California Environmental Protection Agency
Air Resources Board

Detailed California-Modified GREET Pathway for Conversion of Midwest Soybeans to Biodiesel (Fatty Acid Methyl Esters-FAME)

Stationary Source Division

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The Staff of the Air Resources Boards developed this preliminary draft version 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

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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

Detailed California-Modified GREET Pathway for Conversion of Midwest Soybeans to Biodiesel (Fatty Acid Methyl Esters-FAME)

A Well-to-Tank (WTT) Life Cycle Analysis of soybean biodiesel (BD) pathway includes all steps from soybean farming to final finished 100% biodiesel (B100). Tank-to-Wheel (TTW) analysis includes actual combustion of fuel in a motor vehicle for motive power. Together, WTT and TTW analyses are combined to provide a total Well-to-Wheel (WTW) analysis.

A Life Cycle Analysis Model called the **G**reenhouse gases, **R**egulated **E**missions, and **E**nergy use in **T**ransportation (GREET)[1] developed by Argonne National Laboratory has been used to calculate the energy use and greenhouse gas (GHG) emissions generated during the entire process starting from farming soybeans to producing biodiesel and combusting biodiesel in an internal combustion engine. Staff, with assistance from Life Cycle Associates, modified the original GREET model to create a California specific model termed the CA-GREET model. Changes were restricted mostly to input factors (emission factors, generation mix, transportation distances, etc.) with no substantial changes in methodology inherent in the original GREET model. This California modified GREET model (v1.8a, release December 2009) forms the basis of this document. It has been used to calculate the energy use and Greenhouse Gas (GHG) emissions associated with a WTW analysis for Biodiesel from Midwest Soybeans used in a Heavy Duty diesel vehicle.

The CA-GREET model calculates the direct impacts from the production and use of biodiesel. Indirect impacts that could result from the diversion of soybean-derived oil to produce biodiesel has also been analyzed using the GTAP model. Complete details of this analysis for indirect effects is published as a companion document with the release of this fuel pathway document and is available on the Low Carbon Fuel Standard website (www.arb.ca.gov\fuels\lcfs.htm). Only the final result from the GTAP analysis has been used here to allow for a total WTW carbon intensity to be presented in this document.

The pathway described here includes soybean farming, soybean transport, biodiesel production, transport and distribution (T&D) and use of biodiesel in an internal combustion engine. The tailpipe emissions from the combustion of biodiesel is assumed to be the same as Ultra Low Sulfur Diesel (ULSD) and is presented as such in this document. Most of the basic inputs, assumptions, and calculation methodology used in this analysis are provided in the soybean to biodiesel (and renewable diesel) technical document from Argonne[2]. The modifications to the CA-GREET include the use of California specific factors (e.g. biodiesel production, vehicle combustion, etc.).

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

[2] See technical document published by Argonne regarding soybean biodiesel and renewable diesel: “Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels”, H. Huo, et al, March 2008, retrieve from: http://www.transportation.anl.gov/pdfs/AF/467.pdf

Those modifications are detailed in Appendix B. Additional factors that have been modified for California for the use of fuels such as electricity, natural gas, etc. within the state are detailed in companion documents that have been published on the Low Carbon Fuel Standard website[3]. To summarize, the pathway documented here includes soybean farming and soyoil extraction in the Midwest, followed by transportation of soyoil to California. Soyoil is then transesterified to biodiesel and transported to blending stations for use in an internal combustion vehicle.

Figure 1 below shows the discrete components that form the biodiesel pathway starting from soybean farming, soybean transportation, biodiesel production and distribution to refueling stations, and final use in a transportation vehicle.

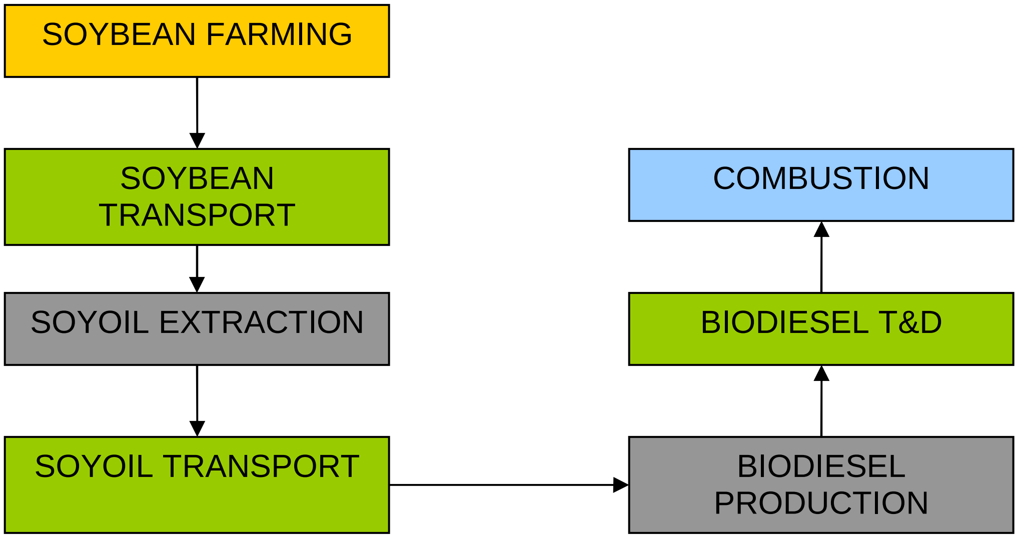

Figure 1. Discrete Components of the Midwest Soybean to Biodiesel Pathway.

This document provides detailed calculations, assumptions, inputs and other necessary information to calculate the energy requirements and GHG emissions for the soybean to biodiesel pathway. Table A below provides a summary of the energy use and GHG emissions per MJ of fuel produced. Expanded details are provided in Appendix A. Input values used in calculations are shown in Appendix B. A description of the co-product allocation methodology used in the analysis is provided in Appendix C.

Several general descriptions and clarification of terminology used throughout this document are:

- CA-GREET employs a recursive methodology to calculate energy consumption and emissions. To calculate WTT energy and emissions, the values being calculated are often utilized in the calculation. For example, crude oil is used as a process fuel to recover crude oil. The total crude oil recovery energy consumption includes the

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[3] See http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

direct crude oil consumption and the energy associated with crude recovery (which is the value being calculated).

- 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 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) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2 equivalent basis using IPCC[4] global warming potential 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.

- Process Efficiency for any step in 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.

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[4] IPCC: Intergovernmental Panel on Climate Change a scientific intergovernmental body tasked to evaluate the risk of climate change caused by human activity established by United Nations in 1988. In 2007, the IPCC values for GHG equivalence (gCO_2e/MJ) are: CH_4 = 25, N_2O = 298, CO_2 = 1. For others GHG, GREET calculates molecular weight of carbon to obtain the GHG equivalence (gCO_2e/MJ):
VOC = 0.85/0.27 = 3.12 and CO = 0.43/.273 = 1.57

Table A. Summary of Energy Consumption and GHG Emissions from a WTW Analysis of Biodiesel Produced from Midwest Soybeans

	Energy Required (Btu/mmBtu)	**Share of Total Energy (%)**	**GHG Emissions (gCO_2e/MJ)**	**Share of Total Emissions (%)**
Well-to-Tank (WTT)				
Soybean Farming	28,625	2.20%	2.17	10.21%
Agricultural Chemicals Production	21,456	1.65%	1.59	7.48%
N_2O Emissions from Fertilizer Use	N/A	N/A	1.66	7.81%
Soybean Transport	6,805	0.52%	0.53	2.49%
Soyoil Extraction	57,054	4.38%	3.83	18.02%
Soyoil Transport	17,734	1.36%	1.37	6.45%
Biodiesel Transesterification	159,684	12.27%	4.89	23.01%
Biodiesel Transport & Dist.	10,055	0.77%	0.76	3.58%
Total WTT	**301,413**	**23.16%**	**16.80**	**79.06%**
Tank -to- Wheel (TTW)				
Carbon in Fuel	1,000,000	76.84%	N/A	N/A
Fossil Carbon in Fuel	N/A	N/A	3.67	17.27%
Vehicle CH_4 and N_2O	N/A	N/A	0.78	3.67%
Total TTW	**1,000,000**	**76.84%**	**4.45**	**20.94%**
Total Well-to-Wheel (WTW)	**1,301,413**	**100%**	**21.25**	**100%**

From Table A above, a WTW analysis of biodiesel indicates that **1,301,413** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy delivered to the vehicle. From a GHG perspective, **21.25** gCO_2e of direct contributions GHG are released during the production of 1 (one) MJ of biodiesel. For indirect land use change, staff estimates **62 gCO_2e/MJ** at this time based on GTAP analysis. The total carbon intensity for soybean derived biodiesel derived from soybeans is **83.25 gCO_2e/MJ**[5].

The values in Table A are pictorially represented in Figure 2, showing specific contributions of each of the discrete components of the fuel pathway. The charts are shown separately for energy use and GHG emissions. From an energy use viewpoint, carbon in fuel (76.84%) dominates the pathway energy use. For GHG emissions, the largest contributions are from soybean production (includes soybean farming, use of

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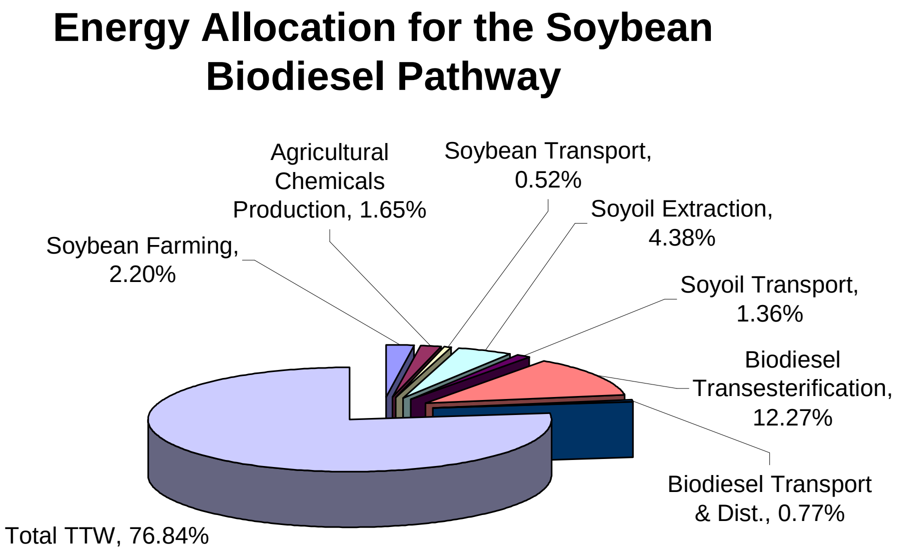
[5] Details of the Land Use Change analysis including information about GTAP is available in Chapter 4 of the LCFS staff report. Specific analysis for this feedstock is available as a December 2009 update on the LCFS website.

agricultural chemicals and consequent N_2O release) (25.50%), BD transesterification (23.01%), and soyoil extraction (18.02%).

Note: Some intermediate values in the Tables in this document have been rounded to appropriate significant figures. Due to this rounding, the final values presented at the bottom of each table may not be exactly reproducible utilizing the values reported in upper sections of tables in this document. The CA-GREET model, however, does account for all relevant digits for each value (or parameter) in calculating emissions for all steps of the pathway and provides an accurate calculation for each step and for the complete pathway.



