California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Biodiesel (Esterified Soyoil) from Midwest Soybeans

Stationary Source Division

Release Date: January 20, 2009

Version: 2.0

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 the California Energy Commission, TIAX, and Life Cycle Associates 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

California-GREET Model Pathway for Biodiesel (Esterified Soyoil) from Midwest Soybeans

A Well-to-Tank (WTT) Life Cycle Analysis of soybean biodiesel 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 analysis are combined to provide a total Well-to-Wheel (WTW) analysis. Because this is a crop-derived fuel, a land use change adder will be applied to the WTW analysis. We are currently evaluating the impacts of biofuels on land use.

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 soybean to producing and combusting biodiesel in an internal combustion engine. The model however, was modified by TIAX under contract to the California Energy Commission during the AB 1007 process[2]. Changes were restricted mostly to input factors (emission factors, generation mix, transportation distances, etc.) with no changes in methodology inherent in the original GREET model. This California-modified GREET model formed the basis for many fuel pathways published by staff in mid-2008. Subsequent to this, the Argonne Model was updated in September 2008. To reflect the update and to incorporate other changes, staff contracted with Life Cycle Associates to update the CA-GREET model. This updated California modified GREET model (v1.8b) (released December 2008) 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.

The pathway described here includes soybean farming, soybean transport, biodiesel production, transport and distribution (T&D) and use of biodiesel (as B100) in an internal combustion engine. The original GREET pathway has been modified to reflect CA production of biodiesel. The pathway documented here includes soybean farming and soyoil extraction in the Midwest, followed by transportation of soyoil to Washington and California. Soyoil is 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 including farming, biodiesel production and distribution to refueling stations, and final use in a transportation vehicle.

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

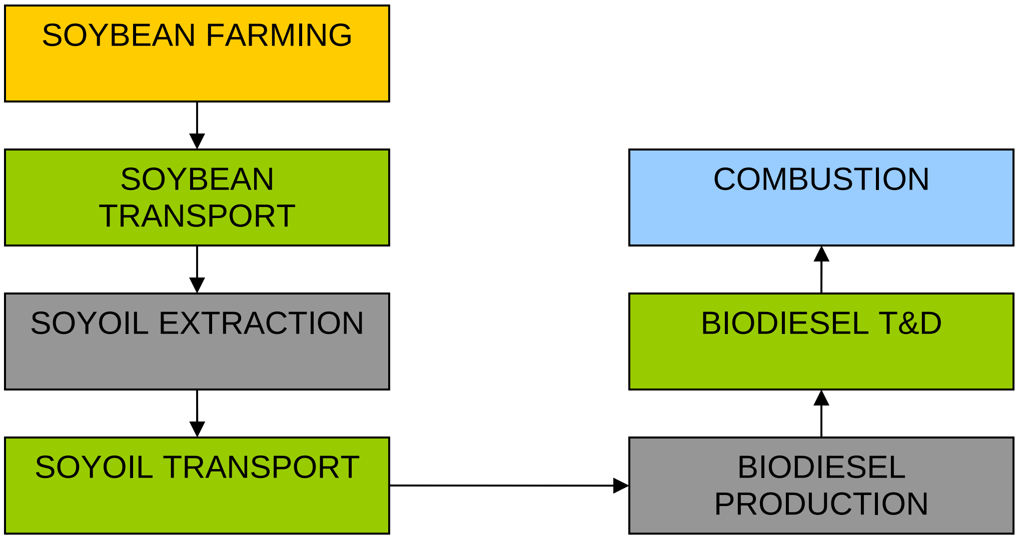

Figure 1. Discrete Components of the Midwest Soybean to Biodiesel Pathway.

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.

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

- 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 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 global warming potential values and included in the total.

- 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.

Table A. Summary of Energy Consumption and GHG Emissions per mmBtu of Biodiesel Produced

	Energy Required (Btu/mmBtu)	Share of Total Energy (%)	GHG Emissions (gCO_2e/MJ)	Share of Total Emissions (%)
Well-to-Tank				
Soybean Farming	67,180	4.9%	5.10	18.9%
Agricultural Chemicals Production	50,358	3.7%	3.73	13.9%
N_2O Emissions from Fertilizer Use	N/A	N/A	3.9	14.5%
Soybean Transport	14,907	1.1%	1.15	4.3%
Soyoil Extraction	119,080	8.7%	6.96	25.8%
Soyoil Transport	19,688	1.4%	1.48	5.5%
Biodiesel Transesterification	72,091	5.3%	2.29	8.5%
Biodiesel Transport & Dist.	19,754	1.4%	1.54	5.7%
Total Well-to-Tank (WTT)	**363,058**	**26.6%**	**26.15**	**97.1%**
Tank To Wheel				
Carbon in Fuel	1,000,000	73.4%	N/A	N/A
Fossil Carbon in Fuel	0	0	0	0.0%
Vehicle CH_4 and N_2O*	N/A	N/A	0.780	2.9%
Total Tank-to-Wheel (TTW)	**1,000,000**	**73.4%**	**0.780**	**2.9%**
Total Well-to-Wheel (WTW)	**1,363,058**	**100%**	**26.93**	**100%**

From Table A above, a WTW analysis of biodiesel indicates that **1,363,058** Btu of energy is required to produce 1 (one) mmBtu of available fuel energy delivered to the vehicle. From a GHG perspective, 26.93 gCO_2e of GHG are released during the production of 1 (one) MJ of biodiesel. Note that land use change impacts if any have not been included in this analysis. Staff is in the process of evaluating these impacts and will modify the results shown here based on the results from the analysis.

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 (73.4%) dominates the pathway energy use. For GHG emissions, the largest contributions are from soybean production (includes soybean farming, use of agricultural chemicals and consequent N_2O release) (47.3% combined) and soyoil extraction (25.8%).

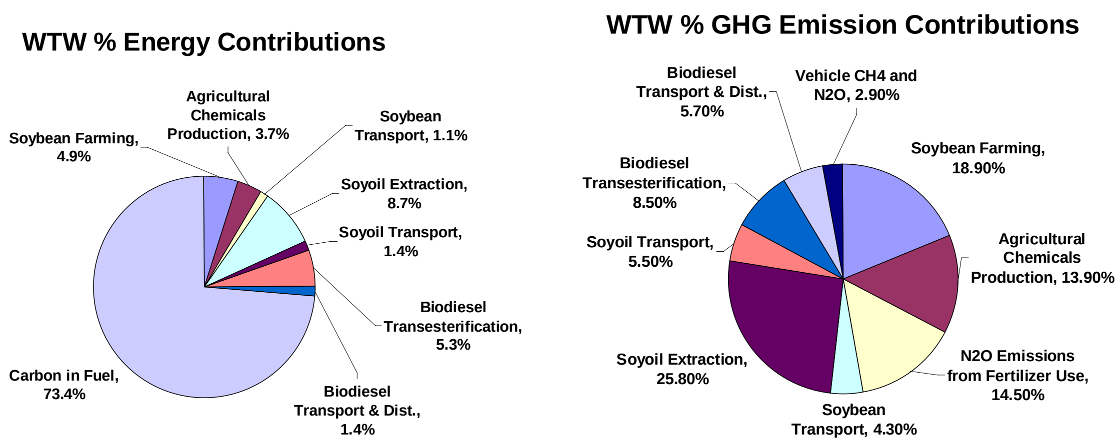

Figure 2. Percent Energy Contribution and Emissions Contribution from Well-to-Wheel (WTW).

