4.1 Combustion Emissions from Fuel Vehicle CO_2 (Carbon in Fuel)

The CA-GREET model considers only the fossil carbon in fuel (expressed as fully oxidized, g CO_2/mmBtu fuel), since biologically derived fuel carbon originates from the atmosphere and the net greenhouse gas impact is neutral. The only fossil carbon in biodiesel originates from the methanol (produced from natural gas) used in soybean oil transesterification. The calculations in Table 4.01 below show the fossil CO_2 emissions per mmBtu and MJ of fuel. The table summarizes the values used in the calculations and also shows the results from the fossil carbon in fuel calculations. The biodiesel production energy and methanol energy share for production shown in Table 4.01 are CA-GREET default values and the remaining values in the table are fuel properties. The calculations shown in this document are for a heavy-duty vehicle.

The total BD processing energy of 2,116 Btu/mmBtu is a GREET default. Esterification requires a methanol input that corresponds to 10% of the biodiesel mass. This methanol energy is input to CA-GREET as fuel shares of 40.9% of the 2,116 Btu of energy input which is equal to 865 Btu/mmBtu. The GHG emissions are calculated based on the fraction of methanol energy in BD and the carbon content of methanol. The calculations are below:

Fossil Carbon in Biodiesel Expressed as CO_2:
(2,116 Btu methanol/mmBtu BD)*(40.9%)/(16,149 Btu/lb BD)*10^6 = 53,592 Btu methanol/mmBtu BD

(53,592 Btu methanol/mmBtu BD)/(57,250 Btu/gal)*(3,006 g/gal)*(37.5% C)*(44.0095 g CO_2/12.011 g C) = 3,869 g CO_2/mmBtu

(3,869 g CO_2/mmBtu)/(1055.055 MJ/mmBtu) = **3.7 g CO_2/MJ**

Table 4.01 Fuel Fossil CO_2 Emissions (g/mmBtu)

Description	Methyl Ester Biodiesel (B100)
BD Production Energy Input (Btu/lb BD)	2,116
BD Lower Heating Value (Btu/gal)	119,550
BD Density (g/gal)	3,361
BD Carbon Ratio (wt%)	77.6 %
MeOH Fuel Production Share	40.9%
MeOH Lower Heating Value (Btu/gal)	57,250
MeOH Density (g/gal)	3,006
MeOH Carbon Ratio (wt%)	37.5%
CO_2/C Mass Ratio (wt%)	44.0095/ 12.011
Fossil Carbon in Fuel (gCO_2e/MJ)	3.7
Fossil Carbon in Fuel (gCO_2e/MJ)	**3.7**

Vehicle CH_4 and N_2O emissions

The CH_4 and N_2O emissions are assumed to be the same as ULSD. The vehicle energy use, N_2O and CH_4 emission rates and final emissions are shown in Table 4.02.

Table 4.02 Vehicle CH_4 and N_2O Emissions

Parameter	2010 Emissions factor (g/mi)	GWP	GHG (gCO2e/MJ)
N_2O	0.048	298	0.735
CH_4	0.035	25	0.045
Vehicle Energy Efficiency	6.1 mi/gal		**0.780**

Total Combustion Emissions

Using Tables 4.01 and 4.02 above, the total GHG emissions from combusting BD in a heavy-duty vehicle is 3.7 + 0.78 = **4.48 gCO2e/MJ.**

APPENDIX B

Input Values for Biodiesel from Used Cooking Oil Pathway

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	CA-GREET
CH_4		25	CA-GREET
N_2O		298	CA-GREET
VOC		3.1	CA-GREET
CO		1.6	CA-GREET
UCO Processing			
Fuel Use Shares			
Natural Gas		82.5%	**Available Plant Data**
Electricity		10.9%	**Available Plant Data**
UCO as fuel		6.6%	**Available Plant Data**
UCO or BD Transportation			
Heavy Duty Diesel Truck		100%	CA-GREET Default
Travel Distance	miles	50	One way
Truck Energy Intensity	Btu/mile-ton	1,028	CA-GREET Default
Biodiesel Production			
BD Allocation Factor		94.5%	CA-GREET Default
BD Yield	lb UCO/lb BD	1.11	CA-GREET Default
Process Shares for the pre-processing of FFAs			
Natural Gas		90.6%	CA-GREET Default
Electricity		9.4%	CA-GREET Default
Equipment shares			
Large Industrial Boiler - Natural Gas		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,198	CA- GREET Default
Small Industrial Boiler – Natural Gas		50%	CA-GREET Default
CO_2 Emission Factor	gCO_2/mmBtu	58,176	CA-GREET Default
Fuels Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Natural Gas	83,686	2,651	NG Liquids - GREET Default
Biodiesel	18,925	2,948	CA- GREET Default
Transportation Mode			
Heavy Diesel Duty Truck	tons	25	UCO (assumed same as BD)
	tons	25	Biodiesel (CA-GREET Default)