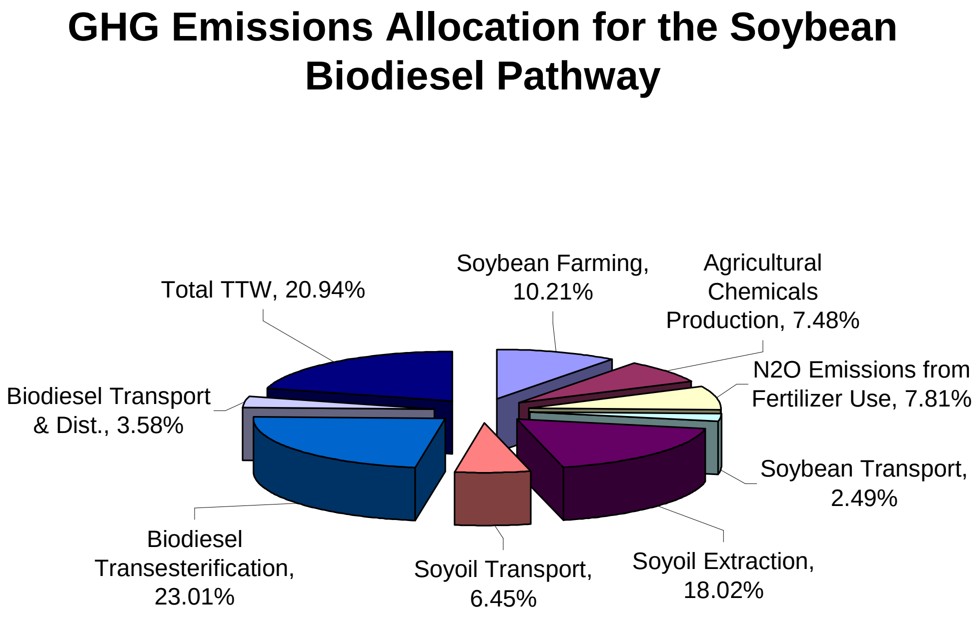


Figure 2. Percent Energy Contribution and GHG Emissions Contributions from a Well-to-Wheel (WTW) Analysis of the Soybean to Biodiesel Pathway

The following sections provide a summary of all the components that form part of the biodiesel pathway. Complete details are provided in Appendix A.

WTT Details

Soybean Farming

The biodiesel production process starts with soybean farming. Table B provides a breakdown of energy use needed for soybean farming. Complete details are provided in Appendix A. Input values used in the analysis are presented in Appendix B. Appendix C provides the details of allocation factors for the biodiesel pathway. In a similar manner, GHG emissions associated with soybean farming are shown in Table C below. Complete details are provided in Appendix A.

Table B. Total Energy Use for Soybean Farming

Fuel Type	**Energy Use**
Diesel (Btu/bushel)	16,543
Gasoline (Btu/bushel)	4,726
Natural Gas (Btu/bushel)	1,725
LPG (Btu/bushel)	1,875
Electricity (Btu/bushel)	1,696
Total Energy Use (Btu/bushel)	**26,564**
Total Energy Use (Btu/mmBtu)	**150,550**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**28,625**

Table C. Total GHG Emissions from Soybean Farming.

GHG Species	**GHG Emissions**
CO_2 (gCO_2e/mmBtu)	2,059
CH_4 (gCO_2e/mmBtu)	3.44
N_2O (gCO_2e/mmBtu)	0.038
CO (gCO_2e/mmBtu)	76.212
VOC (gCO_2e/mmBtu)	4.195
Total GHG Emissions (gCO_2e/mmBtu)	**2,290**
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**2.17**

Chemical Inputs in Soybean Farming

Table D shows the energy necessary for the production of chemicals used in soybean farming. The agricultural chemicals include fertilizers, herbicides and pesticides. Detailed breakdown of chemical inputs utilized in the calculations is provided in Appendix A.

Table D. Total Energy Consumed for Chemical Inputs in Soybean Farming

Inputs	Energy Use
Nitrogen (Btu/bu)	2,805
Phosphate (P_2O_5) (Btu/bu)	2,477
Potash (K_2O) (Btu/bu)	2,740
Herbicides (Btu/bu)	11,756
Pesticides (Btu/bu)	134
Total Energy Consumption (Btu/bu)	**19,912**
Total Energy Consumption (Btu/mmBtu)	**112,486**
Total Energy Consumption (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**21,456**

Table E provides GHG emissions from chemicals input in soybean farming. Complete details are provided in Appendix A.

Table E. Total GHG Emissions for Chemical Inputs in Soybean Farming

GHG Species	GHG Emissions
CO_2 (gCO_2e/mmBtu)	1,588
CH_4 (gCO_2e/mmBtu)	1.979
N_2O (gCO_2e/mmBtu)	0.12
CO (gCO_2e/mmBtu)	1.56
VOC (gCO_2e/mmBtu)	0.645
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.59**

CA-GREET also calculates direct field and downstream N_2O emissions resulting from nitrogen fertilizer input. Agricultural N_2O emissions result from conversion of fixed (natural and anthropogenic) nitrogen in the soil. Fixed nitrogen applied to field crops is either extracted by the crop as a nutrient, absorbed (chemically bound) into organic soil components or entrapped in soil aggregates (chemically unbound). The majority of the chemically bound nitrogen remains stabilized in the organic form in the soil system, while the unbound nitrogen is converted to N_2O, volatilized as nitrate or ammonia, or leached out as nitrate. Field and downstream inputs are significant components of agricultural emissions associated with soybean cultivation. The CA-GREET model includes the impact of agricultural N_2O release and this is summarized in Table F below. Complete details of this are provided in Appendix A.

Table F. Total GHG Emissions from N_2O Release Due to Fertilizer Application

GHG Species	GHG Emissions
GHG Emissions from N_2O Release (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.66**

Soybean Transport

In the CA-GREET model, soybeans are transported from the field to stack by medium duty truck and from stack to a soyoil extraction plant in the Midwest by heavy duty truck. Details of the energy use are shown in Table G. Soybean transport generates GHG emissions and they are shown in Table H. Details of all the calculations are provided in Appendix A.

Table G. Total Energy Required for Soybean Transport

Locations	Energy Use
Field to Stack (Btu/bu)	1,535
Stack to Plant (Btu/bu)	4,780
Total Energy Use (Btu/bu)	**6,315**
Total Energy Use (Btu/mmBtu)	**35,791**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**6,805**

Table H. Total GHG Emissions from Soybean Transport

GHG Species	GHG Emissions
CO_2 ($gCO_2e/mmBtu$)	533
CH_4 ($gCO_2e/mmBtu$)	14.54
N_2O ($gCO_2e/mmBtu$)	4.26
CO ($gCO_2e/mmBtu$)	1.5
VOC ($gCO_2e/mmBtu$)	0.73
Total GHG Emissions ($gCO_2e/mmBtu$)	**554.0**
Total GHG Emissions(with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**0.53**

Soyoil Extraction

Soyoil is then extracted from the soybeans and the energy use and attendant GHG emissions are shown in Table I and Table J respectively. Details of the calculations are shown in Appendix A.

Table I. Total Energy Use for Soyoil Extraction

Fuel Type	Energy Use
NG (Btu/lb)	2,995
Electricity (Btu/lb)	1,460
N-Hexane (Btu/lb)	203
Total Energy Use (Btu/lb)	**4,658**
Total Energy Use (Btu/mmBtu)	**299,958**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**57,054**

Table J. Total GHG Emissions from Soyoil Extraction

GHG Species	GHG Emissions
CO_2 (gCO_2e/mmBtu)	3,686
CH_4 (gCO_2e/mmBtu)	163.2
N_2O (gCO_2e/mmBtu)	7.30
CO (gCO_2e/mmBtu)	4.02
VOC (gCO_2e/mmBtu)	186.99
Total GHG Emissions (gCO_2e/mmBtu)	**4,048**
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**3.83**

Soyoil Transport

The pathway described here considers soyoil extracted in the Midwest and transported by rail to a biodiesel plant in CA. The energy use for transport and associated GHG emissions are shown in Table K and Table L. Details of all the calculations are presented in Appendix A.

Table K. Total Energy Required for Soyoil Transport

Transport (By Rail)	Energy Use
Total Energy for Transport (Btu/mmBtu)	**18,653**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**17,734**

Table L. Total GHG Emissions from Soyoil Transportation

GHG Species	GHG Emissions
CO_2 (gCO_2e/mmBtu)	1,386
CH_4 (gCO_2e/mmBtu)	1.556
N_2O (gCO_2e/mmBtu)	0.03
CO (gCO_2e/mmBtu)	3.547
VOC (gCO_2e/mmBtu)	1.036
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.37**

Biodiesel Production via Transesterification

The soyoil is transesterified in plants in California to produce biodiesel. Table M and Table N provide energy use and attendant GHG emissions from transesterification respectively. Details are provided in Appendix A.

Table M. Total Energy Use for Biodiesel Transesterification

Fuel or Chemicals	Energy Use
NG (Btu/lb)	950
Electricity (Btu/lb)	93
Methanol (Btu/lb)	1,354
Sodium Hydroxide (Btu/lb)	42
Sodium Methoxide (Btu/lb)	209
Hydrochloric Acid (Btu/lb)	63
Total Energy Use (Btu/lb)	**2,712**
Total Energy Use (Btu/mmBtu)	**167,961**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**159,684**

Table N. Total GHG Emissions from Biodiesel Transesterification

GHG Species	GHG Emissions
CO_2 (gCO_2e/mmBtu)	4,710
CH_4 (gCO_2e/mmBtu)	17.19
N_2O (gCO_2e/mmBtu)	0.06
CO (gCO_2e/mmBtu)	3.65
VOC (gCO_2e/mmBtu)	1.77
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**4.89**

Biodiesel Transport and Distribution

Table O and Table P show the respective energy use and GHG emissions from transporting biodiesel in California. Complete details are provided in Appendix A.

Table O. Total Energy Use for Biodiesel Transport and Distribution

	HD Truck from Plant to Bulk Terminal	**HD Truck for Distribution**
Total Energy Use (Btu/mmBtu)	3,094	6,961
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**10,055**	

Table P. Total GHG Emissions from Biodiesel Transport and Distribution

GHG Species	**GHG Emissions**
CO_2 ($gCO_2e/mmBtu$)	770
CH_4 ($gCO_2e/mmBtu$)	0.947
N_2O ($gCO_2e/mmBtu$)	0.019
CO ($gCO_2e/mmBtu$)	1.478
VOC ($gCO_2e/mmBtu$)	0.327
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**0.76**

TTW Details

Biodiesel use in a Heavy Duty Vehicle

The biodiesel is then modeled as being used in a heavy duty vehicle in California. The factors used here are the same as that for a heavy duty diesel truck using ULSD. Table Q provides a summary of TTW emissions from the use of BD in a heavy duty vehicle. Complete details of the calculations are shown in Appendix A.

Table Q. Total GHG Emissions from Using Biodiesel in a Heavy Duty Vehicle

GHG	**GHG Emissions**
CH_4 and N_2O from Vehicle (gCO_2e/MJ)	0.78
Fossil Carbon in Biodiesel (gCO_2e/MJ)	3.67
Total TTW (gCO_2e/MJ)	**4.45**

APPENDIX A

SECTION 1. DETAILED ENERGY CONSUMPTION AND GHG EMISSIONS CALCULATIONS OF SOYBEAN FARMING

1.1 Soybean Farming Energy Consumption

The first step in the soybean to biodiesel pathway is farming. There are two main components of the farming step: direct farming and fertilizer/pesticide/herbicide use. Each is discussed in this section.

Rather than assuming a "farming efficiency", the direct farming energy use is specified in terms of Btu/bushel. A GREET 1.8 default value of **22,087**[6] Btu/bushel has been used in this document. This total energy consumption is split into four different fuel types, resulting in direct energy consumption by fuel as shown in Table 1.01. The analysis assumes the U.S. average region in the CA-GREET model for feedstock production, which consists of U.S. petroleum and U.S. average electricity. Table 1.02 shows the U.S. average electricity mix.

Table 1.01 Direct Energy Consumption for Soybean Farming

Process Fuel Type	Fuel Shares	Fuel Shares Calculations	Direct Energy Consumption, Btu/bushel
Diesel	64.4%	0.644 * 22,087	14,224
Gasoline	17.8%	0.178 * 22,087	3,931
Natural Gas	7.3%	0.073 * 22,087	1,612
Liquid Petroleum Gas	7.6%	0.076 * 22,087	1,679
Electricity	2.9%	0.029 * 22,087	641
Total Direct Energy Consumption Soybean Farming			**22,087**

Table 1.02 U.S. Average Electricity Mix Used for Feedstock Production

Fuel	U.S. Average
Residual oil	2.7%
Natural Gas	18.9%
Coal	50.7%
Nuclear Power	18.7%
Biomass	1.3%
Others	7.7%

Source: Argonne National Laboratory[7]

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[6] Data are from USDA 2007 retrieved from Argonne technical document: "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels", H. Huo, et al, March 2008, p. 13-14

[7] Data are retrieved from Argonne technical document: "Fuel Cycle Comparison of Distributed Power Generation Technologies", A. Elgowayni and M. Wang, November 2008, p. 6-7

To convert the total direct energy shown in Table 1.01 from Btu/bushel to Btu/mmBtu, the parameters shown in Table 1.03 are used.