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 (esterified soyoil) production process starts with soybean farming. Table B provides a breakdown of energy use needed for soybean farming. The table shows values for various fuels used on a per bushel basis. Table B also shows the total energy for soybean farming on a Btu/mmBtu basis with all adjustment and allocation factors applied. Appendix C shows the details of adjustment and allocation factors for the biodiesel pathway. In a similar manner, GHG emissions associated with the 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	Btu/bushel
Diesel	16,543
Gasoline	4,726
Natural Gas	1,725
LPG	1,875
Electricity	1,696
Total Energy for Soybean Farming (Btu/bushel)	**26,564**
Total Energy for Soybean Farming (Btu/mmBtu)	**162,526**
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**67,180**

Table C. Total GHG Emissions from Soybean Farming

GHG	$gCO_2e/mmBtu$
CO_2	4,841
CH_4	8.126
N_2O	0.090
CO	178.874
VOC	9.844
Total GHG (gCO2e/MJ)	**5.10**

Chemical Inputs in Soybean Farming

Table D shows the energy necessary for chemicals inputs to soybean farming. They are included as fertilizers, herbicides and pesticides. Detailed breakdown of chemical inputs utilized in the calculations are provided in Appendix A.

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

Inputs	Btu/bu
Nitrogen	2,805
Phosphate (P_2O_5)	2,477
Potash (K_2O)	2,730
Herbicides	11,756
Pesticides	134
Total Energy Consumption (Btu/bu)	**19,912**
Total Energy Consumption (Btu/mmBtu)	**121,823**
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**50,358**

Table E provides GHG emissions from chemicals input in soybean farming. The fuel consumption and other specifics necessary for this calculation are detailed in Appendix A.

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

GHG	**gCO_2e/mmBtu**
CO_2	3,727
CH_4	4.644
N_2O	0.281
CO	3.668
VOC	1.515
Total (gCO2e/MJ)	**3.73**

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	**gCO_2e/MJ**
N_2O	3.9

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 below. Details of all the calculations are presented in Appendix A.

Table G. Energy Required for Soybean Transport

Locations	Btu/bu
Field to Stack	1433
Stack to Plant	4462
Total Energy (Btu/lb)	**3623**
Total Energy (Btu/mmBtu)	**11,284**
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**14,907**

Table H. GHG Emissions Soybean Transport

GHG	$gCO_2e/mmBtu$
CO_2	1168
CH_4	1.277
N_2O	0.031
CO	2.071
VOC	0.509
Total (gCO2e/MJ)	**1.15**

Soyoil Extraction

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

Table I. Total Energy Use for Soyoil Extraction

Fuel Type	Btu/lb
NG	2,993
Electricity	1,101
N-Hexane	215
Total Energy for Soyoil Extraction (Btu/lb)	**4,309**
Total Energy for Soyoil Extraction (Btu/mmBtu)	**277,481**
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**119,080**

Table J. GHG Emissions Soyoil Extraction

GHG	gCO$_2$e/mmBtu
CO_2	6.550
CH_4	13.943
N_2O	0.070
CO	3.682
VOC	133.692
Total (gCO2e/MJ)	**6.96**

Soybean Oil Transport

The pathway described here models soyoil extracted in the Midwest and transported by rail to a biodiesel plant on the west coast including WA and CA. The energy use for transport and associated GHG emissions are shown in Tables K and L below. Details of all the calculations are presented in Appendix A.

Table K. Energy Required for Soybean Biodiesel Transport and Distribution

Transport (All Rail)	Btu/mmBtu
Total Energy for Transport	**16,038**
Total Energy with Adjustment and Allocation Factors Applied	**19,688**

Table L. GHG Emissions Soybean Biodiesel Transportation and Distribution

GHG	gCO$_2$e/mmBtu
CO_2	1,499
CH_4	1.849
N_2O	0.036
CO	3.971
VOC	1.128
Total (gCO2e/MJ)	**1.48**

Biodiesel Production via Transesterification

The soyoil is transesterified in plants in Washington and California. Table M and N provide energy use and attendant GHG emissions from transesterification respectively. For this document, the energy and emission factors are assumed to be CA for production facilities in both WA and CA. Details are provided in Appendix A.

Table M. Total Energy Use for Biodiesel Transesterification

Fuel or Chemical	Btu/lb
NG	950
Electricity	93
Methanol	1,355
Sodium Hydroxide	42
Sodium Methoxide	209
Hydrochloric Acid	63
Total Energy for Biodiesel Production (Btu/lb)	**2,713**
Total Energy for Biodiesel Production (Btu/mmBtu)	**167,986**
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**72,091**

Table N. GHG Emissions Biodiesel Transesterification

GHG	gCO_2e/mmBtu
CO_2	2209
CH_4	8.061
N_2O	0.017
CO	1.721
VOC	0.839
Total (gCO2e/MJ)	**2.29**

Biodiesel Transport and Distribution

Biodiesel produced in WA is transported via barge to ports in CA and then transported via HD truck to blending terminals in CA. The biodiesel produced in CA is transported via HD trucks directly to blending terminals in CA. Tables O and P show the energy use and GHG emissions from transporting biodiesel respectively.

Table O. Total Energy Use for Biodiesel Transport and Distribution, Btu/mmBtu

	Barge to CA Port	HD Truck from Port to Bulk Terminal	HD Truck for Distribution
Direct Energy (Btu/mmBtu)	11,433	3,182	5,727
Total Direct Energy (Btu/mmBtu)	9,560	3,125	7,069
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**19,754**		

Table P. GHG Emissions Biodiesel Transport and Distribution

GHG	$gCO_2e/mmBtu$
CO_2	1,563
CH_4	1.830
N_2O	0.037
CO	2.744
VOC	0.743
Total (gCO2e/MJ)	**1.54**

TTW Details

Use in a Biodiesel Vehicle

The biodiesel is then used as B100 in a transportation (Heavy Duty) vehicle. The factors used here are for a heavy duty diesel truck using ULSD. Table Q below provides a summary of CH_4 and N_2O from vehicles. The CA-GREET model considers only the fossil carbon in fuel. The total TTW emissions are 0.780 g CO2e/MJ. Complete details of the calculations are shown in Appendix A.

Table Q. GHG from Vehicles Combusting Biodiesel (B100 Blend)

CH_4 and N_2O from Vehicle = 0.780 g CO_2e/MJ **Fossil Carbon in Biodiesel = 0.0 g CO_2e/MJ** **Total TTW = 0.780 g CO_2e/MJ**

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APPENDIX A

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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 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 below shows the U.S. average electricity mix.

