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California-Modified GREET Fuel Pathway: Biodiesel Produced in the Midwestern and the Western U.S. from Corn Oil Extracted at Dry Mill Ethanol Plants that Produce Wet Distiller's Grains with Solubles

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Industrial Strategies Division
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California-Modified GREET Fuel Pathway: Biodiesel Produced in the Midwestern and the Western U.S. from Corn Oil Extracted at Dry Mill Ethanol Plants that Produce Wet Distiller's Grains with Solubles

Prepared By:

Hafizur R. Chowdhury (Lead)
Alexander Mitchell
Chan Pham

Reviewed By:

Wes W. Ingram, Manager, Fuels Evaluation Section
Mike S. Waugh, Chief, Transportation Fuels Branch
Industrial Strategies Division

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California-Modified GREET Fuel Pathway: Biodiesel Produced in the Midwestern and the Western U.S. from Corn Oil Extracted at Dry Mill Ethanol Plants that Produce Wet Distiller's Grains with Solubles

1. Pathway Summary

Air Resources Board (ARB) staff has developed two pathways under Low Carbon Fuel Standard LCFS) for the production of biodiesel from oil extracted from the thin stillage at ethanol plants that produce wet distiller's grains with solubles (WDGS). The pathways calculate the carbon intensity (CI) of California corn oil biodiesel in which the corn oil is produced in midwestern[1] corn ethanol plants and either shipped to California for biodiesel production, or converted to biodiesel in corn-oil-producing states (COPS) and then shipped to California. The pathways describe the production of biodiesel from corn oil extracted at dry mill ethanol plants where ethanol is the primary product. The biodiesel production, finished fuel transport, and finished fuel use calculation methodologies of these pathways are similar to the corresponding pathway components in the LCFS Soybean-to-Biodiesel Pathway (California Air Resources Board, 2009a). Fuel production under the soy and corn oil pathways differs in two ways: the corn oil pathway accounts for the energy and emissions associated with free-fatty acids (FFA) removal; second, emissions from electrical energy use were estimated using energy mixes from the U.S. Environmental Protection Agency's Emissions and Generation Resource Integrated Database (eGRID) (U.S. Environmental Protection Agency, 2014). Feedstock production under the corn oil biodiesel pathways described in this document is unique to these pathways because calculation of the CI for the feedstock production step requires that feedstock production energy consumption and greenhouse gas (GHG) generation be appropriately allocated between corn ethanol and corn oil production. The bulk of this pathway document, therefore, focuses on corn oil production.

The Well-to-Tank (WTT) portion of this Life Cycle Analysis of the corn oil biodiesel pathway includes all steps from corn farming to final finished and delivered 100 percent biodiesel (B100). The Tank-to-Wheels (TTW) portion includes the actual combustion of the resulting fuel in a motor vehicle for motive power. Taken together, the WTT and the TTW analyses comprise a total Well-to-Wheels (WTW) analysis.

A version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) (Argonne National Laboratory and Life Cycle Associates LLC, 2009) model developed by Argonne National Laboratory was used to calculate the energy use and greenhouse gas (GHG) emissions generated during the entire fuel life cycle. Life Cycle Associates LLC modified the original GREET model to create a

[1] South Dakota, Nebraska, Iowa, Minnesota, Wisconsin, Illinois, Indiana, Ohio, and Michigan.

California-specific version known as the CA-GREET model. Changes were restricted mostly to adding California-specific input factors (emission factors, electrical energy generation mixes, transportation distances, etc.); no substantial changes were made to the methodology inherent in the original GREET model on which CA-GREET is based.

The results obtained from the CA-GREET model (v1.8b, released December 2009) are reported in this document. General terms and conventions used in CA-GREET analyses are discussed in Appendix E. Those results consist of the energy use and greenhouse gas (GHG) emissions from the production of biodiesel using corn oil extracted from the process streams at midwestern corn ethanol plants. The pathway assumes that the biodiesel produced is destined for use in heavy-duty-diesel vehicles. Much of the calculation methodology and many of the basic inputs and assumptions used in the corn-oil-to-biodiesel analysis are discussed in the soy biodiesel technical documentation provided by Argonne National Laboratory (Argonne National Laboratory, 2008).