Table 1.03 Biodiesel Pathway Parameters

Soybean Yield (lb/bushel)	Soybean to Soyoil (lbs soybean/lb oil)	Soyoil to BD (lbs oil/lb BD)	BD Density (g/gal)	BD LHV (Btu/gal)	BD LHV (Btu/lb)
60[2]	5.28*	1.04**	3,361[2]	119,550[2]	16,169

* 2007 USDA data for soybeans and soyoil[8]
** GREET default (value documented on Argonne GREET website)[9]

All of the values in Table 1.03 are GREET defaults except for soybean to soy oil use factor (5.28 lb soybean/lb oil compared to the Argonne GREET default of 5.7). This factor has changed to 5.28 to reflect USDA data for the year 2007.

The values provided in Table 1.01 are direct energy consumption per bushel of soybean collected for the farming step. This is not the total energy required however, since CA-GREET accounts for the "upstream" energy associated with each of the fuels utilized to make biodiesel. Upstream energy refers to the process energy necessary to produce the fuel that is utilized in the soybean farming operation. For example, 14,224 Btus of diesel fuel are required to make a bushel of soybean. The total energy associated with the 14,224 Btu of diesel fuel includes the energy to recover the crude and refine it to diesel fuel (or Well-to-Tank energy). Specific details of the calculations are shown in Table 1.05 using factors shown in Table 1.04.

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[8] Retrieved from USDA website November 2009: http://www.fas.usda.gov/psdonline/psdquery
[9] See Argonne website for GREET documentations: http://www.transportation.anl.gov/modeling_simulation/GREET/pdfs/greet_publications.pdf

Table 1.04 Energy Consumption in the WTT Process and Specific Energy of Fuels Used in the Soybean to Biodiesel Pathway

	E:WTT energy (Btu input/Btu product)	**S: Specific Energy (Btu input/Btu product)**
Crude	E_{CR} = 28,284	$S_{CR} = 1+E_{CR}/10^6$
	$E_C = E_{CR}$*Loss Factor $_{T\&D}$ + $E_{C\ T\&D} + E_{CS}$ = 28,284*1 + 10,926 = 39,212	
Residual Oil	E_{ResOil} = 74,239	$S_{Res\ Oil} = 1+(E_C*\text{Loss Factor}_{Crude} + E_{ResOil})/10^6$
Conventional Diesel	E_{diesel} = 123,805	$S_{diesel} = 1+(E_C*\text{Loss Factor}_{diesel}+E_{diesel})/10^6$
Conventional Gasoline	$E_{gasoline}$ = 162,914	$S_{gasoline} = 1+(E_C*\text{Loss Factor}_{gasoline}+E_{gasoline})/10^6$
NG	$E_{NG}=(E_{NG\ Rec} + E_{NG\ Procss})$ *Loss Factor $_{NG}$ + $E_{T\&D}$ = 69,596	$S_{NG} = 1+E_{NG}/10^6$
NG Recovery	$E_{NG\ Rec}$ = 31,148	
NG Processing	$E_{NG\ Procss}$ = 31,854	
NG T&D	$E_{NG\ T\&D}$ = 6,498	
LPG	E_{LPG} = 75,862	$S_{LPG} = 1 + E_{LPG}/10^6$
Coal	E_{coal} = 17,353	$S_{coal} = 1+E_{coal}/10^6$
Uranium	$E_{uranium}$= 1,241,307	$S_{uranium} = 1+E_{uranium}/(6.926*1000*3412)$
Electricity		$S_{Electricity} = (E_{efeedstock}+E_{efuel})/10^6$
as Feedstock	$E_{efeedstock}$ = 85,708	
as Fuel	E_{efuel} = 2,561,534	
Still Gas	E_C = 39,212	$S_C = (1+E_C)/10^6$

Note: Loss Factors are as follows: Crude: 1.0; Diesel: 1.000044; Gasoline: 1.0008 ;NG: 1.0008; LPG: 1.0001. E_{CR} is the energy used for crude recovery, E_C represents energy use for crude processing.

Table 1.05 Soybean Farming Total Adjusted Energy Consumption from Direct Energy Consumption

Fuel Type	Formula	Description	Total Btu/bu
Diesel	14,224 + 14,224 * (39,212 * 1.0000 + 123,805)/ 10^6	14,224 Btu of direct conventional diesel used per bushel soybean. (Table 1.01)	16,543
		energy to recover crude is 39,212 [1] Btu/Btu crude (Table 1.04)	
		Conventional diesel fuel loss factor is 1.0000 (Table 1.04)	
		Energy to produce conventional diesel 123,805 Btu/Btu (Table 1.04)	
Gasoline	3,931 + 3,931 * (39,212 * 1.0008 + 162,914)/ 10^6	3,931 Btu of direct conventional gasoline used per bushel soybean (Table 1.01)	4,726
		Conventional gasoline fuel loss factor is 1.0008 (Table 1.04)	
		Energy to produce gasoline 162,914 Btu/Btu (Table 1.04)	
Natural Gas	1,612 * (1 + 69,596/ 10^6)	1,612 Btu/bu of direct NG use (Table 1.01)	1,725
		Energy to produce NG 69,596 Btu/Btu (Table 1.04)	
LPG	1,679 * [0.40 * (1+ (39,212* 1.0001 + 75,862)/ 10^6) + 0.60 * ((1+ (69,596* 1.0001 + 48,896)/10^6)]	1,679 Btu/bu of direct LPG use (Table 1.01)	1,875
		1.0001 is the petroleum LPG loss factor.	
		energy to recover crude is 39,212 [1] Btu/Btu crude (Table 1.04)	
		Energy to produce LPG from crude 75,862 Btu/Btu (Table 1.04)	
		Energy to produce NG is 69,596 Btu/Btu (Table 1.04)	
		Energy to produce LPG from NG is 48,896 Btu/Btu (CA-GREET default)	
		40% of the LPG is from petroleum, 60% is from NG (CA-GREET default) and is calculated from above	
Electricity	641 (85,708 + 2,561,534)/ 10^6	641 Btu/bu of direct electricity used (Table 1.01)	1,696
		85,708 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity (Table 1.04)	
		2,561,534 Btu used as fuel to produce 1 mmBtu electricity (Table 1.04)	
Total energy for soybean farming, Btu/bushel			26,564
Total energy for soybean farming, Btu/mmBtu = 26,564/60 lbs/bu x 5.28 lbs oil/lb soybean x 1.04 lbs oil/lb BD/16,149 Btu/lb BD x 10^6			150,550
Total adjusted energy for soybean farming, Btu/mmBtu = 150,550 * 20.0% x 95.1% x 1.000039			**28,625**

Note: Well-to-Tank energies for fuels (crude, NG, LPG, etc.) are extracted from the relevant fuel tab in CA-GREET at the bottom in the summary section.

Conversion from Btu/bushel to Btu/mmBtu:

$$\frac{26{,}564 Btu/bu \times 5.28 lbsSB/lbsOil}{60 lbsSB/bu} \times \frac{1.04 lbsOil/lbBD}{16{,}149 Btu/lbBD} \times 10^6$$ = 150,550 Btu/mmBtu

Adjust energy with credit to glycerin and oil mass share:

$150{,}550 Btu/mmBtu \times 20\% \times 95.1\% \times 1.000039 =$ **28,625 Btu/mmBtu**

where:

a) 5.28 lbs of soybean/lb soyoil, 60 lbs/bu, 1.04 lbs oil/lb BD, and 16,149 Btu/lb BD are from table 1.03
b) The oil mass share (20.0%) of total oil extraction energy system (including oil and soybean meal, see Appendix C for complete details)
c) the biodiesel energy share (95.1%) of the overall transesterification system (including biodiesel and glycerin, see Appendix C for complete details)
d) 1.000039 is loss factor is GREET calculations and is detailed below.

The loss factor is calculated as shown below:

$$1 + \frac{\text{0.207 g VOC/mmBtu BD + 0.880 g VOC/mmBtu BD}}{\left[\text{(3,361 g BD/gal)/(119,550 Btu BD/gal)*}10^6\right]} = 1.000039$$

The analysis here uses the mass-based allocation to determine a soybean meal credit and energy allocation to calculate the glycerin credit. The analysis allocates 20.0% of the farming, soybean transport and oil extraction energy and emissions to biodiesel and the balance to soybean meal. The feedstock production and oil transesterification results are allocated based on energy-allocation factors for biodiesel and glycerin. The analysis here uses an energy allocation factor of 95.1% and details of this calculation is provided in Appendix C.

The calculations in Table 1.04 above (and other Tables in this document) utilize Well-to-Tank energy results for all fuels used in the various steps of the biodiesel pathway. For example, in Tables 1.04 and 1.05 the diesel calculation uses the crude recovery WTT energy (39,212 Btu/Btu) and diesel production WTT energy (123,805 Btu/Btu); The LPG calculation uses WTT values (39,212 and 75,862 Btu/Btu) for LPG produced from petroleum and the WTT values (69,596 and 48,896 Btu/Btu) for LPG produced from NG. These values are extracted from the summary section of each individual fuel tab in the CA-GREET model. As with the WTT energy values, the emission tables in the following sections use the WTT emissions values, extracted from CA-GREET in the same manner.

1.2 GHG Emissions from Soybean Farming

GHG emissions are calculated in two steps: direct emissions and upstream emissions. The direct emissions are simply the direct fuel consumption multiplied by the appropriate emission factor. Upstream emissions are the emissions associated with recovery, processing and transport of the fuel. Table 1.06 provides the equipment shares for each fuel type consumed and the corresponding emission factors.

Table 1.06 Emission Factors for Fuel Combustion

	Equipment Type	**Equipment Shares**	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
			g/mmBtu (LHV)				
Diesel	Tractor	80%	107.689	402.578	9.717	0.920	77,204
Diesel	Engine	20%	83.407	362.100	7.526	2.000	77,349
Gasoline	Tractor	100%	532.974	16,291.863	29.974	1.104	49,494
Natural Gas	Reciprocating Engine	100%	41.120	342.445	368.940	1.500	56,551
LPG	Boiler	100%	1.890	10.800	1.080	4.860	68,036

Source: GREET default emission factors

Direct emissions are calculated by multiplying the direct fuel consumption (provided in Table 1.01) by the above emission factors and summing the equipment types per fuel as shown in Table 1.07.

Table 1.07 Direct Emissions from Soybean Farming

Process Fuel	**VOC** g/bushel	**CO** g/bushel	**CH_4** g/bushel	**N_2O** g/bushel	**CO_2** g/bushel
Diesel	1.463	5.611	0.132	0.016	1,099
Gasoline	2.095	64.051	0.118	0.004	195
Natural Gas	0.066	0.552	0.595	0.002	91
LPG	0.003	0.018	0.002	0.008	114
Total Direct	**3.628**	**70.233**	**0.846**	**0.031**	**1,499**

In addition to the direct farming emissions, the emissions associated with recovery, processing and transport of the direct fuel used must be included. The calculation methodology for quantifying the upstream emissions for CO_2 are provided in Table 1.09, with CO_2 emission factors for each fuel producing process shown in Table 1.08. Upstream emissions for all pollutants are summarized in Table 1.10.

