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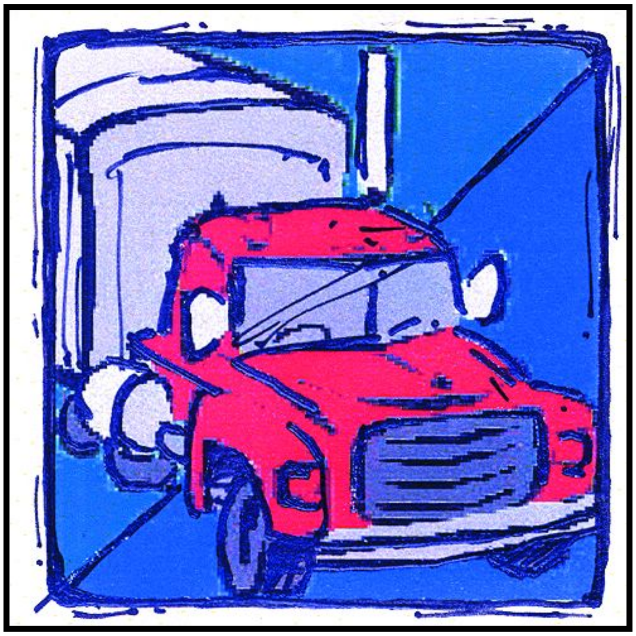
California Environmental Protection Agency
Air Resources Board

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



Stationary Source Division

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

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

CA-GREET Model Pathway for Biodiesel from UCO

The Well-To-Tank (WTT) Life Cycle Analysis of a Biodiesel (BD) fuel pathway from Used Cooking Oil (UCO) includes rendering of UCO, 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 analyses are combined to provide a total Well-To-Wheel (WTW) analysis. Because UCO is a waste product, its production is not included within the system boundary. UCO generated in the Midwest is transported by heavy duty diesel truck to a rendering plant in the Midwest. 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. Since the net difference in GHG emissions is zero, the transportation of UCO to a rendering plant is not included within the system boundary.

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 CA-GREET. The CA-GREET model was utilized to develop a WTW analysis of the conversion of Used Cooking Oil (UCO) into Biodiesel (BD). The approved CA-GREET model and pathway documents published by ARB staff are available from the Low Carbon Fuel Standard (LCFS) website at http://www.arb.ca.gov/fuels/lcfs/workgroups/workgroups.htm#pathways.

This fuel pathway is different from the previously distributed "Detailed California-Modified GREET Pathway for Biodiesel Produced in California from Used Cooking Oil" in that all of the steps for this pathway except for the final distribution and use of the fuel are considered to occur in the Midwest. The carbon intensity difference between UCO-derived biodiesel produced in the Midwest and in California derives from the difference in the feedstocks used to make electricity in the Midwest versus those used to make electricity in California, as well as the distances the finished biodiesel must be transported for final use. Figure S-1 provides a step-by-step description of the various stages 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. Since UCO is considered to be a waste product, the energy used and GHG emissions from

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

its production are not included in this analysis. 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).

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 must be removed prior to its use in an esterification plant. In older rendering plants, considerable amounts of input energy are used to 'cook' the moisture out of the oil. In newer modern plants, only a small input energy is required to essentially 'decant' the water from the oil. These two pathways are referred to below as the "cooking required" and "no cooking required" pathways, respectively. Complete details on all parameters and calculations for both pathways are provided in Appendix A.

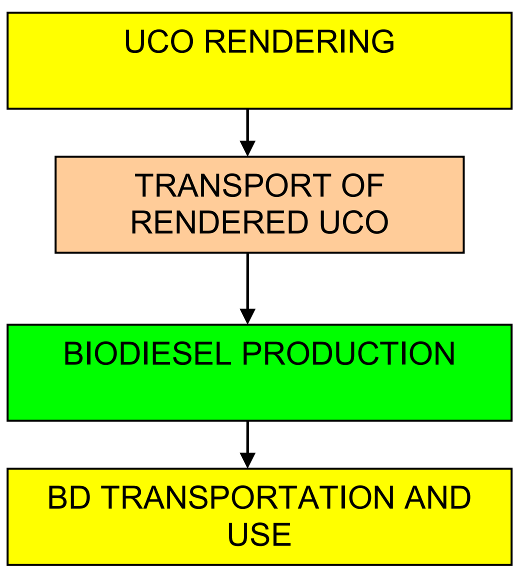

Figure S-1. Discrete Components of Used Cooking Oil to Biodiesel Pathway

This document provides detailed calculations, assumptions, input values, and other information required to calculate the energy use and GHG emissions for both UCO to BD pathways. Details of the inputs for both pathways are provided in Appendix A.

Some of the terminology and conventions used in this document require clarification. That clarification is provided here:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, calculated results are often used in subsequent calculations. For example, natural gas is used as a process fuel to recover natural gas. The total natural gas recovery energy consumption includes the direct natural gas consumption AND the energy associated with natural gas recovery (which is the value being calculated).

