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California Environmental Protection Agency

Air Resources Board

Detailed California-modified GREET Pathway for Conversion of North American Canola to Biodiesel (Fatty Acid Methyl Esters-FAME)

Stationary Source Division

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Preliminary draft version developed by Alternative Fuels Section of the California Air Resources Board for the Low Carbon Fuel Standard Methods 2A-2B Process

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

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SUMMARY

DETAILED CALIFORNIA-MODIFIED GREET PATHWAY FOR CONVERSION OF NORTH AMERICAN CANOLA TO BIODIESEL (FATTY ACID METHYL ESTERS-FAME)

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

A Life Cycle Analysis Model called the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (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 canola to producing biodiesel and combusting biodiesel in an internal combustion engine. Staff 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 (v1.8b, released December 2009) forms the basis of this document. It has been used to calculate the energy use and Greenhouse Gas (GHG) emissions associated with a WTW analysis for Biodiesel from the North American Canola used in a Heavy Duty diesel vehicle. Many of the calculation methodology as well as the basic inputs, assumptions used in the canola to biodiesel analysis are provided in the soybean to biodiesel analysis (and renewable diesel) technical document from Argonne[2]. The modifications to the CA-GREET include the use of California specific factors such as transportation and distribution.[3]

The pathway described here includes canola farming, canola transport, canola oil extraction, transportation of canola oil, biodiesel production, transport and distribution (T&D) and use of biodiesel in an internal combustion engine. The tailpipe emissions from the combustion of biodiesel are assumed to be the same as the corresponding emissions from the combination of Ultra Low Sulfur Diesel (ULSD), and are presented as such in this document. Canola BD production is assumed to be identical to soybean biodiesel production which was published in December 2009 pathway document[4]. To summarize, the North American canola biodiesel pathway includes canola farming and canola oil extraction in Canada, followed by transportation of canola oil to the U.S.

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[1] Argonne National Laboratory (2008). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. http://greet.es.anl.gov/main

[2] "Argonne National Laboratory (2008). "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels": http://www.transportation.anl.gov/pdfs/AF/467.pdf

[3] ARB (2009) Lifecycle Analysis (CA-GREET): http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

[4] ARB (2009) Soybean to BD pathway document: http://www.arb.ca.gov/fuels/lcfs/121409lcfs_soybd.pdf

Canola oil is then transesterified to biodiesel and transported to blending stations for use in an internal combustion vehicle in California. The Canadian canola production is about 95 percent of the total North American production.[5] For this reason the scenario presented here assumes that the farming and the oil extraction to be done in Canada and the oil shipped to the U.S. facilities for biodiesel production and shipping to California.

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

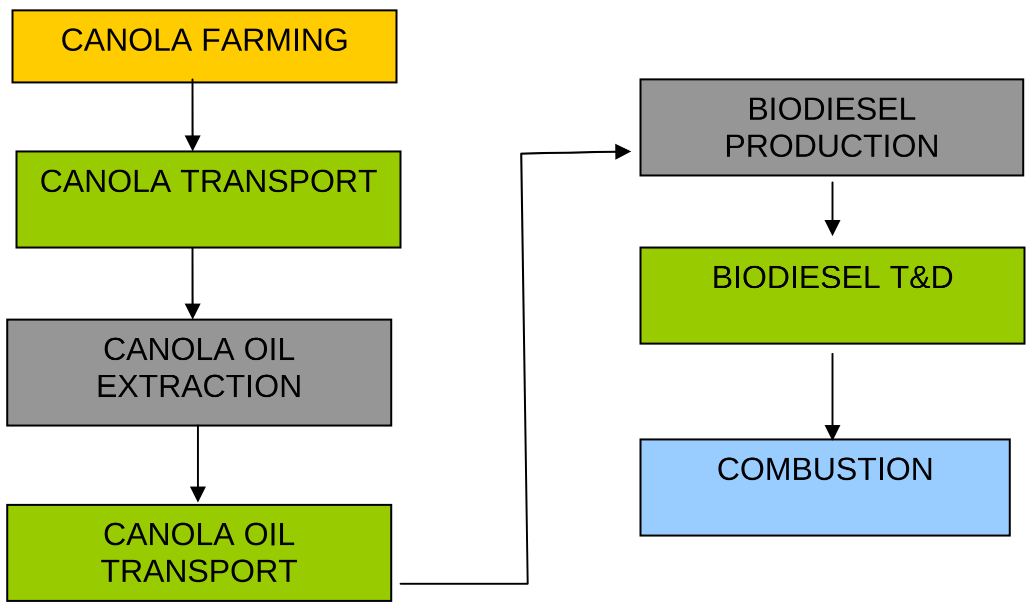

Figure 1. Discrete Components of the North American Canola to Biodiesel Pathway.

This document provides detailed calculations, assumptions, inputs and other necessary information to calculate the energy requirements and GHG emissions for the canola to biodiesel pathway. Table 1 below provides a summary of the energy use and GHG emissions per MJ of fuel produced. Expanded details are provided in Appendix A. Input values used in calculations are shown in Appendix B. A description of the co-product allocation methodology used in the analysis is provided in Appendix C.

The analysis that follows uses conventions and technical terms with specific meanings that are defined here:

- The "Canola Region" includes the canola growing and processing regions in Southern provinces of Canada and the Northern tier states of the U.S. (Figure 2)[6]

[5] U.S.D.A., Foreign Agricultural Services website: http://www.fas.usda.gov/psdonline/psdResult.aspx
[6] Canola Council of Canada website: http://www.canolacouncil.org/gallery/726/canola_growing_region_map.aspx

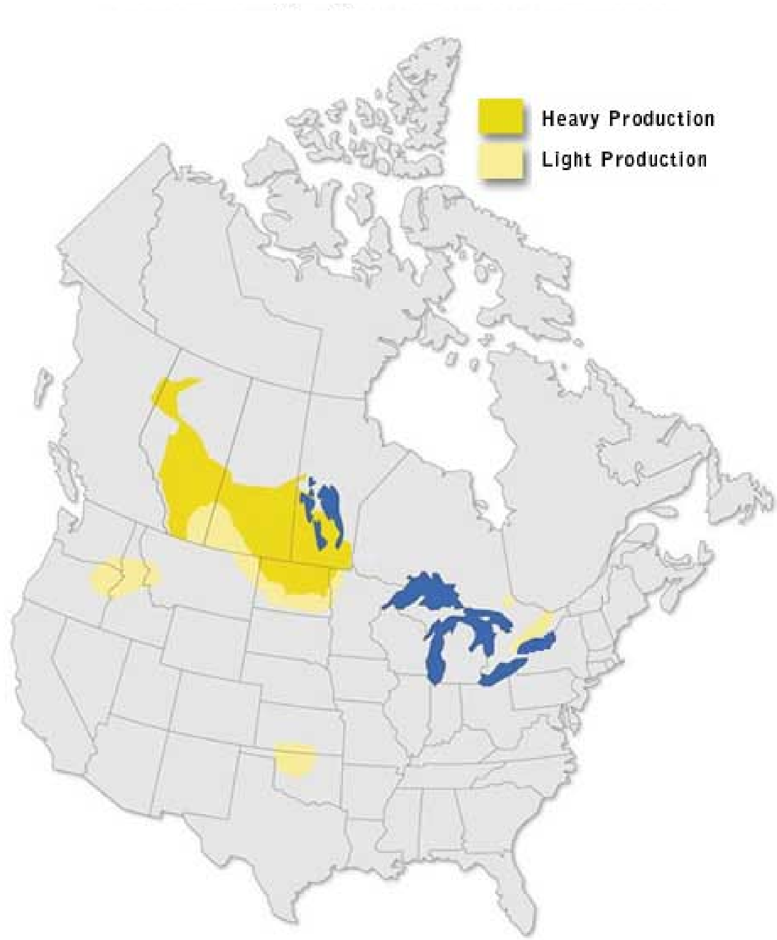

Figure 2. Canola Growing Regions of Canada and the U.S.

- 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 GREET for all energy calculations. MMBTU, mmBTU, mmbtu or any other variation of this unit, if found in this document are synonymous.

- 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[7] 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.

- The input values extracted from reference material may have been in different units than what is used in this document. For example, if a fertilizer value was in kilogram per hectare (kg/ha), we used the standard conversion factors to convert this value to gram per acre (g/ac).

- 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.

[7]. United Nations Intergovernmental Panel on Climate Change (IPCC): Solomon and et al. (2007). In 2007, the IPCC values for GHG equivalence (gCO2e/MJ) are: CH4 = 25, N2O = 298, CO2 = 1. For others GHG, GREET calculates molecular weight of carbon to obtain the GHG equivalence (gCO2e/MJ): VOC = 0.85/0.27 = 3.12 and CO = 0.43/0.273 = 1.57

Table 1. Summary of Energy Consumption and GHG Emissions from a WTW Analysis of Biodiesel Produced from Canadian Canola

	Energy Required (BTU/MMBTU)	**Share of Total Energy (%)**	**GHG Emissions (gCO_2e/MJ)**	**Share of Total Emissions (%)**
Well-to-Tank (WTT)				
Canola Farming	26,687	1.99%	2.08	6.49%
Agricultural Chemicals Production	72,345	5.39%	4.87	15.23%
N_2O Emissions from Fertilizer Use	N/A	N/A	9.50	29.71%
Canola Transport	6,358	0.47%	0.49	1.53%
Canola Oil Extraction	41,201	3.07%	2.65	8.28%
Canola Oil Transport	15,206	1.13%	1.18	3.69%
Biodiesel Transesterification	159,604	11.90%	5.20	16.27%
Biodiesel Transport & Dist.	20,280	1.51%	1.56	4.89%
Total WTT	**341,680**	**25.47%**	**27.54**	**86.09%**
Tank -to- Wheel (TTW)				
Carbon in Fuel	1,000,000	74.53%	N/A	N/A
Fossil Carbon in Fuel	N/A	N/A	3.67	11.47%
Vehicle CH_4 and N_2O	N/A	N/A	0.78	2.44%
Total TTW	1,000,000	74.53%	4.45	13.91%
Total Well-to-Wheel (WTW)	**1,341,680**	**100%**	**31.99**	**100%**

From Table 1 above, a WTW analysis of biodiesel indicates that **1,341,680** BTU of energy is required to produce one MMBTU of available fuel energy delivered to the vehicle. From a GHG perspective, **31.99 gCO2e** of direct contributions GHG are released during the production of one MJ of biodiesel. The ARB indirect land use change impacts for canola biodiesel using the GTAP analysis is pending. Although the federal Environmental Protection Agency's (EPA) indirect land use change analysis uses different methodology and models compared to ARB, staff recommends using the EPA Renewal Fuel Standards 2 (RFS2) international land use change mean value of **31 gCO_2e/MJ**[8], until ARB completes the canola to biodiesel GTAP analysis. Using this value, the total carbon intensity for canola biodiesel derived from canola seeds is **62.99 gCO_2e/MJ**.

8 Federal Register / Vol. 75, No. 187 / Tuesday, Sept. 28, 2010 / Rules and Regulations, TABLE II–1 —LIFECYCLE GHG EMISSIONS FOR CANOLA OIL BIODIESEL, pages.59628-9.

The values provided in Table 1 have been adjusted, by applying adjustments and allocation factors to all the input values. For energy calculations, all energy values were adjusted with a credit to glycerin and oil mass share. The following formulas explain how the total energy used in canola farming of 22,089 BTU/bu is adjusted to the final value of 26,677 BTU/MMBTU.

Conversion from BTU/bushel to BTU/MMBTU:

$$\frac{22{,}089 BTU/bu \times 2.34 lbsCanola/lbsOil}{50 lbsCanola/bu} \times \frac{1.026 lbsOil/lbBD}{16{,}149 Btu/lbBD} \times 10^6 = 65{,}560 \text{ BTU/MMBTU}$$

Adjust energy with credit to glycerin and oil mass share:

$$65{,}560 Btu/mmBtu \times 42.8\% \times 95.1\% \times 1.000039 = 26{,}687 \text{ BTU/MMBTU}$$

where:

a) 2.34 lbs of canola/lb canola oil, 50 lbs/bu, 1.026 lbs oil/lb BD, and 16,149 BTU/lb BD are shown in Table A-3. Biodiesel Pathway Parameters, in Appendix A
b) The oil mass share from total oil extraction energy system, including oil and canola meal is equal to 42.8 percent. See Appendix C for complete details.
c) The biodiesel energy share is equal to 95.1 percent of the overall transesterification system, including biodiesel and glycerin. See Appendix C for complete details)
d) 1.000039 is loss factor in GREET calculations and is detailed below. The loss factor is the amount credited to biodiesel production for material losses incurred in the production process.