Table 1.01. Calculation of Direct Energy Consumption (Btu/bushel) in Soybean Farming

Process Fuel Type	Fuel Shares	Relationship of Recovery Efficiency (0.972) and Fuel Shares	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%

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 Energy Conversion

Soybean Yield (lb/bushel)	Soybean to Soy Oil (lb soybean/lb oil)	Soy Oil to Biodiesel (lb oil/lb BD)	Biodiesel Density (g/gal)	Biodiesel LHV (Btu/gal)
60	5.7	1.04	3,361	119,550

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 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 Btu 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.

Table 1.04 Energy Consumption in the WTT process and Specific Energy of Fuel Components Used as GREET Default

	E:WTT energy (Btu input/Btu product)	**S: Specific Energy (Btu input/Btu product)**
Crude	E_{CR} = 39,212	$S_{CR} = 1+E_{CR}/10^6$
	$E_C = E_{CR}$*Loss Factor$_{T\&D}$ + $E_{C\ T\&D} + E_{CS}$ = 28,284*1 + 10,926 = 39,212	
Res Oil	E_{ResOil} = 74,239	$S_{Res\ Oil} = 1+(E_C$*Loss Factor$_{Crude}$+ $E_{ResOil}) /10^6$
Conventional Diesel	E_{diesel} = 123,805	$S_{Diesel} = 1+(E_C$*Loss Factor$_{Diesel}+E_{Diesel})/ 10^6$
Conventional Gasoline	$E_{Gasoline}$ = 162,914	$S_{Gasoline} = 1+(E_C$*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: 1.0000; 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. Calculation of 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 + 123,804)/ 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 123,804 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)	
Liquid Petroleum Gas	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 (GREET default)	
		40% of the LPG is from petroleum, 60% is from NG (GREET default)	
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 due to soybean farming, Btu/bushel			26,564
Total energy due to soybean farming, Btu/mmBtu = 26,564 Btu/bu / 0.163448			162,526
Total adjusted energy due to soybean farming, Btu/mmBtu = 162,526 * 45.7% * 90.5% * 1.000039			**67,180**

[1] 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.

The adjusted energy takes into account the co-products as follows: 45.7% is the soybean oil extraction energy allocation to soy oil (the balance is allocated to soybean meal), 90.5% is fuel production energy allocation (the balance is allocated to co-products). More information on co-product calculations can be found in Appendix C.

The calculations in Table 1.04 above and others rely on Well-to-Tank energy results for all fuels used in the various steps of the biodiesel pathway. For example, in Table 1.04 the diesel calculation uses the crude recovery WTT energy (39,212 Btu/Btu) and diesel production WTT energy (123,804 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 GREET in the same manner.

In the last row of the above table, the soybean farming energy in Btu/mmBtu biodiesel is proportionalized by:

a) The oil energy share (45.7%) of total oil extraction energy system (including oil and soybean meal) and;
b) the biodiesel energy share (90.5%) of the overall transesterification system (including biodiesel and glycerin).

The equations below to see how these allocations are determined in GREET. Soy oil energy share of total soy oil plus soybean meal system:

$$\frac{16{,}000 \text{ Btu/lb oil}}{\left[(16{,}000 \text{ Btu/lb oil}) + (4{,}246 \text{ Btu/lb meal})(4.48 \text{ lbs meal/lb oil})\right]} = 45.7\%$$

Biodiesel energy share of total biodiesel plus glycerin transesterification system:

$$\frac{16{,}149 \text{ Btu/lb BD}}{\left[(16{,}149 \text{ Btu/lb BD}) + (7{,}979 \text{ Btu/lb gly})(0.213 \text{ lbs gly/lb BD})\right]} = 90.5\%$$

Where BD = biodiesel, meal = soybean meal and gly = glycerin

All values used above are GREET default values. This includes:

a) LHV for soyoil = 16,000 Btu/lb oil
b) LHV for soymeal = 4,246 Btu/lb meal
c) Production ratio of soybean meal to oil = 4.48 lbs meal/lb oil
d) LHV for BD = 16,149 Btu/lb BD
e) LHV for glycerin = 7,979 Btu/lb glycerin
f) Production ratio of glycerin to BD = 0.213 lb glycerin/lb BD

This implies that the soybean meal resulting from oil extraction contains 54.3% of the energy of feedstock throughput and glycerin contains 9.5% of the energy of the total biodiesel plus glycerin products. It is necessary to multiply the farming energy by the product of the co-product energy shares to correctly allocate energy and emissions to fuel production since there are two separate components of fuel production.

Note that these "sub-system" allocation factors are only used to allocate energy and emissions for feedstock production; the allocation factor used to allocate energy and emissions for fuel production is based on the energy balance of the entire product system (see Section 2.1)

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. The diesel tractor emission factors are from ARB's offroad model. GREET default values are also shown.

Table 1.06 Emission Factors for Fuel Combustion, g/mmBtu (LHV)

	Equipment Type	Equipment Shares	VOC	CO	CH_4	N_2O	CO_2
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

Direct emissions are calculated by multiplying the direct fuel consumption (provided in Table 1.1) by the above emission factors and summing the equipment types per fuel—see Table 1.07.

Table 1.07 Soybean Farming Direct Emissions, g/bushel

Process Fuel	VOC	CO	CH_4	N_2O	CO_2
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 all Fuel Contributions to the Fuel Cycles by GREET Default

	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	$SE_{Res\ Oil} = 1+(EF_C*\text{Loss Factor}_{Crude}+EF_{ResOil})/10^6$
Conventional Diesel	EF_{diesel} = 9,389	$SE_{Diesel} = 1+(EF_C*\text{Loss Factor}_{Diesel}+EF_{Diesel})/ 10^6$
Conventional Gasoline	$EF_{Gasoline}$ = 12,124	$SE_{Gasoline} = 1+(EF_C*\text{Loss Factor}_{Gasoline}+EF_{Gasoline})/ 10^6$
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	$SE_C = (1+EF_C)/ 10^6$

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 * (2,926 * 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 + 4,885*1.0001 + 3,168)/ 2)/ 10^6	This formula assumes half of the LPG comes from petroleum and the other half from LNG. 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 LNG 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**

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

Upstream emissions are provided in Table 1.10. Table 1.11 shows the combined direct + 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, g/bu

Process Fuel	VOC	CO	CH_4	N_2O	CO_2
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	0.017	0.026	0.192	0.000	15
Electricity	0.013	0.124	0.176	0.001	141
Total Upstream	**0.265**	**0.495**	**2.367**	**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	0.194	0.008	129
Electricity	0.013	0.124	0.176	0.001	141
Total Emissions	**3.892**	**70.728**	**3.213**	**0.035**	**1,914**
(g/mmBtu)	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
Diesel	9.667	35.862	9.344	0.112	7,875
Gasoline	13.476	392.339	3.143	0.031	1,575
Natural Gas	0.468	3.492	4.910	0.015	609
LPG	0.126	0.271	1.184	0.051	789
Electricity	0.078	0.760	1.077	0.008	863
Total Emissions	23.814	432.724	19.658	0.217	11,712