- "Direct" energy use and GHG emissions refer to the energy released and the GHG emissions resulting from the use of fuel.

- "Upstream" energy use and GHG emissions refer to the energy required for, and the GHG emissions produced from, the production of fuel feedstocks and the conversion of these feedstocks into finished fuel.

- BTU/MMBTU is the energy input necessary in BTU to produce one million BTU of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) of finished fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC Global Warming Potential (GWP) values and included in the total.

- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere and includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights. This method is also used by the IPCC.

- Process Efficiency for any step in CA-GREET is defined as:
  Efficiency = energy output / (energy output + energy consumed)

- Note that rounding of values has not been performed in several tables in this document. This is to allow stakeholders executing runs with the GREET model to compare actual output values from the CA-modified model with values in this document.

Table S-1 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 gCO_2e/MJ, where non-

CO_2 gasses (i.e., CH_4 and N_2O) are converted into CO_2 equivalents. The energy inputs are presented in MMBTU because the calculations in the CA-GREET model use MMBTU.

Table S-1: Summary of Energy Use and GHG Emissions for the Used Cooking Oil (UCO) to Biodiesel Pathway in Which Cooking is Required

	Energy Required (BTU/MMBTU BD)[a]	**% of Total Energy Requirement**	**Emissions (gCO_2e/MJ)**	**% of Total Emissions**
UCO Transport to Rendering Plant	0[b]	0 [b]	0 [b]	0 [b]
Rendering of UCO	88,681	6.84%	5.69	30.42%
UCO Transport (after rendering)	3,912	0.31%	0.30	1.65%
Biodiesel Production	174,956	13.50%	6.06	32.34%
Biodiesel Transport	28,384	2.19%	2.19	11.72%
Total (Well To Tank)	**295,933**	**22.84%**	**14.24**	**76.13%**
Total (Tank To Wheel)	**1, 000,000**	**77.16%**	**4.48**	**23.87%**
Total (Well To Wheel)	**1, 295,933[c]**	**100%[d]**	**18.72**	**100% [d]**

[a] Greet uses 1,000,000 BTU (denoted as MMBTU) as a standard unit of energy
[b]UCO generated in the Midwest is transported by heavy duty diesel truck to a rendering plant in the Midwest. 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 difference in GHG emissions is zero.
[c] This is the total energy required to produce 1,000,000 BTU of available fuel energy
[d] percentages may not add to 100 due to rounding

As shown in the WTW row of Table S-1, **1,295,933** BTU of energy is required to produce one MM BTU of available fuel energy delivered to the vehicle. The GHG emissions associated with the production and use of one MJ of BD total **18.72** gCO_2e.

The values in Table S-1 are illustrated in Figure S-2, which shows the specific energy and GHG contributions of each of the discrete components of the entire fuel pathway. Energy use and GHG emissions are depicted in separate pie charts. Most of the WTW energy is contained in the fuel (77.16%). In the GHG category, biodiesel production by transestirication (32.34%), rendering (30.42%), and combustion (23.87%) contribute the greatest proportion of total emissions.