Table 1.08 CO_2 Emission Factors for Fuels Used in Soybean Farming

	EF:WTT CO_2 Emission Factor (g CO_2 /mmBtu fuel output)	**SE: Specific Emission (g CO_2/mmBtu fuel output)**
Crude	$EF_{CR} = 2{,}961$	$SE_{CR} = 1+EF_{CR}/10^6$
	$EF_C = EF_{CR}*LF_{T\&D} + EF_{C\ T\&D} + EF_{CS}$ + (VOC, CO conversion) = 3,868	
Residual Oil	$EF_{ResOil} = 5{,}613$	$SE_{Res\ Oil} = 1+(EF_C*Loss\ Factor_{Crude}+EF_{ResOil})/10^6$
Conventional Diesel	$EF_{Diesel} = 9{,}389$	$SE_{Diesel} = 1+(EF_C*Loss\ Factor_{Diesel}+EF_{Diesel})/10^6$
Conventional Gasoline	$EF_{Gasoline} = 12{,}124$	$SE_{Gasoline} = 1+(EF_C*Loss\ Factor_{Gasoline}+EF_{Gasoline})/10^6$
NG	$EF_{NG}=(EF_{NG\ Rec} + EF_{NG\ Procss})$ *Loss Factor + $E_{T\&D}$ + $EF_{Non\text{-}combustion}$+ (VOC, CO conversion) = 5,208	$SE_{NG} = 1+EF_{NG}/10^6$
NG Recovery	$E_{NG\ Rec} = 1{,}717$	
NG Processing	$E_{NG\ Procss} = 1{,}858$	
NG T&D	$E_{NG\ T\&D} = 352$	
NG non-combustion	$E_{NG\ non\text{-}combustion} = 1{,}237$	
Coal	$EF_{Coal} = 1{,}411$	$SE_{Coal} = 1+EF_{Coal}/10^6$
Uranium	$EF_{Uranium}= 100{,}325$	$SE_{Uranium} = 1+EF_{Uranium}/(6.926*1000*3412)$
Electricity		$SE_{Electricity} = (EF_{efeedstock}+EF_{efuel})/10^6$
as Feedstock	$EF_{efeedstock} = 6{,}833$	
as Fuel	$EF_{efuel} = 213{,}458$	
Still Gas	$EF_C = 3{,}868$	$SE_C = 1+EF_C/10^6$
LPG	$EF_{LPG} = 5{,}715$	$SE_{LPG} = 1+ EF_{LPG}/10^6$

Note: See Table 1.04 for Loss Factors

Table 1.09 Calculation of Upstream CO_2 Emissions from Direct Farming Energy Consumption

Fuel Type	**Formula**	**Description**	**g/bu**
Diesel	14,224 * (3,868 * 1.0000 + 9,389) / 10^6	14,224 Btu/bu of direct diesel used (Table 1.01)	189
		Crude recovery CO_2 emissions are 3,868[1] g/mmBtu (Table 1.08)	
		Diesel loss factor is 1.0000	
		CO_2 emissions from producing diesel are 9,389 g/mmBtu	
Gasoline	3,931 * (3,868 * 1.0008 + 12,124) / 10^6	3,931 Btu/bu of direct gasoline used (Table 1.01)	63
		Gasoline loss factor is 1.0008	
		CO_2 emissions to produce gasoline 12,124 g/mmBtu (from Table 1.08)	
Natural Gas	1,612 * 5,208 / 10^6	1,612 Btu/bu of direct natural gas used (Table 1.01)	8
		Natural gas recovery CO_2 emissions are 5,208 g/mmBtu	
LPG	1,679 * ((3,868 * 1.0001 + 5,715) * 40% + (4,885 * 1.0001 + 3,168) * 60%) / 10^6	The analysis assumes 40% of the LPG comes from petroleum and the other 60% from NG. 1,679 Btu of direct LPG used per bushel of soybeans produced (Table 1.01)	15
		The crude recovery CO_2 emissions are 3,868 g/mmBtu	
		CO_2 emissions to produce LPG from petroleum 5,715 g/mmBtu	
		CO_2 emissions from production of NG for LPG is 4,885	
		LPG to NG loss factor is 1.0001	
		The emissions associated with producing LPG from NG are 3,168 g/mmBtu.	
Electricity	641 * (6,833 + 213,458) / 10^6	641 Btu of electricity consumed per bushel of soybeans produced (Table 1.01)	141
		CO_2 emissions associated with electricity feedstock and transport is 6,833 g/mmBtu (Table 1.08)	
		CO_2 emissions associated with electricity as fuel is 213,458 g/mmBtu (Table 1.08)	
Total			**416**

Note: Well-to-Tank CO_2 emissions for fuels (crude, NG, LPG, etc.) are extracted from the relevant fuel tab in CA-GREET at the bottom in the summary section.

Upstream emissions are provided in Table 1.10. Table 1.11 shows the combined direct and upstream emissions in g/bu and converted to g/mmBtu and Table 1.12 presents the summary results with allocation and loss factors applied.

Table 1.10 Summary of Upstream Emissions From Soybean Farming

Process Fuel	**VOC** g/bu	**CO** g/bu	**CH_4** g/bu	**N_2O** g/bu	**CO_2** g/bu
Diesel	0.117	0.250	1.395	0.002	189
Gasoline	0.107	0.076	0.396	0.001	63
Natural Gas	0.010	0.019	0.208	0.000	8
LPG	0.018	0.026	0.198	0.000	15
Electricity	0.013	0.124	0.176	0.001	141
Total Upstream Emissions	**0.265**	**0.490**	**2.347**	**0.004**	**416**

Table 1.11 Summary of Total (Direct + Upstream) Emissions from Soybean Farming

(g/bu)	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
Diesel	1.580	5.862	1.527	0.018	1,287
Gasoline	2.203	64.127	0.514	0.005	257
Natural Gas	0.076	0.571	0.803	0.003	100
LPG	0.021	0.044	0.200	0.008	129
Electricity	0.013	0.124	0.176	0.001	141
Total Emissions	**3.893**	**70.724**	**3.194**	**0.035**	**1,914**
(g/mmBtu)	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
Diesel	8.954	33.222	8.654	0.102	7,294
Gasoline	12.485	363.429	2.913	0.028	1,457
Natural Gas	0.431	3.236	4.551	0.017	567
LPG	0.120	0.249	1.133	0.047	730
Electricity	0.074	0.703	0.997	0.006	799
Total Emissions	**22.064**	**400.840**	**18.248**	**0.200**	**10,846**

Sample calculation of CO_2 value to convert from g/bu to g/mmBtu:

$$\frac{(1{,}914 g/bu)\times(5.28 lbsSB/lbOil)\times(1.04 lbsOil/lbBD)}{(16{,}149 Btu/lbBD)\times(60 lbsSB/bu)}\times 10^6 = \textbf{10,846 g/mmBtu.}$$

Table 1.12 Summary of Total (Direct + Upstream) Emissions from Soybean Farming with Allocation and Loss Factors Applied

With Allocation and Loss Factors Applied							
	VOC g/mmBtu	**CO** g/mmBtu	**CH_4** g/mmBtu	**N_2O** g/mmBtu	**CO_2** **g/mmBtu**	**GHG gCO_2e/mmBtu**	**GHG gCO_2e/MJ**
Diesel	1.703	6.317	1.646	0.019	1,387	1,449	1.37
Gasoline	2.374	69.104	0.554	0.005	277	408	0.39
Natural Gas	0.082	0.615	0.865	0.003	108	132	0.12
LPG	0.023	0.047	0.215	0.009	139	147	0.14
Electricity	0.014	0.134	0.190	0.001	152	157	0.15
Total Emissions	**4.195**	**76.217**	**3.470**	**0.038**	**2,062**	**2,293**	**2.17**

1.3 Energy Calculation from Production of Chemical Inputs in Soybean Farming

The next part of the farming energy use is the energy associated with production and transport of fertilizers, pesticides and herbicides. All assumptions described here are CA-GREET default values. The key assumptions are provided in Table 1.13. Note that for each of the products, direct and total energy are calculated based on assumed process energy efficiency and fuel shares. Energy associated with transportation of each product from plant to field is also calculated. Chemical inputs, including fertilizer, herbicide and insecticide, are input on a g-nutrient/bushel (fertilizer) or g-product/bushel (herbicide and pesticide) basis. Table 1.13 presents the CA-GREET chemical inputs per bushel of soybean, the total energy required to produce the chemical product and the calculated upstream fuel cycle energy required to produce a bushel of soybean using these inputs.

Table 1.13 Energy Associated with Fertilizer/Herbicide/Pesticide Use

Product	**Product Use Rate g/bu**	**Total Production Energy Btu/g**	**Total Energy Consumption Btu/bu**
Nitrogen*	61.2	45.84	2,805
Phosphate (P_2O_5)	186.1	13.31	2,477
Potash (K_2O)	325.5	8.42	2,740
Herbicides	43.02	273.26	11,756
Pesticides	0.43	312.43	134
Total Energy Consumption due to Production of Ag. Chemicals Used in Farming (Btu/bu)			19,912 Btu/bu
Total Energy Consumption due to Production of Ag. Chemicals Used in Farming (Btu/mmBtu)			**112,846 Btu/mmBtu**
Total Adjusted Energy Consumption due to Production of Ag. Chemicals Used in Farming (Btu/mmBtu)			**21,456 Btu/mmBtu**

Note: Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate

Calculation to convert from Btu/bu to Btu/mmBtu:

$$\frac{(19{,}912\,Btu/bu)\times(5.28\,lbsSB/lbOil)\times(1.04\,lbsOil/lbBD)}{(16{,}149\,Btu/lbBD)\times(60\,lbsSB/bu)}\times 10^{6} = \textbf{112,846 Btu/mmBtu}$$

To calculate adjusted energy:
112,846 Btu/mmBtu x 20.0% x 95.1% x 1.000039 = **21,456 Btu/mmBtu**

1.4 GHG Emissions Calculation from Production and Application of Chemical Inputs in Soybean Farming

It is assumed that soybean farming utilizes five different farming products: nitrogen fertilizers (ammonia, urea and ammonium nitrate), phosphates, potash, herbicides and pesticides. Table 1.14 provides the emissions associated with farm product use in g/bu, g/mmBtu, and g/mmBtu after allocation and loss factors have been applied.

Table 1.14 GHG Emissions Associated with Fertilizer/Herbicide/Pesticide Use

Product	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG gCO_2e/MJ**
Emissions, g/bu:						
Nitrogen	0.371	0.360	0.128	0.099	146	
Phosphate (P_2O_5)	0.064	0.221	0.262	0.002	183	
Potash (K_2O)	0.039	0.208	0.278	0.002	215	
Herbicides	0.123	0.653	1.155	0.007	919	
Pesticides	0.002	0.009	0.013	0.000	10	
Total	0.599	1.451	1.836	0.111	1,474	
Converted to g/mmBtu:						
Nitrogen*	2.104	2.041	0.723	0.562	830	0.97
Phosphate (P_2O_5)	0.362	1.252	1.487	0.013	1,035	1.02
Potash (K_2O)	0.223	1.178	1.575	0.013	1,220	1.20
Herbicides	0.695	3.699	6.547	0.040	5,208	5.11
Pesticides	0.010	0.051	0.075	0.001	58	0.06
Total	**3.394**	**8.221**	**10.408**	**0.629**	**8,351**	**8.36**
With Allocation and Loss Factors Applied, g/mmBtu:						
Total	**0.645**	**1.56**	**1.979**	**0.12**	**1,588**	**1.59**

*Note: Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate

Calculation to convert from g/bu to g/mmBtu:

$$\frac{(1{,}474 g/bu)\times(5.28 lbsSB/lbOil)\times(1.04 lbsOil/lbBD)}{(16{,}149 Btu/lbBD)\times(60 lbsSB/bu)}\times 10^6 = \textbf{8,351 g/mmBtu}.$$

To calculate adjusted energy: $8{,}351 g/mmBtu \times 20\% \times 95.1\% \times 1.000039 =$ **1,588 g/mmBtu**

1.5 Soil N_2O Release Due to Fertilizer Use

CA-GREET also calculates direct field and downstream N_2O emissions resulting from nitrogen fertilizer input. Agricultural N_2O emissions result from conversion of fixed (natural and anthropogenic) nitrogen in the soil. Fixed nitrogen applied to field crops is either extracted by the crop as a nutrient, absorbed (chemically bound) into organic soil components, or entrapped in soil aggregates (chemically unbound). The majority of the chemically bound nitrogen remains stabilized in the organic form in the soil system, while the unbound nitrogen is converted to N_2O, volatilized as nitrate or ammonia, or leached out as nitrate. Field and downstream inputs are significant components of agricultural emissions associated with soybean cultivation. Table 1.15 shows the two main inputs: fertilizer input (g/bu) and percent conversion of N-input to N_2O. GREET assumes 1.3% of fertilizer-N is ultimately converted to N_2O. The calculation also uses the mass ratio of N_2O to N (44/(2*14).