Note: To convert from Btu/bu to Btu/mmBtu, divide by 0.163448
To calculated adjusted energy multiply by 45.7%*90.5%*1.000039

Table 1.12. Summary of Total (Direct + Upstream) Emissions from *Soybean Farming (gCO_2/*bu*) with Allocation and Loss Factors Applied*

With Allocation and Loss Factors Applied						
	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG gCO_2/MJ**
Diesel	3.996	14.824	3.862	0.046	3,255	3.22
Gasoline	5.570	162.181	1.299	0.013	651	0.91
Natural Gas	0.193	1.444	2.030	0.006	252	0.29
LPG	0.052	0.112	0.489	0.021	326	0.33
Electricity	0.032	0.314	0.445	0.003	357	0.35
Total Emissions, g/mmBtu	**9.844**	**178.874**	**8.126**	**0.090**	**4,841**	**5.10**

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 below presents the 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	2,730
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)			121,823 Btu/mmBtu
Total Adjusted Energy Consumption due to Production of Ag. Chemicals Used in Farming (Btu/mmBtu, with allocation and loss factors)			**50,358 Btu/mmBtu**

Note: Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate
To convert from Btu/bu to Btu/mmBtu, divide by 0.163448
To calculated adjusted energy multiply by 45.7%*90.5%*1.000039

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. For conversion factors and allocation/loss factors, please refer to the table footnotes.

Table 1.14 Life Cycle Emissions Associated with Fertilizer/Herbicide/Pesticide Use

Product	VOC	CO	CH_4	N_2O	CO_2	GHG gCO_2/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*	2.271	2.203	0.781	0.607	896	1.05
Phosphate (P_2O_5)	0.391	1.352	1.606	0.014	1,117	1.10
Potash (K_2O)	0.241	1.272	1.701	0.014	1,317	1.30
Herbicides	0.751	3.993	7.068	0.044	5,622	5.52
Pesticides	0.011	0.055	0.081	0.001	63	0.06
Total	3.664	8.874	11.236	0.679	9,015	9.03
With Allocation and Loss Factors Applied, g/mmBtu:						
Nitrogen*	0.939	0.911	0.323	0.251	370	0.43
Phosphate (P_2O_5)	0.161	0.559	0.664	0.006	462	0.46
Potash (K_2O)	0.100	0.526	0.703	0.006	544	0.54
Herbicides	0.310	1.651	2.922	0.018	2,324	2.28
Pesticides	0.004	0.023	0.033	0.000	26	0.03
Total	1.515	3.668	4.644	0.281	3,727	**3.73**

*Note: Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate
N_2O emissions emissions associated with nitrogen fertilizer applications consist of upstream fertilizer production emissions and direct emissions from fertilizer N converted to N_2O, within the farm system and downstream. To convert from g/bu to g/MJf, divide by 0.163448; To calculated adjusted energy multiply by 45.7%*90.5%*1.000039

1.5 Soil N_2O Release Due to Fertilizer Use

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 below 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/(2x14).

Table 1.15 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 emissions, g-CO_2e/mmBtu	9,942
GHG emissions, g-CO_2e/mmBtu, with allocation and loss factors	4,110
GHG emissions, g-CO_2e/MJ	**3.9**

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

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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 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 or Washington 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 Soybean Transport Parameters and Calculations

	Units	**Field to Stack**	**Stack to Terminal**
Mode		Medium Heavy Duty Truck	Heavy 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	1,433	4,462
Total Energy	Btu/mmBtu	8,764	27,298
Total Adjusted Energy	Btu/mmBtu	3,623	11,284
Total SoybeanTransport Adjusted Energy, Btu/mmBtu		**14,907**	

*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).
Multiply direct diesel use by 1.163 (the ratio of direct energy to WTT energy, see Table 1.3) to arrive at total energy use.
To convert to Btu/MMBtu, divide by 0.163448 MMBtu/Bu
To get total adjusted energy, multiply by 45.7%, 90.5% and 1.000039
Where extra significant figures are shown, they are needed to match calculations in the model.

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. The formula for calculating transport emissions is as follows:

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. As the sample calculations show, the upstream diesel CO_2 emissions value of 13,257 g/mmBtu is used in calculating the upstream CO_2 emissions associated with soybean transport.

Table 2.02 Soybean Transport Parameters and Calculations

	Field to Stack	Stack to Soyoil Extraction Facility	Total Transport
Mode	Medium Heavy Duty Truck	Heavy 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)			
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)	77,809 (77,912)	
Direct Emissions, g/ton			
VOC	1.574	4.115	5.688
CO	5.085	20.973	26.058
CH_4	0.076	0.209	0.285
N_2O	0.128	0.288	0.416
CO_2	3,427	10,668	14,095
Upstream Emissions, g/ton:			
VOC	0.363	1.130	1.493
CO	0.774	2.412	3.186
CH_4	4.315	13.439	17.754
N_2O	0.006	0.020	0.027
CO_2	583	1,816	2,400
Total Adjusted Emissions (with Allocation & Loss Factors), g/mmBtu			
VOC	0.137	0.371	0.509
CO	0.415	1.656	2.071
CH_4	0.311	0.966	1.277
N_2O	0.009	0.022	0.031
CO_2	284	884	1,168
GHGs, g/MJ	0.28	0.87	1.15

Note:[1]Emission factors (EFs) correspond to trip from feedstock origin to destination and the return trip and are listed in the emission factor (*EF* tab) of GREET.
Note: Energy Intensity = LHV / fuel economy / payload
Direct truck energy doubles the miles to take into account round trip energy.
To get total adjusted energy, multiply by 45.7%, 90.5% and 1.000039 (see section 1.1)

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 = [(77,912 g/mmBtu)*(2,199 Btu/ton-mile)+ (77,890 g/mmBtu)*(2,199 g/mmBtu)]*(10 miles)/10^6 = 3,427 g CO_2/ton

Upstream CO_2 emission calculation for a medium heavy 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)

[(13,257 g/mmBtu)*(2,199 Btu/ton-mile)+ (13,257 g/mmBtu)*(2,199 Btu/ton-mile)]*(10 miles)/10^6 = 583 g CO_2/ton

Total adjusted CO_2 emission calculation in g/mmBtu for a medium heavy 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)*(1 ton/2,000 lbs)*(56 lbs/bu)/(0.163448 mmBtu/bu) = 687 g/mmBtu

(687 g/mmBtu)*(45.7% oil energy share)*(90.5% biodiesel energy share)*(1.000039) = 284 g CO_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 soy oil extraction. Since GREET calculates results for feedstock and fuel separately, the 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 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, Camobreco et al. 1998[3]). 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 Calculation of Direct Energy Consumption (Btu/lb) to Extract Oil 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 * 3,533	2,800
Electricity	15.6%	0.156 * 3,533	551
N-Hexane	5.1%	0.051 * 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 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.