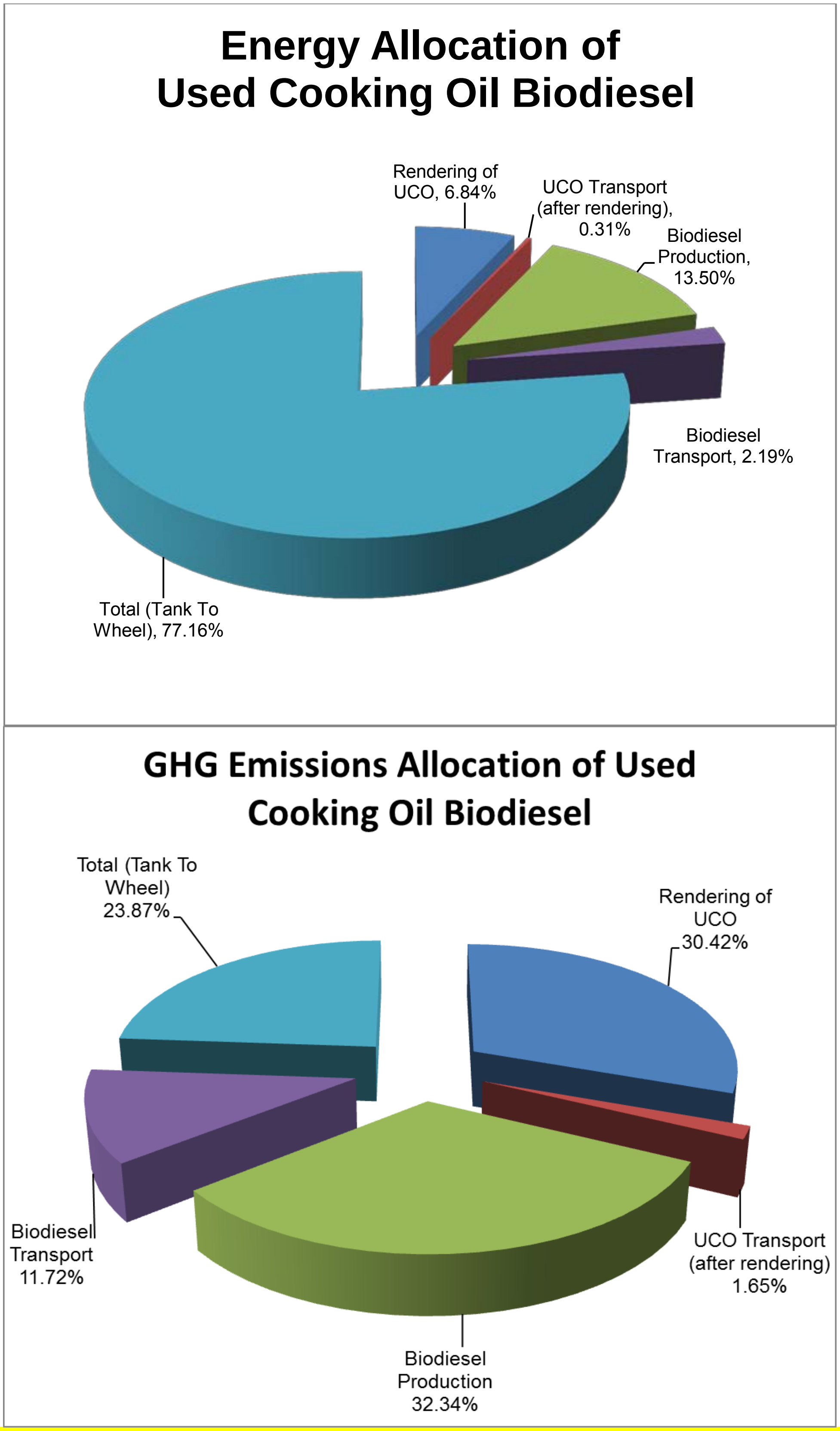

Figure S-2. Contributions to Energy Use and GHG Emissions for the Used Cooking Oil to Biodiesel Pathway

For the pathway in which cooking is not utilized, rendering emissions total to **0.80 gCO_2e/MJ** (compared to **5.69 gCO2e/MJ** for the cooking case). The result is a WTW pathway emission total of **13.83 gCO_2e/MJ**. Table S-2 provides a comparison of WTW GHG emissions for the two UCO pathways. Complete details are provided in Appendix A.

Table S-2: GHG Emissions for the Pathways for UCO to Biodiesel

	'Cooking' required	**No 'cooking' required**
Well to Wheel GHG Emissions (gCO_2e/MJ)	**18.72**	**13.83**

The sections below further summarize the energy use and GHG emissions for the pathway that uses cooking. Complete details are provided in Appendix A.

WTT Details - Transport of UCO to Rendering Plant

UCO generated in the Midwest is transported by heavy duty diesel truck to a rendering plant in the Midwest. 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 the Midwest

Tables S-3 and S-4 provide a summary of the energy use and associated GHG emissions from the rendering of UCO in a Midwest facility in which UCO rendering requires cooking. Details are provided in Appendix A.

Table S-3: Total Energy Use for Rendering of UCO

Energy Result	**Energy**
NG (heat) (BTU/lb UCO)	1,029
Electricity (Midwest) (BTU/lb UCO)	327
Total Energy Use (BTU/lb UCO)	**1,356**
Total Energy Use (BTU/MMBTU)	**87,839**

Table S-4: Total GHG Emissions from Rendering of UCO

	GHG Emissions
CO_2 (g/lb UCO)	87.8
CH_4 (g/lb UCO)	0.161
N_2O (g/lb UCO)	0.001
CO (g/lb UCO)	0.057
VOC (g/lb UCO)	0.010
Total emissions (g/lb UCO)	**92.2**
Total GHG emissions (gCO_2e/MJ)	**5.69**

WTT Details – Biodiesel Production

Pre-Processing of UCO for Converting Free Fatty Acids (FFA)

Tables S-5 and S-6 show the energy use and GHG emissions generated from pre-processing of UCO for converting FFAs respectively. Complete details are shown in Appendix A.

Table S-5: Energy Used for Pre-processing UCO for Converting FFAs

	Energy Use
Natural Gas (BTU/lb BD)	166
Electricity (BTU/lb BD)	47
Total Energy (BTU/lb BD)	**213**
Total Energy Use (BTU/MMBTU)	**12,543**

Table S-6: 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)
VOC	0.000	0.002	0.002
CO	0.004	0.005	0.009
CH_4	0.000	0.025	0.025
N_2O	0.000	0.000	0.000
CO_2	9	4.7	13.7
GHG (gCO_2e/lb UCO)			**14.4**
Total GHGs (gCO_2e/MJ)			**0.80**

Biodiesel Production

Table S-7 shows the total energy BTU necessary for producing one million BTUs of BD from UCO by esterification. Total energy includes the direct and upstream energy used in biodiesel production as well as the direct and upstream energy required to manufacture methanol, sodium hydroxide, sodium methoxide, and hydrochloric acid.