Table 1.15 CA-GREET Inputs and Calculated Emissions for Soil N_2O Associated with Soybean Cultivation

Crop	Soybeans
Fertilizer N input, g/bu	61.2
N content of above/below ground biomass, g/bu	200.7
Percent N conversion to N in N_2O	1.3%
Mass ratio, N_2O formed/N_2O-N, g/g	1.57 (44/28)
N converted, g/bu	3.47
N_2O Emissions, g/bu	5.45
GHG emission, gCO_2e/bu	1,624
GHG emissions, gCO_2e/mmBtu	9,210
GHG emissions, gCO_2e/mmBtu, with allocation and loss factors	1,751
GHG emissions, gCO_2e/MJ	**1.66**

Note: Soil N_2O emissions = (61.2 g-N/bu + 200.7 g-N/bu) * (1.3%) * (44 g N_2O/(2x14) g N_2) = 5.45 g-N_2O/bushel

Calculation to convert from g/bu to g/mmBtu:

$$\frac{(1{,}624 g/bu)\times(5.28 lbsSB/lbOil)\times(1.04 lbsOil/lbBD)}{(16{,}149 Btu/lbBD)\times(60 lbsSB/bu)}\times 10^6 = \mathbf{9{,}210\ gCO_2e/mmBtu}.$$

To calculate adjusted energy:

$$9{,}210 g/mmBtu \times 20\% \times 95.1\% \times 1.000039 = \mathbf{1{,}751\ gCO_2e/mmBtu}$$

SECTION 2. SOYBEAN TRANSPORT

2.1 Energy Calculations for Soybean Transport

Soybeans are transported from the field to a soyoil extraction plant in the Midwest. The CA-GREET soybean transport modes are as follows: medium duty diesel trucks transport soybeans to a stack and heavy duty trucks transport the soybeans to a soyoil extraction facility in the Midwest. The soybean meal is used locally as animal feed and the soybean oil is transported by rail to California for biodiesel production. The transport assumptions and calculations are provided in Table 2.01. See the notes below the table for calculations. All values except the rail transport distance are CA-GREET defaults.

Table 2.01 Transport Parameters and Energy Use Details for Soybean Transport

	Units	**Field to Stack**	**Stack to Terminal**	**Total**
Mode		Medium Heavy Duty Truck	Heavy Duty Truck	
Distance	Miles	10	40	
Payload	Tons	8	15	
Fuel Economy	Mi/gal	7.3	5	
Fuel		Diesel	Diesel	
Lower Heating Value	Btu/gal	128,450	128,450	
Energy Intensity	Btu/ton-mile	2,199	1,713	
Direct Energy	Btu/ton	43,990	137,013	
Total Energy	Btu/ton	51,160	159,349	
Total Energy	Btu/bu	1,535	4,780	6,315
Total Energy	Btu/mmBtu	8,698	27,093	35,791
Total Adjusted Energy	Btu/mmBtu	1,654	5,151	
Total Soybean Transport Adjusted Energy, Btu/mmBtu				**6,805**

*Note:
Energy Intensity = LHV / fuel economy / payload
Direct truck energy doubles the miles to take into account round trip energy.
Total energy includes energy associated with crude recovery and diesel refining (see Table 1.3).

To convert from Btu/bu to Btu/mmBtu:

$$\frac{(1535+4780)(Btu/bu)\times(5.28 lbsOil)\times(1.04 lbsOil/lbDB)\times 10^6}{(60 lbsSB/bu)\times(16{,}149 Btu/lbBD)} = \textbf{35,791 Btu/mmBtu}.$$

To calculate adjusted energy:
(35,791 Btu/mmBtu) x (20.0% x 95.1% x 1.000039) = **6,805 Btu/mmBtu**

2.2 GHG Calculations for Soybean Transport

Soybeans are assumed to be transported as follows in CA-GREET:

- 10 miles by medium duty truck from farm to stack
- 40 miles by heavy duty truck from stack to soyoil extraction plant

It is assumed that only diesel is used as a fuel for the trucks used above. Transport emissions are calculated as shown below:

Emissions g/ton soybean = Emission factor (g/mmBtu) * Btu/ton-mile * miles / 10^6 Btu/mmBtu

The direct emissions are calculated for the trip to the destination and the return trip. The upstream emissions associated with recovering crude and producing diesel are also included. Table 2.02 provides the values used in the calculations. The assumed values for biodiesel density and LHV are 3,361 g/gal and 119,550 Btu/gal, respectively. The sample calculations after the table show the calculations for determining the direct, upstream and total adjusted CO_2 emissions. The WTT values shown in Table 2.03 shows upstream diesel values used to calculate the upstream emissions for diesel truck transport shown in Table 2.02.

Table 2.02 Transport Parameters and GHG Emissions from Soybean Transport

	Field to Stack	**Stack to Soyoil Extraction Facility**	**Total Transport**	**Total Transport (g/bu)**
Mode	Medium Duty Truck	Heavy Duty Truck		
Distance, miles	10	40		
Fuel	Diesel	Diesel		
Energy Intensity, Btu/ton-mile	2,199	1,712		
Emission Factors[1], g/mmBtu Fuel Burned (return trip in parentheses when different)				
VOC	32.110 (39.441)	33.671 (26.392)		
CO	116.107 (115.084)	178.708 (127.443)		
CH_4	1.534 (1.933)	1.524		
N_2O	2.898	2.105		
CO_2	77,912 (77,890)[2]	77,809 (77,912)[2]		
Direct Emissions	**(g/ton)**	**(g/ton)**	**(g/ton)**	**(g/bu)**
VOC	1.574	4.115	5.688	0.17
CO	5.085	20.973	26.058	0.78
CH_4	0.076	0.209	0.285	0.01
N_2O	0.128	0.288	0.416	0.01
CO_2	**3,427**	10,668	14,095	422.85
Upstream Emissions	**(g/ton)**	**(g/ton)**	**(g/ton)**	**(g/bu)**
VOC	0.363	1.130	1.493	0.14
CO	0.774	2.412	3.186	0.15
CH_4	4.315	13.439	17.754	13.32
N_2O	0.006	0.020	0.027	0.24
CO_2	**583**	1,816	2,400	72.0
Total Adjusted Emissions (with Allocation & Loss Factors)				
VOC (**gCO_2e/mmBtu**)				0.73
CO (**gCO_2e/mmBtu**)				1.5
CH_4 (**gCO_2e/mmBtu**)				14.54
N_2O (**gCO_2e/mmBtu**)				4.26
CO_2 (**gCO_2e/mmBtu**)				533
Total GHG Emissions (gCO_2e/mmBtu)				554
Total GHG Emissions (gCO2e/MJ)				**0.53**

Note: [1] Emission factors (EFs) correspond to trip from feedstock origin to destination and the return trip listed in the emission factors (*EF* tab) of CA-GREET. Energy Intensity = LHV/fuel economy/payload

[2] Direct truck energy doubles the miles to take into account round trip energy.

Sample calculation of CO_2 to convert from g/bu to g/mmBtu:

$$\frac{(422.85+72)(g/bu)\times(5.28 lbsSB/lbOil)\times(1.04 lbsOil/lbBD)}{(16{,}149 Btu/lbBD)\times(60 lbsSB/bu)}\times10^6 = \textbf{2,804 gCO}_\textbf{2}\textbf{e/mmBtu}$$

To calculate CO_2 adjusted energy:

$$2{,}804 g/mmBtu\times20\%\times95.1\%\times1.000039 = \textbf{533 gCO}_\textbf{2}\textbf{e/mmBtu}$$

Table 2.03 Upstream Energy Consumption and Emissions from Diesel Production

GHG	**g /mmBtu**
VOC	8.247
CO	17.603
CH_4	98.088
N_2O	0.147
CO_2	13,257

Sample calculations are shown below for CO_2 emissions calculation for a medium heavy duty truck:

Direct CO_2 emissions = [(Diesel origin-to-destination CO_2 EF, g/mmBtu)*(Energy intensity origin-to-destination, Btu/ton-mile) + (Diesel destination-to-origin CO_2 EF, g/mmBtu)*(Energy intensity destination-to-origin)]*(Distance, miles)

Direct CO_2 emissions:

$$\frac{[(77{,}912+77{,}890) gCO_2/mmBtu]\times(2{,}199 Btu/ton-mile)\times10 miles}{10^6} = \textbf{3,427}\ gCO_2/ton$$

Upstream CO_2 emission calculation for a medium duty diesel truck:

Upstream CO_2 emissions = [(Diesel WTT emissions, g/mmBtu)*(Energy intensity origin-to-destination, Btu/ton-mile) + (Diesel WTT emissions, g/mmBtu)*(Energy intensity destination-to-origin)]*(Distance, miles)

$$\frac{(13{,}257 gCO_2/mmBtu)\times(2{,}199 Btu/ton-mile)\times2 ways\times10 miles}{10^6} = \textbf{583}\ gCO_2/ton$$

Total adjusted CO_2 emission calculation in g/mmBtu for a medium duty diesel truck:

(3,427 g CO_2/ton) + (583 g CO_2/ton) = 4,010 g CO_2/ton

(4,010 g CO_2/ton) x (1 ton/2,000 lbs) x 5.28 lbs soybeans/lb oil x 1.04 lbs oil/lb BD/16,149 Btu/lb BD x 10^6 Btu/mmBtu = **682** g/mmBtu

(682 g/mmBtu) x (20.0% oil energy share) x (95.1% biodiesel energy share) x (1.000039) = **130** gCO_2/mmBtu

SECTION 3. SOYOIL EXTRACTION

3.1 Energy Calculations for Soyoil Extraction

Once the soybeans have arrived at a soyoil extraction facility, the oil needs to be extracted from the beans. The U.S. average electricity mix is assumed for soyoil extraction. Since CA-GREET calculates results for feedstock and fuel separately, the CA-GREET model is used to calculate soybean production results (using U.S. average electricity mix) and biodiesel production results (using CA marginal electricity mix) separately. The default Argonne GREET soy oil extraction energy input double counts the natural gas energy required for extraction. To address this inconsistency, a value of 2,800 Btu/lb oil is assumed for NG energy, based on the original GREET NG input (Sheehan, et al. 1998[10]). The analysis uses GREET defaults for electricity (551 Btu/lb oil) and hexane (182 Btu/lb oil). Table 3.01 provides the direct energy consumption values based on GREET default total energy consumption and split by fuel type.

Table 3.01 Direct Energy Consumption for Soyoil Extraction from Soybeans

Process Fuel Type	Fuel Shares	Relationship of Extraction Energy and Fuel Shares	Direct Energy Consumption, Btu/lb soyoil
Natural gas	79.2%	0.792 x 3,533	2,800
Electricity	15.6%	0.156 x 3,533	551
N-Hexane	5.1%	0.051 x 3,533	182
Direct Energy Consumption for Soyoil Extraction			**3,533**

The values provided in Table 3.01 are direct energy consumption per lb of soyoil extracted. This is not the total energy required, however, since CA-GREET accounts for the “upstream” energy associated with each of the fuels utilized to extract the soyoil. Table 3.02 demonstrates how the direct energy consumption values shown in Table 3.01 are utilized to calculate total energy required to extract soyoil.

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[10] Sheehan, J., V. Camobreco, et al. (1998). "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus." Prepared for U.S. Department of Energy, Office of Fuels Development – Table 78, p.134

Table 3.02 Total Energy Use from Direct Energy Use for Soyoil Extraction

Fuel Type	Formula	Description	Btu/lb soyoil
Natural Gas	$2{,}800 + 2{,}800*(69{,}596)/10^6$	2,800 Btu/lb soyoil of direct NG fuel use (Table 3.01)	2,995
		69,596 is the energy required to recover, process and transport 1 mmBtu of NG for stationary use	
Electricity	$551*(85{,}708 + 2{,}561{,}534)/10^6$	551 Btu/lb soyoil direct electricity use (Table 3.01)	1,460
		85,708 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.	
		2,561,534 Btu fuel used to produce 1 mmBtu electricity.	
N-Hexane	$182 + 182 * (39{,}212*1.0001 + 75{,}862)/10^6$	182 Btu/lb soyoil direct N-Hexane use. GREET uses LPG values for N-Hexane (Table 3.01)	203
		The energy to recover crude is 39,212 Btu/mmBtu crude.	
		1.0001 is the loss factor for LPG.	
		To refine & transport LPG 75,862 Btu/mmBtu LPG are used (Table 1.3)	
Total Energy Consumption for Soyoil Extraction (Btu/lb oil)			**4,658**
Total Energy Consumption for Soyoil Extraction (Btu/mmBtu)			**299,958**
Total Adjusted Energy Consumption for Soyoil Extraction (Btu/mmBtu)			**57,054**

The soyoil extraction energy is converted from the per lb soyoil basis to a per mmBtu biodiesel basis as follows:

Soyoil Extraction Energy:

$$\frac{(4{,}658\,Btu/lbOil)\times(1.04\,lbOil/lbBD)\times(10^6\,Btu/mmBtu)}{16{,}149\,Btu/lbBD} = \mathbf{299{,}958\ Btu/mmBtu}$$

299,958 Btu/mmBtu x 20.0% x 95.1% x 1.000039 = **57,054 Btu/mmBtu**

3.2 GHG Calculations for Soyoil Extraction

The emissions associated with soyoil extraction are two-fold: the direct combustion emissions and the upstream emissions due to recovery, processing and transport of the process fuels utilized. In soyoil extraction, it is assumed that natural gas, electricity and N-hexane (a petroleum based solvent) are the process fuels. Table 3.03 provides the direct emissions associated with soyoil extraction. These direct emissions are determined by multiplying the direct energy use (provided in Table 3.01) by the appropriate combustion emission factors for the fuel type and combustion equipment used. Note that electricity has no direct emissions. It is assumed that the natural gas is split equally between a large industrial boiler and a small industrial boiler (CA-GREET default). A sample calculation showing how the natural gas CO_2 direct emissions was calculated is shown below Table 3.03.