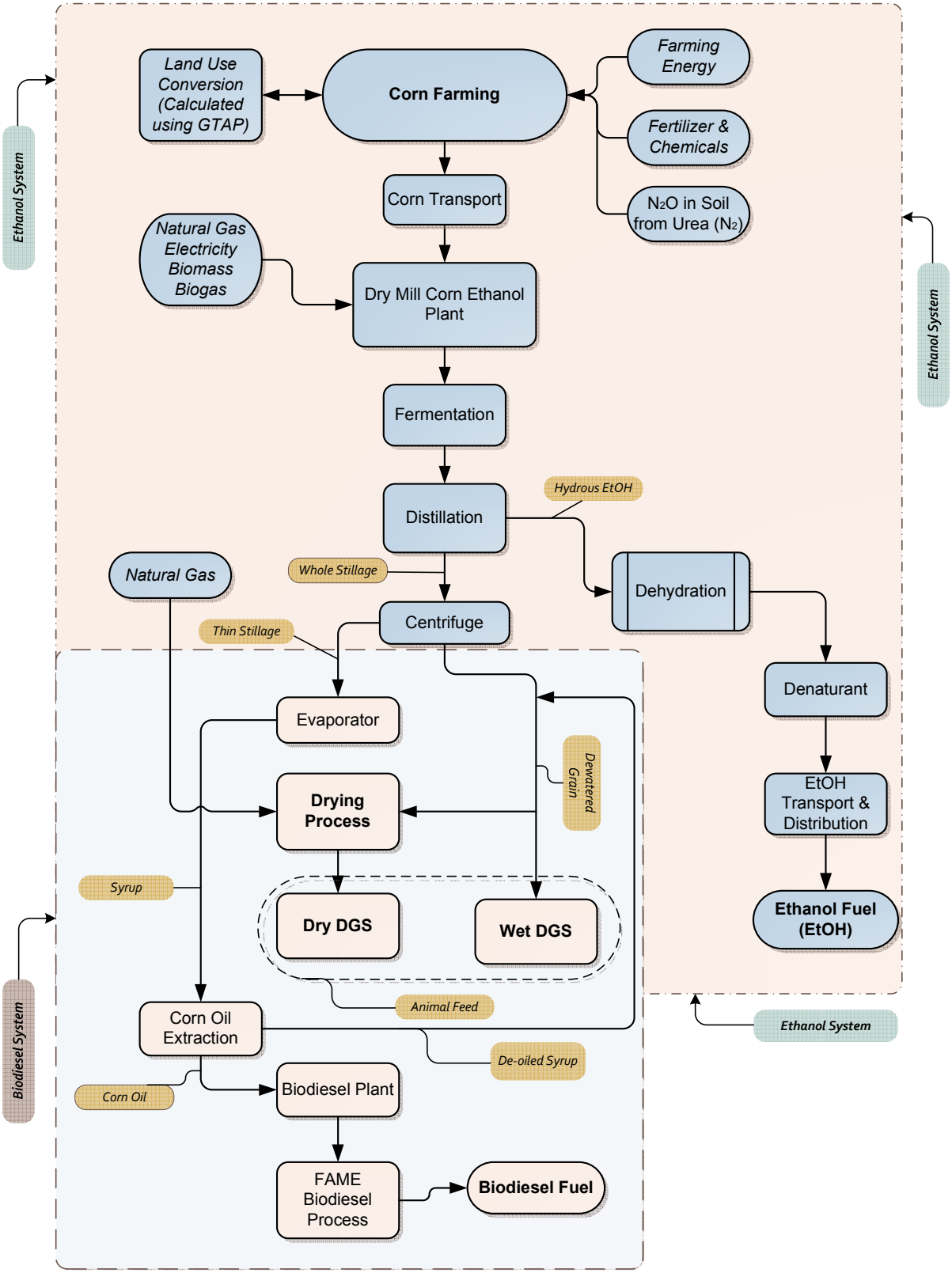
This document contains staff's estimate of the carbon intensity of biodiesel fuel produced from corn oil extracted from the thin stillage at dry mill ethanol plants. Using information provided by GreenShift Corporation (GreenShift Corporation, 2009), staff estimated the energy use and carbon intensity associated with the extraction of corn oil at dry mill ethanol plants. In this analysis, staff assumes that corn oil extraction equipment will be retrofitted to pre-existing corn ethanol plants. Staff estimates that corn oil biodiesel produced from oil extracted at plants producing WDGS will have a carbon intensity of 29.06 gCO_2e/MJ when production occurs in California and 29.27 gCO_2e/MJ when production occurs in COPS.

Because the difference between these CI values is not significant, the higher of the two (29.27 gCO_2e/MJ) will serve as the single Method 1 pathway CI for WDGS-associated corn oil biodiesel produced in the COPS, or western U.S.[2]

These values do not include any emissions resulting from the market-driven conversion of non-agricultural land to agricultural use (land use change, or LUC). The allocation of LUC emissions in this analysis is discussed below. Figure 1 illustrates this corn oil biodiesel production process. The pathway developed in this document pertains only to biodiesel produced from corn oil extracted in ethanol plants where DGS in not dried. Another pathway document covers biodiesel produced from corn oil associated with dry DGS (California Air Resources Board, 2011).

[2] Montana, Wyoming, Colorado, New Mexico, Arizona, Utah, Idaho, Washington, Oregon, Nevada, and California.