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

The analysis here uses the mass-based allocation to determine a canola meal credit and energy allocation to calculate the glycerin credit. The analysis allocates 42.8 percent of the farming, canola transport and oil extraction energy and emissions to biodiesel and the balance to canola meal. The feedstock production and oil transesterification results are allocated based on energy-allocation factors for biodiesel and glycerin. The analysis here uses an energy allocation factor of 95.1 percent and details of this calculation are provided in Appendix C.

Some additional assumptions used for the North American canola biodiesel scenario.

- For energy calculations we selected the CA-GREET's U.S. average option for energy use, since GREET does not have the Canadian average.

- We input the canola data into CA-GREET, not the GHGenius model for Canadian fuels.

- For fertilizers, there are N_2O emissions resulting from the use of nitrogen based fertilizers. The Intergovernmental Panel on Climate Change (IPCC) has estimated average N_2O emissions based on nitrogen application in soil and the model uses this value to estimate N_2O emissions from the use of fertilizers. For N_2O emissions, to be consistent with previous pathways, we use the IPCC default value of 1.325 percent, referenced from an Argonne study for soybean-derived biodiesel.[9] The Report by the Canola Council of Canada uses 0.76 percent from a study in Canada.[10]

- Sulfur is required as an essential fertilizer for canola farming. We did not include this in our analysis, lacking production emissions data in GREET. We will do further research and seek public comment for including sulfur input at later date.
- The transportation distances from the canola oil extraction facility to the biodiesel plant and subsequently to California by rail is assumed to be a total of 2,000 miles. In this analysis, we assumed 1,200 miles from the canola oil extraction facility to the biodiesel plant and 800 miles for shipping of biodiesel by rail to California. (Switching the 1,200 miles and the 800 miles for the two sections of the rail journey results in no net change in the CI value, if any). It is assumed that 80% of the BD is transported by heavy duty truck 50 miles from the railyard to a bulk terminal; the remaining 20% is stored in a bulk terminal next to the railyard, and distributed directly. The BD is then transported 90 miles by heavy duty truck from the bulk terminal to refueling stations.
- The CA-GREET model 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. However for ease of use of the readers, some intermediate values in the Tables provided 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 the upper sections of tables in this document.
- The values in Table 1 are pictorially represented in Figure 2, showing specific contributions of each of the discrete components of the fuel pathway. Energy use and GHG emissions are shown in separate charts. From an energy use viewpoint, carbon in fuel is about 74.53 percent and dominates the pathway energy use. For GHG emissions, the largest contribution is from N_2O release (29.63 percent), BD transesterification (16.29 percent), and agricultural chemical production (15.24 percent).

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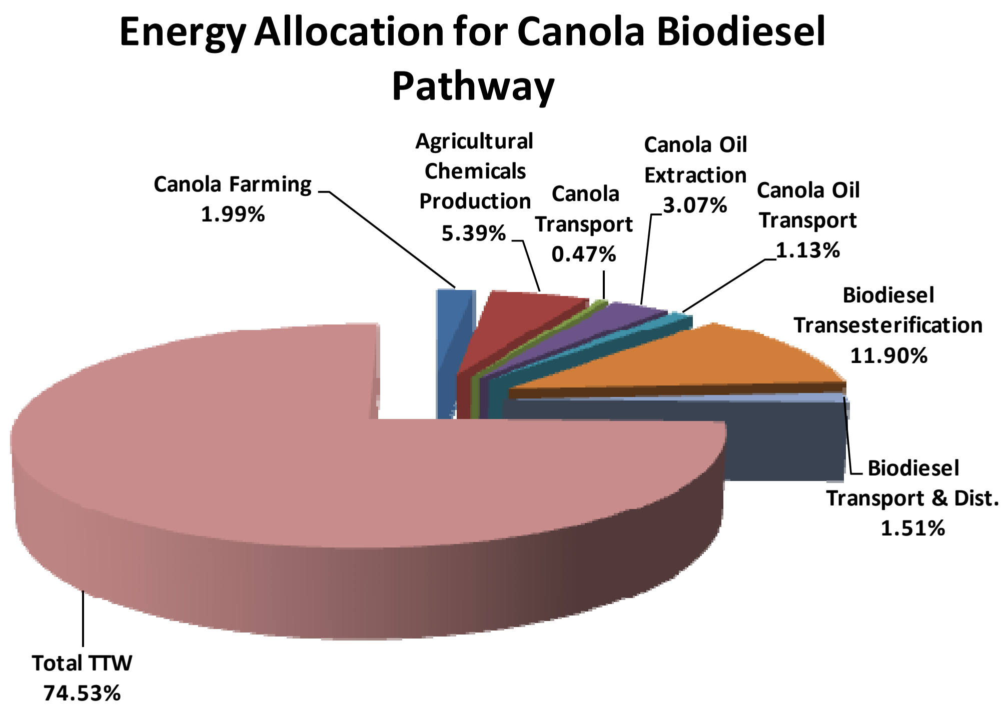
[9] Argonne National Laboratory (2008). "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels". p. 18
http://www.transportation.anl.gov/pdfs/AF/467.pdf

[10] P. Rochette et al. Canadian Journal of Soil Science (2008). "Estimation of N_2O emissions from agricultural soils in Canada. Development of a country-specific methodology".



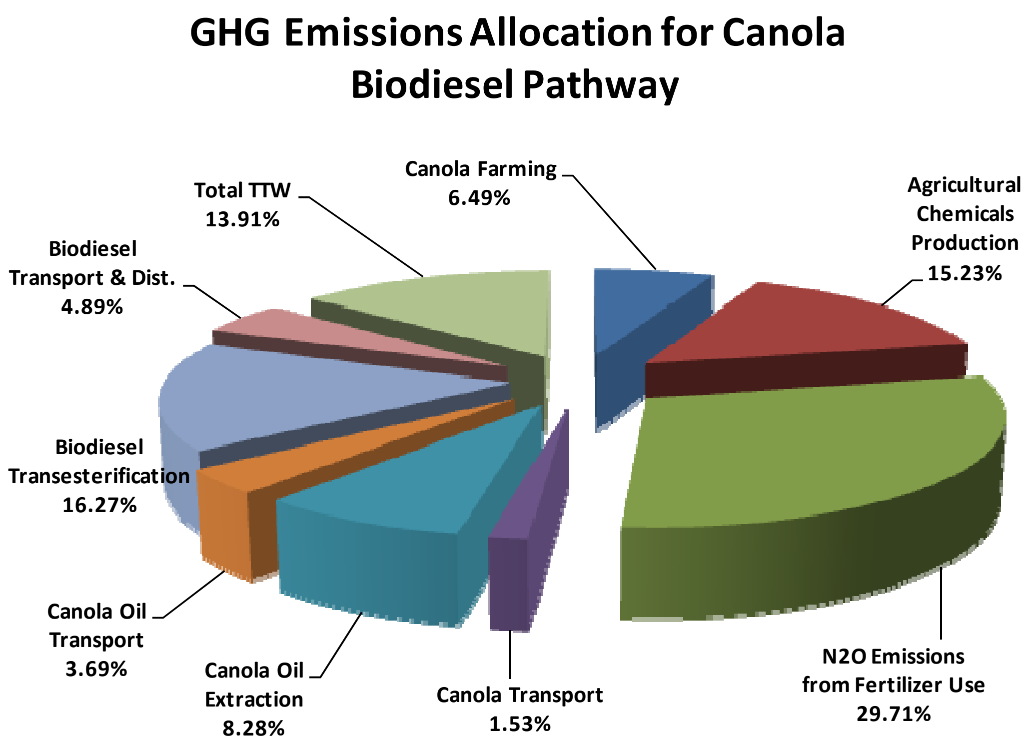


Figure 3. Percent Energy Contribution and GHG Emissions Contributions from a Well-to-Wheel (WTW) Analysis of the Canola to Biodiesel Pathway

The following sections provide a summary of the components that form the full canola biodiesel pathway. Details are provided in Appendix A.

WTT Details

Canola Farming

The biodiesel production process starts with canola farming. Table 2 provides a breakdown of energy use needed for canola farming. Complete details are provided in Appendix A. The input values used in the analysis are presented in Appendix B. Appendix C provides detail on the allocation factors for the biodiesel pathway. In a similar manner, the GHG emissions associated with canola farming are shown in Table 3 below. Details including calculations are provided in Appendix A.

Table 2. Total Energy Use for Canola Farming

Fuel Type	Energy Use
Diesel (BTU/bushel)[a]	18,332
Electricity (BTU/bushel) [a]	3,757
Total Energy Use (BTU/bushel)	**22,089**
Total Energy Use (BTU/MMBTU)	**65,560**
Total Energy Use (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**26,687**

[a] *(S&T)[2] Consultants. Report prepared for Canola Council of Canada, (March 2010). "Canola LCA Data."*

Table 3. Total GHG Emissions from Canola Farming.

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	2,101
CH_4 (gCO_2e/MMBTU)	63
N_2O (gCO_2e/MMBTU)	8
CO (gCO_2e/MMBTU)	13
VOC (gCO_2e/MMBTU)	7
Total GHG Emissions (gCO_2e/MMBTU)	**2,192**
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**2.08**

Chemical Inputs in Canola Farming

Table 4 shows the energy necessary for the production of chemicals used in canola farming. The agricultural chemicals include fertilizers, herbicides and insecticides. A detailed breakdown of chemical inputs utilized in the calculations is provided in Appendix A.

Table 4. Total Energy Consumed for Chemical Inputs in Canola Farming

Inputs	Energy Use
Nitrogen (BTU/bu)[a]	52,117
Phosphate (P_2O_5) (BTU/bu) [a]	4,035
Potash (K_2O) (BTU/bu) [a]	1,914
Herbicides (BTU/bu) [a]	1,417
insecticides (BTU/bu) [a]	422
Total Energy Consumption (BTU/bu)	**59,904**
Total Energy Consumption (BTU/MMBTU)	**177,794**
Total Energy Consumption (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**72,345**

[a] United Nations Food and Agriculture Organization. www.fao.org/ag/agl/fertistat

Table 5 provides GHG emissions from chemicals input in canola farming. Details are provided in Appendix A.

Table 5. Total GHG Emissions for Chemical Inputs in Canola Farming

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	4,337
CH_4 (gCO_2e/MMBTU)	95.8
N_2O (gCO_2e/MMBTU)	665.7
CO (gCO_2e/MMBTU)	14.0
VOC (gCO_2e/MMBTU)	26.8
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**4.87**

CA-GREET also calculates direct field and downstream N_2O emissions resulting from nitrogen fertilizer input. Agricultural N_2O emissions result from the 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 but not chemically bound. 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 inputs are significant components of agricultural emissions associated with canola cultivation. The CA-GREET model includes the impact of agricultural N_2O release and these impacts are summarized in Table 6 below. Details on N_2O impact estimation are provided in Appendix A.

Table 6. Total GHG Emissions from N_2O Release Due to Fertilizer Application

GHG Species	GHG Emissions
GHG emissions, gCO_2e/MMBTU	24,632
GHG emissions, gCO_2e/MMBTU, with allocation and loss factors	10,027
GHG Emissions from N_2O Release (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**9.50**

Canola Transport

In the CA-GREET model used here, canola is transported 10 miles from the field to the stack by medium duty truck and 40 miles from the stack to a canola oil extraction plant in the Canola Region by heavy duty truck. Details of this transport-related energy use are shown in Table 7. The GHG emissions generated by this transport are summarized in Table 8. The calculations behind the values in Table 7 and Table 8 are provided in Appendix A.

