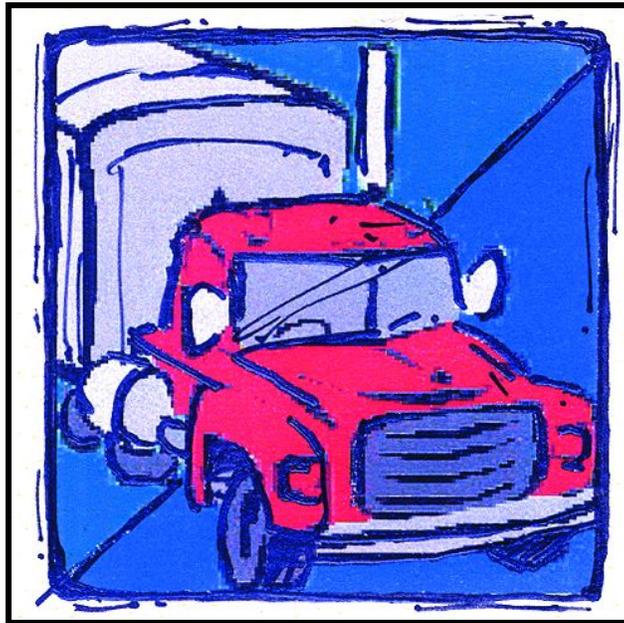


Detailed California-Modified GREET Pathway for Biodiesel Produced in California from Used Cooking Oil



Stationary Source Division
Release Date: September 23, 2009
Version: 2.0

Preliminary draft version developed by Alternative Fuels Section and Fuels Section of the California Air Resources Board as part of the Low Carbon Fuel Standard Regulatory Process

The ARB acknowledges contributions from Life Cycle Associates (under contract with the California Energy Commission) during the development of this document

When reviewing this document, please submit comments directly to:

Anil Prabhu: aprabhu@arb.ca.gov

Chan Pham: cpham@arb.ca.gov

Alan Glabe: aglabe@arb.ca.gov

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

TABLE OF CONTENTS

TABLE OF CONTENTS	i
LIST OF FIGURES.....	ii
LIST OF TABLES.....	ii
SUMMARY	1
CA-GREET Model Pathway for Biodiesel from UCO	2
APPENDIX A	11
Section 1. Energy Consumption and GHG Emissions from Transport of Used Cooking Oil	12
1.1 Transport of Used Cooking Oil to Rendering Plant	12
1.2 Energy for Rendering UCO in California	12
1.3 Greenhouse Gas Emissions from Rendering of UCO in California	15
1.4 Energy Use for Transport of Rendered UCO to a BD Production Plant	17
1.5 GHG Calculations for Transport of Rendered UCO to a Biodiesel Production Plant.....	18
Section 2. Biodiesel Production	19
2.1 Energy for Pre-Processing of UCO (Free Fatty Acid Conversion).....	19
2.2 Greenhouse Gas Emissions from Biodiesel Production.....	22
Section 3. Biodiesel Transport and Distribution	24
3.1 Energy Calculations for Biodiesel Transport to Retail Stations	24
3.2 GHG Calculations for Biodiesel Transport to Retail Stations	25
Section 4. GHG Emissions from a Biodiesel-Fueled Vehicle	26
4.1 Combustion Emissions from Fuel Vehicle CO ₂ (Carbon in Fuel)	26
APPENDIX B	28
Input Values for Biodiesel from Used Cooking Oil Pathway	28

LIST OF FIGURES

Figure 1. Discrete Components of Used Cooking Oil to Biodiesel Pathway.....	3
Figure 2. Contributions to Energy Use and GHG Emissions for the Used Cooking Oil to Biodiesel Pathway.....	5
Figure 3. Configuration for UCO Conversion to Biodiesel.	19