Figure 1. Corn Oil Biodiesel and Ethanol Process System Boundary for a Dry Mill Corn Ethanol Plant



The production of corn ethanol and corn oil as a biodiesel feedstock at the same plant can complicate the separate estimation of carbon intensity values for these two products. The emissions associated with agricultural chemical production, corn farming operations, and corn transportation, for example, could be allocated in whole or in part to each product. A number of methods have been used to accomplish allocations such as this. Emissions could be allocated on the basis of the total energy content of each product, for example. In this analysis, staff has decided to allocate all of the emissions associated with agricultural chemical production, corn farming operations, corn transportation, and ethanol production to the carbon intensity value of the ethanol produced at the ethanol plant, and none to the carbon intensity of the corn oil. The basis for this allocation lies in the nature of the corn oil extraction equipment installed in corn ethanol plants. Corn oil extraction equipment is installed in pre-existing corn ethanol plants. However, ethanol will continue to be the primary product at corn ethanol plants, and ethanol production will continue to be the primary reason for the construction of new corn ethanol plants. The retrofitting of corn oil extraction equipment to existing corn ethanol plants is an indication of corn oil's status as a secondary product. That secondary status should be reflected in the carbon intensity of the fuel made from this feedstock. Because corn oil extraction capability is added to plants built primarily to produce corn ethanol, all of the energy use and emissions normally attributed to ethanol production—including indirect land use change emissions—should properly remain with the ethanol. Only the additional energy use, change in co-product credits, and emissions associated with the operation of corn oil extraction equipment should be allocated to the fuel produced from that oil.

Table 1 below summarizes the energy used and GHGs emitted from the production of biodiesel from corn oil. A well-to-wheels (WTW) analysis of biodiesel indicates that for each MMBtu of corn oil biodiesel fuel energy produced 1,296,511.96 Btu of energy is required for California production and 1,295,484.71 Btu for COPS production.

Table 1. Summary of Energy Consumed and GHGs Emitted in the Production of Biodiesel from Corn Oil Extracted at Dry Mill Ethanol Plants that Produce Wet DGS

Process Parameters	CA Energy Required (Btu/MMBtu)	CA Carbon Intensity (gCO_2e/MJ of Biodiesel)	COPS Energy Required (Btu/MMBtu	COPS Carbon Intensity (gCO_2e/MJ of Biodiesel)
Well-to-Tank (WTT)				
Corn Oil Extraction	78,945.36	5.76	78,945.36	5.76
Corn Oil Transport and Distribution	26,006.09	2.20	3,671.28	0.31
Corn Oil Free-fatty Acids (FFA) Pre-treatment	12,504.43	0.70	13,304.85	0.86
Biodiesel Transesterification	160,517.77	4.97	162,752.58	5.46
Biodiesel Transportation and Distribution	10,880.07	0.82	29,152.40	2.27
Reduced DGS Credit due to Reduced DGS[a] mass	7,658.24	10.16	7,658.24	10.16
Total WTT	**295,511.96**	**24.61**	**295,484.71**	**24.82**
Tank-to-Wheel (TTW)				
Carbon in Fuel	1,000,000[b]	N/A	1,000,000[b]	N/A
Fossil Carbon in Fuel	N/A	3.67	N/A	3.67
Vehicle CH_4 and N_2O	N/A	0.78	N/A	0.78
Total TTW	**1,000,000**	**4.45**	**1,000,000**	**4.45**
Total CI Well-to-Wheel (WTW)	**1,296,511.96**	**29.06**	**1,295,484.71**	**29.27**

[a]DGS earns a credit for displacing corn in the livestock feed market (California Air Resources Board, 2009a). This credit reduction is charged to the Biodiesel.
[b]This value represents the basis of the energy emissions values reported in this table: 1 million Btu of corn-oil-biodiesel fuel energy.

As Table 1 shows, the production and use of one MJ of corn oil biodiesel, where the corn oil is extracted at a plant that produces WDGS, results in 29.06 gCO_2e when production occurs in California, and 29.27 gCO_2e when production occurs in COPS. In this analysis, the carbon intensity of corn oil biodiesel is calculated by considering the incremental emissions that occur from the operation of corn oil extraction equipment, the transportation of the feedstock and finished fuel, the production of biodiesel from corn oil, the reduction in DGS co-product mass, and the combustion of that biodiesel in a motor vehicle. Because the difference between the California and COPS CI values is not significant, the COPS value of 29.27 gCO_2e/MJ will serve as the single CI for WDGS-associated corn oil biodiesel produced in the COPS, or the western U.S. The COPS values appearing in Table 1 are discussed at more length later in this document. Additional comparative analyses of two CI values are presented in Appendix C.