Table 3.03 Direct Emissions from Soyoil Extraction

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas (g/lb Soyoil)	0.006	0.063	0.003	0.001	163
N-Hexane (g/lb Soyoil)	4.813				
Total GHG Emissions (g/lb Soyoil)	**4.819**	**0.063**	**0.003**	**0.001**	**163**

Natural gas direct CO_2 emissions:

$$\frac{(2{,}800\,BtuNG/lbOil)\times[(50\%\times 58{,}198\,gCO_2/mmBtu)+(50\%\times 58{,}176\,gCO_2/mmBtu)]}{10^6}=$$

163 g/lb oil

In addition to direct emissions from fuel combustion, the emissions associated with recovery, processing and transport of the fuels used to extract the soyoil must be quantified. Table 3.04 shows how the upstream CO_2 emissions are quantified from the direct fuel consumption. Table 3.05 provides the upstream emissions for all GHGs.

Table 3.04 Upstream CO_2 Emissions from Direct Energy Use for Soyoil Extraction

Fuel Type	**Formula**	**Description**	**gCO_2/lb soyoil**
Natural Gas	$2{,}800*(5{,}208)/10^6$	2,800 Btu/lb soyoil of direct NG fuel use (Table 3.01)	15
		5,208 grams of CO_2 are emitted in recovery, processing and transporting 1 mmBtu of natural gas for stationary use.	
Electricity	$551*(6{,}833 + 213{,}458)/10^6$	551 Btu/lb soyoil direct electricity use (Table 3.01)	121
		To recover, process, and transport fuel to the power plants, 6,833 g of CO_2/mmBtu are emitted.	
		Production of electricity releases 213,458 g CO_2 /mmBtu of electricity produced.	
N-Hexane	$182*(3{,}868*1.000116 + 5{,}715)/10^6$	182 Btu/lb soyoil direct N-Hexane use (Table 3.01)	2
		The CO_2 emitted from crude recovery is 3,868 g/mmBtu.	
		1.000116 is the loss factor for LPG	
		5,715 g/mmBtu CO_2 is from LPG refining & transport	
Total Upstream CO_2 Emissions for Soyoil Extraction			**138**

Table 3.05 Upstream Emissions from Soyoil Extraction

Product	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
Natural Gas (g/lb Soyoil)	0.018	0.032	0.361	0.000	15
Electricity (g/lb Soyoil)	0.011	0.107	0.152	0.001	121
N-Hexane (g/lb Soyoil)	0.002	0.003	0.017	0.000	2
Total GHG Emissions (g/lb Soyoil)	**0.030**	**0.142**	**0.530**	**0.001**	**138**

Finally, the direct and upstream emissions are summed and converted from g/lb soyoil basis to g/mmBtu biodiesel basis. The allocation and loss factors are then applied. Table 3.06 provides the total emissions associated with soyoil extraction.

Table 3.06 Total GHG Emissions from Soyoil Extraction

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG Emissions**
Total Emissions (Direct + Upstream), g/lb soyoil						
Natural Gas	0.023	0.096	0.364	0.001	178	
Electricity	0.011	0.107	0.152	0.001	121	
N-Hexane	4.815	0.003	0.017	0.000	2	
Total	4.849	0.206	0.533	0.002	**301**	
Total Emissions (Direct + Upstream), converted to g/mmBtu						
Natural Gas	1.481	6.183	23.442	0.064	11,463	
Electricity	0.708	6.891	9.789	0.064	7,793	
N-Hexane	310.094	0.193	1.095	-	129	
Total	312.283	13.267	34.326	0.129	**19,385**	
Total Adjusted Emissions (with Allocation and Loss Factors), g/mmBtu						
Natural Gas	0.282	1.176	4.457	0.012	2,180	
Electricity	0.135	1.310	1.861	0.012	1,482	
N-Hexane	58.962	0.037	0.208	-	24	
Total Adjusted Emissions in gCO_2e/mmBtu						**gCO_2e/MJ**
Natural Gas	0.89	1.87	111.47	3.65	2180.4	2.18
Electricity	0.42	2.09	46.55	3.65	1482.2	1.45
N-Hexane	185.68	0.06	5.21	0.00	24.50	0.20
Total	**186.99**	**4.02**	**163.2**	**7.30**	**3,687**	**3.83**

Sample calculation of CO_2 to convert from g/lb soyoil to g/mmBtu biodiesel:

$$\frac{(301 g / lbSoyOil) \times (1.04 lbsSoyOil / lbBD)}{(16{,}149 Btu / lbBD)} \times 10^6 = \mathbf{19{,}385\ g/mmBtu}$$

To calculate CO_2 with adjusted energy:

$$19{,}385 g / mmBtu \times 20\% \times 95.1\% \times 1.000039 = \mathbf{3{,}687\ gCO_2e/mmBtu}$$

SECTION 4. SOYOIL TRANSPORT

4.1 Energy Calculations for Soyoil Transport

As discussed in the previous section, soyoil is produced at a crushing facility in the Midwest and then transported via rail to California for biodiesel production. The rail transport distance (1,400 miles) reflects transport of soyoil to California. For the CA-GREET BD pathway, appropriate modifications have been made to incorporate soybean oil transport to California. Note that the analysis here assumes that soybean oil and biodiesel have the same heating value, which is a reasonable assumption; the error introduced by the difference is small.

The transport parameters and energy use are shown below in Table 4.01. The energy intensity for rail shown in the table is a CA-GREET default value and the following two values, 518,000 Btu/ton, and 16,038 are based on multiplying factors in the table together; the total energy is based on the direct energy and the upstream diesel factor (see Table 4.01).

The energy allocation factor used for soy oil transport is the same energy factor (95.1%) for soy oil calculated in Section 1.1.

Table 4.01 Parameters and Energy Use for Soyoil Transport

	Units	**Crushing facility to BD Plant**
Mode		Rail
Distance	Miles	1,400
Fuel		Diesel
Lower Heating Value	Btu/gal	119,550
Density	g/gal	3,361
Energy Intensity	Btu/ton-mile	370
*Direct Energy	Btu/ton	518,000
*Direct Energy	Btu/mmBtu	**16,038**
***Total Energy**	**Btu/mmBtu**	**18,653**
Total Allocated and Adjusted Energy	**Btu/mmBtu**	**17,734**

*Note: Rail miles not doubled.
Total energy includes energy associated with crude recovery and diesel refining (see Table 1.3).

Direct Energy (Btu/ton) = (370 Btu/ton-mile) x (1,400 miles) = 518,000 Btu/ton
Direct Energy (Btu/mmBtu) = (518,000 Btu/ton) x (1 ton/2,000 lbs) x (1 lb/454 g) x (3,361 g/gal)/(119,550 Btu/gal) x10^6 = **16,038 Btu/mmBtu**

Total Energy (Btu/mmBtu, not adjusted) = (16,038 Btu/mmBtu) x (1 + 0.163 Btu/Btu diesel upstream) = **18,653 Btu/mmBtu**
Total Energy (Btu/mmBtu, adjusted) = (18,653 Btu/mmBtu x 95.1% x 1.000039) = **17,734 Btu/mmBtu**
where 0.163 Btu/Btu diesel is the upstream energy associated with producing 1 Btu of diesel.

4.2 GHG Calculations for Soyoil Transport

As discussed in the previous section, soyoil is transported 1,400 miles from the Midwest to California. Table 4.02 shows the diesel rail emission factors, direct emissions, upstream emissions and total emissions with allocation and loss factors applied. The direct emissions and upstream emissions are calculated exactly as shown for soybean transport in Section 2.2.

Table 4.02 Soybean Oil Transport Parameters and Calculations

Transport Details	**Soybean Crushing Facility to BD Plant**
Mode	Rail
Distance, miles	1,400
Fuel	Diesel
Energy Intensity, Btu/ton-mile	370
Emission Factors, g/mmBtu Fuel Burned	
VOC	59.700
CO	215.000
CH_4	3.940
N_2O	2.000
CO_2	77,664
Direct Emissions, g/mmBtu Fuel Transported	
VOC	0.957
CO	3.448
CH_4	0.063
N_2O	0.032
CO_2	1,246
Upstream Emissions, g/mmBtu Fuel Transported	
VOC	0.132
CO	0.282
CH_4	1.573
N_2O	0.002
CO_2	213
Total Emissions, including allocation and loss factors g/mmBtu Fuel Transported	
VOC	1.036
CO	3.547
CH_4	1.556
N_2O	0.033
CO_2	1,386
Total GHG Emissions (gCO_2e/MJ)	**1.37**

Sample calculations of CO_2 emissions from locomotive
Direct CO_2 emission from diesel locomotive:

$$\frac{(3{,}361 gBD/gal)\times(77{,}664) gCO_2/mmBtu\times(370 Btu/ton-mile)\times 1{,}400 miles}{(119{,}550 Btu/galBD\times 454 g/lb\times 2000 lbs/ton)} =$$

1,246gCO_2/mmBtu

Upstream CO_2 emission from diesel locomotive:

$$\frac{(3{,}361 gRD/gal)\times(13{,}257 gCO_2/mmBtu)\times(370 Btu/ton-mile)\times 1400 miles}{(119{,}550 Btu/gal\times 454 g/lb\times 2000 lbs/ton)} =$$

213 gCO_2/mmBtu

Total CO_2 emissions adjusted to energy:
(1,246+213) gCO_2/mmBtu x 95.1% x 1.000039 = **1,386 gCO_2/mmBtu**

Note: Final values shown above were calculated on Microsoft Excel, where contributing factors were not rounding resulting final values are different than the actual calculating operations (Similar calculations for VOC, CO, CH_4, and N_2O.)

SECTION 5. BIODIESEL PRODUCTION

5.1 Energy Calculations for Biodiesel Production

After the soyoil is extracted and transported, biodiesel fuel is produced via the transesterification process. The first step in calculating the total adjusted energy consumption is determining the direct energy use. The direct energy consumption is 2,116 Btu/lb of biodiesel, a CA-GREET default. The process fuel inputs are presented in Table 5.01

Table 5.01 Direct Energy Consumption for Soyoil Transesterification

Process Fuel Type	Fuel Shares	Relationship of Biodiesel Production and Fuel Shares	Direct Energy Consumption, Btu/lb biodiesel
Natural gas	42.0%	0.420 x 2,116	889
Electricity	2.2%	0.022 x 2,116	47
Methanol	40.9%	0.049 x 2,116	865
Sodium hydroxide	2.0%	0.020 x 2,116	42
Sodium methoxide	9.9%	0.099 x 2,116	209
Hydrochloric acid	3.0%	0.030 x 2,116	63
Direct Energy Consumption for Soybean Oil Transesterification			**2,116**

The values provided in Table 5.01 are direct energy consumption per lb of biodiesel produced. This is not the total energy required however, since GREET accounts for the "upstream" energy associated with each of the fuels utilized to produce the biodiesel. Table 5.02 demonstrates how the direct energy consumption values shown in Table 5.01 are utilized to calculate total energy required for soyoil transesterification.