LIST OF TABLES

Table A. Summary of Energy Use and GHG Emissions for the Used Cooking Oil (UCO) to Biodiesel Pathway.....	4
Table B. GHG Emissions for the Pathways for UCO to Biodiesel	6
Table C. Total Energy Use for Rendering of UCO	7
Table D. Total GHG Emissions from Rendering of UCO.....	7
Table E. Energy Used for Pre-processing UCO for Converting FFAs	8
Table F. GHG Emissions for Pre-processing of UCO for Converting FFAs.....	8
Table G. Energy Consumed for Biodiesel Production	8
Table H. Total GHG Emissions for Biodiesel Production.....	9
Table I. Energy Use for Transportation and Distribution of BD.....	9
Table J. GHG Emissions from Transporting and Distributing BD	9
Table K. Combustion Emissions for BD	10
Table 1.01 Energy for Processing Used Cooking Oil	13
Table 1.02 Direct and Upstream Energy Use for Rendering UCO in CA.....	14
Table 1.03 GHG Emissions from Direct and Upstream Energy Used in Rendering of UCO in California	15
Table 1.04 Transport Parameters for Rendered UCO.....	17
Table 1.05 Direct, Upstream and Total Energy for Transport of Rendered UCO to a BD Production Plant.....	17
Table 1.06 GHG Emission Results for Transport of Rendered UCO.....	18
Table 2.01 Calculation of Direct Energy Consumption (Btu/lb BD) for Pre-processing of UCO to Convert FFAs	20
Table 2.02 Calculation of Direct and Upstream Energy Consumption (Btu/lb BD) for Pre-processing of UCO to Convert FFAs.....	20
Table 2.03 Total and Allocated Energy Consumption for Pre-Processing of UCO to Convert FFAs	21
Table 2.04 Calculation of Direct and Upstream Energy Consumption (Btu/lb BD) for BD Production	21
Table 2.05 Total Energy Consumption for BD Production.....	22
Table 2.06 Direct, Upstream and Total Greenhouse Gas Emissions for Pre-processing of UCO to Convert FFAs	23
Table 2.07 Direct, Upstream and Total Greenhouse Gas Emissions for BD Production.....	23
Table 3.01 Biodiesel Transport Parameters and Results	24
Table 3.02 Biodiesel Greenhouse Gas Emissions	25
Table 4.01 Fuel Fossil CO ₂ Emissions (g/mmBtu)	27
Table 4.02 Vehicle CH ₄ and N ₂ O Emissions	27

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 rendering of UCO and conversion of the rendered UCO to Biodiesel and transporting the finished fuel for use in a vehicle. 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 **Greenhouse gases, Regulated Emissions, and Energy use in Transportation (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 BD production, transport of BD and use in a heavy-duty vehicle. The CA-GREET model and pathway documents published by staff are available from the Low Carbon Fuel Standard (LCFS) website at 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 for this pathway are considered to occur within California. Figure 1 provides a step-wise description of the various steps in the UCO to BD pathway. The steps include UCO rendering, transport of the rendered UCO to a biodiesel production plant, production of BD via esterification at a production 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 CH₄ and N₂O 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).

This document provides complete details of two pathways for UCO to BD and they include:

- Conversion of waste oil (Used Cooking Oil) to biodiesel (fatty acid-methyl esters –FAME) where ‘cooking’ is required
- Conversion of waste oil (Used Cooking Oil) to biodiesel (fatty acid-methyl esters –FAME) where ‘cooking’ is not required

Moisture in cooking oil has to be removed prior to its use in an esterification plant. In older rendering plants, considerable amounts of input energy is used to ‘cook’ the oil to remove moisture from the oil and this pathway is modeled as one where cooking; is used. In newer modern plants, only a small input

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

energy is required to essentially ‘decant’ the water from the oil and this pathway is modeled here as one that does not require ‘cooking’. Complete details of all parameters and calculations are provided in Appendix A.

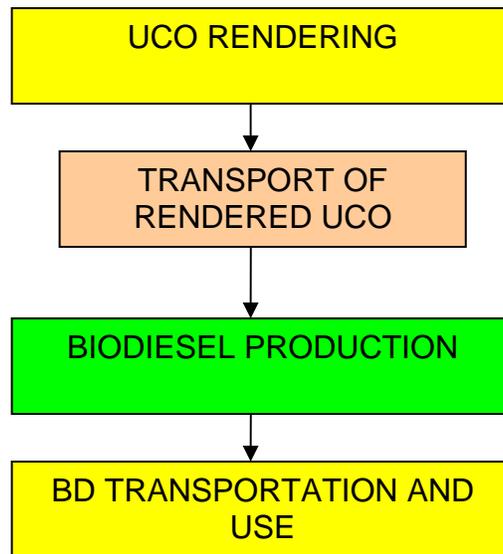


Figure 1. Discrete Components of Used Cooking Oil to Biodiesel Pathway

This document provides detailed calculations, assumptions, input values, and other information required to calculate the energy use and GHG emissions for a UCO to BD pathway which uses ‘cooking’. For the pathway that does not include ‘cooking’ only the energy inputs for rendering have to be changed to calculate the WTW emissions. Details of the inputs for both pathways are provided in Appendix A.