[3] 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 3.02 Calculation of Total Energy Use from Direct Energy Use for Soyoil Extraction

Fuel Type	Formula	Description	Btu/lb soyoil
Natural Gas	2,800 + 2,800*(68,910)/10^6	2,800 Btu/lb soyoil of direct NG fuel use (Table 3.01)	2,993
		68,910 is the energy required to recover, process and transport 1 mmBtu of NG for stationary use	
Electricity	551* (111,649 + 1,884,989)/ 10^6	551 Btu/lb soyoil direct electricity use (Table 3.01)	1,101
		111,649 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity.	
		1,884,989 Btu fuel used to produce 1 mmBtu electricity.	
N-Hexane	182 + 182 * (102,711*1.0001 + 76,715)/ 10^6	182 Btu/lb soyoil direct N-Hexane use. GREET uses LPG values for N-Hexane (Table 3.01)	215
		The energy to recover crude is 102,711 Btu/mmBtu crude.	
		1.0001 is the loss factor for LPG.	
		To refine & transport LPG, 76,715 Btu/mmBtuBtu LPG are used (Table 1.3)	
Total Energy Consumption for Soyoil Extraction (Btu/lb oil)			**4,309**
Total Energy Consumption for Soyoil Extraction (Btu/mmBtu)			**277,481**
Total Adjusted Energy Consumption for Soyoil Extraction (Btu/mmBtu)			**119,080**

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

Soyoil Extraction Energy = 4,309 Btu/lb oil * 1.04 lb oil/lb BD * 3361 g BD/gal BD / 454 g/lb /119,550 Btu/gal BD * 10^6 Btu/mmBtu = 277,481 Btu/mmBtu

CA-GREET allocates energy for soybean farming, soy oil extraction, and esterification to the co-products. To determine the final adjusted energy consumption to extract the oil, we need to multiply by the total extraction energy by the fuel energy allocation factor for the entire production system; this factor is different from the two allocation factors used in the feedstock production calculation, which are the subsystem factors for soy oil energy share (45.7%) of total products (soy oil plus soybean meal) and the fuel energy allocation factor (90.5%) for transesterification (products include biodiesel and glycerin). The allocation factor for the entire fuel system (42.9%) is determined as the biodiesel energy in Btu/lb biodiesel produced divided by the sum of the biodiesel energy plus the glycerin energy plus the soybean meal energy (see equation below). CA-GREET 1.8b provides displacement, market value and hybrid allocation methods for co-product calculations as well.

Biodiesel Energy share for Entire System:

$$\frac{16{,}149 \text{ Btu/lb BD}}{\left[16{,}149 \text{ Btu/lb BD} + (7{,}979 \text{ Btu/lb gly})(0.213 \text{ lb gly/lb BD}) + (1.04 \text{ lb oil/lb BD})(4.48 \text{ lb meal/lb oil})(4{,}246 \text{ Btu/lb meal})\right]} = 42.9\%$$

Where BD = biodiesel, gly = glycerin and meal = soybean meal

The loss factor associated with biodiesel production in GREET is 1.000039.

The adjusted energy consumption is:
Total Adjusted Extraction Energy = 277,481 * 42.9% * 1.000039 = 119,080 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 (CO_2 emission factor is provided in Table 1.08). 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 were calculated is shown below Table 3.03.

Table 3.03 Direct Emissions from Soyoil Extraction, gGHG/lb Soyoil

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas	0.006	0.063	0.003	0.001	163
N-Hexane	4.813				
Total	**4.819**	**0.063**	**0.003**	**0.001**	**163**

Natural gas direct CO_2 emissions:
(2,800 Btu NG/lb oil)[(50%)(58,198 g CO_2/mmBtu) + 50%)(58,176 g CO_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 Calculation of Upstream CO_2 Emissions from Direct Energy Use For Soyoil Extraction

Fuel Type	Formula	Description	gCO_2/lb soyoil
Natural Gas	2,800*(5,052)/10^6	2,800 Btu/lb soyoil of direct NG fuel use (Table 3.2)	14
		5,052 grams of CO_2 are emitted in recovery, processing and transporting 1 mmBtu of natural gas for stationary use.	
Electricity	551* (8,281 + 96,250)/ 10^6	551 Btu/lb soyoil direct electricity use (Table 3.2).	58
		To recover, process, and transport fuel to the power plants, 8,281 g of CO_2/mmBtu are emitted.	
		Production of electricity releases 96,250 g CO_2 /mmBtu of electricity produced.	
N-Hexane	182 * (2,926*1.000116 + 5,488)/ 10^6	182 Btu/lb soyoil direct N-Hexane use (Table 3.2).	2
		The CO_2 emitted from crude recovery is 7,085 g/mmBtu.	
		1.0001 is the loss factor for LPG	
		5,350 g/mmBtu CO_2 is from LPG refining & transport	
Total Upstream CO_2 Emissions for Soyoil Extraction			**74**

Table 3.05 Upstream Emissions from Soyoil Extraction, g/lb Soyoil

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas	0.018	0.032	0.361	0.000	14
Electricity	0.009	0.032	0.121	0.001	58
N-Hexane	0.002	0.006	0.020	0.000	2
Total	**0.028**	**0.070**	**0.501**	**0.002**	**74**

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 Emissions from Soyoil Extraction

	VOC	CO	CH_4	N_2O	CO_2	GHG gCO_2e/MJ
Total Emissions (Direct + Upstream), g/lb soyoil						
Natural Gas	0.023	0.095	0.364	0.001	177	
Electricity	0.009	0.032	0.121	0.001	58	
N-Hexane	4.815	0.006	0.020	0.000	2	
Total	4.847	0.133	0.504	0.003	237	
***Total Emissions (Direct + Upstream), converted to g/mmBtu**						
Natural Gas	1.491	6.142	23.425	0.069	11,404	
Electricity	0.564	2.066	7.793	0.092	3,713	
N-Hexane	310.103	0.373	1.272	0.002	146	
Total	312.158	8.580	32.490	0.163	15,262	
****Total Adjusted Emissions (with Allocation & Loss Factors), g/mmBtu**						
Natural Gas	0.640	2.636	10.053	0.029	4,894	4.89
Electricity	0.242	0.886	3.344	0.039	1,593	1.60
N-Hexane	133.080	0.160	0.546	0.001	63	0.47
Total	**133.962**	**3.682**	**13.943**	**0.070**	**6,550**	**6.96**

Note:
*To convert from g/lb soy oil to g/mmBtu biodiesel: see table 2.2
**To obtain total adjusted energy multiply total emissions by 42.9% and 1.000039; see Section 2.1 for explanation

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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 the west coast (Washington and California) for biodiesel production. The rail transport distance (1,400 miles) reflects the weighted average of 71% of soy oil transport to Washington and 29% transport directly to California. For the CA-GREET BD pathway, appropriate modifications have been made to incorporate soybean oil transport to WA and CA. Note that this approach 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 calculations below table).

The energy allocation factor used for soy oil transport is the same energy factor (90.5%) for soy oil calculated in Section 1.1. The 45.7% soy oil factor is not used because the oil has already been extracted from the soybeans and only the glycerin transport allocation needs to be subtracted out.