Table 7. Total Energy Required for Canola Transport

Locations	Energy Use
Field to Stack (BTU/bu)	1,279
Stack to Plant (BTU/bu)	3,984
Total Energy Use (BTU/bu)	**5,263**
Total Energy Use (BTU/MMBTU)	**15,620**
Total Energy Use (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**6,358**

Table 8. Total GHG Emissions from Canola Transport

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	498
CH_4 (gCO_2e/MMBTU)	13.6
N_2O (gCO_2e/MMBTU)	4.0
CO (gCO_2e/MMBTU)	1.4
VOC (gCO_2e/MMBTU)	0.7
Total GHG Emissions (gCO_2e/MMBTU)	**518**
Total GHG Emissions(with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**0.49**

Canola Oil Extraction

The energy use and attendant GHG emissions associated with canola extraction are shown in Table 9 and Table 10 respectively. Default CA-GREET used for canola oil extraction are identical to the values used in the ARB's soybean biodiesel pathway.[11] The calculations behind the values in these tables are shown in Appendix A.

Table 9. Total Energy Use for Canola Oil Extraction

Fuel Type	Energy Use
NG (BTU/lb)	1,077
Electricity (BTU/lb)	471
N-Hexane (BTU/lb)	46
Total Energy Use (BTU/lb)	**1,594**
Total Energy Use (BTU/MMBTU)	**101,215**
Total Energy Use (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**41,201**

Table 10. Total GHG Emissions from Canola Oil Extraction

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	2,671
CH_4 (gCO_2e/MMBTU)	118.6
N_2O (gCO_2e/MMBTU)	5.8
CO (gCO_2e/MMBTU)	2.9
VOC (gCO_2e/MMBTU)	1.0
Total GHG Emissions (gCO_2e/MMBTU)	**2,799**
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**2.65**

Canola oil Transport

Following extraction, the canola oil is transported by rail to the US biodiesel plants and the finished biodiesel fuel is shipped to California. The energy used for transport and the associated GHG emissions are shown in Table 11 and Table 12.

Table 11. Total Energy Required for Canola Oil Transportation

Transport (By Rail)	Energy Use
Total Energy for Transport (BTU/MMBTU)	15,988
Total Energy Use (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**15,206**

[11] ARB (2009) Soybean to BD pathway document: http://www.arb.ca.gov/fuels/lcfs/121409lcfs_soybd.pdf

Table 12. Total GHG Emissions from Canola Oil Transportation

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	1,189
CH_4 (gCO_2e/MMBTU)	33.3
N_2O (gCO_2e/MMBTU)	8.4
CO (gCO_2e/MMBTU)	4.8
VOC (gCO_2e/MMBTU)	2.8
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.18**

Biodiesel Production via Transesterification

The canola oil is transesterified in plants in the U.S. to produce biodiesel. Table 13 and Table 14 provide energy use and attendant GHG emissions from transesterification respectively. Details are provided in Appendix A.

Table 13. Total Energy Use for Biodiesel Transesterification

Fuel or Chemicals	Energy Use [a]
NG (BTU/lb)	950
Electricity (BTU/lb)	93
Methanol (BTU/lb)	1,354
Sodium Hydroxide (BTU/lb)	42
Sodium Methoxide (BTU/lb)	209
Hydrochloric Acid (BTU/lb)	63
Total Energy Use (BTU/lb)	**2,711**
Total Energy Use (BTU/MMBTU)	**167,878**
Total Energy Use (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**159,604**

[a] ARB (2009) Soybean to BD pathway document: *http://www.arb.ca.gov/fuels/lcfs/121409lcfs_soybd.pdf*

Table 14. Total GHG Emissions from Biodiesel Transesterification

GHG Species	GHG Emissions
CO_2 (gCO_2e/MMBTU)	4,710
CH_4 (gCO_2e/MMBTU)	17.19
N_2O (gCO_2e/MMBTU)	0.06
CO (gCO_2e/MMBTU)	3.65
VOC (gCO_2e/MMBTU)	1.77
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**5.20**

Biodiesel Transport and Distribution

Table 15 and Table 16 show the respective energy use and GHG emissions from transporting biodiesel to California.

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

- BD is transported 800 miles by rail to a railyard in CA.
- 80% transported 50 miles by heavy duty diesel truck (HDD) from railyard in CA to a bulk terminal, while the 20% remaining is stored at bulk terminal next to the railyard.
- 100% distributed 90 miles by heavy duty truck in CA.

Complete details are provided in Appendix A.

Table 15. Total Energy Use for Biodiesel Transport and Distribution

	Plant by Rail to a California Railyard	**HD Truck from Railyard to Bulk Terminal**	**HD Truck for Distribution**
Total Energy Use (BTU/MMBTU)	10,659	2,960	6,661
Total Energy Use (with Adjustment and Allocation Factors Applied, BTU/MMBTU)	**20,280**		

Table 16. Total GHG Emissions from Biodiesel Transport and Distribution

GHG Species	**GHG Emissions**
CO_2 (gCO_2e/MMBTU)	1,645
CH_4 (gCO_2e/MMBTU)	1.82
N_2O (gCO_2e/MMBTU)	0.04
CO (gCO_2e/MMBTU)	3.65
VOC (gCO_2e/MMBTU)	0.96
Total GHG Emissions (with Adjustment and Allocation Factors Applied, gCO_2e/MJ)	**1.56**

TTW Details

Biodiesel use in a Heavy Duty Vehicle

The biodiesel is then modeled as being used in a heavy duty vehicle in California. The factors used here are the same as that for a heavy duty diesel truck using ULSD. Table 17 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 17. Total GHG Emissions from Using Biodiesel in a Heavy Duty Vehicle

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

APPENDIX A

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

1.1 Canola Farming Energy Consumption

The first step in the canola to biodiesel pathway is the cultivation of canola. There are two main components of the farming step: direct farming and fertilizer, insecticide, herbicide use. The input values are for farming in Canada. Each of the components is discussed in this section.

This pathway assumes that farming occurs in the Canola Region in Canada and the U.S. But the majority of the feedstock for canola biodiesel is supplied by Canada. For example, in the 2008/2009 production year, Canada produced 12.4 million tons of canola on 6.4 million hectares, whereas the US produced about 0.66 million tons in an area 0.40 million hectares (about five percent of the Canadian production[12]). Because the Southern Canadian provinces and North Dakota in the U.S. occupy similar agro-climatic zone, this analysis assumes that Canadian and American canola farming practices are similar. Most North American canola is grown in this region[13]

Canola direct farming energy use is specified in units of BTU/bushel. The total energy consumption is split into two different fuel types, resulting in direct energy consumption of 17,182 BTU/bushel as shown in Table A-1. The analysis assumes the U.S. average power generation region in the CA-GREET model for feedstock production, which consists of U.S. petroleum and U.S. average electricity. Table A-2 shows the U.S. average electricity mix.

Table A-1. Direct Energy Consumption for Canola Farming

Process Fuel Type	Fuel Shares	Fuel Shares Calculations	Direct Energy Consumption, BTU/bushel
Diesel	0.9174	0.9174*17,182	15,763
Electricity	0.0826	0.0826*17,182	1,419
Total Direct Energy Consumption Canola Farming			**17,182**

[12] U.S.D.A., Foreign Agricultural Services website http://www.fas.usda.gov/psdonline/psdResult.aspx
[13] U.S.D.A.website: http://www.nass.usda.gov/Charts_and_Maps/Crops_County/pdf/CA-PL09-RGBChor.pdf

Table A-2. U.S. Average Electricity Mix Used for Feedstock Production

Fuel	U.S. Average[a]
Residual oil	2.70%
Natural Gas	18.90%
Coal	50.70%
Nuclear Power	18.70%
Biomass	1.30%
Others	7.70%

[a] Argonne National Laboratory (November 2008). "Fuel Cycle Comparison of Distributed Power Generation Technologies."

To convert the total direct energy shown in Table A-1 from BTU/bushel to BTU/MMBTU, the parameters shown in Table A-3 are used.

Table A-3. Biodiesel Pathway Parameters

Canola Yield (lb/bushel)	Canola to Canola oil (lbs canola/lb oil)	Canola oil to BD (lbs oil/lb BD)	BD Density (g/gal)	BD LHV (BTU/gal)	BD LHV (BTU/lb)
50[a]	2.34[a]	1.026[a]	3,361[b]	119,550[b]	16,149[b]

[a] $(S\&T)^2$ Consultants. Report prepared for Canola Council of Canada, (March 2010). "Canola LCA Data."
[b] Argonne National Laboratory (November 2008). "Fuel Cycle Comparison of Distributed Power Generation Technologies."

The values provided in Table A-1 constitute direct energy consumption per bushel of canola collected for the farming step. This is not the total energy required however, since CA-GREET accounts for the "upstream" energy associated with each of the fuels utilized to make biodiesel. Upstream energy refers to the process energy necessary to produce the fuel that is utilized in the canola farming operation. For example, 15,763 BTU of diesel fuel are required to produce a bushel of canola. The total energy associated with the 15,763 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 A-5 using factors shown in Table A-4.

Table A-4. Energy Consumption in the WTT Process and Specific Energy of Fuels Used in the Canola to Biodiesel Pathway

Fuel Type	**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[a] $_{T\&D}$ + $E_{C\ T\&D}$ + E_{CS} = 28,284*1 + 10,926 = 39,212	
Residual Oil	E_{ResOil} = 74,239	$S_{Res\ Oil} = 1+(E_C$*Loss Factor[a] $_{Crude}$+ $E_{ResOil}) /10^6$
Conventional Diesel	E_{diesel} = 123,805	$S_{diesel} = 1+(E_C$*Loss Factor[a] $_{diesel}$+$E_{diesel})/ 10^6$
Conventional Gasoline	$E_{gasoline}$ = 162,914	$S_{gasoline} = 1+(E_C$*Loss Factor[a] $_{gasoline}$ +$E_{gasoline})/ 10^6$
NG	$E_{NG}=(E_{NG\ Rec} + E_{NG\ Procss})$ *LossFactor[a] $_{NG}$ + $E_{T\&D}$ = 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	$S_C = (1+E_C)/ 10^6$

[a] Loss Factors: Crude: 1.0; Diesel: 1.000044; Gasoline: 1.0008 ;NG: 1.0008; LPG: 1.0001. ECR is the energy used for crude recovery, EC represents energy use for crude processing.

Table A-5. Canola Farming Total Adjusted Energy Consumption from Direct Energy Consumption

Fuel Type	Formula	Description	Total BTU/bu
Diesel	15,762.5 + 15,762.5 * (39,212 * 1.0000 + 123,805)/ 10^6	15,762.5 BTU of direct conventional diesel used per bushel Canola. (Table A-1)	18,332
		energy to recover crude is 39,212 [1] BTU/BTU crude (Table 1.04)	
		Conventional diesel fuel loss factor is 1.000016 (Table A-4)	
		Energy to produce conventional diesel 123,805[a] BTU/BTU (Table A-4)	
Electricity	1,419 (85,708 + 2,561,534)/ 10^6	1,419 BTU/bu of direct electricity used (Table A-1)	3,757
		85,708[a] BTU of energy used to recover and transport sufficient feedstock to generate 1 MMBTU electricity (Table A-4)	
		2,561,534[a] BTU used as fuel to produce 1 MMBTU electricity (Table A-4)	
Total energy for Canola farming, BTU/bushel			22,089
Total energy for Canola farming, BTU/MMBTU = 22,089/50 lbs/bu x 2.34 lbs oil/lb Canola x 1.026 lbs oil/lb BD/16,149 BTU/lb BD x 10^6			65,560
Total adjusted energy for Canola farming, BTU/MMBTU = 65,560 x 42.8% x 95.1% x 1.000039			**26,687**

[a] Well-to-Tank energies for fuels, crude, NG, LPG, etc., are extracted from the relevant fuel tab in CA-GREET at the bottom in the summary section.

