California Environmental Protection Agency

Air Resources Board

Detailed California-Modified GREET Pathway for Conversion of Midwest Soybeans to Renewable Diesel

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-GREET Pathway for Conversion of Midwest Soybeans to Renewable Diesel

A Well-To-Tank (WTT) fuel cycle analysis of the soybean derived renewable diesel pathway includes all steps from soybean farming to final finished 100% Renewable Diesel. A 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.

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 and combusting renewable diesel 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 Renewable Diesel from Midwest Soybeans used in a Heavy Duty diesel vehicle.

The CA-GREET model calculates the direct impacts from the production and use of renewable diesel. Indirect impacts that could result from the diversion of soybean derived oil to produce renewable diesel has 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, soyoil extraction, renewable diesel production, transport and distribution (T&D) and use of Renewable Diesel in an internal combustion engine. The pathway documented here includes soybean farming and soyoil extraction in the Midwest, followed by transportation of soyoil by rail to California. Renewable diesel produced in California is transported to fueling stations for use in heavy-duty vehicles in California.

Most of the basic inputs, assumptions, and calculation methodology used in this analysis are provided in the soybean to biodiesel (and renewable diesel) technical

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

document from Argonne[2]. The modifications to the CA-GREET include the use of California specific factors (e.g. renewable diesel production, vehicle combustion, etc.). 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 transformed to renewable diesel and transported to blending stations for use in an internal combustion vehicle.

Renewable Diesel in the CA-GREET model is considered as RD II – this process co-produces propane and is similar to the Neste Oil Renewable Diesel production process[4]. Figure 1 below shows the discrete components that form the renewable diesel pathway including farming, transport of soybeans, soyoil extraction and transport, renewable diesel production and distribution to refueling stations and final use in a transportation vehicle.

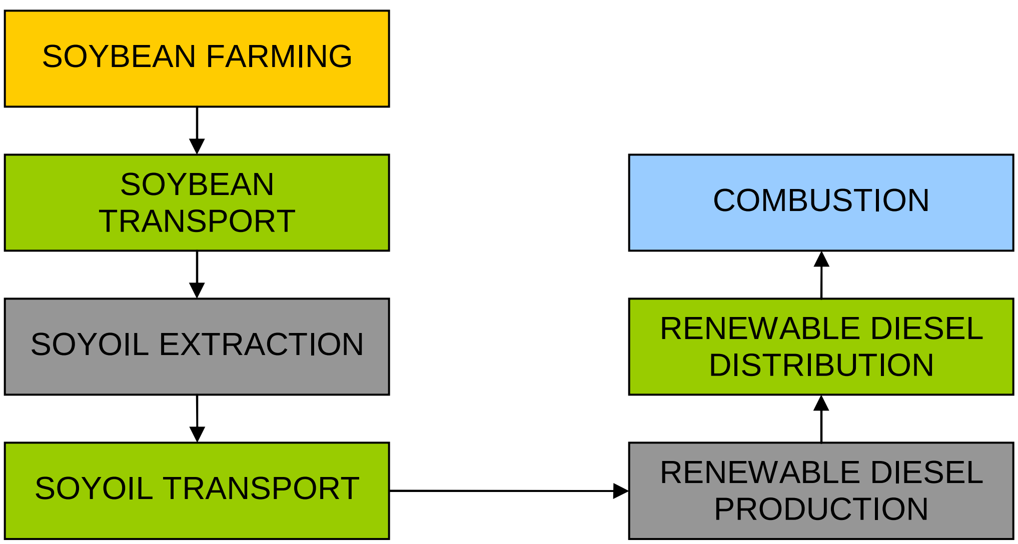

Figure 1. Discrete Components of the Midwest Soybean to Renewable Diesel Pathway.

This document provides detailed calculations, assumptions, inputs and other necessary information to calculate the energy requirements and GHG emissions for the soybean to renewable diesel (RD) pathway. Table A below provides a summary of the energy use

[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
[3] See http://www.arb.ca.gov/fuels/lcfs/lcfs.htm
[4] Neste Oil Technology to produce the Renewable Diesel – presented in 2006 at the Climate Change Technology Symposium Sacramento, California: http://www.climatechange.ca.gov/events/2006-06-27+28_symposium/presentations/Hodge_Cal_NESTE_OIL.PDF

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. Details of co-product methodologies used for this pathway are 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 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 CA-GREET for all energy calculations.

- gCO_2e/MJ provides the total greenhouse gas emissions on a CO_2 equivalent basis per unit of energy (MJ) for a given fuel. Methane (CH_4) and nitrous oxide (N_2O) are

- converted to a CO_2 equivalent basis using IPCC[5] 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 CA-GREET is defined as:

  Efficiency = energy output / (energy output + energy consumed)

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

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[5] 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 for Renewable Diesel Produced from Midwest Soybeans

	Energy Required (Btu/mmBtu)	% Total Energy	GHG Emissions (gCO_2e/MJ)	% Total Emissions
Well to Tank				
Soybean Farming	27,416	2.15%	2.08	10.32%
Fertilizer/Pesticide/Herbicide	20,550	1.61%	1.52	7.54%
N_2O Emissions from Fertilizer Use	n/a	n/a	1.59	7.89%
Soybean Transport	6,518	0.51%	0.50	2.48%
Soyoil Extraction	54,627	4.29%	3.67	18.20%
Soyoil Transport	15,046	1.18%	1.17	5.80%
Renewable Diesel Production	140,142	11.02%	8.19	40.63%
Renewable Diesel Distribution	8,662	0.68%	0.66	3.27%
Total Well to Tank (WTT)	**272,961**	**21.44%**	**19.38**	**96.13%**
Tank To Wheel				
Carbon in Fuel	1,000,000		n/a	n/a
Vehicle CH_4 and N_2O	n/a	n/a	0.78	
Total Tank to Wheel (TTW)	**1,000,000**	**78.56%**	**0.78**	**3.87%**
Total Well to Wheel (WTW)	**1, 272,961**	**100%**	**20.16**	**100%**

From Table A above, a WTW analysis of renewable diesel indicates that **1, 272,961**Btu of energy is required to produce 1 (one) mmBtu of available fuel energy delivered to the vehicle. From a GHG perspective, **20.16** gCO_2e of direct contributions of GHG are released during the production and use of 1 (one) MJ of renewable diesel. 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 **82.16 gCO_2e/MJ**[6].