Table A provides a summary of the Well-To-Tank (WTT) and Tank-To-Wheel (TTW) energy use and GHG emissions for the pathway that utilizes ‘cooking’ of the oil to remove moisture. Energy use is presented as Btu/mmBtu and GHG emissions are reported as g CO₂e/MJ, where non-CO₂ gasses (i.e., CH₄ and N₂O) are converted into CO₂ equivalents.

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

PRELIMINARY DRAFT DISTRIBUTED FOR PUBLIC COMMENT

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

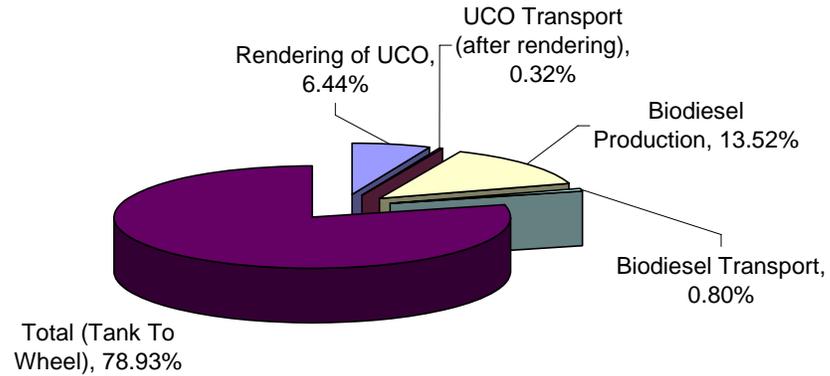
	Energy Required (Btu/mmBtu BD)	% Energy Contribution	Emissions (gCO₂e/MJ)	% Emissions Contribution
UCO Transport to Rendering Plant	0	0	0	0
Rendering of UCO	81,577	6.44%	4.73	29.86%
UCO Transport (after rendering)	4,081	0.32%	0.31	1.96%
Biodiesel Production	171,293	13.52%	5.56	35.10%
Biodiesel Transport	10,055	0.80%	0.76	4.80%
Total (Well To Tank)	267,006	21.07%	11.36	71.72%
Combustion Emissions	n/a	n/a	4.48	28.28%
Total (Tank To Wheel)	1,000,000	78.93%	4.48	28.28%
Total (Well To Wheel)	1,267,006	100%	15.84	100%

Note: percentages may not add to 100 due to rounding

From Table A, the WTW analysis of BD from UCO indicates that **1,267,006** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy delivered to the vehicle. From a GHG perspective, **15.84** gCO₂e 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 (78.93%). From a GHG perspective, biodiesel production (35.10%), rendering (29.86%), and combustion (28.28%) are the largest contributors to this pathway.

Energy Allocation of Used Cooking Oil Biodiesel



GHG Emissions Allocation of Used Cooking Oil Biodiesel

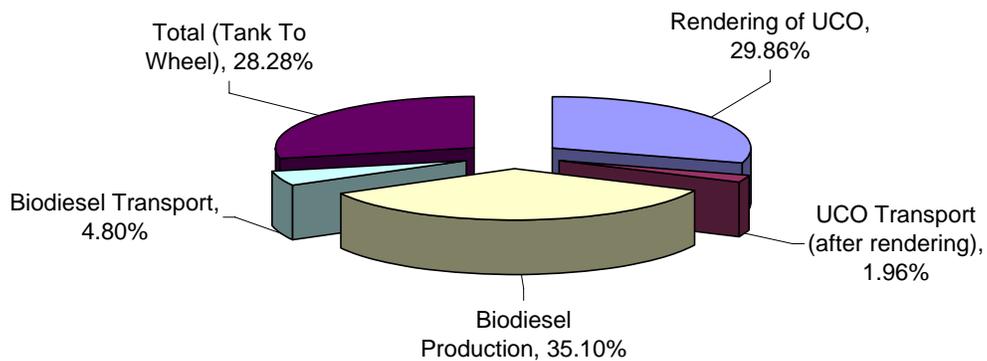


Figure 2. Contributions to Energy Use and GHG Emissions for the Used Cooking Oil to Biodiesel Pathway