Table S-7: Energy Consumed for Biodiesel Production

	Energy
Natural Gas (BTU/lb BD)	951
Electricity (BTU/lb BD)	140
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)	**2,758**
Total BD Production Energy (BTU/MMBTU)	**162,416**

Table S-8 provides GHG emissions resulting from BD production. The source of these emissions is the consumption of the energy summarized in Table S-7. The fuel consumption data and other factors behind this calculation are detailed in Appendix A.

Table S-8: Total GHG Emissions for Biodiesel Production

GHG	**GHG Emissions**
CO_2 (g/lb of BD)	86.5
CH_4 (g/lb of BD)	0.295
N_2O (g/lb of BD)	0.001
CO (g/lb of BD)	0.070
VOC (g/lb of BD)	0.031
Total GHG emissions (gCO_2e/MMBTU)	**5,845**
Total GHG emissions (gCO_2e/MJ)	**5.27**

WTT Details - Biodiesel Transport

Tables S-9 and S-10 provide the energy use and GHG emissions from transporting and distributing BD respectively. Details of all the calculations are presented in Appendix A.

Table S-9: Energy Use for Transportation and Distribution of BD

Transport mode	Energy Use
BD transport by HDD from Plant to bulk terminal	3,094
BD transportation by rail to bulk terminal (BTU/MMBTU)	17,734
BD distribution by HDD truck (BTU/MMBTU)	6,961
Total Energy use (BTU/MMBTU)	**28,384**

Table S-10: GHG Emissions from Transporting and Distributing BD

GHGs	Emissions
CO_2	2.11
CH_4 (converted to CO_2e)	0.06
N_2O (converted to CO_2e)	0.01
CO (converted to CO_2)	0.02
VOC (converted to CO_2)	<0.01
Total GHGs (gCO_2e/MJ)	**2.19**

TTW Details - Carbon in Biodiesel

The combustion of BD in a heavy-duty vehicle results in emissions of (details of which are provided in Appendix A) equal **4.48** gCO2/MJ.

APPENDIX A

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

This document provides complete details of the pathway from UCO rendering and Biodiesel production in the Midwest to final use in a heavy-duty vehicle in California.

1.1 Transport of Used Cooking Oil to Rendering Plant

Used cooking oil (UCO) generated in the Midwest is transported by heavy duty diesel truck to a rendering plant in the Midwest. The alternative fate of UCO is transport to a landfill. The transport distance from UCO origination point to the landfill is assumed in this analysis to be equal to the distance between the point of origination and the rendering plant. Therefore, the net life cycle emissions for UCO transport to a rendering plant are considered to be zero.

1.2 Energy for Rendering UCO in the Midwest

Depending on its source, UCO 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 is required to process used cooking oil than to render animal by-products.

As shown in Table 1.01 the amount of energy used to process UCO varies across an order of magnitude: 9,259 – 938 BTU/gal. The width of this range is primarily due to the different methods used to remove the moisture from the feedstock. To a lesser extent, it may also be due to differing assumptions about the moisture content of the raw UCO. The energy use average (8,026 BTU/gallon) 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 four-plant average shown in Table 1.01 was used to calculate rendering emissions in this analysis.

The lowest figure listed in Table 1.01 for rendering energy use (last row in Table 1.01) represents the average of several modern plants in the U.S. that are dedicated to processing UCO. In these plants, the UCO is not processed in a cooker as it is in rendering plants[2]. Instead, the UCO is heated until it liquefies in order to break the oil-water emulsion. The liquefied grease is filtered and the water and sediment are 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. These lower rendering energy values were used to develop the no-cooking UCO pathway in the lookup table

The lookup table value for the cooking process uses a thermal processing input of 8,026 Btu/gal (all Natural gas on a HHV basis) and an electrical input of 0.241 kWh/gal (Midwest 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. For the non-cooking process, total thermal energy use is 125 Btu/gallon and electricity use is 0.06 kWh/gal.

When calculating the pathway value for the no-cooking process, only the rendering thermal and electrical energy inputs were changed. 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 (Midwest electricity) were used to calculate the GHG emissions. All other pathway inputs and assumptions were unchanged from those used in the cooking process analysis.

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

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[a]			
Plant 1	7,250	0.259	cooking required
Plant 2	8,213	0.112	cooking required
Plant 3	7,383	0.309	cooking required
Plant 4	9,259	0.284	cooking required
Average Plants 1-4	8,026	0.241	cooking required
Natural Resources Canada, 2005[b]	2,440	0.337	Based on 40% water in UCO, reduced mechanically to 14.3% before rendering
Fats Proteins Research Foundation, 2005[c]	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[d]	1103	0.012	Basis for figures not specified in source document
Modern plants dedicated to UCO processing (Industry Sourced Data, 2009)[e]	938	0.060	Water removed by heating used oil and allowing water to settle; no evaporation

[a] Wellons, Fred, Tellurian Biodiesel, Personal Communication, June 2, 2009.
[b] Natural Resources Canada, 2005.
[c] Fats Proteins Research Foundation, 2005.
[d] CSIRO, The Greenhouse and Air Quality Emissions of Biodiesel Blends in Australia. Victoria, Australia. August, 2007.
[e] Personal Communication with Industry Representative, June 23, 2009.