Conversion from BTU/bushel to BTU/MMBTU:

$$\frac{22{,}089 Btu/bu \times 2.34 lbsCanola/lbsOil}{50 lbsCanola/bu} \times \frac{1.026 lbsOil/lbBD}{16{,}149 Btu/lbBD} \times 10^6$$ = 65,560 BTU/MMBTU

Adjust energy with credit to glycerin and oil mass share:

$65{,}560 Btu/mmBtu \times 42.8\% \times 95.1\% \times 1.000039 =$ **26,687 BTU/MMBTU**

As shown on page 6 of the Summary:

e) 2.34 lbs of canola/lb canola oil, 50 lbs/bu, 1.026 lbs oil/lb BD, and 16,149 BTU/lb BD are from Table A-3
f) The oil mass share from total oil extraction energy system, including oil and canola meal is equal to 42.8 percent. See Appendix C for complete details.
g) The biodiesel energy share is equal to 95.1 percent of the overall transesterification system, including biodiesel and glycerin. See Appendix C for complete details)
h) 1.000039 is loss factor in GREET calculations and is detailed below.

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

As stated earlier, this analysis uses the mass-based allocation method to determine a canola meal credit and energy allocation to calculate the glycerin credit. The canola oil extraction rate is assumed to be 42.8 percent. For allocation, 42.8 percent of the farming, canola transport and oil extraction energy and emissions are allocated to biodiesel, while the balance, equal to 57.2 percent is allocated to canola meal. The feedstock production and oil transesterification results are allocated based on energy-allocation factors for biodiesel and glycerin. The analysis here uses an energy allocation factor of 95.1 percent and details of this calculation are provided in Appendix C.

The calculations in Table A-4 above (and other Tables in this document) utilize Well-to-Tank energy results for all fuels used in the various steps of the biodiesel pathway. For example, in Table A-4 and Table A-5 the diesel calculation uses the crude recovery WTT energy of 39,212 BTU/BTU and diesel production WTT energy of 123,805 BTU/BTU. 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 Canola 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 the recovery, processing and transport of the fuel. Table A-6 provides the equipment shares for each fuel type consumed and the corresponding emission factors.

Table A-6. Emission Factors for Fuel Combustion[a]

Fuel	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

[a] Argonne National laboratory. GREET documents. GREET default emission factors documented in the technical assessment documents: http://greet.es.anl.gov/

Direct emissions are calculated by multiplying the direct fuel consumption (provided in Table A-1) by the emission factors in Table A-6 and summing the equipment types per fuel as shown in Table A-7.

Table A-7. Direct Emissions from Canola Farming

Process Fuel	**VOC g/bu**	**CO g/bu**	**CH_4 g/bu**	**N_2O g/bu**	**CO_2 g/bu**
Diesel	1.621	6.218	0.146	0.018	1,217
Electricity	0.005	0.253	0.006	0.003	303
Total Direct	**1.626**	**6.471**	**0.152**	**0.021**	**1,520**

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 A-9 , with CO_2 emission factors for each fuel producing process shown in Table A-8. Upstream emissions for all pollutants are summarized in Table A-10.

Table A-8. CO_2 Emission Factors for Fuels Used in Canola Farming

Fuel Type	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	$SE_{Res\ Oil} = 1+(EF_C*\text{Loss Factor}^a_{Crude}+ EF_{ResOil})/10^6$
Conventional Diesel	EF_{diesel} = 9,389	$SE_{diesel} = 1+(EF_C*\text{Loss Factor}^a_{Diesel}+EF_{Diesel})/ 10^6$
Conventional Gasoline	$EF_{gasoline}$ = 12,124	$SE_{gasoline} = 1+(EF_C*\text{Loss Factor}^a_{gasoline}+EF_{Gasoline})/ 10^6$
NG	$EF_{NG}=(EF_{NG\ Rec} + EF_{NG\ Procss})$ *Loss Factor ^{a}+ $E_{T\&D} + EF_{Non\text{-}combustion}$+ (VOC, CO conversion) = 5,208	$SE_{NG} = 1+EF_{NG}/10^6$
NG Recovery	$E_{NG\ Rec}$ = 1,717	
NG Processing	$E_{NG\ Procss}$ = 1,858	
NG T&D	$E_{NG\ T\&D}$ = 352	
NG non-combustion	$E_{NG\ non\text{-}combustion}$ = 1,237	
Coal	EF_{coal} = 1,411	$SE_{coal} = 1+EF_{Coal}/10^6$
Uranium	$EF_{uranium}$= 100,325	$SE_{uranium} = 1+EF_{uranium}/(6.926*1000*3412)$
Electricity		$SE_{Electricity} = (EF_{efeedstock}+EF_{efuel})/10^6$
as Feedstock	$EF_{efeedstock}$ = 6,833	
as Fuel	EF_{efuel} = 213,458	
Still Gas	EF_C = 3,868	$SE_C = 1+EF_C/10^6$
LPG	EF_{LPG} = 5,715	$SE_{LPG} = 1+ EF_{LPG}/10^6$

[a] Loss Factors: Crude: 1.0; Diesel: 1.000044; Gasoline: 1.0008 ;NG: 1.0008; LPG: 1.0001. ECR is the energy used for crude recovery, EC represents energy use for crude processing

Table A-9. Calculation of Upstream CO_2 Emissions from Direct Farming Energy Consumption

<table>
<tr><th>Fuel Type</th><th>Formula</th><th>Description</th><th>g/bu</th></tr>
<tr><td rowspan="4">Diesel</td><td rowspan="4">15,763 * (3,868 * 1.0000 + 9,389) / 10^6</td><td>15,763 BTU/bu of direct diesel used (Table A-1)</td><td rowspan="4">209</td></tr>
<tr><td>Crude recovery CO_2 emissions are 3,868[1] g/MMBTU (Table A-8)</td></tr>
<tr><td>Diesel loss factor is 1.0000</td></tr>
<tr><td>CO_2 emissions from producing diesel are 9,389 [a] g/MMBTU</td></tr>
<tr><td rowspan="2">Electricity</td><td rowspan="2">1,419 * 6,833 / 10^6</td><td>1419 BTU of electricity consumed per bushel of Canola produced (Table A-1)</td><td rowspan="2">10</td></tr>
<tr><td>CO_2 emissions associated with electricity feedstock and transport is 6,833 [a] g/MMBTU (Table A-8)</td></tr>
<tr><td colspan="3">Total</td><td>219</td></tr>
</table>

[a] 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 A-10. Table A-11 shows the combined direct and upstream emissions in g/bu and converted to g/MMBTU and Table A-12 presents the summary results with allocation and loss factors applied.

Table A-10. Summary of Upstream Emissions From Canola Farming

Process Fuel	VOC g/bu	CO g/bu	CH_4 g/bu	N_2O g/bu	CO_2 g/bu
Diesel	0.130	0.277	1.546	0.002	209
Electricity	0.024	0.022	0.384	0.000	10
Total Upstream Emissions	**0.154**	**0.300**	**1.930**	**0.003**	**219**

Table A-11. Summary of Total (Direct + Upstream) Emissions from Canola Farming

Process Fuel	VOC	CO	CH_4	N_2O	CO_2
Diesel	1.751	6.496	1.692	0.020	1,426
Electricity	0.028	0.275	0.390	0.003	313
Total Emissions (g/bu)	**1.779**	**6.771**	**2.082**	**0.023**	**1,739**
Process Fuel	**VOC**	**CO**	**CH_4**	**N_2O**	**CO_2**
Diesel	5.197	19.278	5.023	0.060	4,233
Electricity	0.084	0.816	1.158	0.008	928
Total Emissions (g/MMBTU)	**5.281**	**20.095**	**6.181**	**0.069**	**5,161**

Sample calculation conversion of CO_2 value from g/bu to g/MMBTU (Table A-11):

$$\frac{1{,}739 g / bu \times 2.34 lbsCanola / lbsOil}{50 lbsCanola / bu} \times \frac{1.026 lbsOil / lbBD}{16{,}149 Btu / lbBD} \times 10^6 = \textbf{5,161 g/MMBTU.}$$

Table A-12. Summary of Total (Direct + Upstream) Emissions from Canola Farming with Allocation and Loss Factors Applied

With Allocation and Loss Factors Applied							
	VOC g/MMBTU	**CO g/MMBTU**	**CH_4 g/MMBTU**	**N_2O g/MMBTU**	**CO_2 g/MMBTU**	**GHG gCO_2e/ MMBTU**	**GHG gCO_2e/ MJ**
Diesel	2.115	7.847	2.045	0.024	1,723	1,801	1.71
Electricity	0.034	0.332	0.471	0.003	378	391	0.37
Total Emissions	**2.15**	**8.18**	**2.52**	**0.028**	**2,101**	**2,192**	**2.08**

1.3 Energy Calculation from Production of Chemical Inputs in Canola Farming

The Canadian agricultural chemical data used in this analysis are from the United Nations (UN) Food and Agriculture Organization's (FAO) Fertistat database, which reports fertilizer use by crop and by country, between 1988 and 2004[14]. Table A-13 presents the CA-GREET chemical inputs per bushel of canola, the total energy required to produce the chemical products, and the calculated upstream fuel cycle energy required to produce a bushel of canola using these inputs. The energy values for nitrogen, phosphate and potash are almost identical to the values reported by the Canola Council of Canada's (CCC) 2010 Report[15]. The values stated on that report for

[14] United Nations Food and Agriculture Organization: www.fao.org/ag/agl/fertistat/
[15] (S&T)2 Consultants. Report prepared for Canola Council of Canada, (March 2010). "Canola LCA Data."

nitrogen, phosphate and potash are 1,115, 392 and 90 g/bu respectively. A chemical ingredient not included in Table 13, but is used extensively in canola farming is sulfur. The CCC Report shows canola farming sulfur use of 192 g/bu. Sulfur is required as an essential fertilizer for canola farming. We did not include this in our analysis, lacking production emissions data in GREET. We will do further research and seek public comment for including sulfur input at later date.

Note that for each of the products, direct and total energy are calculated based on assumed process energy efficiency and fuel shares. The energy associated with the transportation of each product from plant to field is also calculated. Chemical inputs are on a gram-nutrient/bushel (fertilizer) or gram-product/bushel (herbicide and insecticide) basis.

Table A-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[a]	1136.97	45.84	52,117
Phosphate (P_2O_5)	303.19	13.31	4,035
Potash (K_2O)	227.39	8.42	1,914
Herbicides	5.18	273.26	1,417
Insecticides	1.35	312.43	422
Total Energy Consumption due to Production of Ag. Chemicals Used in Farming (BTU/bu)			59,904 BTU/bu
Total Energy Consumption due to Production of Ag. Chemicals Used in Farming (BTU/MMBTU)			**177,794**
Total Adjusted Energy Consumption due to Production of Ag. Chemicals Used in Farming (BTU/MMBTU)			**72,373**

[a] Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate

Calculation to convert from BTU/bu to BTU/MMBTU (Table A-13):

$$\frac{(59{,}904 Btu/bu) \times (2.34 lbsCanola/lbOil) \times (1.026 lbsOil/lbBD)}{(16{,}149 Btu/lbBD) \times (50 lbsCanola/bu)} \times 10^6 =$$

177,794 BTU/MMBTU

To calculate total adjusted energy (Table A-13):
177,794 BTU/MMBTU x 42.8% x 95.1% x 1.000039 = **72,373 BTU/MMBTU**

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

This analysis assumes that canola farming utilizes five different farming products: nitrogen fertilizers (ammonia, urea and ammonium nitrate), phosphates, potash, herbicides and insecticides. Table A-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 A-14. GHG Emissions Associated with Fertilizer/Herbicide/Insecticide Use

Product	VOC	CO	CH_4	N_2O	CO_2	GHG gCO_2e/MJ
Emissions, g/bu:						
Nitrogen[a]	6.896	6.689	2.371	1.842	2,720	
Phosphate (P_2O_5)	0.104	0.360	0.428	0.004	183	
Potash (K_2O)	0.028	0.145	0.194	0.002	544	
Herbicides	0.015	0.079	0.139	0.001	111	
Pesticides	0.006	0.028	0.041	0.000	32	
Total	7.048	7.301	3.173	1.849	3,590	
Converted to g/MMBTU:						
Nitrogen[a]	20.467	19.853	7.036	5.468	8,072	9.45
Phosphate (P_2O_5)	0.309	1.068	1.269	0.011	542	0.55
Potash (K_2O)	0.082	0.431	0.576	0.005	1,614	1.55
Herbicides	0.044	0.233	0.413	0.003	329	0.32
Pesticides	0.016	0.083	0.123	0.001	96	0.09
Total	**20.918**	**21.669**	**9.417**	**5.488**	**10,654**	**11.97**
With Allocation and Loss Factors Applied, g/MMBTU:						
Total	**8.515**	**8.821**	**3.833**	**2.234**	**4,337**	**4.87**