PRELIMINARY DRAFT DISTRIBUTED FOR PUBLIC COMMENT

For the pathway where 'cooking' is not utilized, rendering emissions are calculated to be **0.65 gCO₂e/MJ** (compared to the 4.73 gCO₂e/MJ for the 'cooking' case) which therefore provides a WTW pathway emissions of 11.76 gCO₂e/MJ. Table B provides a comparison of WTW GHG emissions for the two pathways for UCO to BD. Complete details are provided in Appendix A.

Table B. GHG Emissions for the Pathways for UCO to Biodiesel

	'Cooking' required	No 'cooking' required
Well to Wheel GHG Emissions (gCO₂e/MJ)	15.84	11.76

Sections below provide further details of the energy use and GHG emissions for the pathway that uses ‘cooking’ detailed in this document. Complete details are provided in Appendix A.

WTT Details - Transport of UCO to Rendering Plant

Used cooking oil (UCO) generated in California is transported by heavy duty diesel truck to a rendering plant in California. The alternative fate of UCO is transport to a landfill, which is assumed to be the same transport distance on average as UCO transport to a rendering plant. Therefore, the net emissions for UCO transport to a rendering plant are assumed to be zero.

WTT Details - Rendering of UCO in CA

Tables C and D 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 C. Total Energy Use for Rendering of UCO

Energy Result	Energy
NG (heat) (Btu/lb UCO)	1,026
Electricity (CA marginal) (Btu/lb UCO)	219
Total Energy Use (Btu/lb UCO)	1,248
Total Energy Use (Btu/mmBtu)	81,577

Table D. Total GHG Emissions from Rendering of UCO

	GHG Emissions
CO ₂ (g/lb UCO)	72
CH ₄ (g/lb UCO)	0.149
N ₂ O (g/lb UCO)	0.001
CO (g/lb UCO)	0.039
VOC (g/lb UCO)	0.010
Total emissions (g/lb UCO)	76
Total GHG emissions (gCO₂e/MJ)	4.73

WTT Details – Biodiesel Production**Pre-Processing of UCO for Converting FFAs**

Tables E and F 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 E. Energy Used for Pre-processing UCO for Converting FFAs

	Energy Use
Natural Gas (Btu/lb BD)	166
Electricity (Btu/lb BD)	32
Total Energy (Btu/lb BD)	197
Total Energy Use (Btu/mmBtu)	11,616

Table F. 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	0.0	0.026	0.024
N ₂ O	0.0	0.0	0.0
CO ₂	10.0	2.522	11.0
GHG (gCO₂e/lb UCO)			12.09
Total GHGs (gCO₂e/MJ)			0.67

Biodiesel Production

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

Table G. 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)	159,677

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

Table H. 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 ₂ O (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 (gCO₂e/MJ)	4.89

WTT Details - Biodiesel Transport

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

Table I. Energy Use for Transportation and Distribution of BD

Transport mode	Energy Use
BD transportation by truck to bulk terminal (Btu/mmBtu)	3,094
BD distribution by HDD truck (Btu/mmBtu)	6,961
Total Energy use (Btu/mmBtu)	10,055

Table J. GHG Emissions from Transporting and Distributing BD

GHGs	Emissions
CO ₂	0.73
CH ₄ (converted to CO ₂ e)	0.02
N ₂ O (converted to CO ₂ e)	<0.01
CO (converted to CO ₂)	<0.01
VOC (converted to CO ₂)	<0.01
Total GHGs (gCO₂e/MJ)	0.76

TTW Details - Carbon in Biodiesel

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

Table K. Combustion Emissions for BD

Total GHG Emissions = 4.48 g CO ₂ e/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 alternative fate of UCO is transport to a landfill, which is assumed to be the same transport distance on average as UCO transport to a rendering plant. Therefore, the net life cycle emissions for UCO transport to a rendering plant is considered to be zero.

1.2 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.

Table 1.01 presents the range of processing energy inputs based on available literature and survey data. 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 four Western United States plants for the pathway analyzed here are based on older rendering plants in the U.S., which process UCO in their cookers. The average of the four plants is shown in Table 1.01 and has been used in calculating the rendering emissions for the pathway that utilizes 'cooking' of UCO.