The energy consumed in the direct UCO processing step is calculated as shown in Table 1.02. This value applies to the cooking process. Upstream energy calculation details are presented below:

Upstream NG Energy:
(963 BTU/lb UCO)*(68,865 BTU/MMBTU NG)/10^6 = **66 BTU/lb UCO**
(68,865 BTU/MMBTU is the energy in natural gas required to produce 1,000,000 BTU of natural gas)

Upstream Electricity Energy:

(110 BTU/lb UCO)*((99,790 BTU/MMBTU Feedstock) + (2,877,173 BTU/MMBTU Electricity))/10^6 – (110 BTU/MMBTU direct energy) = **217 BTU/lb UCO**
(99,790 BTU/MMBTU is the energy in feedstocks required to produce 1,000,000 BTU of electricity)

Table 1.02 Direct and Upstream Energy Use for Rendering UCO in the Midwest

Inputs	Direct	Upstream Energy	Total Energy
NG (heat) (BTU/lb UCO)	((7,224[a] BTU/gal LHV) / (7.5 lbs/gal)) = 963.2	67.5[b]	1,031
Electricity (Midwest) (BTU/lb UCO)	(0.241 kWh/gal) *(3,412 BTU/kWh) /(7.5 gal/lb) = 11.2	315.5[b]	326.4
Total Energy Input (BTU/lb UCO)	**974.1**	**383**	**1,357**
Convert to BTU/MMBTU BD			**92,282**[c]
Allocated Energy Use for Rendering (BTU/MMBTU BD*)			**88,681**

[a] 7,224 is the LHV calculated from the HHV value of 8,026 from Table 1.01.
[b] Upstream energy is from WTT energy of NG and electricity documents published by ARB and found at: http://www.arb.ca.gov/fuels/lcfs/workgroups/workgroups.htm#pathways.
[c] 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). Allocated energy is calculated using 95.1% energy allocation factor (see section 2).

1.3 Greenhouse Gas Emissions from Rendering of UCO in the Midwest

The 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 the Midwest

Emission Species	Direct Emissions (g/lb UCO)	Upstream Emissions (g/lb UCO)	Total Emissions (g/lb UCO)
VOC	0.004	0.007	0.011
CO	0.024	0.033	0.057
CH_4	0.036	0.125	0.161
N_2O	0.000	0.001	0.001
CO_2	**56.9**	**30.6**	87.7
Total Emissions	**57.9**	**33.9**	**91.9**
Total Emissions (BTU/MMBTU BD)			**6,315**[b]
Total Emissions (gCO_2e/MJ)			**5.99**
Total Allocated Emissions* (gCO_2e/MJ)			**5.69**

[a] Upstream energy is from WTT energy of NG and electricity documents published by ARB and found at: http://www.arb.ca.gov/fuels/lcfs/workgroups/workgroups.htm#pathways.
[b] 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).
[c] Allocated energy is calculated using 95.1% energy allocation factor (see section 2).

Example CO_2 emissions[3] Calculations

Direct CO_2:
((963 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 = **56 .9gCO_2/lb UCO**

The upstream CO_2 emissions from the NG and electricity used:

Upstream CO_2:
((963 BTU NG/lb UCO)*(5,239 NG WTT CO_2 Emissions)+(110 BTU/lb UCO)*((233,154 g/MMBTU))/10^6 = **30.6 gCO_2/lb UCO**

When analyzing the no-cooking pathway, 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 (Midwest electricity mix) were used to calculate the GHG emissions. These values are shown in Table 1.01.

The GHG emission value for rendering where no cooking is required is calculated to be **0.80** gCO_2e/MJ, which is **4.89** gCO_2e/MJ lower than the rendering emissions for the cooking process (**5.69** gCO_2e/MJ as shown in Table 1.03). This is the only difference between the total WTW 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 the Midwest. The average Midwest parameters are used in CA-GREET for UCO transport; these include Midwest 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

[3] Emission Factors for boilers of electricity feedstocks used are from CA-GREET and are available in the BD from soybean pathway document published in 12/2009 (www.arb.ca.gov/fuels/lcfs/121409lcfs_soyrd.pdf).

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	17,056
Total Energy (BTU/ton processed UCO)	119,816
Total Energy (BTU/MMBTU BD)	**4,118**[a]
Total Allocated* Energy (BTU/MMBTU BD)	**3,915**

[a] To convert from BTU/lb wet UCO to BTU/MMBTU BD:
(119,816 BTU/ton processed UCO)/(2,000 lbs/ton)*(1.11 lb UCO/lb BD)/(16,149 BTU/lb BD) = 4,118 BTU/MMBTU BD.
[b] Allocated energy is calculated using 95.1% energy allocation factor (see section 2).