The values in Table A are illustrated in Figure 2, showing specific contributions of each of the discrete components of the fuel pathway. The charts are shown separately for

[6] 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.

energy use and GHG emissions. From an energy use viewpoint, carbon in fuel (78.56%) dominates the pathway energy use. For GHG emissions, the largest contributions are from renewable diesel production (40.63%), soybean production (includes soybean farming, use of agricultural chemicals and consequent N_2O release) (25.75%), and soyoil extraction (18.20%).

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.

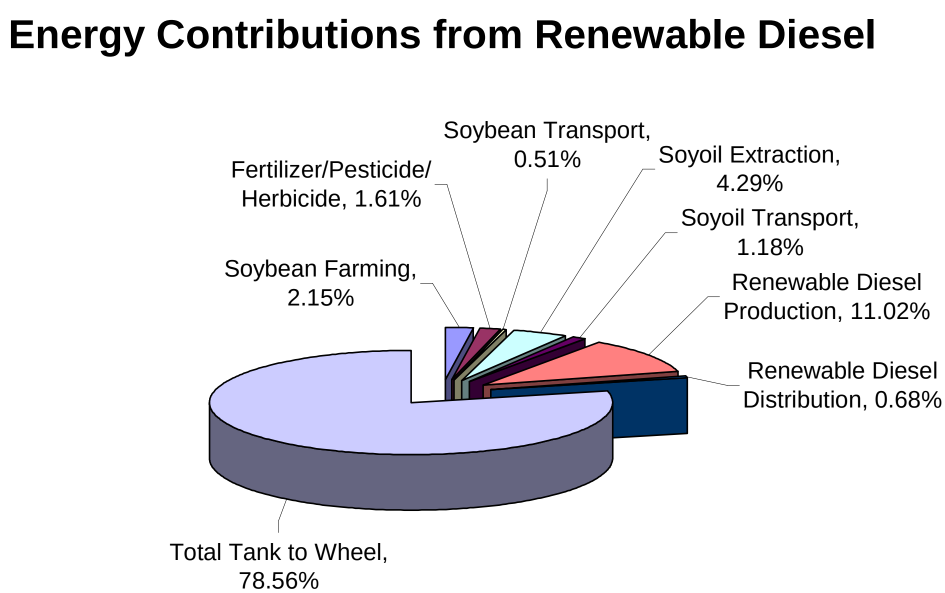

Figure 2. Percent Energy Contributions to a Well-to-Wheel (WTW) Analysis of Renewable Diesel Produced from Midwest Soybeans

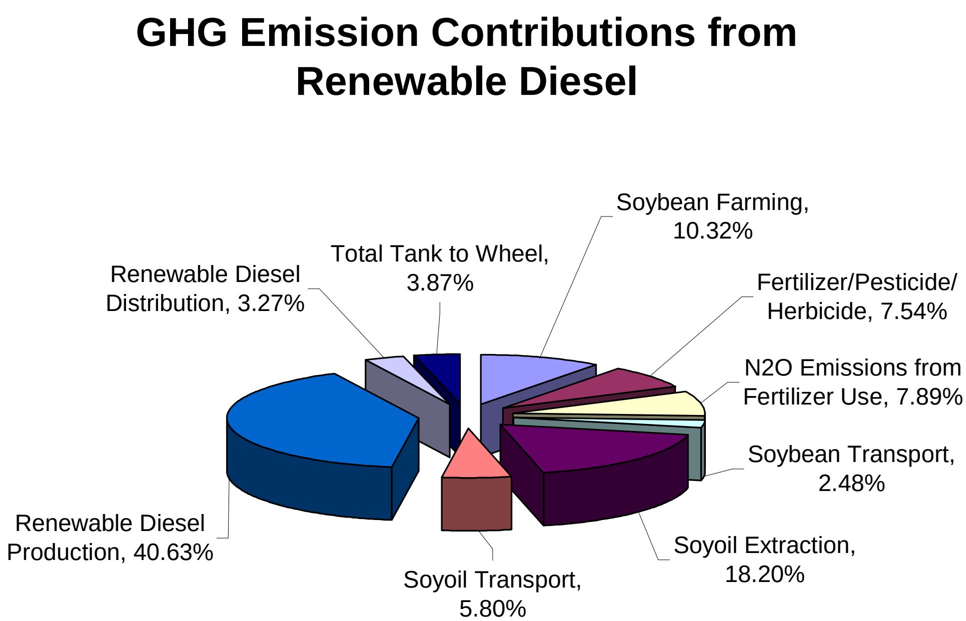

Figure 3. Percent GHG Emissions Contributions to a Well-to-Wheel (WTW) Analysis of Renewable Diesel Produced from Midwest Soybeans

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

WTT Details - Soybean Farming

The renewable diesel production process starts with soybean farming. Table B provides a breakdown of energy use needed for soybean farming. Appendix C provides the details of adjustment and allocation factors for the renewable diesel pathway. In a similar manner, GHG emissions associated with soybean farming are shown in Table C. Complete details are provided in Appendix A.

Table B. Total Energy Use for Soybean Farming

Fuel Type	Energy Use
Diesel (Btu/bu)	16,543
Gasoline (Btu/bu)	4,726
Natural Gas (Btu/bu)	1,725
LPG (Btu/bu)	1,875
Electricity (Btu/bu)	1,696
Total Energy for Soybean Farming (Btu/bu)	**26,564**
Total Energy for Soybean Farming (Btu/mmBtu)	**145,017**
Total Energy with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**27,416**

Table C. Total GHG Emissions from Soybean Farming

GHG Species	GHG Emissions
VOC (gCO_2e/MJ)	0.01
CO (gCO_2e/MJ)	0.11
CH_4 (gCO_2e/MJ)	0.08
N_2O (gCO_2e/MJ)	0.01
CO_2 (gCO_2e/MJ)	1.87
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**2.08**

WTT Details-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

Chemical Inputs	Energy Use
Nitrogen (Btu/bu)	2,805
Phosphate (P_2O_5) (Btu/bu)	2,477
Potash (K_2O) (Btu/bu)	2,730
Herbicides (Btu/bu)	11,756
Pesticides (Btu/bu)	134
Total Energy Consumption (Btu/bu)	**19,912**
Total Energy Consumption (Btu/mmBtu)	**108,699**
Total Energy Consumption with Adjustment and Allocation Factors Applied (Btu/mmBtu)	**20,550**

Table E provides GHG emissions from chemicals input in soybean farming. The fuel consumption and other details are provided in Appendix A.