Table 4.01 Soybean Oil Transport Parameters and Calculations (Modeled as Biodiesel)

	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**	**19,688**

*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)(1,400 miles) = 518,000 Btu/ton

Direct Energy (Btu/mmBtu) = (518,000 Btu/ton)(1 ton/2,000 lbs)(1 lb/454 g)*(3,361 g/gal)/(119,550 Btu/gal)*10^6 = 16,038 Btu/mmBtu

Total Energy (Btu/mmBtu, not adjusted) = (16,038 Btu/mmBtu)(1 + 0.228 Btu/Btu diesel upstream) = 19,688 Btu/mmBtu where 0.228 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 to Washington (71%) and California (29%) with a weighted average distance of 1,400 miles. Table 4.02 below shows the diesel rail emission factors, direct emissions, upstream emissions and total emissions with allocation and loss factors applied.

Table 4.02 Soybean Oil Transport Parameters and Calculations

Transport Leg	**Soybean Crushing Facility to BD Plant**
Mode	Rail
Distance, miles	1,400
Fuel	Diesel
Energy Intensity, Btu/ton-mile	370
Emission Factors[1], 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	0.170
CO	0.522
CH_4	1.786
N_2O	0.003
CO_2	254
Total Emissions, including allocation and loss factors g/mmBtu Fuel Transported	
VOC	1.128
CO	3.971
CH_4	1.849
N_2O	0.036
CO_2	1,499
GHGs, g/MJ	**1.48**

[1]Rail miles not doubled.

The direct emissions and upstream emissions are calculated exactly as shown for soybean transport in Section 2.2.

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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. Calculation of Direct Energy Consumption (Btu/lb biodiesel) 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 * 2,116	889
Electricity	2.2%	0.022 * 2,116	47
Methanol	40.9%	0.049 * 2,116	865
Sodium hydroxide	2.0%	0.020 * 2,116	42
Sodium methoxide	9.9%	0.099 * 2,116	209
Hydrochloric acid	3.0%	0.030 * 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 Calculation of Total Energy Use from Direct Energy Use for Biodiesel Production

Fuel Type	Formula	Description	Btu/lb Biodiesel
Natural gas	889 + 889 * (68,910)/10^6	889 Btu/lb biodiesel of direct NG fuel use (Table 5.1).	950
		68,910 is the energy required to recover, process and transport a mmBtu of NG for stationary use	
Electricity	47* (111,649 + 1,884,989)/ 10^6	47 Btu/lb biodiesel direct electricity use (Table 5.1)	93
		111,649 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 * (31,832 * 1.0002 + 533,323)/ 10^6	865 Btu/lb biodiesel direct methanol use (Table 5.1)	1,355
		NG recovery, processing and delivery is 31,832 Btu/mmBtu methanol (GREET calculation).	
		1.0002 methanol loss factor	
		Methanol production is 533,323 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)			2,713
Total Energy Consumption for Biodiesel Production (Btu/mmBtu)			167,986
Total Adjusted Energy Consumption for Biodiesel Production (Btu/mmBtu)			**72,091**

Values used in upstream calculations are extracted from the summary section of the relevant fuel tab in GREET. The energy loss accounts for fact that approximately 40% of energy in soybeans is converted to fuel.

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

Total Energy = 2,713 Btu/lb biodiesel / 454 g/lb * 3,361 g/gal / 119,550 Btu/gal * 10^6 Btu/mmBtu = 167,986 Btu/mmBtu

Total Adjusted Energy = 167,986 Btu/mmBtu * 42.9% * 1.000039 = **72,091** 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, g/lb Biodiesel

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas	0.002	0.020	0.001	0.000	52
Total	**0.002**	**0.020**	**0.001**	**0.000**	**52**

Note: Only NG has direct emissions by 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 Calculation of Upstream CO_2 Emissions from Direct Energy Use for Soyoil Extraction

<table>
<tr><th>Fuel Type</th><th>Formula</th><th>Description</th><th>gCO₂/lb biodiesel</th></tr>
<tr><td rowspan="2">Natural Gas</td><td rowspan="2">889 * (5,052)/10^6</td><td>889 Btu/lb biodiesel of direct NG fuel use (Table 5.2)</td><td rowspan="2">4</td></tr>
<tr><td>5,052 g of CO2 are emitted in recovery, processing and transporting 1 mmBtu of natural gas for stationary use</td></tr>
<tr><td rowspan="3">Electricity</td><td rowspan="3">47* (8,281 + 96,250)/ 10^6</td><td>46 Btu/lb biodiesel direct electricity use (Table 5.2)</td><td rowspan="3">5</td></tr>
<tr><td>To recover, process and transport fuel to the power plants, 8,281 g of CO2 are emitted per mmBtu of electricity produced</td></tr>
<tr><td>Electricity production releases 96,250 g CO2/mmBtu of electricity</td></tr>
<tr><td rowspan="4">Methanol</td><td rowspan="4">865 * (3,231*1.0002 + 18,550)/ 10^6</td><td>865 Btu/lb soyoil direct methanol use (Table 5.2)</td><td rowspan="4">19</td></tr>
<tr><td>NG recovery, processing and transport results in 4,781 g CO2/mmBtu methanol</td></tr>
<tr><td>1.00002 is the loss factor for methanol production</td></tr>
<tr><td>Methanol production results in 18,550 g CO2/mmBtu methanol</td></tr>
<tr><td colspan="3">Total Upstream CO2 Emissions for Biodiesel Production</td><td>28</td></tr>
</table>

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

Table 5.05 Upstream Emissions from Biodiesel Production, g/lb Biodiesel

Product	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
Natural Gas	0.006	0.010	0.114	0.000	4
Electricity	0.001	0.003	0.010	0.000	5
Methanol	0.022	0.029	0.166	0.000	19
Total	**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 Emissions from Biodiesel Production

	VOC	**CO**	**CH_4**	**N_2O**	**CO_2**	**GHG (g/MJ)**
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	0.473	1.949	7.435	0.022	3,619	
Electricity	0.048	0.174	0.658	0.008	313	
Methanol	1.434	1.886	10.690	0.011	1,214	
Total	1.955	4.009	18.783	0.040	5,147	
Total Adjusted Emissions (with Allocation & Loss Factors), g/mmBtu						
Natural Gas	0.203	0.837	3.191	0.009	1,553	1.55
Electricity	0.020	0.075	0.282	0.003	134	0.14
Methanol	0.615	0.809	4.588	0.005	521	0.61
Total	**0.839**	**1.721**	**8.061**	**0.017**	**2,209**	**2.29**

Note: To obtain total adjusted energy, multiply by 42.9% and 1.000039.

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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.