[a] Nitrogen split: 70.7% Ammonia, 21.1% Urea, 8.2% Ammonium Nitrate

Calculation to convert from g/bu to g/MMBTU (Table A-14):

$$\frac{(3{,}590\, g/bu)\times(2.34\, lbsCanola/lbOil)\times(1.026\, lbsOil/lbBD)}{(16{,}149\, Btu/lbBD)\times(50\, lbsCanola/bu)}\times 10^{6} = \textbf{10,654 g/MMBTU}.$$

To calculate adjusted energy (Table A-14):

$$10{,}654\, g/mmBtu \times 42.8\% \times 95.1\% \times 1.000039 = \textbf{4,335 g/MMBTU}$$

1.5 Soil N_2O Release Due to Fertilizer Use

CA-GREET also calculates direct field and downstream N_2O emissions resulting from nitrogen fertilizer input. Agricultural N_2O emissions result from conversion of fixed (natural and anthropogenic) nitrogen in the soil. Fixed nitrogen applied to field crops is either extracted by the crop as a nutrient, absorbed (chemically bound) into organic soil components, or entrapped but not chemically bound in soil aggregates. 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 canola cultivation. Table A-15 shows the two main inputs: fertilizer input (g/bu) and percent conversion of N-input to N_2O. GREET assumes 1.32% of fertilizer-N is ultimately converted to N_2O.[16] The calculation also uses the mass ratio of N_2O to N (44/(2x14)).

Table A-15. CA-GREET Inputs and Calculated Emissions for Soil N_2O Associated with Canola Cultivation

Crop	Canola[a]
Fertilizer N input, g/bu	1,136.97
N content of above/below ground biomass, g/bu	200.7
Percent N conversion to N in N_2O	1.33%
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	27.85
GHG emission, gCO_2e/bu	8299
GHG emissions, gCO_2e/MMBTU	24,632
GHG emissions, gCO_2e/MMBTU, with allocation and loss factors	**10,027**
GHG emissions, gCO_2e/MJ	**9.50**

[a] Soil N_2O emissions = (1,136.97 g-N/bu + 200.7 g-N/bu) * (1.325%) * (44 g N_2O/(2x14) g N_2) = 27.75 g-N_2O/bushel

Sample calculation to convert from g/bu to g/MMBTU (Table 15):

$$\frac{(8{,}299\,g/bu)\times(2.34\,lbsSB/lbOil)\times(1.04\,lbsOil/lbBD)}{(16{,}149\,Btu/lbBD)\times(50\,lbsSB/bu)}\times10^{6} =$$ **24,632 gCO_2e/MMBTU**.

To calculate adjusted energy (Table 15):

$$24{,}632\,g/mmBtu\times42.8\%\times95.1\%\times1.000039=$$ **10,027 gCO_2e/MMBTU**

[16] Argonne National Lab (2008). "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels". p. 18

SECTION 2. CANOLA TRANSPORT

2.1 Energy Calculations for Canola Transport

Canola is transported from the field to a canola oil extraction plant in Canada. The CA-GREET canola transport modes are as follows: medium duty diesel trucks transport canola to a stack and heavy duty trucks transport the canola to a canola oil extraction facility. The canola meal is used locally as animal feed and the canola oil is transported by rail to a US plant for biodiesel production, and the finished product is shipped to California. Assumptions and calculations behind the reported field to terminal transport are from the field to terminal is provided in Table A-16. All values except the rail transport distance are CA-GREET defaults.

Canola is 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 canola oil extraction plant

It is assumed that only diesel is used as a fuel for the trucks. Transport emissions are calculated as shown below:
Emissions g/ton canola = Emission factor (g/MMBTU) * BTU/ton-mile * miles / 10^6 BTU/MMBTU

Table A-16. Transport Parameters and Energy Use Details for Canola 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[a]	BTU/ton-mile	2,199	1,713	
Direct Energy[b]	BTU/ton	43,990	137,013	
Total Energy[c]	BTU/ton	51,160	159,349	
Total Energy	BTU/bu	1,279	3,984	5,263
Total Energy	BTU/MMBTU	3,796	11,824	15,620
Total Adjusted Energy	BTU/MMBTU	**1,545**	**4,813**	
Total Canola Transport Adjusted Energy, BTU/MMBTU				**6,358**

[a] Energy Intensity = LHV / fuel economy / payload
[b] Direct truck energy doubles the miles to take into account round trip energy.
[c] Total energy includes energy associated with crude recovery and diesel refining (see Table A-13).

To convert from BTU/bu to BTU/MMBTU (Table 16):

$$\frac{(1{,}279+3{,}984)(Btu/bu)\times(2.34 lbsOil)\times(1.026 lbsOil/lbBD)\times 10^6}{(50 lbsCanola/bu)\times(16{,}149 Btu/lbBD)}$$ = **15,620 BTU/MMBTU**.

To calculate adjusted energy (Table 16):
(15,620 BTU/MMBTU) x (42.8% x 95.1% x 1.000039) = **6,358 BTU/MMBTU**

2.2 GHG Calculations for Canola Transport

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 A-17 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 A-18 shows upstream diesel values used to calculate the upstream emissions for diesel truck transport shown in Table A-17.

Table A-17. Transport Parameters and GHG Emissions from Canola Transport

	Field to Stack	**Stack to Canola oil Extraction Facility**	**Total Transport**	**Total Transport (g/bu)**
Mode	Medium Duty Truck	Heavy Duty Truck		
Distance, miles	10	40		
Fuel	Diesel	Diesel		
Energy Intensity[a], BTU/ton-mile	2,199	1,712		
Emission Factors[b], g/MMBTU Fuel Burned (return trip in parentheses when different)[c]				
VOC	32.110 (39.441)	33.671 (26.392)		
CO	116.107 (115.084)	178.708 (127.443)		
CH_4	1.534 (1.933)	1.524		
N_2O	2.898	2.105		
CO_2	77,912 (77,890)[2]	77,809 (77,912)[2]		
Direct Emissions	**(g/ton)**	**(g/ton)**	**(g/ton)**	**(g/bu)**
VOC	1.574	4.115	5.688	0.142
CO	5.085	20.973	26.058	0.651
CH_4	0.076	0.209	0.285	0.007
N_2O	0.128	0.288	0.416	0.010
CO_2	**3,427**	10,668	14,095	352
Upstream Emissions	**(g/ton)**	**(g/ton)**	**(g/ton)**	**(g/bu)**
VOC	0.363	1.130	1.493	0.037
CO	0.774	2.412	3.186	0.080
CH_4	4.315	13.439	17.754	0.444
N_2O	0.006	0.020	0.027	0.001
CO_2	**583**	1,816	2,400	60
Total Adjusted Emissions (with Allocation & Loss Factors)				
VOC (**gCO_2e/MMBTU**)				**0.683**
CO (**gCO_2e/MMBTU**)				**1.407**
CH_4 (**gCO_2e/MMBTU**)				**13.621**
N_2O (**gCO_2e/MMBTU**)				**3.982**
CO_2 (**gCO_2e/MMBTU**)				**498**
Total GHG Emissions (gCO_2e/MMBTU)				518
Total GHG Emissions (gCO2e/MJ)				**0.49**

[a] Energy Intensity = LHV/fuel economy/payload
[b] Emission factors (EFs) correspond to trip from feedstock origin to destination and the return trip listed in the emission factors (*EF* tab) of CA-GREET.
[c] Direct truck energy doubles the miles to take into account round trip energy.

Sample calculations shown below are for CO_2 emissions calculation for Canoal Transport (Table 17):

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

$$\frac{(352+60)(g/bu)\times(2.34 lbsCanola/lbOil)\times(1.026 lbsOil/lbBD)}{(16{,}149 Btu/lbBD)\times(50 lbsCanola/bu)}\times 10^6 =$$

1,224 gCO_2/MMBTU

To calculate CO_2 adjusted energy:

$1{,}224 g/mmBtu \times 42.8\% \times 95.1\% \times 1.000039 =$ **498 gCO_2/MMBTU**

Table A-18. 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

The WTT values shown in Table A-18 shows upstream diesel values used to calculate the upstream emissions for diesel truck transport shown in Table A-17.

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:

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

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

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

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

(4,010 g CO_2/ton) x (1 ton/2,000 lbs) x 2.34 lbs canola /lb oil x 1.026 lbs oil/lb BD/16,149 BTU/lb BD / 50 lbs Canola /bu x 10^6 BTU/MMBTU = **298 gCO_2**/MMBTU

(298 gCO_2e /MMBTU) x (42.8% oil energy share) x (95.1% biodiesel energy share) x (1.000039) = **121** gCO_2/MMBTU

SECTION 3. CANOLA OIL EXTRACTION

3.1 Energy Calculations for Canola oil Extraction

Once the canola has arrived at a canola oil extraction facility in Canada, the oil needs to be extracted from the seeds. The U.S. average electricity mix is assumed for canola oil extraction. Since CA-GREET does not include values for the Canadian electricity mix, the U.S. average electricity mix is used in CA-GREET to calculate canola production and biodiesel production. 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[17]). Similarly to the soybean BD, the analysis uses GREET defaults for electricity (551 BTU/lb oil) and hexane (182 BTU/lb oil). Table A-19 provides the direct energy consumption values based on GREET default total energy consumption and split by fuel type.

Table A-19. Direct Energy Consumption for Canola oil Extraction from Canola

Process Fuel Type	Fuel Shares	Relationship of Extraction Energy and Fuel Shares	Direct Energy Consumption, BTU/lb canola oil
Natural gas	82.10%	0.821 x 1,226	1,006
Electricity	14.50%	0.145 x 1,226	178
N-Hexane	3.40%	0.034 x 1,226	42
Direct Energy Consumption for Canola oil Extraction			**1,226**

The values provided in Table A-19 are direct energy consumption per lb of canola oil 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 canola oil. Table A-20 demonstrates how the direct energy consumption values shown in Table A-19 are utilized to calculate total energy required to extract canola oil.

[17] 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 A-20. Total Energy Use from Direct Energy Use for Canola oil Extraction

Fuel Type	**Formula**	**Description**	**BTU/lb Canola oil**
Natural Gas	1,006 + 1,006 *(69,596)/106	1,006 BTU/lb Canola oil of direct NG fuel use (Table A-19)	1,077
		69,596 is the energy required to recover, process and transport 1 MMBTU of NG for stationary use	
Electricity	178* (85,708 + 2,561,534)/ 106	178 BTU/lb Canola oil direct electricity use (Table A-19)	471
		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	42 + 42 * (39,212*1.0001 + 75,862)/ 106	42 BTU/lbs canola oil, direct N-Hexane use. GREET uses LPG values for N-Hexane (Table A-19)	46
		The energy to recover crude is 39,212 BTU/MMBTU crude.	
		1.000116 is the loss factor for LPG.	
		To refine & transport LPG 75,862 BTU/MMBTU LPG are used (Table A-4)	
Total Energy Consumption for Canola oil Extraction (BTU/lb oil)			**1,594**
Total Energy Consumption for Canola oil Extraction (BTU/MMBTU)			**101,215**
Total Adjusted Energy Consumption for Canola oil Extraction (BTU/MMBTU)			**41,201**

The canola oil extraction energy is converted from the per lb canola oil basis to a per MMBTU biodiesel basis as follows (Table A-20):

Canola oil Extraction Energy:

$$\frac{(1{,}603\,Btu/lbOil)\times(1.026\,lbOil/lbBD)\times(10^{6}\,Btu/mmBtu)}{16{,}149\,Btu/lbBD}$$ = **101,215 BTU/MMBTU**

101,788 BTU/MMBTU x 42.8% x 95.1% x 1.000039 = **41,201 BTU/MMBTU**

3.2 GHG Calculations for Canola oil Extraction

The emissions associated with canola oil extraction are two-fold: the direct combustion emissions and the upstream emissions due to recovery, processing and transport of the process fuels utilized. In canola oil extraction, it is assumed that natural gas, electricity and N-hexane (a petroleum based solvent) are the process fuels. Table A-21 provides the direct emissions associated with canola oil extraction. These direct emissions are determined by multiplying the direct energy use (provided in Table A-19) by the appropriate combustion emission factors for the fuel type and combustion equipment used. Hexane has no direct emissions and 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 are calculated is shown below Table A-21.