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

GHG Species	GHG Emissions
VOC (gCO_2e/MJ)	<0.01
CO (gCO_2e/MJ)	<0.01
CH_4 (gCO_2e/MJ)	0.05
N_2O (gCO_2e/MJ)	0.03
CO_2 (gCO_2e/MJ)	1.44
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.52**

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. 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
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.59**

WTT Details-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 (Adjusted, Btu/bu)	**6,315**
Total Energy Use (Adjusted, Btu/mmBtu)	**34,475**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**6,518**

Table H. Total GHG Emissions Soybean Transport

GHG	GHG Emissions
CO_2 (gCO_2e/MJ)	0.48
CH_4 (gCO_2e/MJ)	0.02
N_2O (gCO_2e/MJ)	0.01
CO (gCO_2e/MJ)	<0.01
VOC (gCO_2e/MJ)	<0.01
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**0.50**

WTT Details-Soyoil Extraction

Soyoil is 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	Energy Use
NG (Btu/lb)	2,995
Electricity (Btu/lb)	1,406
N-Hexane (Btu/lb)	203
Total Energy for Soyoil Extraction (Btu/lb)	**4,658**
Total Energy for Soyoil Extraction (Btu/mmBtu)	**288,934**
Total Energy (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**54,627**

Table J. Total GHG Emissions Soyoil Extraction

GHG Species	GHG Emissions
CO_2 (gCO_2e/MJ)	3.35
CH_4 (gCO_2e/MJ)	0.15
N_2O (gCO_2e/MJ)	0.01
CO (gCO_2e/MJ)	<0.01
VOC (gCO_2e/MJ)	0.17
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**3.67**

WTT Details-Soybean Oil Transport

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

Table K. Total Energy Required for Soyoil Transport

Transport (By Rail)	Btu/mmBtu
Total Energy for Rail Transport	**13,685**
Total Energy Use (with Adjustment and Allocation Factors Applied)	**15,046**

Table L. Total GHG Emissions from Soyoil Transport

GHG Species	GHG Emissions
CO_2 (gCO_2e/MJ)	1.13
CH_4 (gCO_2e/MJ)	0.03
N_2O (gCO_2e/MJ)	<0.01
CO (gCO_2e/MJ)	<0.01
VOC (gCO_2e/MJ)	<0.01
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.17**

WTT Details- Renewable Diesel Production via Hydrogenation

Renewable diesel is produced by hydrogenating soyoil in production plants in California. Tables M and N provide energy use and attendant GHG emissions from renewable diesel production, respectively. Details are provided in Appendix A.

Table M. Total Energy Use for Renewable Diesel Production

Fuel or Chemical	Energy Use
NG (Btu/lb)	88
Electricity (Btu/lb)	264
Methanol (Btu/lb)	2,453
Total Energy Use (Btu/mmBtu)	**148,248**
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**140,142**

Table N. Total GHG Emissions from Renewable Diesel Production

GHG Species	GHG Emissions
CO_2 (gCO_2e/MJ)	7.77
CH_4 (gCO_2e/MJ)	0.40
N_2O (gCO_2e/MJ)	0.01
CO (gCO_2e/MJ)	<0.01
VOC (gCO_2e/MJ)	<0.01
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**8.19**

WTT Details-Renewable Diesel Transport and Distribution

Tables O and 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 Renewable Diesel Transport and Distribution

	HD Truck for Transport	**HD Truck for Distribution**
Energy Use with Adjustment and Allocation Factors Applied (Btu/mmBtu)	2,665	5,997
Total Energy Use (with Adjustment and Allocation Factors Applied, Btu/mmBtu)	**8,662**	

Table P. Total GHG Emissions from Renewable Diesel Transport and Distribution

GHG Species	**GHG Emissions**
CO_2 (gCO_2e/MJ)	0.63
CH_4 (gCO_2e/MJ)	0.02
N_2O (gCO_2e/MJ)	<0.01
CO (gCO_2e/MJ)	<0.01
VOC (gCO_2e/MJ)	<0.01
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**0.66**

TTW Details- Renewable Diesel Use in a Compression Ignition Vehicle

The renewable diesel 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 below 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 Vehicles Combusting Renewable Diesel

GHG Species	**GHG Emissions**
CH_4 and N_2O from Vehicle (gCO_2e/MJ)	0.78
Fossil Carbon in RD (gCO_2e/MJ)	0.00
Total TTW GHG Emissions (gCO_2e/MJ)	**0.78**

APPENDIX A

SECTION 1. DETAILED ENERGY CONSUMPTION AND GHG EMISSIONS CALCULATION FOR SOYBEAN FARMING

1.1 Soybean Farming Energy Consumption

The first step in the soybean to renewable diesel 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 (version 1.8b) default value of **22,087**[7] 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	Relationship to 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%

Source: Argonne National Laboratory[8]

[7] 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
[8] 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 of RD, a conversion factor is calculated using values shown in Table 1.03.

Table 1.03. Renewable Diesel Pathway Parameters

Soybean Yield (lb/bushel)	Soybean to Soy Oil (lb soybean/ lb oil)	Soy Oil to RD (lb oil/lb RD)	RD Density (g/gal)	RD LHV (Btu/gal)	RD LHV (Btu/lb)
60	5.28*	1.174**	2,948	122,887	18,925

*2007 USDA data for soybeans and soyoil[9]
**GREET defaults (values obtained from various sources and documented on GREET website)[10]

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 renewable diesel. 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.