Table 5.02 Total Energy Use from Direct Energy Use for Biodiesel Production

Fuel Type	**Formula**	**Description**	**Btu/lb Biodiesel**
Natural gas	889 + 889 * (68,865)/10^6	889 Btu/lb biodiesel of direct NG fuel use (Table 5.1).	950
		68,865 is the energy required to recover, process and transport a mmBtu of NG for stationary use	
Electricity	47* (111,573 + 1,884,989)/ 10^6	47 Btu/lb biodiesel direct electricity use (Table 5.1)	93
		111,573 Btu of energy used to recover and transport feedstock to generate 1 mmBtu electricity.	
		1,884,989 Btu fuel used to produce 1 mmBtu electricity.	
Methanol	865 + 865 * (31,792 * 1.0002 + 532,954)/ 10^6	865 Btu/lb biodiesel direct methanol use (Table 5.1)	1,354
		NG recovery, processing and delivery is 31,792 Btu/mmBtu methanol (GREET calculation).	
		1.0002 methanol loss factor	
		Methanol production is 532,954 Btu/mmBtu methanol produced (GREET calculation).	
Sodium Hydroxide		(GREET default)	42
Sodium Methoxide		(GREET default)	209
Hydrochloric Acid		(GREET default)	63
Total Energy Consumption for Biodiesel Production (Btu/lb)			2,712
Total Energy Consumption for Biodiesel Production (Btu/mmBtu)			**167,961**
Total Adjusted Energy Consumption for Biodiesel Production (Btu/mmBtu)			**159,684**

To convert from Btu/lb biodiesel to Btu/mmBtu biodiesel use:

Total Energy: 2,712 Btu/lb biodiesel / 16,149 Btu/lb BD * 10^6 = **167,961 Btu/mmBtu**

Total Adjusted Energy: 167,961 Btu/mmBtu x 95.1% x 1.000039 =
159,684 Btu/mmBtu

5.2 GHG Calculations from Biodiesel Production

Once the soyoil has been transported to a biodiesel facility, biodiesel is produced through transesterification. Once again, there are direct emissions resulting from direct fuel consumption and upstream emissions from recovery, processing and transport of these fuels. The fuels consumed in this stage are natural gas, electricity and methanol. As in the soyoil extraction stage, the natural gas is assumed to be split evenly between large and small industrial boilers. The natural gas emission factors are the same as those used for soyoil extraction. The electricity mix is assumed to be California marginal mix.

Direct emissions are calculated by multiplying direct fuel consumption (please refer to Table 3.06 section 3.2 above) by the appropriate emissions factors. Direct emissions for biodiesel production are provided in Table 5.03 (no allocation factors applied). Only natural gas has direct emissions.

Table 5.03 Direct Emissions from Biodiesel Production

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas (g/lb Biodiesel)	0.002	0.020	0.001	0.000	52
Total Direct Emissions (g/lb Biodiesel)	**0.002**	**0.020**	**0.001**	**0.000**	**52**

Note: Only NG has direct emissions for CA-GREET calculations

The upstream emissions are calculated from the direct energy consumption as illustrated in Table 5.04 for CO_2. The upstream emissions for each of the pollutants are summarized in Table 5.05. Please refer to Table 5.02 for direct fuel consumption values.

Table 5.04 Upstream CO_2 Emissions from Direct Energy Use for Biodiesel Production

Fuel Type	Formula	Description	gCO_2/lb biodiesel
Natural Gas	889 * (5,050)/10^6	889 Btu/lb biodiesel of direct NG fuel use (Table 5.2)	4
		5,050 g of CO_2 are emitted in recovery, processing and transporting 1 mmBtu of natural gas for stationary use	
Electricity	47* (8,277 + 96,250)/ 10^6	47 Btu/lb biodiesel direct electricity use (Table 5.2)	5
		To recover, process and transport fuel to the power plants, 8,277 g of CO_2 are emitted per mmBtu of electricity produced	
		Electricity production releases 96,250 g CO_2/mmBtu of electricity	
Methanol	865 * (3,229*1.0002 + 18,530)/ 10^6	865 Btu/lb soyoil direct methanol use (Table 5.2)	19
		NG recovery, processing and transport results in 3,229 g CO_2/mmBtu methanol	
		1.00002 is the loss factor for methanol production	
		Methanol production results in 18,530 g CO_2/mmBtu methanol	
Total Upstream CO_2 Emissions for Biodiesel Production			**28**

Note: As in previous tables, the upstream values shown in the third column of the table are summary WTT values from fuel sheets in CA-GREET.

Table 5.05 Upstream Emissions from Biodiesel Production

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas (g/lb Biodiesel)	0.006	0.010	0.114	0.000	4
Electricity (g/lb Biodiesel)	0.001	0.003	0.010	0.000	5
Methanol (g/lb Biodiesel)	0.022	0.029	0.166	0.000	19
Total Emissions (g/lb Biodiesel)	**0.029**	**0.042**	**0.291**	**0.000**	**28**

Finally, the direct and upstream emissions are summed and converted from g/lb biodiesel basis to g/mmBtu biodiesel basis. The allocation and loss factors are also applied. Table 5.06 provides the total emissions associated with biodiesel production.

Table 5.06 Total GHG Emissions from Biodiesel Production

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG Emissions**
Total Emissions (Direct + Upstream), g/lb biodiesel						
Natural Gas	0.007	0.030	0.115	0.000	56	
Electricity	0.001	0.003	0.010	0.000	5	
Methanol	0.022	0.029	0.166	0.000	19	
Total	0.030	0.062	0.292	0.001	80	
Total Emissions (Direct + Upstream), converted to g/mmBtu biodiesel						
Natural Gas	0.433	1.858	7.121	-	3,468	
Electricity	0.062	0.186	0.619	-	310	
Methanol	1.362	1.796	10.279	-	1,177	
Total	1.858	3.839	18.082	0.062	4,954	
Total Adjusted Emissions (with Allocation & Loss Factors), g/mmBtu						
Natural Gas	0.412	1.766	6.770	-	3,297	
Electricity	0.059	0.177	0.589	-	294	
Methanol	1.295	1.707	9.773	-	1,119	
Total GHG Emissions	1.77	3.65	17.19	0.06	4,710	
Total GHG Emissions (gCO_2e/MJ)						**4.89**

Note: To obtain total adjusted energy, multiply by 95.1% and 1.000039 as shown in Table 5.05.

SECTION 6. BIODIESEL TRANSPORT AND DISTRIBUTION

6.1 Energy Calculations for Biodiesel Transport to Retail Stations

The next step in the biodiesel pathway is transport from the production plant to the retail station. Table 6.01 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 trucking distance input in CA-GREET includes hauling biodiesel to a petroleum terminal for blending followed by distribution to a fueling station as a blended fuel. 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 soybean transport and soyoil transport. Btu/ton-mile is converted to Btu/ton, which is converted to Btu/mmBtu fuel for both legs of the trip. Next, the upstream Btu/mmBtu for each mode of transport is calculated the same way as shown in Section 2.2, using the Btu/ton-mile values shown in Table 6.01. Finally, the energy for each mode is multiplied by the mode share shown in Table 6.01 to yield the total energy. No allocation factor adjustment is made for biodiesel transport.

Table 6.01 Transport Parameters and Energy Use for Biodiesel Transport and Distribution

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 [2] (Btu/mmBtu)		**3,094**	**6,961**	**10,055**

[1] Return trip energy intensity in parenthesis, if different from trip from origin to destination.

[2] Apply 80% of the mode shares for BD transport and 100% for BD distribution

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.

6.2 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 6.02 shows the direct emissions, upstream emissions (without accounting for mode share) and total emissions, accounting for mode share.

Table 6.02 GHG Emissions from Biodiesel Transport and Distribution

	Plant to Bulk Terminal	**Fuel Distribution**	**Total Transport**
Mode	HDD Truck	HDD Truck	
Mode Share	80%	100%	
Distance, miles	50	90	
Fuel	Diesel	Diesel	
Direct CO_2 Emission (gCO_2/mmBtu)	77,809 (77,912)[2]	77,809 (77,912)[2]	
Upstream CO_2 Emission (gCO_2/mmBtu)	15,186[3]	15,186	
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_2O	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_2O	0.001	0.001	
CO_2	48	**87**	
Total Emissions[1], (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_2O	0.006	0.013	0.019
CO_2	237	533	770
GHG Emissions (g/mmBtu)	247	556	802
GHG Emissions (gCO_2e/MJ)	**0.23**	**0.53**	**0.76**

[1] Includes the mode share.

[2] Return Trip from destination to origin emissions in parenthesis (GREET calculation, cells AD41 and AD54 of the *EF* tab of the CA-GREET model))
[3] Upstream Energy of diesel from GREET calculation (cell B184, *T&D* tab of the CA-GREET model)

The emissions shown in Table 6.02 are determined the same way as the soy oil transport is calculated (Table 4.02).

Sample calculation of CO_2 emissions for heavy duty truck distribution (residual oil):
Direct Emissions =

$$\frac{(3{,}361 g/gal) \times (77{,}809 + 77{,}912)(gCO2/mmBtu) \times 1{,}028(Btu/ton-mile) \times 90 miles}{(119{,}550 Btu/gal) \times (454 g/lb) \times (2000 lb/ton)} =$$

446 g CO_2/mmBtu

Upstream emissions =

$$\frac{(3{,}361 g/gal) \times (15{,}186 + 15{,}186)(gCO2/mmBtu) \times 1{,}028(Btu/ton-mile) \times 90 miles}{(119{,}550 Btu/gal) \times (454 g/lb) \times (2000 lb/ton)} =$$

87 g CO_2/mmBtu

Total Emissions = 446 g/mmBtu + 87 g/mmBtu = **533 gCO_2/mmBtu**
(Similar calculations for VOC, CO, CH_4 and N_2O to get results in table 6.02)

SECTION 7. GHG EMISSIONS FROM A BIODIESEL-FUELED VEHICLE

7.1 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 7.01 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 carbon in fuel calculations. The biodiesel production energy and methanol energy share for production shown in Table 7.01 are CA-GREET default values and the remaining values in the table are fuel properties. The equation is shown at the bottom of Table 7.01.

The total BD processing energy of 2,116 Btu/mmBtu is based on the AB1007 analysis. 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 (540 Btu/mmBtu = 2,116 x 40.9% /16,149 Btu/lb) and the carbon content of methanol (5.4% x 70 = 3.67 g/MJ). 16,149 Btu/lb is the LHV of BD on a per pound basis.

Table 7.01 GHG Emissions from Fossil Carbon in Biodiesel

Description	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)	**3.67**

Detailed Calculation of Fossil carbon in biodiesel:

Energy share of Methanol production:

$$\frac{(2{,}116 Btu/lbBD)\times(40.9\%)\times(3{,}361 g/gal)}{(454 g/lb)\times(119{,}550 Btu/gal)}$$ = 5.4% energy

CO_2 in Methanol Production:

$$\frac{(3{,}006 gMeOH/gal)\times(37.5\%)\times(44 gCO_2)}{(57{,}250 Btu/gal)\times(12 gC)\times(1{,}055 MJ/mmBtu)}\times 10^6 =$$ 68.4 gCO_2/MJ methanol

Fossil Carbon: 5.4% x (68.4 gCO_2/MJ) = **3.67 gCO_2/MJ**

Vehicle CH_4 and N_2O emissions

The CH_4 and N_2O emissions are assumed to be the same as ULSD. ULSD emission factors for heavy duty trucks was provided in the ULSD document and are shown in Table 7.02. The vehicle energy use, N_2O and CH_4 emission rates and final emissions are shown in Table 7.02

Table 7.02 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**

APPENDIX B

MIDWEST SOYBEAN FOR BIODIESEL

Scenario: Soybean from Midwest transported to California for Biodiesel Production Pathway - Input Values

Parameters	Units	Values	Note
GHG Equivalent			
CO$_2$		1	
CH$_4$		25	
N$_2$O		298	
VOC		3.04	
CO		1.6	
Soybean Farming			
Direct Farming Efficiency		97.2%	
Fuel Use Shares			
Diesel		64.4%	
Gasoline		17.8%	
Natural Gas		7.3%	
LPG		7.6%	
Electricity		2.9%	
Cultivation Equipment Shares			
Diesel Farming Tractor		80%	
CO$_2$ Emission Factor	g/mmBtu	77,411	
Diesel Engine		20%	
CO$_2$ Emission Factor	g/mmBtu	77,401	
Gasoline Farming Tractor		100%	
CO$_2$ Emission Factor	g/mmBtu	75,645	
Natural Gas Reciprocating Engine		100%	
CO$_2$ Emission Factor	g/mmBru	56,551	
LPG Commercial Boiler		100%	
CO$_2$ Emission Factor	g/mmBtu	68,036	
Soybean Farming			
Soybean direct energy use	Btu/bu	22,087	
Soybean yield	lbs/bu	60	
Soybean T&D			
Transported from Soybean Field to Stack			
by medium truck	miles	10	2,199 Btu/mile-ton Energy Intensity
fuel consumption	mi/gal	7.3	capacity 8 tons/trip
CO$_2$ emission factor origin-destination	g/mmBtu	77,912	
CO$_2$ emission factor destination-origin	g/mmBtu	77,890	
Transported from Stack to BD Plant			
by heavy duty diesel truck	miles	40	1,713 Btu/mile-ton Energy Intensity
fuel consumption	mi/gal	5	capacity 15 tons/trip
CO$_2$ emission factor origin-destination	g/mmBtu	77,913	
CO$_2$ emission factor destination-origin	g/mmBtu	77,809	
Transported from Terminal to Biodiesel Plant			
by rail	miles	1,400	370 Btu/mile-ton Energy Intensity
CO$_2$ emission factor	g/mmBtu	77,664	
Chemicals Inputs			
Nitrogen	g/bu	61.2	
NH3			
Production Efficiency		82.4%	
Shares in Nitrogen Production		70.7%	
CO$_2$ Emission Factor	g/g	2.475	
Transported from plant to bulk center			

by ocean tanker	miles	3,000	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
Parameters	**Units**	**Values**	**Note**
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton by truck
Urea			
Production Efficiency		46.7%	
Shares in Nitrogen Production		21.1%	
Transported from plant to bulk center			
by ocean tanker	miles	5,200	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
Ammonium Nitrate			
Production Efficiency		35%	
Shares in Nitrogen Production		8.2%	
Transported from plant to bulk center			
by ocean tanker	miles	3,700	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
P_2O_5	g/bu	186.1	
H_3PO_4			
Feedstock input	tons	n/a	
Transported from plant to bulk center			
by ocean tanker	miles	4,400	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
H_2SO_4			
Feedstock input	tons	2.674	
Transported from plant to bulk center			
by ocean tanker	miles	1,500	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton

Parameters	Units	Values	Note
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
P Rock			
Feedstock input	tons	3.525	
Transported from plant to bulk center			
by ocean tanker	miles	4,400	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
K_2O	g/bu	571.5	
Transported from plant to bulk center			
by ocean tanker	miles	3,900	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
Herbicide	g/bu	43.02	
Transported from plant to bulk center			
by ocean tanker	miles	4,000	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
Pesticide	g/bu	0.43	
Transported from plant to bulk center			
by ocean tanker	miles	4,000	48 Btu/mile-ton to destination and 43 Btu/mile-ton reverse
by rail	miles	750	370 Btu/mile-ton
by barge	miles	400	403 Btu/mile-ton
Transported from bulk center to mixer			
by heavy duty diesel truck	miles	50	1,142 Btu/mile-ton to and from destination back
Transported from mixer to farm			
by heavy duty diesel truck	miles	30	2,199 Btu/mile-ton to and from destination back
Co-Product Credit			
Soy Oil Yield	lb/bu	11.36	
	lb/lb SB	0.189	or 5.28 lbs soy bean / lbs soy oil
	lb/lb BD	1.04	

Biodiesel Production			
Soyoil Extraction			
Soyoil Extraction Efficiency		97.2%	
Soyoil Extraction Energy Share		20%	
Energy use	Btu/lb	5,867	
NG used		87.5%	
Large NG Boiler	g/mmBtu	*58,198*	50% usage
Small NG Boiler	g/mmBtu	*58,176*	50% usage
Electricity used		9.4%	
N-Hexane used		3.1%	
Soil Oil Transport			
Mileage travel by rail	miles	1,400	
Energy Intensity	Btu/ton-mile	370	
Soyoil Transesterification			
Soyoil Transesterification Allocation		95.1%	
Energy use	Btu/lb	2,116	
NG used		42%	
Large NG Boiler	g/mmBtu	*58,198*	50% usage
Small NG Boiler	g/mmBtu	*58,176*	50% usage
Electricity used		2.2%	
Methanol used		40.9%	
Sodium Hydroxide used		2%	
Sodium Methoxide		9.9%	
Hydrochloric Acid		3%	
Transportation and Distribution			
Transported by HHD truck	miles	90	1,028 Btu/mile-ton Energy Intensity both ways
Fuels Properties	**LHV (Btu/gal)**	**Density (g/gal)**	
Crude	129,670	3,205	
RO	140,353	3,752	
Conventional Diesel	128,450	3,167	
Conventional Gasoline	116,090	2,819	
CaRFG	111,289	2,828	
CARBOB	113,300	2,767	
Natural Gas	83,868	2,651	
EtOH	76,330	2,988	Anhydrous ethanol (neat)
EtOH	77,254	2,983	Denatured ethanol
Still Gas	128,590		
Glycerin	7979 Btu/lb		
Soybean Transportation Cargo Capacity			
Medium Duty Truck	tons	8	
Heavy Duty Truck	tons	15	
Biodiesel Yield			
From Soybean	gal/bu	1.47	
From Soyoil	gal/lb	0.14	
From Glycerin	lb/lb Glycerin	9.51	

APPENDIX C
CO-PRODUCT METHODOLOGY

Co-Product Allocation Methodology for Soyoil Derived Biodiesel

Biodiesel, consisting of fatty-acid methyl esters (FAME), and non-ester renewable diesel (NERD) are produced using plant-derived oils. There are a variety of potential feedstock oils (see table C-1), but the dominant pathway is soybean oil-based biodiesel and this pathway is modeled in CA-GREET and detailed in this document. This Appendix discusses the co-products of soybean biodiesel and the allocation method used in CA-GREET for determining co-product credits; the renewable diesel pathway (NERD) and its co-products are not discussed here.

Table C-1. Biodiesel Co-Products

Fuel	Feedstock	Co-products
Biodiesel (esterified)	Soybean oil	Soybean meal, glycerin
Biodiesel (esterified)	Canola Oil	Canola meal, glycerin
Biodiesel (esterified)	Mustard seed	Seed meal, glycerin
Biodiesel (esterified)	Palm oil	Various
Biodiesel (esterified)	Used Cooking Oil	Glycerin

Pressing oil from soybeans yields protein rich soybean meal valued as an animal feed. Transesterification of the processed oil with methanol yields biodiesel (FAME) and glycerin, which can be sold in crude form, or distilled to 99% or higher purity for sale to the cosmetic and pharmaceutical industries. The CA-GREET model calculates co-product credits for these and the methodology used in the analysis in this document is provided below.

Co-Product Allocation methods

Allocation methods apportion the inputs and emissions from a process amongst the various co-produced outputs based on some characteristic of the process input, outputs, or operation. The advantage of using the allocation approach is that the analysis can be completed based on the inputs and emissions associated with a more narrowly-defined process. This simplifies the analysis and eliminates certain uncertainties and these have been used in the soybean to biodiesel pathway analysis using CA-GREET. Mass based allocation has been used for the soybean meal/oil production pathway component and energy based allocation has been used for the biodiesel/glycerin production step.

Soybean Production and Soyoil Extraction

The crushing of soybean produces soybean meal and soyoil. USDA data from 2007 indicates that 5.28 bushels of soybeans are required to produce 1 pound of soyoil. The balance is left over as soybean meal, a nutritive supplement for animal feed. Based on the USDA data, approportioning the impacts of soybean farming to soybean meal and soyoil works out to approximately 80% being allocated to soybeans and 20% to soyoil[11]. Using this information, all relevant GHG emissions attributable to soybean farming up to soyoil extraction are apportioned to 20% to the biodiesel pathway analysis.

Biodiesel Energy Allocation

The glycerin co-product is accounted for in CA-GREET using allocation by energy content. This is accomplished indirectly, by multiplying the fuel energy and emission results by the energy proportion of the fuel or oil in the product system.

The energy allocation factor is the energy fraction of biodiesel (FAME) to the energy ratio of biodiesel to the total biodiesel plus glycerin product system (Equation C-1 shows the ratio in words and C-2 shows the actual calculation):

$$\frac{\text{Biodiesel Energy Content}}{(\text{Biodiesel Energy Content + Glycerin Energy Content})} \qquad \text{(C-1)}$$

$$\frac{16{,}149\, Btu/lbBD}{(16{,}149\, Btu/lbBD) + (7{,}979\, Btu/lbGlycerine) \times (0.105\, lbsGlycerine/lbBD)} = 95.1\% \qquad \text{(C-2)}$$

where BD = biodiesel

Note: The value of 0.105 pounds of glycerin for every pound of biodiesel produced is obtained from the analysis presented below.

Glycerin Yield

The transesterification of plant oils is the primary method used in today's biodiesel plants (Huo, et al. 2008[12]). In this process, plant oils such as soybean oil are combined with methanol in the presence of a catalyst (acid or base) to produce fatty acid methyl esters (FAMEs) and co-product glycerin. The mixture of FAMEs is the biodiesel product. Figure C-1 illustrates this process, in which R in the figure represents the hydrocarbon chain for the fatty acids in the triglycerides comprising the oil. As the figure shows, 1 mole of oil triglycerides reacts with 3 moles of alcohol to yield 3 moles of FAME and 1 mole of glycerol (glycerin) in the transesterification reaction.

The theoretical stoichiometric mass ratio of glycerin to FAME can be determined by the distribution of fatty acids in the oil feedstock. The typical fatty acid profile for soybean oil is shown below in Table C-2, based on data from the Institute of Shortening and

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[11] Actual data works out to 80.6% to soybean meal and 19.4% to soyoil. To ensure consistency with the GTAP model analysis which utilizes the 80:20 ratio, the same has been adopted for the CA-GREET analysis.

[12] Huo, H., et al. (2008). Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels. Argonne National Laboratory, Energy Systems Division Report ANL/ESD/08-2, March 2008.

Edible Oils[13]. As the table shows, the weighted average molecular weight (MW) for FAME produced from soybean oil is 292.3 g/mol. The MW for glycerin is 92.1 g/mol, indicating a glycerin-to-FAME mass ratio of 0.105, as shown below:

$$\frac{92.1\text{ g/mol glycerin}}{(3\text{ mol FAME/mol glycerin})*(292.3\text{ g/mol FAME})} = 0.105\text{ g glycerin/g FAME}$$

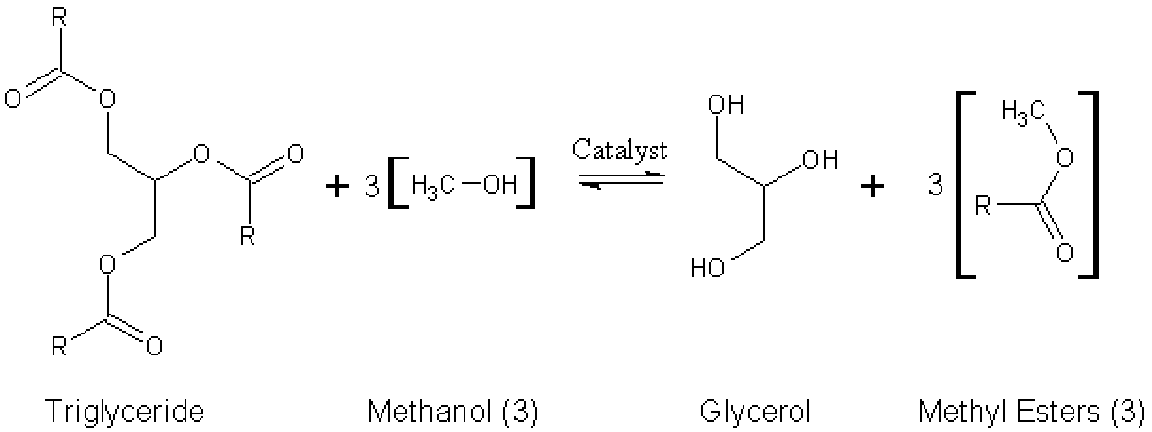

Figure C-1. Transesterification of plant oil to biodiesel

This theoretical yield ratio corresponds closely to the yields cited in the JRC/CONCAWE/EUCAR (2008) study[14] (0.106) and Huo, et al.[12] (0.116) for soybean-derived FAME. The actual glycerin yield under real-world operating conditions can be slightly lower than the theoretical yield since feedstock conversion is less than 100%; recovered crude glycerin contains small quantities of unreacted methanol and unwanted products from side reactions. For the analysis here, the 0.105 value has been used.

Table C-2 . Distribution of Fatty Acids in Soybean Oil Triglycerides

Fatty acid	**Mass Share**	**Fatty Acid MW (g/mol)**	**Methyl Ester MW (g/mol)**
Linolenic Acid	7.0%	278.4	292.5
Linoleic Acid	54.0%	280.4	294.5
Oleic Acid	24.0%	282.5	296.5
Stearic Acid	4.0%	284.5	298.5
Palmitic Acid	11.0%	256.4	270.5
Weighted Average	100%	**278.3**	**292.3**

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[13] Institute of Shortening and Edible Oils (2006), "Food Fats and Oils," ninth edition, available at http://www.iseo.org/foodfatsoils.pdf

[14] JRC, CONCAWE, EUCAR (2008), "Wells to Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context," Version 3.0, Appendix 4.