Table A-21. Direct Emissions from Canola oil Extraction

Parameters	GHG Emission g/lb oil
VOC	**0.003**
NG	0.002
Electricity	0.001
N-Hexan	0.000
CO	**0.054**
NG	0.023
Electricity	0.032
N-Hexan	0.000
CH4	**0.002**
NG	0.001
Electricity	0.001
N-Hexan	
N2O	**0.001**
NG	0.000
Electricity	0.000
N-Hexan	0.000
CO2	**96.51**
NG	58.56
Electricity	37.94
N-Hexan	0.000

Sample calculation of natural gas direct CO_2 emissions (Table A-21):

$$\frac{(1{,}006\,BtuNG / lbOil) \times [(50\% \times 58{,}198\,gCO_2 / mmBtu) + (50\% \times 58{,}176\,gCO_2 / mmBtu)]}{10^6} =$$

58.6 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 canola oil must be quantified. Table A-22 shows how the upstream CO_2 emissions are quantified from the direct fuel consumption. Table A-23 provides the upstream emissions for all gases.

Table A-22. Upstream CO_2 Emissions from Direct Energy Use for Canola oil Extraction

Fuel Type	Formula	Description	gCO_2/lb canola oil
Natural Gas	$1{,}006 \times (5{,}208)/10^6$	1,006 BTU/lb Canola oil of direct NG fuel use (Table A-19)	5.24
		5,208 grams of CO_2 are emitted in recovery, processing and transporting 1 MMBTU of natural gas for stationary use.	
Electricity	$178 \times (6{,}833 + 213{,}458)/10^6$	178 BTU/lb canola oil direct electricity use (Table A-19)	39.16
		To recover, process, and transport fuel to the power plants, 6,833 g of CO2/MMBTU are emitted.	
		Production of electricity releases 213,458 g CO_2 /MMBTU of electricity produced.	
N-Hexane	$42 \times (3{,}868+1.000116 + 5{,}715)/10^6$	42 BTU/lb canola oil, direct N-Hexane use (Table A-19)	0.40
		The CO_2 emitted from crude recovery is 3,868 g/MMBTU.	
		1.000116 is the loss factor for LPG	
		5,715 g/MMBTU CO_2 is from LPG refining & transport	
Total Upstream CO_2 Emissions for Canola Oil Extraction			**44.80**

Table A-23. Upstream Emissions from Canola Oil Extraction

Parameters	GHG Emission g/lb oil
VOC	**0.010**
NG	0.006
Electricity	0.003
N-Hexane	0.000
CO	**0.015**
NG	0.012
Electricity	0.003
N-Hexane	0.001
CH4	**0.182**
NG	0.130
Electricity	0.048
N-Hexane	
N2O	**0.000**
NG	0.000
Electricity	0.000
N-Hexane	0.000
CO2	**6.86**
NG	5.242
Electricity	1.215
N-Hexane	0.399

Finally, the direct and upstream emissions are summed and converted from g/lb canola oil basis to g/MMBTU biodiesel basis. The allocation and loss factors are then applied. Table A-24 provides the total emissions associated with canola oil extraction.

Table A-24. Total GHG Emissions from Canola Oil Extraction

	VOC	CO	CH_4	N_2O	CO_2	GHG Emissions
Total Emissions (Direct + Upstream), g/lb canola oil						
Natural Gas	0.008	0.034	0.131	0.000	63.8	
Electricity	0.004	0.034	0.049	0.000	39.2	
N-Hexane	0.000	0.001	0.004	0.000	0.339	
Total	0.012	0.070	0.184	0.001	**103.4**	
Total Emissions (Direct + Upstream), converted to g/MMBTU						
Natural Gas	0.528	2.186	8.305	0.024	4053	
Electricity	0.226	2.188	3.103	0.023	2487	
N-Hexane	0.022	0.044	0.252	0.000	25.37	
Total	0.776	4.418	11.661	0.047	**6,565**	
Total Adjusted Emissions (with Allocation and Loss Factors), g/MMBTU						
Natural Gas	0.215	0.889	3.380	0.010	1,649	
Electricity	0.092	0.890	1.263	0.009	1,012	
N-Hexane	0.009	0.018	0.103	0.000	10	
Total	0.316	1.798	4.745	0.019	2671	
Total Adjusted Emissions in gCO_2e/MMBTU						**gCO_2e/MJ**
Natural Gas	0.677	1.417	84.49	2.94	1,649	1.56
Electricity	0.289	1.418	31.57	2.76	1,012	0.96
N-Hexane	0.028	0.028	2.56	0.04	10	0.01
Total	**0.994**	**2.863**	**118.62**	**5.75**	**2,671**	**2.65**

Sample calculation of CO_2 to convert from g/lb canola oil to g/MMBTU biodiesel (Table A-24):

$$\frac{(103.4 g / lbCanolaOil) \times (1.026 lbsCanolaOil / lbBD)}{(16{,}149 Btu / lbBD)} \times 10^6 = \mathbf{6{,}565\ gCO_2/MMBTU}$$

To calculate CO_2 with adjusted energy (Table A-24):

$$6{,}565 g / mmBtu \times 42.8\% \times 95.1\% \times 1.000039 = \mathbf{2{,}671\ gCO_2/MMBTU}$$

SECTION 4. CANOLA OIL TRANSPORT

4.1 Energy Calculations for Canola oil Transport

As discussed in the previous section, canola oil is produced at a crushing facility in Canada and then transported via rail and truck to biodiesel facilities in the US and the biodiesel is shipped via rail or truck to California. The rail transport distance of 1,200 miles reflects transport of canola oil from the crushing facility to the biodiesel plant and 800 miles for biodiesel shipped to California. Note that the analysis here assumes that canola oil and biodiesel have the same heating value, which is a reasonable assumption; the error introduced by this assumption difference is small.

The transport parameters and energy use are shown below in Table A-25. The energy intensity for rail shown in the table is a CA-GREET default value and the following two values, 444,000 BTU/ton, and 13,747 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 A-25).

The energy allocation factor used for canola oil transport is the same energy factor of 95.1% for canola oil calculated in Section 1.1.

Table A-25. Parameters and Energy Use for Canola oil Transport

	Units	**Crushing facility to BD Plant**
Mode		Rail
Distance[a]	Miles	1,200
Fuel		Diesel
Lower Heating Value	BTU/gal	119,550
Density	g/gal	3,361
Energy Intensity	BTU/ton-mile	370
*Direct Energy	BTU/ton	444,000
*Direct Energy	BTU/MMBTU	**13,747**
***Total Energy[b]**	**BTU/MMBTU**	**15,988**
Total Allocated and Adjusted Energy	**BTU/MMBTU**	**15,206**

[a] Rail miles not doubled.
[b] Total energy includes energy associated with crude recovery and diesel refining (see Table A-4).

Direct Energy (BTU/ton) = (370 BTU/ton-mile) x (1,200 miles) = 444,000 BTU/ton

Direct Energy (BTU/MMBTU) = (444,000 BTU/ton) x (1 ton/2,000 lbs) x (1 lb/454 g) x (3,361 g/gal)/(119,550 BTU/gal) x10^6 = **13,747 BTU/MMBTU**

Total Energy (BTU/MMBTU, not adjusted) = (**13,747** BTU/MMBTU) x (1 + 0.163 BTU/BTU diesel upstream) = **15,988 BTU/MMBTU**
Total Energy (BTU/MMBTU, adjusted) = (15,988 BTU/MMBTU x 95.1% x 1.000039) = **15,206 BTU/MMBTU**
where 0.163 BTU/BTU diesel is the upstream energy associated with producing 1 BTU of diesel.

4.2 GHG Calculations for Canola oil Transport

As discussed in the previous section, the rail transport distance of 1,200 miles reflects transport of canola oil from the crushing facility to the biodiesel plant. We assume that the crushing plant and the BD plant are located next to a railyard. As a result, no transportation from the crushing plant or the BD plant to a railyard is required. Table A-26 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 canola transport in Section 2.2.

Table A-26. Canola Oil Transport Parameters and Calculations

Transport Details	**Canola Crushing Facility to BD Plant, BD fuel shipped to California**
Mode	Rail
Distance, miles	1,200
Fuel	Diesel
Energy Intensity, BTU/ton-mile	370
Emission Factors, g/MMBTU Fuel Burned	
VOC	51.2
CO	184.3
CH_4	3.4
N_2O	1.7
CO_2	66,569
Direct Emissions, g/MMBTU Fuel Transported	
VOC	0.821
CO	2.956
CH_4	0.054
N_2O	0.027
CO_2	1,068
Upstream Emissions, g/MMBTU Fuel Transported	
VOC	0.113
CO	0.242
CH_4	1.348
N_2O	0.002
CO_2	182
Total Emissions, including allocation and loss factors g/MMBTU Fuel Transported	
VOC	2.797
CO	4.843
CH_4	33.350
N_2O	8.364
CO_2	1,189
Total GHG Emissions (gCO_2e/MJ)	**1.18**

Sample calculations of CO_2 emissions from locomotive (Table A-26):

Direct CO_2 emission from diesel locomotive:

$$\frac{(3{,}361 gBD/gal) \times (77{,}664) gCO_2/mmBtu \times (370 Btu/ton-mile) \times 1{,}200 miles}{(119{,}550 Btu/galBD \times 454 g/lb \times 2000 lbs/ton)} =$$

1,068 gCO_2/MMBTU

Upstream CO_2 emission from diesel locomotive:

$$\frac{(3{,}361 gRD/gal)\times(13{,}257 gCO_2/mmBtu)\times(370 Btu/ton-mile)\times 1{,}200 miles}{(119{,}550 Btu/gal\times 454 g/lb\times 2000 lbs/ton)} =$$

182 gCO_2/MMBTU

Total CO_2 emissions adjusted to energy:
(1,068+182) gCO_2/MMBTU x 95.1% x 1.000039 = **1,189 gCO_2/MMBTU**

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

SECTION 5. BIODIESEL PRODUCTION

After the canola oil 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 A-27. These values are identical to the biodiesel production direct energy consumption in the ARB's soybean to biodiesel pathway.[18]

Table A-27. Direct Energy Consumption for Canola Transesterification

Process Fuel Type	Fuel Shares	Relationship of Biodiesel Production and Fuel Shares	Direct Energy Consumption, BTU/lb biodiesel
Natural gas	42.00%	0.420 x 2,116	889
Electricity	2.20%	0.022 x 2,116	47
Methanol	40.90%	0.049 x 2,116	865
Sodium hydroxide	2.00%	0.020 x 2,116	42
Sodium methoxide	9.90%	0.099 x 2,116	209
Hydrochloric acid	3.00%	0.030 x 2,116	63
Direct Energy Consumption for Canola Oil Transesterification			**2,116**

The values provided in Table A-27 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 A-28 demonstrates how the direct energy consumption values shown in Table A-27 are utilized to calculate total energy required for canola oil transesterification.