[9] Retrieved from USDA website November 2009: http://www.fas.usda.gov/psdonline/psdquery
[10] 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 Renewable Diesel 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*1.0 + 10,926 = 39,212	
Residual 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	$S_{Coal} = 1+ E_{coal}/10^6$
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

<table>
<tr><th>Fuel Type</th><th>Formula</th><th>Description</th><th>Total Btu/bu</th></tr>
<tr><td rowspan="4">Diesel</td><td rowspan="4">$14,224 + 14,224 * (39,212 * 1.0000 + 123,804)/ 10^6$</td><td>14,224 Btu of direct conventional diesel used per bushel soybean. (Table 1.01)</td><td rowspan="4">16,543</td></tr>
<tr><td>energy to recover crude is 39,212 Btu/Btu crude (Table 1.04)</td></tr>
<tr><td>Conventional diesel fuel loss factor is 1.000044 (Table 1.04)</td></tr>
<tr><td>Energy to produce conventional diesel 123,804 Btu/Btu (Table 1.04)</td></tr>
<tr><td rowspan="3">Gasoline</td><td rowspan="3">$3,931 + 3,931 * (39,212 * 1.0008 + 162,914)/ 10^6$</td><td>3,931 Btu of direct conventional gasoline used per bushel soybean (Table 1.01)</td><td rowspan="3">4,726</td></tr>
<tr><td>Conventional gasoline fuel loss factor is 1.0008 (Table 1.04)</td></tr>
<tr><td>Energy to produce gasoline 162,914 Btu/Btu (Table 1.04)</td></tr>
<tr><td rowspan="2">Natural Gas</td><td rowspan="2">$1,612 * (1 + 69,596/ 10^6)$</td><td>1,612 Btu/bu of direct NG use (Table 1.01)</td><td rowspan="2">1,725</td></tr>
<tr><td>Energy to produce NG 69,596 Btu/Btu (Table 1.04)</td></tr>
<tr><td rowspan="7">Liquid Petroleum Gas</td><td rowspan="7">$1,679 * [0.40 * (1+ (39,212* 1.0001 + 75,862)/ 10^6) + 0.60 * ((1+ (69,596* 1.0001 + 48,896)/10^6)]$</td><td>1,679 Btu/bu of direct LPG use (Table 1.01)</td><td rowspan="7">1,875</td></tr>
<tr><td>1.0001 is the petroleum LPG loss factor.</td></tr>
<tr><td>energy to recover crude is 39,212 [1] Btu/Btu crude (Table 1.04)</td></tr>
<tr><td>Energy to produce LPG from crude 75,862 Btu/Btu (Table 1.04)</td></tr>
<tr><td>Energy to produce NG is 69,596 Btu/Btu (Table 1.04)</td></tr>
<tr><td>Energy to produce LPG from NG is 48,896 Btu/Btu (CA-GREET default)</td></tr>
<tr><td>40% of the LPG is from petroleum, 60% is from NG (CA-GREET default)</td></tr>
<tr><td rowspan="3">Electricity</td><td rowspan="3">$641 (85,708 + 2,561,534)/ 10^6$</td><td>641 Btu/bu of direct electricity used (Table 1.01)</td><td rowspan="3">1,696</td></tr>
<tr><td>99,970 Btu of energy used to recover and transport sufficient feedstock to generate 1 mmBtu electricity (Table 1.04)</td></tr>
<tr><td>2,561,534 Btu used as fuel to produce 1 mmBtu electricity (Table 1.04)</td></tr>
<tr><td colspan="3">Total energy for soybean farming, Btu/bushel</td><td>26,564</td></tr>
<tr><td colspan="3">Total energy for soybean farming, Btu/mmBtu = $26,564/60$ lbs/bu*5.28 lbs SB/lb Oil* 1.174 lbs oil/lb RD/18,925 Btu/lb RD * 10^6</td><td>145,017</td></tr>
<tr><td colspan="3">Total adjusted energy due to soybean farming, Btu/mmBtu = 145,017 * 20.0% * 94.5% * 1.000045</td><td>27,416</td></tr>
</table>

Note: Well to tank energies for fuels (crude, NG, LPG, etc.) may be found in the summary section of the relevant fuel tabs of the CA-GREET model.

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a) 5.28 lbs oil/lb soybean, 60 lbs/bu, 1.174 lbs oil/lb RD, and 16,149 Btu/lb RD are from Table 1.03
b) The oil mass share (20.0%) of total oil extraction energy system (including oil and soybean meal) and;
c) the renewable diesel energy share (94.5%) of the overall hydrogenation system (including renewable diesel and propane).
d) 1.000045 is loss factor is GREET calculations

The loss factor is calculated as shown below:

$$1+\frac{0.207\,gVOC/mmBtuRD+0.880\,gVOC/mmBtuRD}{[(2{,}948\,gRD/gal)/(122{,}887\,BtuRD/gal)\times 10^{6}}=1.000045$$

The analysis here uses the mass-based allocation to determine a soybean meal credit and energy allocation to calculate the propane credit. The analysis allocates 20.0% of the farming, soybean transport and oil extraction energy and emissions to renewable diesel and the balance to soybean meal. The feedstock production and renewable diesel production results are allocated based on energy-allocation factors for renewable diesel and propane. The analysis here uses an energy allocation factor of 94.5% and details of this calculation is provided in Appendix C.

The calculations in Table 1.05 above and others rely on Well-to-Tank energy results for all fuels used in the various steps of the renewable diesel pathway. For example, in Table 1.05, the diesel calculation uses values in Table 1.04 for the 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 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

Direct emissions are calculated by multiplying the direct fuel consumption (provided in Table 1.01) by the emission factors in Table 1.06 and summing the results by fuel type (see Table 1.07 below).

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 Emissions	**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 CO_2 emissions is provided in Table 1.09, with emission factors for each fuel 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	$SE_{Res\ Oil} = 1+(EF_C*\text{Loss Factor}_{Crude} + EF_{ResOil})/10^6$
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	$EF_{NG}=(EF_{NG\ Rec} + EF_{NG\ Process})$ *Loss Factor + $E_{T\&D} + EF_{Non-combustion}$ + (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	$E_{NG\ non-combustion}$ = 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 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 + upstream emissions in g/bu, converted to g/mmBtu and Table 1.12 shows the details and the total 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	**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	8.625	32.001	8.336	0.098	7,026
Gasoline	12.026	350.072	2.806	0.027	1,403
Natural Gas	0.415	3.117	4.384	0.016	546
LPG	0.116	0.240	1.091	0.046	703
Electricity	0.071	0.677	0.961	0.005	770
Total Emissions	**21.253**	**386.107**	**17.577**	**0.193**	**10,447**

To convert from g/bu to g/mmBtu: g/bu / 60 lbs/bu x 5.28 lbs SB / lb Oil x 1.174 lbs oil / lb RD / 18,925 Btu / lb RD x 10^6

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 Emissions gCO_2e/MJ**
Diesel	1.631	6.050	1.576	0.019	1,328	1.32
Gasoline	2.274	66.186	0.531	0.005	265	0.37
Natural Gas	0.078	0.589	0.829	0.003	103	0.12
LPG	0.022	0.045	0.206	0.009	133	0.13
Electricity	0.013	0.128	0.182	0.001	146	0.14
Total GHG Emissions	**4.018**	**72.999**	**3.323**	**0.036**	**1,975**	**2.08**