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

The analysis assumes 50 miles of heavy duty truck transport from a UCO processing plant to the fuel plant. Transport emissions were calculated in GREET in g/ton of processed UCO, and 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_2O	0.298
CO_2	8,005
Upstream Emissions (g/ton Processed UCO)	
VOC	0.851
CO	1.831
CH_4	10.124
N_2O	0.016
CO_2	1,381
Total Emissions, (g/ton Processed UCO)	
VOC	4.527
CO	13.709
CH_4	10.302
N_2O	0.314
CO_2	9,566
GHG Emissions (g/ton processed UCO)	9,773
GHGs (g/MMBTU BD)	**336**[a]
GHGs (g/MJ BD)	**0.32**
Allocated GHGs* (g/MJ BD)	**0.30**

[a] To convert from g/ton processed UCO to g/MMBTU BD: (9,773 BTU/ton processed UCO)/(2,000 lbs/ton)*(1.11 lb UCO/lb BD)/(16,149 BTU/lb BD) = **336 g/MMBTU BD.**

Section 2. Biodiesel Production

2.1 Energy for Pre-Processing 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. ARB assumes 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[4]. The acid esterification process consumes on average 1,862 BTUs 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[5]. Since roughly equal quantities of UCO are processed using each method, this analysis uses an energy consumption value equal to the average of the two methods. 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.

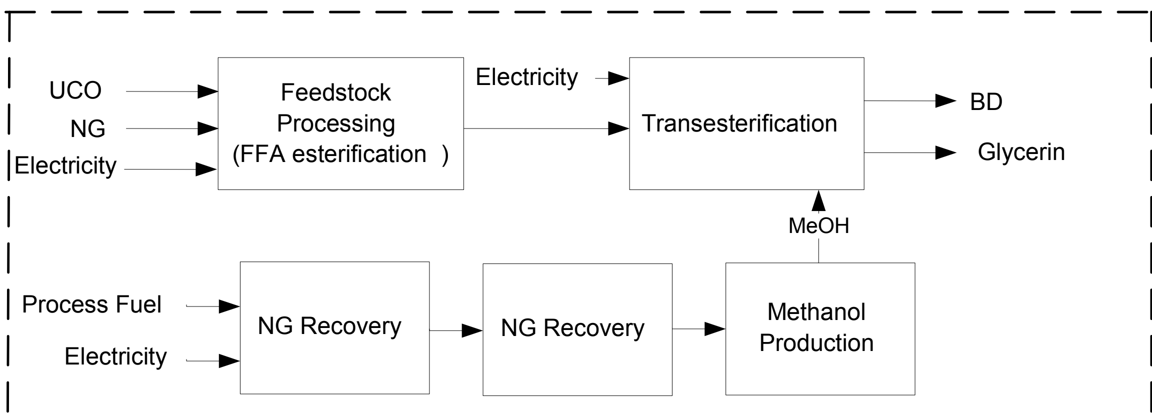

Figure 2.1. Schematic for UCO Conversion to Biodiesel.

The process inputs for FFA pre-processing are presented in Table 2.01. The Midwest electricity mix was used for this analysis.

[4] Based on a personal communication with Wellons, Fred, Tellurian Biodiesel, June 23, 2009.
[5] 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**

Table 2.01 reports the direct energy consumption per lb of BD produced. The natural gas input is based on 1,292 BTU/gal BD HHV (1,163 BTU/gal LHV). The total energy includes the direct and upstream energy components. The total energy requirement is then allocated among the BD fuel and co-product glycerin based on energy content of each and the glycerin yield (see the allocation factor calculation below). Table 2.02 shows the total energy consumption (in BTU/lb) and allocated energy consumption (in BTU/lb BD and BTU/MMBTU BD).

BD Allocation Factor: $\frac{\frac{16149 Btu}{lb\ BD}}{16{,}149\frac{Btu}{lb\ BD}+(7{,}979\frac{Btu}{lb\ Glycerine}*0.105\ lb\frac{Glycerine}{lb}BD)}$ = 95.1%

Table 2.02 describes the direct and upstream energy inputs for each fuel. Table 2.03 presents the total energy required for the pre-processing steps that 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+70,079[a]/10^6) = 11	166
Electricity	16*(99,790 /10^6) = 1.58	16*(2,877,173[c])/10^6 = 45.5	47
Direct and Upstream Energy Input (BTU/lb BD)			**213**

[a] Energy of NG as fuel: 70,079BTU/MMBTU
[b] Energy of Electricity as feedstock: 99,790BTU/MMBTU
[c] Energy of Electricity as fuel: 2,877,173BTU/MMBTU

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

Energy Consumption	Value
Total Energy (BTU/lb BD)	213
Total Energy (BTU/MMBTU BD)	13,190[a]
Total Adjusted Energy* (BTU/MMBTU BD)	**12,540[,c]**