[18] ARB (December 2009). Detailed California-Modified GREET Pathway for Conversion of Midwest Soybeans to Biodiesel (Fatty Acid Methyl Esters-FAME) p. 40: http://www.arb.ca.gov/fuels/lcfs/121409lcfs_soybd.pdf

Table A-28. Total Energy Use from Direct Energy Use for Biodiesel Production

Fuel Type	Formula	Description	BTU/lb Biodiesel
Natural gas	889 + 889 * (68,865)/10^6	889 BTU/lb biodiesel of direct NG fuel use (Table 5.1).	950
		68,865 is the energy required to recover, process and transport a MMBTU of NG for stationary use	
Electricity	47* (111,573 + 1,884,989)/ 10^6	47 BTU/lb biodiesel direct electricity use (Table 5.1)	93
		111,573 BTU of energy used to recover and transport feedstock to generate 1 MMBTU electricity.	
		1,884,989 BTU fuel used to produce 1 MMBTU electricity.	
Methanol	865 + 865 * (31,792 * 1.0002 + 532,954)/ 10^6	865 BTU/lb biodiesel direct methanol use (Table 5.1)	1,354
		NG recovery, processing and delivery is 31,792 BTU/MMBTU methanol (GREET calculation).	
		1.0002 methanol loss factor	
		Methanol production is 532,954 BTU/MMBTU methanol produced (GREET calculation).	
Sodium Hydroxide		(GREET default)	42
Sodium Methoxide		(GREET default)	209
Hydrochloric Acid		(GREET default)	63
Total Energy Consumption for Biodiesel Production (BTU/lb)			2,711
Total Energy Consumption for Biodiesel Production (BTU/MMBTU)			**167,882**
Total Adjusted Energy Consumption for Biodiesel Production (BTU/MMBTU)			**159,668**

To convert from Btu/lb biodiesel to Btu/MMBtu biodiesel use (Table A-28):

Total Energy: 2,712 Btu/lb biodiesel / 16,149 Btu/lb BD * 10^6 = **167,882 Btu/MMBtu**

Total Adjusted Energy: 167,961 Btu/MMBtu x 95.1% x 1.000039 =
159,668 Btu/MMBtu

5.2 GHG Calculations from Biodiesel Production

Once the canola oil 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 canola oil 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 soy oil extraction. The electricity mix is assumed to be U.S average.

Direct emissions are calculated by multiplying direct fuel consumption (please refer to Table A-24, Section 3.2 above) by the appropriate emissions factors. Direct emissions for biodiesel production are provided in Table A-29 (no allocation factors applied). Only natural gas has direct emissions.

Table A-29. Direct Emissions from Biodiesel Production

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas[a] (g/lb Biodiesel)	0.002	0.02	0.001	0	52
Total Direct Emissions (g/lb Biodiesel)	**0.002**	**0.02**	**0.001**	**0**	**52**

[a] Only NG has direct emissions for CA-GREET calculations

The upstream emissions are calculated from the direct energy consumption as illustrated in Table A-30 for CO2. The upstream emissions for each of the pollutants are summarized in Table A-31. Please refer to Table A-28 for direct fuel consumption values.

Table A-30. Upstream CO_2 Emissions from Direct Energy Use for Biodiesel Production

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

[a] As in previous tables, the upstream values shown in the third column of the table are summary WTT values from fuel sheets in CA-GREET

Table A-31. Upstream Emissions from Biodiesel Production

Product	VOC	CO	CH_4	N_2O	CO_2
Natural Gas (g/lb Biodiesel)	0.006	0.01	0.114	0	4.0
Electricity (g/lb Biodiesel)	0.001	0.003	0.01	0	5.0
Methanol (g/lb Biodiesel)	0.022	0.029	0.166	0	19.0
Total Emissions (g/lb Biodiesel)	**0.029**	**0.042**	**0.291**	**0**	**28.0**

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 A-32 provides the total emissions associated with biodiesel production

Table A-32. Total GHG Emissions from Biodiesel Production

	VOC	CO	CH_4	N_2O	CO_2	GHG Emissions
Total Emissions (Direct + Upstream), g/lb biodiesel						
Natural Gas	0.007	0.03	0.115	0	56	
Electricity	0.001	0.003	0.01	0	5	
Methanol	0.022	0.029	0.166	0	19	
Total	0.03	0.062	0.292	0.001	80	
Total Emissions (Direct + Upstream), converted to g/MMBTU biodiesel						
Natural Gas	0.433	1.858	7.121	-	3,468	
Electricity	0.062	0.186	0.619	-	310	
Methanol	1.362	1.796	10.279	-	1,177	
Total	1.858	3.839	18.082	0.062	4,954	
Total Adjusted Emissions (with Allocation & Loss Factors), g/MMBTU[a]						
Natural Gas	0.412	1.766	6.77	-	3,297	
Electricity	0.059	0.177	0.589	-	294	
Methanol	1.295	1.707	9.773	-	1,119	
Total GHG Emissions	1.77	3.65	17.19	0.06	4,710	
Total GHG Emissions (gCO_2e/MJ)						**5.20**

[a] To obtain total adjusted energy, multiply by 95.1% and 1.000039

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. Figure A-1 and

Table A-33 provide the transport assumptions and calculations for this final step. Biodiesel is assumed to travel 800 miles by rail from a BD plant outside of California to a railyard in California. It is assumed that 80% of the BD is transported by heavy duty truck 50 miles from the railyard to a bulk terminal; the remaining 20% is stored in a bulk terminal next to the railyard, and distributed directly. The BD is then transported 90 miles by heavy duty truck from the bulk terminal to refueling stations. The trucking distances used as inputs in CA-GREET includes hauling biodiesel 50 miles (80% of the BD) from a railyard to a petroleum terminal for blending followed by 90 miles distribution to a fueling station as a blended fuel.

As shown in

Table A-33, the transportation and distribution energy values are converted from BTU/ton-mile to total energy as follows.

1. The energy and emissions are calculated the same here as for soybean transport and soy oil transport. BTU/ton-mile is converted to BTU/ton, which is converted to BTU/MMBTU fuel for both legs of the trip.
2. Next, the upstream BTU/MMBTU for each mode of transport is calculated the same way as shown in Section 2.2, Canola Transport, using the BTU/ton-mile values shown in
3.
4. Table A-33.
5. Finally, the energy for each mode is multiplied by the mode share shown in
6. Table A-33 to yield the total energy. No allocation factor adjustment is made for biodiesel transport

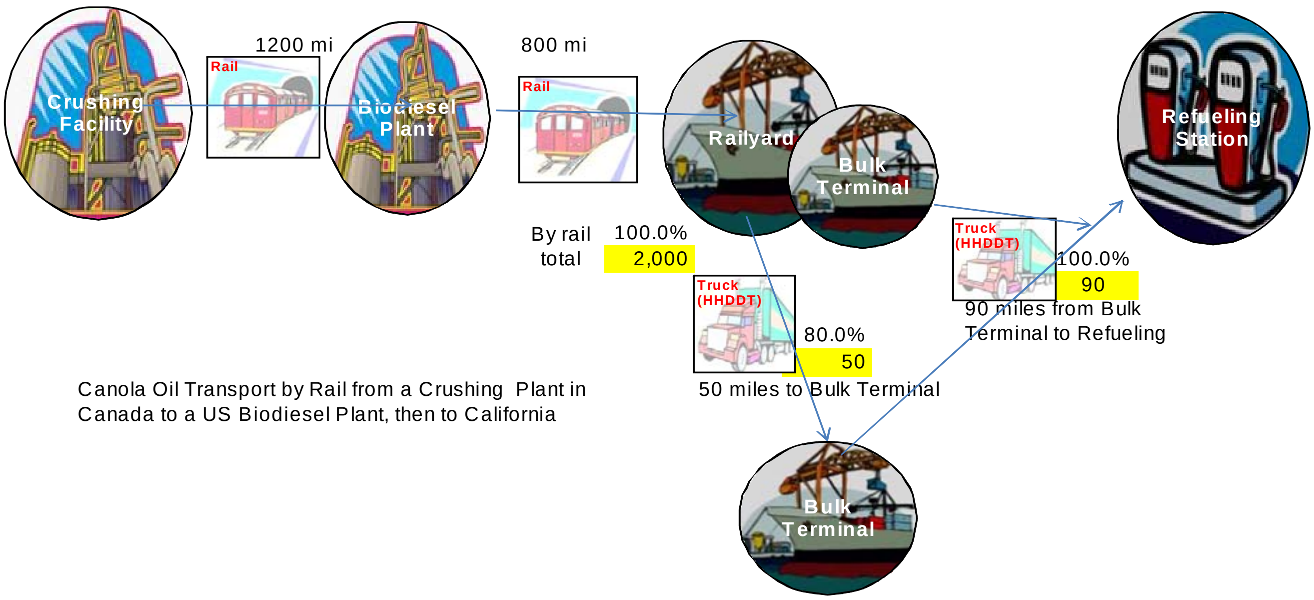


Figure A-1. Transportation of canola from Extraction, to Biodiesel Plant, to Distribution

Table A-33 Transport Parameters and Energy Use for Biodiesel Transport and Distribution

Parameter	Units	Plant by Rail to CA	Railyard to Bulk Terminal[a,b]	Distribution[a,b]	Total
Mode	-	Rail	Heavy Duty Truck	Heavy Duty Truck	
Shares	%	100%	80%	100%	
Distance	Miles	800	50	90	
Payload	Tons		25	25	
Fuel Economy	mi/gal		5	5	
Fuel	-		Diesel	Diesel	
Fuel LHV	BTU/gal	119,550	128,450	128,450	
Energy Intensity	BTU/ton-mile	370	1,028	1,028	
Direct Energy (BTU/MMBTU)		9,165	3,182	5,727	
Upstream Energy (BTU/MMBTU)		1,494	519	934	
Total Energy (BTU/MMBTU)		10,659	3,700	6,661	
Total BD T&D Energy (BTU/MMBTU)		**10,659**	**2,960**	**6,661**	**20,280**

[a] Direct truck energy doubles the miles to take into account round trip energy
[b] Apply 80% of the mode shares for BD transport and 100% for BD distribution

6.2 GHG Calculations for Biodiesel Transport to Retail Stations

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

- BD is transported 800 miles by rail from a BD plant to a railyard in CA.
- 80% transported 50 miles by heavy duty diesel truck (HDD) from railyard in CA to a bulk terminal, while the 20% remaining is stored at bulk terminal next to the railyard.
- 100% distributed 90 miles by heavy duty truck from a bulk terminal to a refueling station in CA.

Table A-34 shows the direct emissions, upstream emissions (without accounting for mode share) and total emissions, accounting for mode share.

Table A-34. GHG Emissions from Biodiesel Transport and Distribution

	Plant by Rail to CA	**Railyard to Bulk Terminal**[a]	**Fuel Distribution**	**Total Transport**
Mode	Rail	**HDD Truck**	**HDD Truck**	
Mode Share	100%	**80%**	**100%**	
Distance, miles	800	**50**	**90**	
Fuel		Diesel	Diesel	
Direct CO_2 Emission (gCO_2/MMBTU)		77,809 (77,912)[2]	77,809 (77,912)[2]	
Upstream CO_2 Emission (gCO_2/MMBTU)		7,394	13,304	
Energy Intensity, BTU/ton-mile		1,028	1,028	
Direct Emissions (g/MMBTU)				
VOC	0.547	0.096	0.172	
CO	1.970	0.487	0.877	
CH_4	0.036	0.005	0.009	
N_2O	0.018	0.007	0.012	
CO_2	**712**	**248**	**446**	
Upstream Emissions (g/MMBTU)				
VOC	0.076	0.026	0.047	
CO	0.161	0.056	0.101	
CH_4	0.899	0.312	0.562	
N_2O	0.001	0.000	0.001	
CO_2	**121**	**42**	**76**	
Total Emissions[a]**, (g/MMBTU)**				
VOC	0.623	0.122	0.219	0.964
CO	2.132	0.543	0.977	3.652
CH_4	0.935	0.317	0.570	1.822
N_2O	0.020	0.007	0.013	0.040
CO_2	833	290	522	1645
GHG Emissions (g/MMBTU)	868	241	542	1652
GHG Emissions (gCO_2e/MJ)	**0.823**	**0.228**	**0.514**	**1.57**

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

The emissions shown in Table A-34 are determined the same way as the canola oil transport is calculated Table A-26.