The lowest figure listed in Table 1.01 for rendering energy use (bottom entry of Table 1.01) 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 plants². 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

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

PRELIMINARY DRAFT DISTRIBUTED FOR PUBLIC COMMENT

for the processing of UCO in a rendering plant cooker. These lower values of rendering energy use have been used to develop the GHG emissions for the second pathway in this document and labeled as one that does not use 'cooking'.

The pathway that uses 'cooking' uses a thermal processing input of 8,026 Btu/gallon (all Natural gas on a HHV basis) and an electrical input of 0.241 kWh/gal (marginal California electricity) which is the average of plants 1-4 in Table 1.01. For use in the CA-GREET model the energy input (NG) is converted to a Btu/lb UCO basis using a density of 7.5 lb/gal for UCO.

When analyzing the pathway with no 'cooking' only the rendering thermal and electrical energy inputs were changed to calculate the GHG emissions. For the pathway modeled here, a thermal energy input of 938 Btu/gal (Natural gas derived, HHV basis) and an electrical energy input of 0.060 kWh/gal (marginal California electricity) was used to calculate the GHG emissions with all other pathway inputs and assumptions being the same as that for the pathway where 'cooking' is considered.

Table 1.01 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	
Average Plants 1-4	8,026	0.241	
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.

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.

The direct energy and upstream energy consumption of the processing process is calculated as shown in Table 1.02. This is for the pathway where 'cooking' is considered. Details of the calculations for direct and upstream energy are presented below:

Upstream NG Energy:

$$(963 \text{ Btu/lb UCO}) * (68,865 \text{ Btu/mmBtu NG}) / 10^6 = \mathbf{66 \text{ Btu/lb UCO}}$$

Upstream Electricity Energy:

$$(110 \text{ Btu/lb UCO}) * ((111,573 \text{ Btu/mmBtu Feedstock}) + (1,884,989 \text{ Btu/mmBtu Electricity})) / 10^6 - (110 \text{ Btu/mmBtu direct energy}) = \mathbf{175 \text{ Btu/lb UCO}}$$

Table 1.02 Direct and Upstream Energy Use for Rendering UCO in CA

Inputs	Direct	Upstream Energy	Total Energy
NG (heat) (Btu/lb UCO)	$((7,224 \text{ Btu/gal LHV}) / (7.5 \text{ lbs/gal})) = 963$	66	1,029
Electricity (CA marginal) (Btu/lb UCO)	$(0.241 \text{ kWh/gal}) * (3,412 \text{ Btu/kWh}) / (7.5 \text{ gal/lb}) = 110$	109	219
Total Energy Input	1,073	175	1,248
Convert to Btu/mmBtu BD			85,809
Allocated Energy Use for Rendering (Btu/mmBtu BD*)			81,577

Note: 7,224 is the LHV calculated from the HHV value of 8026 from Table 1.01. Upstream energy is from WTT energy of NG and electricity documents⁸. 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 95.1% energy allocation factor (see section 2)

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

1.3 Greenhouse Gas Emissions from Rendering of UCO in California

Details of GHG emissions from the rendering process are shown in Table 1.03.

Table 1.03 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	0.002	0.008	0.010
CO	0.022	0.017	0.039
CH ₄	0.001	0.148	0.149
N ₂ O	0.000	0.000	0.001
CO ₂	56	16	72
Total Emissions	56	20	76
Total Emissions (gCO₂e/mmBtu BD)			5,250
Total Emissions (gCO₂e/mmBtu BD)			4.98
Total Allocated Emissions* (gCO₂e/MJ)			4.73

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 95.1% energy allocation factor (see section 2).