[a] To convert BTU/lb BD to BTU/MMBTU BD:
(213 BTU/lb UCO)/(16,149 BTU/lb BD)*10^6 = 13,190 BTU/MMBTU BD
[b] To convert BTU/MMBTU BD to energy-allocated BTU/MMBTU:
(13,190 BTU/MMBTU BD)*(95.1%) = 13,377 BTU/MMBTU
[c] Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.00004)

After FFA conversion, the intermediate UCO product is esterified like soybean oil. This analysis assumes the same esterification input parameters used for soybean oil esterification to biodiesel. Table 2.04 presents the direct and upstream energy for BD production (UCO esterification) including the manufacture of methanol, sodium hydroxide, sodium methoxide, and hydrochloric acid. 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 Component	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+70,079/10^6)	951
Electricity	2.2%	(2.2%)*(2,116) = 47	47*(99,790+2,877,173) /10^6	138.6
Methanol	40.9%	(40.9%)*(2,116) = 865	865*(31,909*1.000+532,483)/10^6	1,353.9
Sodium Hydroxide	2.0%	(2.0%)*(2,116) = 42	-	42.3
Sodium Methoxide	9.9%	(9.9%)*(2,116) = 209	-	209.5
Hydrochloric Acid	3.0%	(3.0%)*(2,116) = 63	-	63.5
Total Energy (BTU/lb BD)				**2,758.8**

Table 2.05 Total Energy Consumption for BD Production

Energy Consumption	Value
Total Energy (BTU/lb BD)	2,758.8
Total Energy (BTU/MMBTU BD)	170,836[a]
Total Adjusted Energy* (BTU/MMBTU BD)	**162,416[b,c]**

[a] To convert BTU/lb BD to BTU/MMBTU BD:
(2,758.8 BTU/lb BD)/(16,149 BTU/lb BD)*10^6 = 170,836 BTU/MMBTU BD
BTU/MMBTU BD (where 16,194 BTU/lb is assumed LHV of BD)
[b] To convert BTU/MMBTU BD to energy-allocated BTU/MMBTU:
(170,836 BTU/MMBTU)*(95.1%) = 162,416 BTU/MMBTU
[c] Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.00004)

2.2 Greenhouse Gas Emissions from Biodiesel Production

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

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. There are no direct electricity emissions

Upstream CO_2 Emissions:
[(155 BTU NG/lb BD)*(5,239 g/MMBTU)+(16 BTU electricity/lb BD)*((7,755 g/MMBTU Feedstock)+(233,154 g/MMBTU Electricity))]/10^6 = **4.5 g/lb BD**

where 5,239 g/MMBTU is the upstream emissions for NG production. 7,755 g/MMBTU and 233,154 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	0.002	0.002
CO	0.004	0.005	0.009
CH_4	0.000	0.025	0.025
N_2O	0.000	0.000	0.000
CO_2	9.1	4.5	13.6
GHG (gCO_2e/lb BD)			**14.3**[a]
GHG (gCO_2e/MMBTU)			**887**[b]
Total GHG (g/MJ)			**0.84**
Total Adjusted GHG (g/MJ)			**0.80**[c]

[a] Adjusted to Global Warming Potential factors: CH_4: 25, N_2O: 298, CO_2: 1
[b]To convert from g/lb BD to g/MMBTU BD:
(14.3 g/lb BD)/(16,149 BTU/lb BD)*10^6 = 887 BTU/MMBTU BD
[c] Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.00004)

Direct, upstream, and total greenhouse gas emissions for UCO esterification (BD production) are shown in Table 2.07. The average Midwest 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	0.01	0.02	0.03
CO	0.03	0.04	0.07
CH_4	0.13	0.17	0.3
N_2O	0.00	0.00	0.00
CO_2	54.9	31.6	86.5
GHG (gCO_2e/lb BD)			**94.3**[a]
GHG (gCO_2e/MMBTU)			**5,841**[b]
Total GHG (g/MJ)			**5.54**
Total Adjusted GHG (g/MJ)			**5.26**[c]

[a] Adjusted to Global Warming Potential: CH_4: 25, N_2O: 298, CO_2: 1
[b] To convert from g/lb BD to g/MMBTU BD:
(94.3 g/lb BD)/(16,149 BTU/lb BD)*10^6 = 5,841 BTU/MMBTU BD (where 16,194 BTU/lb is the assumed LHV of BD)
[c] Total adjusted energy includes allocation (95.1%) and downstream loss factor (1.00004)

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 the Midwest to a retail station in California. Table 3.01 provides the transport assumptions and calculations for this final step.