Sample calculation of CO_2 emissions for heavy duty truck distribution (residual oil, Table A-34):

Direct Emissions =

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

446 gCO_2/MMBTU

Upstream emissions =

$$\frac{(3{,}361\ g\ /\ gal\ ) \times (13{,}304\ + 13{,}304\ )(\ gCO\ 2\ /\ mmBtu\ \ ) \times 1{,}028\ (\ Btu\ \ /\ ton\ \ -\ mile\ \ ) \times 90\ miles}{(119\ {,}550\ \ Btu\ \ /\ gal\ \ ) \times (\ 454\ \ g\ \ /\ lb\ ) \times (\ 2000\ \ lb\ \ /\ ton\ \ )}$$

=

76 gCO_2/MMBTU

Total Emissions = 446 g/MMBTU + 76 g/MMBTU = **522 gCO_2/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 canola oil transesterification. The calculations in Table A-35 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 A-35 are CA-GREET default values and the remaining values in the table are fuel properties. The equation is shown at the bottom of Table A-35.

The total BD processing energy of 2,116 BTU/MMBTU is based on the soybean BD pathway analysis.[19] Esterification requires a methanol input that corresponds to 10% of the biodiesel mass. This methanol energy is input to CA-GREET as fuel shares of 40.9% of the 2,116 BTU of energy input which is equal to 865 BTU/MMBTU.

The GHG emissions are calculated based on the fraction of methanol energy in BD (540 BTU/MMBTU = 2,116 x 40.9% /16,149 BTU/lb) and the carbon content of methanol (5.4% x 70 = 3.67 g/MJ). 16,149 BTU/lb is the LHV of BD on a per pound basis.

[19] ARB (December 2009). Detailed California-Modified GREET Pathway for Conversion of Midwest Soybeans to Biodiesel (Fatty Acid Methyl Esters-FAME) p. 40: http://www.arb.ca.gov/fuels/lcfs/121409lcfs_soybd.pdf

Table A-35. GHG Emissions from Fossil Carbon in Biodiesel

Description	Biodiesel (B100)
BD Production Energy Input (BTU/lb BD)	2,116
BD Lower Heating Value (BTU/gal)	119,550
BD Density (g/gal)	3,361
BD Carbon Ratio (wt%)	77.6 %
MeOH Fuel Production Share	40.9%
MeOH Lower Heating Value (BTU/gal)	57,250
MeOH Density (g/gal)	3,006
MeOH Carbon Ratio (wt%)	37.5%
CO_2/C Mass Ratio (wt%)	44.0095/ 12.011
Fossil Carbon in Fuel (gCO_2e/MJ)	**3.67**

Detailed Calculation of Fossil carbon in biodiesel (Table A-35):

Energy share of Methanol production:

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

CO_2 in Methanol Production:

$$\frac{(3{,}006 gMeOH / gal) \times (37.5\%) \times (44 gCO_2)}{(57{,}250 Btu / gal) \times (12 gC) \times (1{,}055 MJ / mmBtu)} \times 10^6 = 68.4 \text{ gCO}_2\text{/MJ methanol}$$

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

Vehicle CH_4 and N_2O emissions

The CH_4 and N_2O emissions are assumed to be the same as ULSD. ULSD emission factors for heavy duty trucks were provided in the ULSD document and are shown in Table A-36. The vehicle energy use, N_2O and CH_4 emission rates and final emissions are shown in Table A-36.

Table A-36. Vehicle CH_4 and N_2O Emissions

Parameter	2010 Emissions factor (g/mi)	GWP	GHG (gCO2e/MJ)
N_2O	0.048	298	0.735
CH_4	0.035	25	0.045
Vehicle Energy Efficiency	6.1 mi/gal		**0.78**

APPENDIX B
CANOLA FOR BIODIESEL

Table B-1. Pathway Scenario: North American Canola from Canada transported to California for Biodiesel Consumption - Input Values

Parameters	Units	Values	Note
GHG Equivalent			
CO_2		1	
CH_4		25	
N_2O		298	
VOC		3.04	
CO		1.6	
Canola Farming			
Direct Farming Efficiency		97.20%	
Fuel Use Shares			
Diesel		91.74%	
Electricity		8.26%	
Cultivation Equipment Shares			
Diesel Farming Tractor		80%	
CO_2 Emission Factor	g/MMBTU	77,725	
Diesel Engine		20%	
CO_2 Emission Factor	g/MMBTU	77,804	
Canola Farming			
Canola direct energy use	BTU/bu	15,763	
Canola yield	lbs/bu	50	
Canola T&D			
Transported from Canola 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	2,000	370 BTU/mile-ton Energy Intensity
CO_2 emission factor	g/MMBTU	77,664	
Chemicals Inputs			
Nitrogen	g/bu	1136.97	
NH3			
Production Efficiency		82.40%	
Shares in Nitrogen Production		70.70%	

Parameters	Units	Values	Note
CO_2 Emission Factor	g/g	2.475	
Transported from plant to bulk center			
by ocean tanker	miles	3,000	48 BTU/mile-ton to destination and 43 BTU/mile-ton reverse
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		46.70%	
Shares in Nitrogen Production		21.10%	
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		8.20%	
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	303.19	
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
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	227.39	
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	5.18	
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
Insecticide	g/bu	1.35	
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			
Canola Oil Yield	lb/bu	21.4	

Parameters	Units	Values	Note
	lb/lb SB	0.428	or 5.28 lbs canola / lbs canola oil
	lb/lb BD	1.026	
Biodiesel Production			
Canola oil Extraction			
Canola oil Extraction Efficiency		97.20%	
Canola oil Extraction Energy Share		42.8%	
Energy use	BTU/lb	5,867	
NG used		87.50%	
Large NG Boiler	g/MMBTU	*58,198*	50% usage
Small NG Boiler	g/MMBTU	*58,176*	50% usage
Electricity used		9.40%	
N-Hexane used		3.1%	
Canola Oil Transport			
Mileage travel by rail	miles	1,200	
Energy Intensity	BTU/ton-mile	370	
Canola oil Transesterification			
Canola oil Transesterification Allocation		95.10%	
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		2.20%	
Methanol used		40.90%	
Sodium Hydroxide used		2%	
Sodium Methoxide		9.90%	
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	
Still Gas	128,590		
Glycerin	7,979 BTU/lb		
Canola Transportation Cargo Capacity			
Medium Duty Truck	tons	8	
Heavy Duty Truck	tons	15	
Biodiesel Yield			
From Canola	gal/bu	2.81	
From Canola oil	gal/lb	0.13	
From Glycerin	lb/lb Glycerin	9.52	

APPENDIX C
CO-PRODUCT METHODOLOGY

Co-Product Allocation Methodology for Canola oil Derived Biodiesel

Biodiesel, consisting of fatty-acid methyl esters (FAME), and non-ester renewable diesel (NERD) are produced using plant-derived oils. There are a variety of potential feedstock oils, each producing co-products (see Table C-1). This Appendix discusses the co-products of canola biodiesel and the allocation method used in CA-GREET for determining co-product credits; the renewable diesel pathway (NERD) and its co-products are not discussed here.

Table C-1. Biodiesel Co-Products

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

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

Co-Product Allocation methods

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

Canola Production and Canola oil Extraction

The crushing of canola produces canola meal and canola oil. USDA data from 2007 indicates that 2.34 pounds of canola are required to produce one pound of canola oil. The balance is canola meal, a nutritive supplement for animal feed. Based on the

USDA data, proportioning the impacts of canola farming to canola meal and canola oil works out to approximately 57 percent being allocated to canola meal and 43 percent to canola oil[20]. Using this information, 43 percent of the relevant GHG emissions attributable to canola farming up to canola oil extraction are apportioned to the biodiesel pathway analysis.

Biodiesel Energy Allocation

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

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

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

$$\frac{16{,}149\,Btu/lbBD}{(16{,}149\,Btu/lbBD) + (7{,}979\,Btu/lbGlycerine)\times(0.104\,lbsGlycerine/lbBD)} = 95.1\% \qquad \text{(C-2)}$$

The value of 0.104 pounds of glycerin for every pound of biodiesel produced is obtained from the analysis presented below.

Glycerin Yield

The transesterification of plant oils is the primary method used in today's biodiesel plants [21]. In this process, plant oils such as canola oil are combined with methanol in the presence of a catalyst (acid or base) to produce fatty acid methyl esters (FAMEs) and co-product glycerin. The mixture of FAMEs is the biodiesel product. Figure C-1 illustrates this process, in which R in the figure represents the hydrocarbon chain for the fatty acids in the triglycerides comprising the oil. As the figure shows, 1 mole of oil triglycerides reacts with 3 moles of alcohol to yield 3 moles of FAME and 1 mole of glycerol (glycerin) in the transesterification reaction.

The theoretical stoichiometric mass ratio of glycerin to FAME can be determined by the distribution of fatty acids in the oil feedstock. The typical fatty acid profile for canola and soy oil is shown below in Table C-2, based on data from the Institute of Shortening and Edible Oils[22]. As the table shows, the weighted average molecular weight (MW) for

[20] Actual data works out to 57.2% of canola meal and 42.8% of canola oil.
[21] "Argonne Natioal Laboratory (2008). "Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels": http://www.transportation.anl.gov/pdfs/AF/467.pdf
[22] Institute of Shortening and Edible Oils (2006), "Food Fats and Oils," ninth edition: http://www.iseo.org/foodfatsoils.pdf

FAME produced from canola oil is **294.7** g/mol. The MW for glycerin is 92.1 g/mol, indicating a glycerin-to-FAME mass ratio of 0.104, as shown below:

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

Fatty acid	Mass Share	Fatty Acid MW (g/mol)	Methyl Ester MW (g/mol)
Linolenic Acid	10.00%	278.4	292.5
Linoleic Acid	22.00%	280.4	294.5
Oleic Acid	62.00%	282.5	296.5
Stearic Acid	2.00%	284.5	298.5
Palmitic Acid	4.00%	256.4	270.5
Weighted Average	**100%**	**280.624**	**294.66**

$$\frac{92.1 g / mol\ glycerin}{(3 mol\ FAME / mol\ glycerin) * (294.7 g / mol\ FAME)} = .104 g\ glycerin / g\ FAME$$

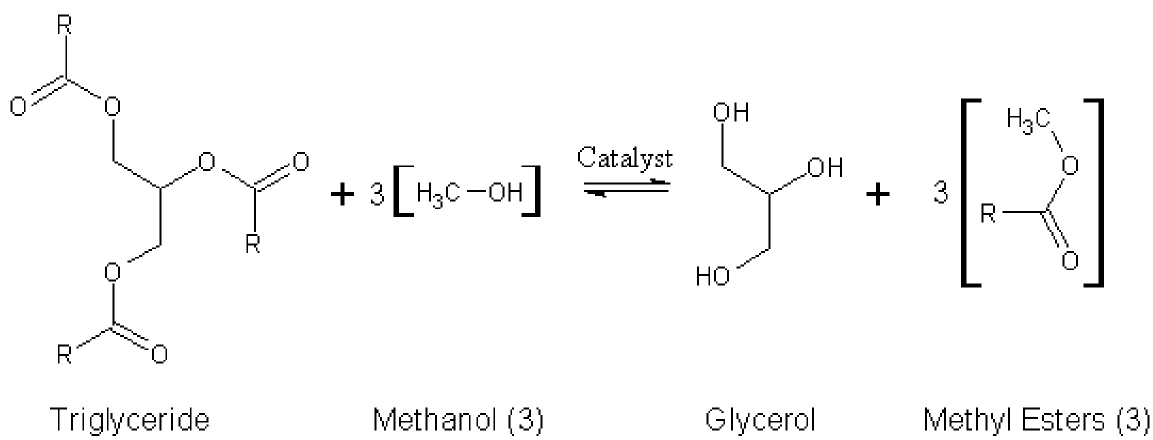


Figure C-1. Transesterification of plant oil to biodiesel

For this analysis, the 0.104 value has been used. This theoretical yield ratio corresponds closely to the yields cited by a European Union Joint Research Council study value of 0.10623 and Argonne National Laboratory study value of 0.116 for soy-derived FAME[21 above.] The actual glycerin yield under real-world operating conditions can be slightly lower than the theoretical yield since feedstock conversion is less than 100 percent; recovered crude glycerin contains small quantities of unreacted methanol and unwanted products from side reactions.

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

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