1.3 Energy Consumption Due to Use of Farming Chemicals

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	2,730
Herbicides	43.02	273.26	11,756
Pesticides	0.43	312.43	134
Total Energy Consumption due to Farm Product Use (Btu/bu)			19,912
Total Energy Consumption due to Farm Product Use (Btu/mmBtu)			108,699
Total Adjusted Energy Consumption due to Farm Product Use (Btu/mmBtu, with allocation and loss factors)			**20,550**

Note: Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate
To convert from Btu/bu to Btu/mmBtu: g/bu /60 lbs / bu x 5.28 lbs SB / lb Oil x 1.174 lbs oil / lb RD / 18,925 Btu / lb RD x 10^6
To calculate adjusted energy multiply by 20.0% x 94.5% x 1.000045

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 Emissions
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*	2.026	1.966	0.697	0.541	799	0.94
Phosphate (P_2O_5)	0.349	1.206	1.433	0.013	997	0.99
Potash (K_2O)	0.215	1.135	1.517	0.012	1,175	1.16
Herbicides	0.670	3.563	6.306	0.039	5,016	4.92
Pesticides	0.010	0.049	0.072	0.001	56	0.06
Total	3.269	7.918	10.025	0.606	8,044	8.05
With Allocation and Loss Factors Applied, g/mmBtu:						
Total GHG Emissions (gCO_2e/MJ)	**0.618**	**1.497**	**1.895**	**0.115**	**1,521**	**1.52**

Note: N_2O emissions shown above are limited to those emissions resulting from fertilizer/pesticide/herbicide production and transport emissions.
1) Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate
2) To convert from Btu/bu to Btu/mmBtu:
g/bu / 60 lbs/bu x 5.28 lbs SB / lb Oil x 1.174 lbs oil / lb RD / 18,925 Btu/lb RD x 10^6
3) To calculate adjusted energy:
multiply by 20.0% x 94.5% x 1.000045

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

Parameters	Input or Calculated Values
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	8,871
GHG emissions, gCO_2e/mmBtu, with allocation and loss factors	1,677
GHG emissions, gCO_2e/MJ	**1.59**

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

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

$$\frac{(1{,}624 g/bu)\times(5.28 lbsSB/lbOil)\times(1.174 lbsOil/lbRD)}{(16{,}149 Btu/lbBD)\times(60 lbsSB/bu)}\times 10^6 = \textbf{8,871 gCO}_2\textbf{e/mmBtu}.$$

To calculate adjusted energy: $8{,}871 g/mmBtu \times 94.5\% \times 1.000045 =$ **1,677 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	8,379	26,097	**34,475**
Total Adjusted Energy	Btu/mmBtu	1,584	5,151	
Total Soybean Transport Adjusted Energy, Btu/mmBtu				**6,518**

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:

$$\frac{(1{,}535 + 4{,}780)(Btu/bu) \times (5.28 lbsOil/lbsSB) \times (1.174 lbsOil/lbRD) \times 10^6}{(60 lbsSB/bu) \times (18{,}925 Btu/lbRD)} =$$

34,475 Btu/mmBtu.

To calculate adjusted energy:
(34,475 Btu/mmBtu) x 20.0% x 94.5% x 1.000045 = **6,518 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) x Btu/ton-mile x 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 renewable diesel density and LHV are 2,948 g/gal and 122,887 Btu/gal, respectively. The sample calculations after the table show the calculations for determining the direct, upstream and total adjusted CO_2 emissions. 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 (g/ton)**	**Total Transport**
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)	77,809 (77,912)		
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**)				0.222
CO (**gCO_2e/mmBtu**)				0.906
CH_4 (**gCO_2e/mmBtu**)				0.559
N_2O (**gCO_2e/mmBtu**)				0.014
CO_2 (**gCO_2e/mmBtu**)	**129**			**511**
Total GHGs (gCO_2e/mmBtu)				**531**
Total GHG Emissions (gCO_2e/MJ)	**0.12**	**0.38**		**0.50**

Note: 1.Emission factors (EFs) correspond to trip from feedstock origin to destination and the return trip and are listed in the emission factors (*EF* tab) of CA-GREET model.

Sample calculations for CO_2 in Table above:

Direct CO_2 emission from diesel HDD and Medium HDD trucks

$$\frac{(422.85+72)(g/bu)\times(5.28 lbsSB/lbOil)\times(1.174 lbsOil/lbRD)}{(18{,}925 Btu/lbRD)\times(60 lbsSB/bu)}\times10^6 = \textbf{2,701 g/mmBtu}$$

$$(2{,}701 g/mmBtu)\times(20\%)\times(94.5\%)\times1.000045 = \textbf{511 g/mmBtu}$$

Table 2.03. Upstream Energy Consumption and Emissions from Diesel Production

GHG	g/mmBtu
VOC	8.247
CO	17.603
CH_4	98.09
N_2O	0.147
CO_2	13,257

Sample calculations are shown below for CO_2 emissions calculation for a medium duty truck as shown in Table 2.02:

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:

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

= **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)

$$\frac{(13{,}257 gCO_2/mmBtu)\times(2{,}199 Btu/ton-mile)\times 2 ways\times 10 miles}{10^6} = \textbf{583 gCO}_2\textbf{/ton}$$

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

$$\frac{(3{,}427+583) gCO_2/ton\times(1 ton/2000 lbs)\times 5.28 lbsSB/lbOil\times 1.174 lbsOil/lbRD}{18{,}925 Btu/lb}\times10^6$$

= **657 gCO_2/mmBtu**

(657 gCO_2/mmBtu) x (20.0% oil energy share) x (94.5% biodiesel energy share) x (1.000045) = **129 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 soy oil 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 renewable diesel 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[11]). 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.