Example Calculations of CO₂ emissions⁹

Direct CO₂:

$$((963 \text{ Btu NG/lb UCO})[50\%*(58,198 \text{ g/mmBtu utility boiler CO}_2 \text{ EF}) + 50\%*(58,176 \text{ g/mmBtu utility boiler CO}_2 \text{ EF})]/10^6) = \mathbf{56 \text{ g/lb UCO}}$$

The upstream CO₂ emissions of the NG and electricity used

Upstream CO₂:

$$((963 \text{ Btu NG/lb UCO})*(5,050 \text{ NG WTT CO}_2 \text{ Emissions})+(963 \text{ Btu/lb UCO})*((8,277 \text{ g/mmBtu feedstock}) + (96,250 \text{ g/mmBtu}))/10^6) = \mathbf{16 \text{ g/lb UCO}}$$

When analyzing the pathway with no ‘cooking’ only the rendering thermal and electrical energy inputs were changed to calculate the GHG emissions. For the pathway modeled here, a thermal energy input of 938 Btu/gal (Natural gas derived, HHV basis) and an electrical energy input of 0.060 kWh/gal (marginal California electricity) was used to calculate the GHG emissions. These values are shown in Table 1.01.

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.

PRELIMINARY DRAFT DISTRIBUTED FOR PUBLIC COMMENT

The value of GHG emissions for rendering is calculated to be **0.65** gCO₂e/MJ which is lower than the rendering emissions for the 'cooking' process of **4.73** gCO₂e/MJ from Table 1.03. This difference is the only difference between the total WTW pathway emissions for the two pathways analyzed here.

1.4 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 1.04.

Table 1.04 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 1.05. Transportation of UCO for BD production requires **4,081 Btu/mmBtu** BD produced. An energy-based allocation factor (95.1%) 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 1.05 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	102,760
Upstream Energy from Transportation Fuel Used	22,148
Total Energy (Btu/ton processed UCO)	124,908
Total Energy (Btu/mmBtu BD)	4,293
Total Allocated* Energy (Btu/mmBtu BD)	4,081

Note: To convert from Btu/lb wet UCO to Btu/mmBtu BD:
 $(124,908 \text{ Btu/ton processed UCO}) / (2,000 \text{ lbs/ton}) * (1.11 \text{ lb UCO/lb BD}) / (16,149 \text{ Btu/lb BD}) = 4,293 \text{ Btu/mmBtu BD}$. *Calculate allocated energy input using 95.1% energy allocation factor (see section 2).

1.5 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 1.06 shows the direct emissions, upstream emissions and total emissions.

Table 1.06 GHG 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	3.676
CO	11.879
CH ₄	0.178
N ₂ O	0.298
CO ₂	8,005
Upstream Emissions (g/ton Processed UCO)	
VOC	0.972
CO	2.624
CH ₄	11.606
N ₂ O	0.020
CO ₂	1,560
Total Emissions, (g/ton Processed UCO)	
VOC	4.648
CO	14.503
CH ₄	11.784
N ₂ O	0.318
CO ₂	9,566
GHG Emissions (g/ton processed UCO)	9,992
GHGs (g/mmBtu BD)	343
GHGs (g/MJ BD)	0.33
Allocated GHGs* (g/MJ BD)	0.31

Note: To convert from g/ton processed UCO to g/mmBtu BD:
 $(9,992 \text{ Btu/ton processed UCO}) / (2,000 \text{ lbs/ton}) * (1.11 \text{ lb UCO/lb BD}) / (16,149 \text{ Btu/lb BD}) = 343 \text{ g/mmBtu BD.}$

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 esterification¹⁰. 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 produced¹¹. Since roughly equal quantities of UCO are processed using each method, this analysis uses the average energy consumption of these two to 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 shows the fuel production configuration.

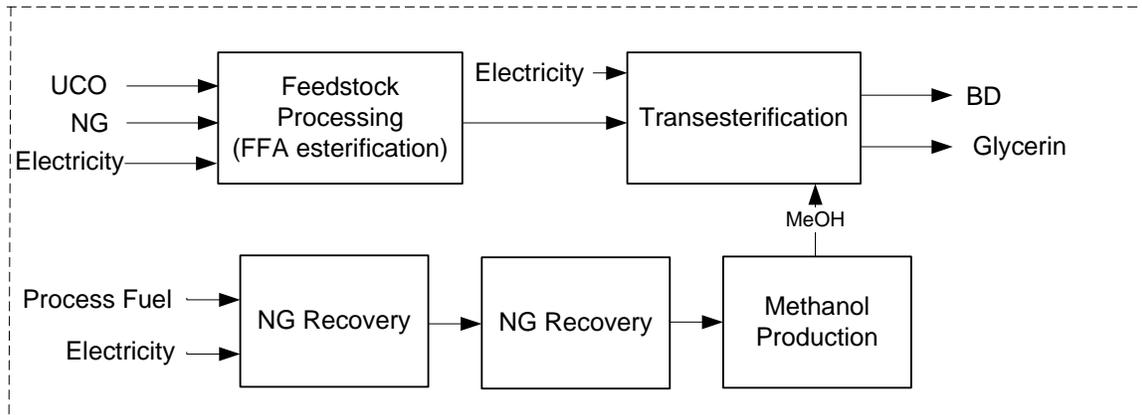


Figure 3. Configuration for UCO Conversion to Biodiesel.