In CA-GREET, 71% of the fuel is transported from a plant in Washington to a California port by barge and then distributed by heavy duty truck to refueling stations and the remaining 29% is produced in California and then distributed in the same manner. 80% of the biodiesel is also transported by heavy duty truck 50 miles from the plant to bulk terminal. The trucking distance input in 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 soy oil transport: Btu/ton-mile are 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 Biodiesel Transport Parameters and Calculations

	Units	Bulk Terminal to CA Port	Plant to Bulk Terminal	Distribution
Mode		Barge	Heavy Duty Truck	Heavy Duty Truck
Shares %		71%	80%	100%
Distance	Miles	520	50	90
Payload	Tons	22,500	25	25
Fuel Economy	mi/gal		5	5
Fuel		Residual Oil	Diesel	Diesel
Lower Heating Value	Btu/gal	140,353	128,450	128,450
Energy Intensity[1]	Btu/ton-mile	403 (307)	1,028	1,028
Energy to transport HCl	Btu/mmBtu			39
Direct Energy (Btu/mmBtu)[2]		11,433	3,182	5,727
Total Direct Energy (Btu/mmBtu)		9,560	3,125	7,069
Total Direct Energy T&D (Btu/mmBtu)		**19,754**		

[1]Return trip energy intensity in parenthesis, if different from trip from origin to destination. [2]Excludes mode share, which is accounted for in the total energy
Note: Energy Intensity = LHV / fuel economy / payload = 1,028 Btu/mile-ton
Direct truck energy doubles the miles to take into account round trip energy.

6.2 GHG Calculations for Biodiesel Transport to Retail Stations

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

- 71% transported 520 miles by barge from biodiesel plant in Washington to CA port
- 80% transported 50 miles by heavy duty truck from plants in Washington and CA to bulk terminal
- 100% distributed 90 miles by heavy duty truck

Table 6.02 below shows the direct emissions, upstream emissions (without accounting for mode share) and total emissions, accounting for mode share. Sample calculations below the table show how CO_2 emissions are calculated for barge transport.

The basic calculation is as follows:

Direct Emissions (g/mmBtu biodiesel) = biodiesel density (g/gal) / biodiesel LHV (Btu/gal) / 454 g/lb / 2,000 lb/ton * Energy Intensity (Btu/ton-mile) * miles (roundtrip) * Emission factor (g/mmBtu)

Please refer to Table 6.01 for specific parameter values in the above formula.

The upstream diesel energy and the upstream energy and emissions for residual oil used as transport fuel is shown below in Table 6.02.

Table 6.02 Upstream Emissions Associated with Diesel Fuel and Residual Oil Used as a Transport Fuel

Emission Species	Diesel (g/mmBtu)	Residual Oil (g/mmBtu)
VOC	10.615	9.386
CO	32.573	31.408
CH_4	111.333	108.459
N_2O	0.216	0.188
CO_2	15,813	12,329

These upstream values are used to calculate the total emissions

Table 6.03 Soybean Biodiesel Transport Emission Factors and Calculations, g/mmBtu

	Bulk Terminal to CA Port	**Bulk Terminal to CA Port**	**Fuel Distribution**	**Total Transport**
Mode	Barge	Truck	Heavy Duty Truck	
Mode Share	71%	80%	100%	
Distance, miles	520	50	90	
Fuel	Residual Oil	Diesel	Diesel	
Energy Intensity, Btu/ton-mile	403 (307)	1,028	1,028	
Emission Factors for Biodiesel Transport, g/mmBtu fuel burned (Return Trip EFs in Parenthesis, if Different)				
VOC	38.861 (43.127)	33.671 (26.392)	33.671 (26.392)	
CO	103.497 (135.779)	178.708 (127.443)	178.708 (127.443)	
CH_4	1.904 (2.113)	1.524	1.524	
N_2O	2.000	2.105	2.105	
CO_2	84,792 (84,728)	77,809 (77,912)	77,809 (77,912)	
Direct Emissions, g/mmBtu[1]				
VOC	0.465	0.096	0.172	
CO	1.343	0.487	0.877	
CH_4	0.023	0.005	0.009	
N_2O	0.023	0.007	0.012	
CO_2	969	248	446	
VOC	0.107	0.034	0.061	
CO	0.359	0.104	0.187	
CH_4	1.240	0.354	0.638	
N_2O	0.002	0.001	0.001	
CO_2	141	50	91	
Total Emissions, g/mmBtu				
VOC	0.407	0.103	0.233	0.743
CO	1.208	0.473	1.063	2.744
CH_4	0.897	0.287	0.646	1.830
N_2O	0.018	0.006	0.013	0.037
CO_2	788	238	536	1,563
GHGs, g/MJ	**0.78**	**0.24**	**0.53**	**1.54**

[1]Note: Direct and upstream emissions exclude mode share; total emissions accounts for mode share
Energy Intensity = LHV / fuel economy / payload
Direct truck energy doubles the miles to take into account round trip energy.

The emissions shown in Table 3.03 are determined the same way as the soy oil transport is calculated.

Calculation of CO_2 emissions for barge transport (residual oil):
Direct Emissions = [(3,361 g/gal)/(119,550 Btu/gal)/(454 g/lb)/(2,000 lb/ton)(84,792 g/mmBtu)(403 Btu/ton-mile) + (84,728 g/mmBtu)(307 Btu/ton-mile)]*(520 miles) = 969 g CO_2/mmBtu

Upstream emissions = [(3,361 g/gal)/(119,550 Btu/gal)/(454 g/lb)/(2,000 lb/ton)(12,329 g/mmBtu upstream)(403 Btu/ton-mile) + (12,329 g/mmBtu upstream)(307 Btu/ton-mile)]*(520 miles) = 141 g CO_2/mmBtu

Total Emissions = [(969 g/mmBtu) + (141 g/mmBtu)]*(71%) = **788 gCO2/mmBtu**

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 1.07 below show the fossil CO_2 emissions per mmBtu and MJ of fuel. The table summarizes the values used in the calculations and also shows the results from the 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 calculations shown in this document are for a heavy duty vehicle.*

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% /16,145 Btu/lb) and the carbon content of methanol (5.4% x 70 = 3.7 g/MJ). 16,145 Btu/lb is the LHV of BD on a per lb basis. A carbon credit equal in magnitude must be given for the fossil carbon in the co-product glycerin produced, because the glycerin produced displaces petroleum-derived glycerin; the methanol: glycerin carbon ratio is 1:1, yielding a net zero fossil carbon emission for fuel combustion.

Table 7.1 GHG Emissions from Fuel

Description	Methy Ester Biodiesel (B100)
BD Production Energy Input (Btu/lb BD)	2,116
BD Lower Heating Value (Btu/gal)	119,550
BD Density (g/gal)	3,361
BD Carbon Ratio (wt%)	77.6 %
MeOH Fuel Production Share	40.9%
MeOH Lower Heating Value (Btu/gal)	57,250
MeOH Density (g/gal)	3,006
MeOH Carbon Ratio (wt%)	37.5%
CO_2/C Mass Ratio (wt%)	44.0095/ 12.011
Fossil Carbon in Fuel (gCO_2e/MJ)	3.7
Fossil Carbon Credit in Glycerin (gCO_2e/MJ)	-3.7
Fossil Carbon in Fuel (gCO_2e/MJ)	**0.0**

Calculation: Fossil carbon in B100
5.4% energy =2116*40.9%*3361/454/119550
68.4 gCO2/MJ methanol=3006/57250*37.5%*44.0095/12.011*948
3.7 g C as CO2/MJ from methanol = 5.4% x 68.4