[11] 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)			**4,657.6**
Total Energy Consumption for Soyoil Extraction (Btu/mmBtu)			**288,934**
Total Adjusted Energy Consumption for Soyoil Extraction (Btu/mmBtu)			**54,627**

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

Soyoil Extraction Energy:

$$\frac{(4{,}657.62\,Btu/lbOil)\times(1.174\,lbOil/lbRD)\times10^{6}}{18{,}924.93\,Btu/lbRD}$$ = **288,934 Btu/mmBtu**

288,934 Btu/mmBtu x 20.0% x 94.5% x 1.000045 = **54,627 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 were calculated is shown in 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	**4.82**	**0.063**	**0.003**	**0.001**	**163**

Sample calculation of CO_2 above from Natural Gas:

$$\frac{(2{,}800\,BtuNG/lbOil)\times[(50\%\times 58{,}198\,gCO2/mmBtu)+(50\%\times 58{,}176\,gCO2/mmBtu)]}{10^6} =$$

163 g/lb Soyoil

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 3.2)	14.6
		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 3.2).	121.4
		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 3.2).	1.7
		The CO_2 emitted from crude recovery is 3,868 g/mmBtu.	
		1.0001 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	1.427	5.955	22.581	0.062	11,042	
Electricity	0.682	6.638	9.429	0.062	7,506	
N-Hexane	298.696	0.186	1.055	-	124	
Total	300.806	12.779	33.064	0.124	**18,672**	
Total Adjusted Emissions (with Allocation and Loss Factors), g/mmBtu						
Natural Gas	0.270	1.126	4.269	0.012	2,088	
Electricity	0.129	1.255	1.783	0.012	1,419	
N-Hexane	56.473	0.035	0.199	-	23	
Total Adjusted Emissions in gCO_2e/mmBtu						**gCO_2e/MJ**
Natural Gas	0.841	1.769	106.730	3.495	2,088	2.09
Electricity	0.402	1.972	44.568	3.495	1,419	1.39
N-Hexane	176.007	0.055	4.985	-	23	0.19
Total	177.250	3.797	156.283	6.990	**3,530**	**3.67**

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

$$\frac{(301\ g\ /\ lb\ Soy\ Oil)\times(1.17\ lbs\ Soy\ Oil\ /\ lb\ BD)}{(18{,}925\ Btu\ /\ lb\ BD)}\times 10^6 = \mathbf{18{,}672\ g/mmBtu}$$

To calculate CO_2 adjusted energy:

$$18{,}672\ g\ /\ mmBtu \times 20\% \times 94.5\% \times 1.000045 = \mathbf{3{,}530\ gCO_2e/mmBtu}$$

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 renewable diesel production. The rail transport distance (1,400 miles) reflects transport to California. For the CA-GREET RD pathway, appropriate modifications have been made to incorporate soybean oil transport to CA. Note that this approach assumes that soybean oil and renewable diesel 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 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 (94.5%) for soy oil calculated in Section 1.1.

Table 4.01. Parameters and Energy Use for Soyoil Transport

	Units	**Crushing facility to RD 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	**13,685**
***Total Energy**	**Btu/mmBtu**	**15,917**
Total Allocated and Adjusted Energy	**Btu/mmBtu**	**15,046**

*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):

$$518{,}000\,Btu/ton \times \frac{1\,ton}{18{,}925\,Btu/lb \times 2{,}000\,lbs} \times 10^{6}$$ = **13,685 Btu/mmBtu**

Total Energy (Btu/mmBtu, not adjusted) =
(13,685 Btu/mmBtu) x (1 + 0.163 Btu/Btu diesel upstream) = **15,917 Btu/mmBtu**
Total Energy (Btu/mmBtu, adjusted) =
15,917 Btu/mmBtu x 94.5% x 1.000045 = **15,046 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 Soyoil Transport Parameters and Calculations

Transport Leg	**Soybean Crushing Facility to RD Plant**
Mode	Rail
Distance, miles	1,400*
Fuel Burned	Diesel
Energy Intensity, Btu/ton-mile	370
Emission Factors[1], g/mmBtu Fuel Burned	
VOC	59.70
CO	215.00
CH_4	3.940
N_2O	2.00
CO_2	77,664
Direct Emissions, g/mmBtu Fuel Transported	
VOC	0.825
CO	2.971
CH_4	0.054
N_2O	0.028
CO_2	**1,063**
Upstream Emissions, g/mmBtu Fuel Transported	
VOC	0.114
CO	0.243
CH_4	1.355
N_2O	0.002
CO_2	**183**
Total Emissions, including allocation and loss factors g/mmBtu Fuel Transported	
VOC	0.887
CO	3.038
CH_4	1.333
N_2O	0.028
CO_2	**1,188**
Total GHG Emissions (gCO_2e/MJ)	**1.17**

* Rail miles not doubled.

Sample calculations for CO_2 as shown in Table 4.02 above:

Direct CO_2 emission from diesel locomotive:

$$\frac{(2{,}948\,gBD/gal)\times(77{,}664)\,gCO_2/mmBtu\times(370\,Btu/ton-mile)\times 1{,}400\,miles}{(122{,}887\,Btu/galBD\times 454\,g/lb\times 2000\,lbs/ton)} =$$

1,063gCO_2/mmBtu

Upstream CO_2 emission from diesel locomotive:

$$\frac{(2{,}948\,gRD/gal)\times(13{,}257\,gCO_2/mmBtu)\times(370\,Btu/ton-mile)\times 1400\,miles}{(122{,}887\,Btu/gal\times 454\,g/lb\times 2000\,lbs/ton)} =$$

183 gCO_2/mmBtu

Total CO_2 emission adjusted to energy:
(1,063+183) gCO_2/mmBtu x 94.5% x 1.000045 = **1,188 gCO_2/mmBtu**

Similar calculations are performed for VOC, CO, CH_4, and N_2O.

SECTION 5. RENEWABLE DIESEL PRODUCTION

5.1 Energy Calculations for Renewable diesel Production

After the soyoil is extracted and transported, renewable diesel fuel is produced via hydrogenation technology known as the UOP-HDO[12] standalone hydrogenation process for renewable diesel II[13]. The first step in calculating the total adjusted energy consumption is determining the direct energy use. The direct energy consumption is 1,851 Btu/lb of renewable diesel, a CA-GREET default. The process fuel inputs are presented in Table 5.01.