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.

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	$((1,163 \text{ Btu/gal LHV}) / (7.5 \text{ lbs/gal})) = 155$	155
Electricity	$(0.03475 \text{ kWh/gal}) * (3,412 \text{ Btu/kWh}) / (7.5 \text{ gal/lb}) = 16$	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 shows the total energy consumption (in Btu/lb) and allocated energy consumption (in Btu/lb BD and Btu/mmBtu BD).

$$\text{BD Allocation Factor} = \frac{16,149 \text{ Btu/lb BD}}{(16,149 \text{ Btu/lb BD} + (7,979 \text{ Btu/lb glycerin}) * (0.105 \text{ lb propane/lb BD}))} = 95.1\%$$

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)	12,218
Total Adjusted Energy* (Btu/mmBtu BD)	11,616

Note:

Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.000)

To convert Btu/lb BD to Btu/mmBtu BD:

$(197 \text{ Btu/lb UCO}) / (16,149 \text{ Btu/lb BD}) * 10^6 = 12,218 \text{ Btu/mmBtu BD}$

To convert Btu/mmBtu BD to energy-allocated Btu/mmBtu:

$(12,218 \text{ Btu/mmBtu BD}) * (95.1\%) = 11,616 \text{ Btu/mmBtu}$

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 biodiesel¹³. Table 2.04 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
Total Energy (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)	159,677

Note:

Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.000)

To convert Btu/lb BD to Btu/mmBtu BD:

$$(2,712 \text{ Btu/lb BD}) / (16,149 \text{ Btu/lb BD}) * 10^6 = 167,961 \text{ Btu/mmBtu BD}$$

Btu/mmBtu BD (where 16,194 Btu/lb is assumed LHV of BD)

To convert Btu/mmBtu BD to energy-allocated Btu/mmBtu:

$$(167,961 \text{ Btu/mmBtu}) * (95.1\%) = 159,677 \text{ Btu/mmBtu}$$

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 CO₂ emissions are shown below.

Direct CO₂ Emissions:

$$(155 \text{ Btu NG/lb BD}) * (50\% * (58,198 \text{ g/mmBtu NG}) + 50\% * (58,176 \text{ g/mmBtu NG})) / 10^6 = 9 \text{ g/lb BD}$$

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 CO₂ Emissions:

$$[(155 \text{ Btu NG/lb BD}) * (5,050 \text{ g/mmBtu}) + (16 \text{ Btu electricity/lb BD}) * ((8,277 \text{ g/mmBtu Feedstock}) + (96,250 \text{ g/mmBtu Electricity}))] / 10^6 = 2 \text{ g/lb BD}$$

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 ₂ O	0.000	0.000	0.000
CO ₂	9	2	11
GHG (gCO₂e/lb BD)¹			12.09
GHG (gCO₂e/mmBtu)¹			748
Total GHG (g/MJ)			0.71
Total Adjusted² GHG (g/MJ)			0.67

Note:

- Adjusted to Global Warming Potential: CH₄: 25, N₂O: 298, CO₂: 1
 - Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.000)
- To convert from g/lb BD to g/mmBtu BD:
 $(12.09 \text{ g/lb BD}) / (16,149 \text{ Btu/lb BD}) * 10^6 = 748 \text{ Btu/mmBtu BD}$

Direct, upstream and total greenhouse gas emissions for UCO esterification (BD production) are shown 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 ₂ O	0.000	0.000	0.001
CO ₂	52	28	80
GHG (gCO₂e/lb BD)			87.6
GHG (gCO₂e/mmBtu)			5,423
Total GHG (g/MJ)			5.14
Total Adjusted² GHG (g/MJ)			4.89

Note:

- Adjusted to Global Warming Potential: CH₄: 25, N₂O: 298, CO₂: 1
- To convert from g/lb BD to g/mmBtu BD:
 $(87.6 \text{ g/lb BD}) / (16,149 \text{ Btu/lb BD}) * 10^6 = 5,423 \text{ Btu/mmBtu BD}$ (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		3,182	5,727	
Upstream Energy (Btu/mmBtu) ¹		686	1,234	
Total Energy (Btu/mmBtu) ¹		3,867	6,961	
Total BD T&D Energy (Btu/mmBtu)		3,094	6,961	10,055

¹Excludes 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 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	0.096	0.172	
CO	0.487	0.877	
CH ₄	0.005	0.009	
N ₂ O	0.007	0.012	
CO ₂	248	446	
Upstream Emissions (g/mmBtu)			
VOC	0.030	0.054	
CO	0.081	0.146	
CH ₄	0.359	0.647	
N ₂ O	0.001	0.001	
CO ₂	48	87	
Total Emissions¹, (g/mmBtu)			
VOC	0.101	0.226	0.327
CO	0.455	1.023	1.478
CH ₄	0.291	0.656	0.947
N ₂ O	0.006	0.013	0.019
CO ₂	237	533	770
GHGs (g/mmBtu)	247	556	802
GHGs (g/MJ)	0.23	0.46	0.76

¹Includes the mode share.

Section 4. GHG Emissions from a Biodiesel-Fueled Vehicle

4.1 Combustion Emissions from Fuel Vehicle CO₂ (Carbon in Fuel)

The CA-GREET model considers only the fossil carbon in fuel (expressed as fully oxidized, g CO₂/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 show the fossil CO₂ 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 CO₂:

$$(2,116 \text{ Btu methanol/mmBtu BD}) \cdot (40.9\%) / (16,149 \text{ Btu/lb BD}) \cdot 10^6 = 53,592 \text{ Btu methanol/mmBtu BD}$$

$$(53,592 \text{ Btu methanol/mmBtu BD}) / (57,250 \text{ Btu/gal}) \cdot (3,006 \text{ g/gal}) \cdot (37.5\% \text{ C}) \cdot (44.0095 \text{ g CO}_2 / 12.011 \text{ g C}) = 3,869 \text{ g CO}_2 / \text{mmBtu}$$

$$(3,869 \text{ g CO}_2 / \text{mmBtu}) / (1055 \text{ MJ/mmBtu}) = \mathbf{3.7 \text{ g CO}_2 / \text{MJ}}$$

Table 4.01 Fuel Fossil CO₂ 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 (gCO₂e/MJ)	3.7

Vehicle CH₄ and N₂O emissions

The CH₄ and N₂O emissions are assumed to be the same as ULSD. The vehicle energy use, N₂O and CH₄ emission rates and final emissions are shown in Table 4.02.

Table 4.02 Vehicle CH₄ and N₂O Emissions

Parameter	2010 Emissions factor (g/mi)	GWP	GHG (gCO ₂ e/MJ)
N ₂ O	0.048	298	0.735
CH ₄	0.035	25	0.045
Vehicle Energy Efficiency	6.1 mi/gal		0.78

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 ₂ O		298	CA-GREET
VOC		3.1	CA-GREET
CO		1.6	CA-GREET
UCO or BD Transportation			
<i>Heavy Duty Diesel Truck</i>		100%	CA-GREET Default
<i>Travel Distance</i>	miles	50	One way
<i>Truck Energy Intensity</i>	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			
<i>Natural Gas</i>		90.6%	CA-GREET Default
<i>Electricity</i>		9.4%	CA-GREET Default
Equipment shares			
Large Industrial Boiler - Natural Gas		50%	CA-GREET Default
<i>CO₂ Emission Factor</i>	gCO ₂ /mmBtu	58,198	CA- GREET Default
Small Industrial Boiler – Natural Gas		50%	CA-GREET Default
<i>CO₂ Emission Factor</i>	gCO ₂ /mmBtu	58,176	CA-GREET Default
Fuels Properties			
	LHV (Btu/gal)	Density (g/gal)	
<i>Natural Gas</i>	83,686	2,651	NG Liquids - GREET Default
<i>Biodiesel</i>	18,925	2,948	CA- GREET Default
Transportation Mode			
<i>Heavy Diesel Duty Truck</i>	tons	25	UCO (assumed same as BD)
	tons	25	Biodiesel (CA-GREET Default)