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		**0.780**

Note: uses LHV of BD of 119,550 Btu/gal

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APPENDIX B
MIDWEST SOYBEAN FOR BIODIESEL

Scenario: Soybean Biodiesel Pathway Input Values

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.1	
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			

Parameters	Units	Values	Note
by ocean tanker	miles	3,000	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 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	2.08	

Biodiesel Production			
Soyoil Extraction			
Soyoil Extraction Efficiency		97.2%	
Soyoil Extraction Energy Share		45.7%	
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		90.5%	
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		
Soybean Transportation Cargo Capacity			
Barge	tons	20,000	
Medium Duty Truck	tons	8	
Heavy Duty Truck	tons	15	
Biodiesel Yield			
From Soybean	gal/bu	1.37	
From Soyoil	gal/lb	0.14	
From Biodiesel	gal/lb	0.135	

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APPENDIX C
BIODIESEL CO-PRODUCT

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), but the dominant pathway considered is soybean oil-based biodiesel and this pathway is modeled in GREET. This document discusses the co-products of soybean biodiesel and the allocation method used in GREET for determining co-product credits; the renewable diesel pathway (NERD) and its co-products are not discussed here.

Pressing oil yields protein rich soybean meal valued as 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 GREET model calculates credits for these two co-products based on the energy content ratio of the product stream (see next sections).

Table C-1. Biodiesel and Renewable Diesel 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)	Yellow grease	Glycerin
Renewable Diesel (non esterified)	Soybean oil	Soybean meal, LPG
Renewable Diesel (non esterified)	Canola Oil	Canola meal, LPG
Renewable Diesel (non esterified)	Mustard seed	Seed meal, LPG
Renewable Diesel (non esterified)	Palm oil	Palm meal

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. Life cycle data for substitute co-products are not required as they are when using the substitution method. This simplifies the analysis and eliminates certain uncertainties, however in general, this method is less representative of the real impact of co-products than is the substitution method.

Biodiesel Energy Allocation

Soybean meal and glycerin co-products are accounted for in 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. This is somewhat complicated, because there are subsystem energy allocation factors, for soybean oil extraction, and total system allocation factors based on all products generated. The subsystem allocation factors are used to calculate the adjusted feedstock and feedstock transport life cycle results while the total system allocation factors are applied only to fuel production (oil extraction and transesterification). This will become clearer as you read below about how each component of the life cycle is adjusted to account for co-products and fuel loss.

Allocation and Loss Factor Calculations

Soybean Production and Transport

Life cycle energy and emissions resulting from soybean production and transport, including fuel inputs for farming and fertilizer, herbicide and pesticide use are adjusted using two energy allocation factors, based on subsystem energy ratios.

The first subsystem energy allocation factor is the energy fraction of extracted soybean oil of the total oil and soybean meal product system (Equation 1a shows the ratio in words and 1b shows the actual calculation):

$$\frac{\text{Soybean Oil Energy Content}}{(\text{Soybean Oil Energy Content + Soybean Meal Energy Content})} \qquad (1a)$$

$$\frac{\text{16,000 Btu/lb oil}}{\left[(\text{16,000 Btu/lb oil}) + (\text{4,246 Btu/lb meal})(\text{4.48 lbs meal/lb oil})\right]} = 45.7\% \qquad (1b)$$

Where BD = biodiesel and meal = soybean meal

The second subsystem 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 2a shows the ratio in words and 2b shows the actual calculation):

$$\frac{\text{Biodiesel Energy Content}}{(\text{Biodiesel Energy Content + Glycerin Energy Content})} \qquad (2a)$$

$$\frac{\text{16,149 Btu/lb BD}}{\left[(\text{16,149 Btu/lb BD}) + (\text{7,979 Btu/lb gly})(\text{0.213 lbs gly/lb BD})\right]} = 90.5\% \qquad (2b)$$

Where BD = biodiesel and gly = glycerin

The energy and emissions results for feedstock production and transport are multiplied by these two factors and then by the loss factor for biodiesel, 1.000039, which is based on fuel VOC loss from bulk terminals and refueling station. The loss factor is calculated below (Equation 3) and the adjusted farming energy is shown as an example in Equation 4, based on 161,478 Btu/mmBtu farming energy.

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

Adjusted life cycle energy for soybean farming (not including chemical inputs):

$$(\text{161,478 Btu/mmBtu})(45.7\%)(90.5\%)(1.000039) = \text{66,750 Btu/mmBtu} \qquad (4)$$

Soybean Oil Extraction
Soybean oil extraction and oil transesterification are adjusted using the total system energy allocation factor to account for co-products. This factor is simply the ratio of energy in biodiesel produced to the total energy of biodiesel, soybean meal and glycerin (see Equations 5a and 5b).

$$\frac{\text{Biodiesel Energy Content}}{\text{(Biodiesel Energy Content + Soybean Meal Energy Content + Glycerin Energy Content)}} \quad (5a)$$

$$\frac{16{,}149\ \text{Btu/lb BD}}{\left[16{,}149\ \text{Btu/lb BD} + (7{,}979\ \text{Btu/lb gly})(0.213\ \text{lb gly/lb BD}) + (1.04\ \text{lb oil/lb BD})(4.48\ \text{lb meal/lb oil})(4{,}246\ \text{Btu/lb meal})\right]} = 42.9\% \quad (5b)$$

Where BD = biodiesel, gly = glycerin and meal = soybean meal

Thus, the life cycle energy and emissions associated with soybean oil extraction are multiplied by 42.9% to account for soybean meal production and 1.000039 to account for loss of volatile fuel components throughout the transport system. Equation 6 below shows the total oil extraction energy multiplied by the allocation factor to account for co-products.

(456,881 Btu/mmBtu)(42.9%)(1.000039) = 196,069 Btu/mmBtu (6)

Soybean Oil Transport
Soybean oil transport is not modeled in GREET, but soybean oil has similar properties to biodiesel and therefore biodiesel transport is modeled in GREET for determination of soybean oil transport results in GREET. Only the 90.5% allocation factor (biodiesel to biodiesel + glycerin) and loss factor are used for soybean oil transport energy and emission results because the soybean meal has already been removed from the product system at this point (it is used locally as animal feed). Equation 7 below shows the total soybean oil energy adjusted to account for co-products and multiplied by the biodiesel loss factor.

(18,539 Btu/mmBtu)(90.5%)(1.000039) = 16,774 Btu/mmBtu (7)

Soybean oil Transesterification
Soybean oil transesterification (biodiesel production) energy and emission results are multiplied by the same total system energy factor (42.9%) used for soybean oil extraction and calculated in Section 2.2. Like the other results, the adjusted energy and emissions are multiplied by the biodiesel loss factor, 1.000039. Equation 8 below shows the total transesterification energy adjusted to account for co-products and fuel loss.

(172,127 Btu/mmBtu)(42.9%)(1.000039) = 73,868 Btu/mmBtu (8)

Biodiesel Transport and Distribution

Biodiesel transport involves only the biodiesel being transported, so life cycle energy and emissions don't need to be adjusted with allocation factors.