Table 5.01 Direct Energy Consumption for Production of Renewable Diesel

Process Fuel Type	Fuel Shares	Relationship of Renewable diesel Production and Fuel Shares	Direct Energy Consumption, Btu/lb renewable diesel
Natural gas	4.5%	0.045 x 1,851	83
Electricity	7.1%	0.071 x 1,851	132
Hydrogen	88.4%	0.884 x 1,851	1,636
Direct Energy Consumption for Soybean Oil Hydrogenation			**1,851**

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

[12] Renewable Diesel II is produced by UOP hydrogenation technology using a stand alone processing unit to process bio-feedstock (UOP is a company owned by subsidiary of Honeywell International)
[13] H. Huo, M. Wang, C.Bloyd, and V.Putsche – 2008 - *"Life-cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels"* – Argonne National Laboratory

Table 5.02. Total Energy Use from Direct Energy Use for Production of Renewable Diesel

Fuel Type	Formula	Description	Btu/lb RD
Natural gas	83 + 83*(68,910)/10^6	83 Btu/lb RD of direct NG fuel use (Table 5.1). 68,910 is the energy required to recover, process and transport a mmBtu of NG for stationary use	88
Electricity	132* (111,649 + 1,884,989)/ 10^6	132 Btu/lb RD direct electricity use (Table 5.1) 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.	264
Hydrogen	1636*(1,000,000 + 514,341)/ 10^6	1,636 Btu/lb RD direct hydrogen use (Table 5.1) 514,341Btu to produce and transport hydrogen	2,453
Total Energy Consumption for RD Production (Btu/lb)			2,806
Convert to Btu/mmBtu			**148,248**
Total Adjusted Energy Consumption for Renewable Diesel Production (Btu/mmBtu)			**140,142**

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

Total Energy = 2,806 Btu/lb RD / 18,925 Btu/lb x10^6 = **148,248 Btu/mmBtu**

Total Adjusted Energy = 148,248 Btu/mmBtu x 94.5% x 1.000045 = **140,142 Btu/mmBtu**

5.2 GHG Calculations from Renewable Diesel Production

Once the soyoil has been transported to a renewable diesel facility, renewable diesel is produced through hydrogenation. Once again, there are direct emissions resulting from direct fuel consumption and upstream emissions from recovery, processing and transport of these process fuels. The fuels consumed in this stage are natural gas, electricity and hydrogen. 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 the production of renewable diesel are provided in Table 5.03.

Table 5.03. Direct Emissions from Renewable Diesel Production

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas (g/lb RD)	0.000	0.002	0.000	0.000	5
Total Direct Emissions (g/lb RD)	**0.000**	**0.002**	**0.000**	**0.000**	**5**

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 for Renewable Diesel Production

Fuel Type	Formula	Description	gCO_2/lb RD
Natural Gas	83 * (5,050)/10^6	83 Btu/lb RD of direct NG fuel use (Table 5.2)	0
		5,050 g of CO2 are emitted in recovery, processing and transporting 1 mmBtu of natural gas for stationary use	
Electricity	132* (8,277 + 96,250)/ 10^6	132 Btu/lb RD direct electricity use (Table 5.2)	14
		To recover, process and transport fuel to the power plants, 8,277 g of CO2 are emitted per mmBtu of electricity produced	
		Electricity production releases 96,250 g CO2 /mmBtu of electricity	
Hydrogen	1636 * (89,445)/ 10^6	1,636 Btu/lb RD direct hydrogen use (Table 5.2)	145
		Energy to produce hydrogen as a feedstock is 89,445 g CO2/mmBtu	
Total Upstream CO_2 Emissions for Soy Renewable Diesel Production			**159**

Note: As in previous tables, the upstream values shown in the third column of the table may be found in the summary sections of the appropriate fuel sheets in CA-GREET.

Table 5.05. Upstream Emissions from Renewable Diesel Production

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas (g/lb RD)	0.001	0.001	0.011	0.000	0
Electricity (g/lb RD)	0.002	0.008	0.029	0.000	14
Hydrogen (g/lb RD)	0.018	0.049	0.297	0.000	145
Total Emissions (g/lb RD)	**0.021**	**0.057**	**0.336**	**0.001**	**159**

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

Table 5.06. Total GHG Emissions from Renewable Diesel Production

	VOC	CO	CH_4	N_2O	CO_2	GHG Emissions
Total Emissions (Direct + Upstream), g/lb RD						
Natural Gas	0.001	0.003	0.011	0.000	5	
Electricity	0.002	0.008	0.029	0.000	14	
Hydrogen	0.018	0.049	0.297	0.000	145	
Total	0.021	0.059	0.336	0.001	164	
Total Emissions (Direct + Upstream), converted to g/mmBtu RD						
Natural Gas	0.036	0.148	0.567	0.002	276	
Electricity	0.111	0.406	1.532	0.018	730	
Hydrogen	0.977	2.576	15.674	0.015	7,670	
Total	1.124	3.131	17.773	0.035	8,676	
Total Adjusted Emissions (with Allocation & Loss Factors), g/mmBtu						
Natural Gas	0.034	0.140	0.536	0.002	261	
Electricity	0.105	0.384	1.449	0.017	690	
Hydrogen	0.924	2.435	14.817	0.014	7,251	
Total GHG Emissions	1.063	2.959	16.801	0.033	**8,202**	
Total GHG Emissions (gCO_2e/MJ)						**8.19**

SECTION 6. RENEWABLE DIESEL TRANSPORT AND DISTRIBUTION

6.1 Energy Calculations for Renewable Diesel Transport to Retail Stations

The next step in the renewable diesel pathway is transport from the production plant in California to a retail station. Table 6.01 provides the transport assumptions and calculations for this final step.

80% of the renewable diesel is transported by heavy-duty truck 50 miles from the plant to bulk terminal; the remaining 20% is distributed directly from the plant. Renewable diesel is then transported 90 miles by heavy-duty truck from the bulk terminal to refueling stations. 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 transport of renewable diesel. The calculations for transport energy and emissions are similar to that for the soyoil derived biodiesel pathway published on the Low Carbon Fuel Standard website (www.arb.ca.gov\fuels\lcfs\lcfs.htm).

Table 6.01 Transport Parameters and Energy Use for the Transport and Distribution of Renewable Diesel

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

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

6.2 GHG Calculations for Renewable Diesel Transport to Retail Stations

Renewable Diesel 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 provides the direct emissions, upstream emissions (without accounting for mode share), and total emissions, accounting for mode share.