This analysis assumes that 80 % of the BD is transported by heavy duty truck from a plant in the Midwest to a bulk terminal in the Midwest, and then 100% of the BD is transported 1,400 miles by rail from a Midwestern bulk terminal to a bulk terminal in California. Finally, the BD is transported 90 miles by heavy duty truck from a California bulk terminal to refueling stations. The energy and emissions are calculated the same here as they are in ARB's BD from soy oil pathway document (http://www.arb.ca.gov/fuels/lcfs/lcfs.htm). BTU/ton-mile factors are converted to BTU/ton, and then 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	Plant to Bulk Terminal	Bulk Terminal to CA Bulk Terminal	Distribution	Total
Mode	Heavy Duty Truck	Rail	Heavy Duty Truck	
Mode Shares	80%	100%	100%	
Distance, miles	50	1,400	90	
Payload, tons	25	25	25	
Fuel Economy, mi/gal	5		5	
Fuel	Diesel	Diesel	Diesel	
Fuel LHV, BTU/gal	128,450	128,450	128,450	
Energy Intensity, BTU/ton-mile	1,028[a]	336[a]	1,028[a]	
Direct Energy (BTU/MMBTU)	2,545	16,038[b]	5,727[b]	24,311
Upstream Energy (BTU/MMBTU)	422	2,662	951	4,035
Total Energy (BTU/MMBTU)	**2,968**	**18,700**	**6,678**	**28,384**

[a] Energy Intensity = LHV / fuel economy / payload = 1,028 BTU/mile-ton
[b] Direct truck energy doubles the miles to take into account round trip energy

Table 3.02 Biodiesel Greenhouse Gas Emissions

	Plant to Bulk Terminal	**Bulk Terminal to CA Bulk Terminal**	**Fuel Distribution**	**Total Transport**
Mode	HDD Truck	Rail	HDD Truck	
Mode Share	80%	100%	100%	
Distance, miles	50	1,400	90	
Fuel	Diesel	Diesel	Diesel	
Energy Intensity, BTU/ton-mile	1,028	370	1,028	
Direct Emissions (g/MMBTU)				
VOC	0.076	0.957	0.172	1.225
CO	0.39	3.448	0.877	4.812
CH_4	0.004	0.063	0.009	0.077
N_2O	0.005	0.032	0.012	0.051
CO_2	198	1,246	446	1940
Upstream Emissions (g/MMBTU)				
VOC	0.021	0.132	0.054	0.216
CO	0.045	0.282	0.146	0.509
CH_4	0.251	1.573	0.647	2.579
N_2O	0.000	0.002	0.001	0.004
CO_2	34	213	87	348
Total Emissions, including loss factor (g/MMBTU Fuel Transported)				
VOC	0.098	1.089	0.226	1.416
CO	0.435	3.733	1.023	5.211
CH_4	0.255	1.636	0.656	2.583
N_2O	0.006	0.034	0.013	0.053
CO_2	232	1,459	533	2,230
GHGs (gCO_2e/MMBTU)	247	1520	556	2323
GHGs (gCO_2e/MJ)	**0.23**	**1.44**	**0.53**	**2.19**

Sample calculations of CO_2 emissions from a locomotive:

Direct CO2 emission from diesel locomotive:

$$= \frac{(3{,}361\ \mathit{gBD / gal}) \times (77{,}664\ \mathit{gCO_2\ / MMBTU}) \times (370\ \mathit{BTU / ton\text{-}mile}) \times (1400\ \mathit{miles})}{(119{,}550\ \mathit{BTU / galBD} \times 454\ \mathit{g / lb} \times 2000\ \mathit{lbs / ton})}$$

= **1,246 g / MMBTU**

Upstream CO_2 emission from diesel locomotive:

$$= \frac{(3{,}361\ \mathit{gBD / gal}) \times (13{,}257\ \mathit{gCO_2\ / MMBTU}) \times (370\ \mathit{BTU / ton\text{-}mile}) \times (1400\ \mathit{miles})}{(119{,}550\ \mathit{BTU / galBD} \times 454\ \mathit{g / lb} \times 2000\ \mathit{lbs / ton})}$$

= 214 g / MMBTU

Section 4. GHG Emissions from a Biodiesel-Fueled Vehicle

4.1 GHG Emissions from the Combustion of Fuel in a Motor Vehicle

The CA-GREET model considers only the fossil carbon in fuel (expressed as fully oxidized, gCO_2/MMBTU fuel), since biologically derived fuel carbon originates from the atmosphere, the net greenhouse gas impact is assumed to be neutral. The only fossil carbon in biodiesel originates from the methanol (produced from natural gas) used in UCO transesterification. The calculations in Table 4.01 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 apply to 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)/(1055MJ/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 %
Methanol Fuel Production Share	40.9%
Methanol Lower Heating Value (BTU/gal)	57,250
Methanol Density (g/gal)	3,006
Methanol Carbon Ratio (wt%)	37.5%
CO_2/C Mass Ratio (wt%)	44.0095/ 12.011
Fossil Carbon in Fuel (gCO_2e/MJ)	**3.7**

Vehicle CH_4 and N_2O emissions

The tailpipe CH_4 and N_2O emissions associated with UCO-based BD are assumed to be the same as the corresponding ULSD emissions. 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		**0.78**

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_2O		298	CA-GREET
VOC		3.1	CA-GREET
CO		1.6	CA-GREET
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)
Rendered UCO transport	miles	50	From rendering plant to BD plant (100% by truck)
BD Transport	miles	50	From plant to bulk terminal (80% by truck)
	miles	1,400	To California (100% by rail)
BD Distribution	Miles	90	To refueling station (100% by truck)

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