Table 6.02 GHG Emissions from Transport and Distribution of Renewable Diesel

	Plant to Bulk Terminal	**Fuel Distribution**	**Total Transport**
Mode	**HDD Truck**	**HDD Truck**	
Mode Share	80%	100%	
Distance, miles	50	90	
Fuel	Diesel	Diesel	
CO_2 EF, g/mmBtu	77,809 (77,912)	77,912 (77,890)	
Energy Intensity, Btu/ton-mile	1,028	1,028	
GHG Species	**Emissions**	**Emissions**	
Direct Emissions[1] (g/mmBtu)			
VOC	0.082	0.148	
CO	0.420	0.755	
CH_4	0.004	0.008	
N_2O	0.006	0.010	
CO_2	213	**384**	
Upstream Emissions[1] (g/mmBtu)			
VOC	0.0296	0.047	
CO	0.07	0.126	
CH_4	0.310	0.557	
N_2O	0.001	0.001	
CO_2	42	**75**	
Total Emissions[2], (g/mmBtu)			
VOC	0.086	0.047	0.281
CO	0.392	0.126	1.273
CH_4	0.251	0.557	0.816
N_2O	0.005	0.001	0.016
CO_2	204	459	663
GHG Emissions (gCO_2e/mmBtu)	212.7	478.5	691.2
GHG Emissions (gCO_2e/MJ)	**0.20**	**0.46**	**0.66**

[1] Direct and upstream emissions exclude mode share; total emissions accounts for mode share
[2]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.

Sample calculations of CO2 values bolded above:

Direct CO_2 emission from diesel HDD truck:

$$\frac{(2{,}984 gRD/gal)\times(77{,}912+77{,}890)gCO_2/mmBtu\times(1{,}028 Btu/ton-mile)\times 90 miles}{(122{,}887 Btu/gal\times 454 g/lb\times 2000 lbs/ton)} =$$

384 CO_2g/mmBtu

Upstream CO_2 emission from diesel HDD truck:

$$\frac{(2{,}984 gRD/gal)\times 13{,}257 gCO_2/mmBtu\times(1{,}028 Btu/ton-mile)\times 2 ways\times 90 miles}{(122{,}887 Btu/gal\times 454 g/lb\times 2000 lbs/ton)} =$$

75 gCO_2/mmBtu

SECTION 7. GHG EMISSIONS FROM A RENEWABLE DIESEL-FUELED VEHICLE

7.1 Combustion Emissions from Fuel

The CA-GREET model considers only the fossil carbon in fuel (expressed as fully oxidized, gCO_2/mmBtu fuel), since biologically derived fuel carbon originates from the atmosphere and the net greenhouse gas impact is neutral. Because all of the carbon in the fuel is derived from soybeans, there are no fossil CO_2 emissions from the RD vehicle. The biomass derived CO_2 emissions are based on RD fuel properties and are calculated as follows:

Vehicle CO_2 = 0.871 g C/g RD * 2,948 g RD/gal / 122,887 Btu/gal * 44/12 * 10^6 / 1,055
= **72.62** g/MJ

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 7.01. The vehicle energy use, N_2O and CH_4 emission rates and final emissions are shown in Table 7.01.

Table 7.01 Vehicle CH_4 and N_2O Emissions

Parameter	2010 Emissions factor (g/mi)	GWP	GHG (gCO_2e/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

Renewable Diesel Pathway Input Values

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.12	
CO		1.57	
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 RD 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 Renewable Diesel 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			

Parameters	Units	Values	Note
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
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 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

Parameters	Units	Values	Note
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	
Renewable Diesel Production			
Soyoil Extraction			
Soyoil yield	lbs SB/lb Soyoil	5.28	
Soyoil Extraction Efficiency		97.2%	
Soyoil Extraction Energy Share		20.0%	
Energy use	Btu/lb	5,867	
NG used		79.2%	
Large NG Boiler	g/mmBtu	*58,198*	50% usage
Small NG Boiler	g/mmBtu	*58,176*	50% usage
Electricity used		15.6%	
N-Hexane used		5.1%	
Soil Oil Transport			
Mileage travel by rail	miles	1,400	
Energy Intensity	Btu/ton-mile	370	
Soyoil Hydrogenation			
Soyoil Hydrogenation		94.5%	
Energy use	Btu/lb	2,116	
NG used		4.5%	
Large NG Boiler	g/mmBtu	*58,198*	50% usage
Small NG Boiler	g/mmBtu	*58,176*	50% usage
Electricity used		7.1%	
Methanol used		88.4%	
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	
LPG	75,862		
Natural Gas	83,868	2,651	
Still Gas	128,590		
Soybean Transportation Cargo Capacity			
Medium Duty Truck	tons	8	
Heavy Duty Truck	tons	15	
Renewable Diesel Yield			
From Soybean	gal/bu	1.49	
From Soyoil	gal/lb	0.14	
From Soydiesel	gal/lb	0.135	

APPENDIX C
CO-PRODUCT AND LOSS FACTOR

Co-Product Allocation Methodology for Soyoil Derived Renewable Diesel

Biodiesel, consisting of fatty-acid methyl esters (FAME), and non-ester renewable diesel are produced using plant-derived oils. There are a variety of potential feedstock oils (see table C-1), but the pathway detailed here is soybean oil-based renewable diesel. This Appendix discusses the co-products of soybean renewable diesel and the allocation method used in CA-GREET for determining co-product credits.

Table C-1. Renewable Diesel Co-Products

Fuel	Feedstock	Co-products
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

Pressing oil yields protein rich soybean meal valued as animal feed. Hydrogenation of the processed oil yields renewable diesel and propane, the latter which can be used as an energy source within the refinery or sold for use as propane in other applications. 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 component and energy based allocation has been used for the renewable diesel/propane 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 apportioning, the impacts of soybean farming to soybean meal and soyoil approximately works out to 80% being allocated to soybeans and 20% to soyoil[14]. Using this information, all relevant GHG emissions attributable to soybean farming up to soyoil extraction are apportioned to 20% to the biodiesel pathway analysis.

[14] 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.

Renewable Diesel Energy Allocation

The propane 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 renewable diesel to the energy ratio of renewable diesel to the total renewable diesel plus propane product system (Equation 1a shows the ratio in words and 1b shows the actual calculation):

$$\frac{Renewable\_Diesel\_Energy\_Content}{(Renewable\_Energy\_Content + Propane\_Energy\_Content}$$

$$\frac{\text{Biodiesel Energy Content}}{\text{(Biodiesel Energy Content + Glycerin Energy Content)}} \quad (1a)$$

$$\frac{18{,}925 Btu/lbRD}{18{,}925 Btu/lbRD + (18{,}568 Btu/lb Propane \times 0.059 lbs Propane/lbRD)} = 94.5\% \quad (1b)$$

where RD = renewable diesel