2. Description of the Corn Oil Extraction Process

Corn oil can be produced at corn ethanol plants by extracting the oil from the stillage that emerges from the fermentation and distillation processes. Oil is extracted before DGS processing occurs. Corn oil extraction systems can be added to existing corn ethanol plants to increase the total volume of fuel that is produced per unit of corn processed. The installation of corn oil extraction equipment in an existing corn ethanol plant can allow production of biodiesel without affecting ethanol production volumes (GreenShift Corporation, 2009).

Although GreenShift's is not the only available extraction process, more information is publicly available on the GreenShift process than is available on competing systems. For this reason, staff's analysis in this document is based on the GreenShift process and GreenShift's estimates of energy consumption for corn oil extraction. The system commercialized by GreenShift is designed to be retrofitted into existing dry mill ethanol plants. GreenShift's systems are of two types. The first system, referred to as Corn Oil Extraction System (COES) I, extracts corn oil from the thin stillage after it is removed from the whole stillage through centrifuging. In this system, the partially concentrated thin stillage is heated and the corn oil is extracted by separation in a second centrifuge. Steam is used in heat exchangers to raise the temperature of the thin stillage for extraction. After extraction of the corn oil, thermal energy from the stillage is recovered in heat exchangers and returned to heat the incoming stillage. Appendix D contains a more detailed discussion of the GreenShift process.

The thin stillage generally contains about 30 percent of the oil available in the corn. COES I can recover most of this corn oil, depending on site-specific conditions. A typical ethanol plant uses corn that contains about four percent by weight corn oil which, in the absence of corn oil extraction, passes through the process, ending up in the DGS. The corn processed by a 50-million gallon per year ethanol plant contains about 5 million gallons of corn oil. COES I system can recover about 1.5 million of those gallons, equivalent to 3 gallons of corn oil per 100 gallons of ethanol.

GreenShift's second corn oil extraction system, referred to as COES II, is an extraction extension that frees an additional 30 percent of the corn oil that is bound in the whole stillage prior to the separation of the wet cake from the thin stillage in a centrifuge. The wet cake, however, contains about 40 percent of the total oil from the grain. COES II is a washing technique that frees this oil from the wet cake so that it is recoverable in the COES I system. The additional oil made available to the COES I system generally doubles the production of corn oil. COES I and II together can extract 60 to 70 percent of the corn oil passing through the plant, which translates to about six to seven gallons of corn oil per 100 gallons of ethanol produced.

Because the COES II system has not been widely adopted, the results presented in this analysis are based on the operation of COES I alone.

3. Corn Oil Extraction Energy Use and GHG Emissions

Electric power and steam are supplied to the corn oil extraction equipment from the ethanol plant's existing power systems. According to GreenShift (GreenShift Corporation, 2009), operating a COES I system requires about 0.01 kWh per gallon of ethanol produced. This electrical energy is used to power the motors on the centrifuge and the pumps. This electricity use is equivalent to about 34 Btu per gallon of ethanol produced. Table 2 summarizes the total energy use for corn oil extraction. The total electrical and thermal energy values appearing in Table 2 consist of both upstream and direct consumption. Detailed calculations are provided in Appendix A.

Table 2. Greenhouse-Gas-Generating Energy Consumed[a] to Extract Corn Oil at Ethanol Plants Producing Wet DGS

Fuel Production System[b]	Source of Energy Consumption	Upstream Energy Required by the Ethanol Plant		In-Plant Energy Consumption	Total Energy Use
		Fuel Production	Electrical Energy Generation		
Ethanol System	Natural Gas (Btu/gal)	12.64	N/A[c]	180	192.64
	Electricity (Btu/gal)	105.18	2.65	34[d]	105.18[d]
	Total Energy (Btu/gal)	297.82	2.65		297.82
	Total Energy (Btu/MMBtu)				3,901.68
Biodiesel System	Conversion from Ethanol to BD Basis (Btu/MMBtu)[e]				83,037.85
	Co-product and Loss Factor Adjustments (Btu/MMBtu)[f]				**78,945.36[g]**

[a]Although the natural gas combusted in the ethanol plant generates GHG emissions, the electricity used in the plant does not. The only emissions generated by the use of electrical energy are those associated with the production of the feedstock fuels for the generating plants, and the operation of those generating plants. In the case of natural gas, emissions are generated by natural gas extraction and transport, and by in-plant use.
[b]Please see Figure 1.
[c]Upstream natural gas production is independent from upstream electricity generation.
[d]This electrical energy consumption (34 Btu) is needed to produce one gallon of corn oil. The total electrical energy (105.18 Btu) shown does not include this in-plant energy consumption because the consumption of this energy in the plant does not generate GHGs.
[e]The conversion to a Biodiesel (BD) basis utilizes ethanol and BD lower-heating values and a corn oil yield of 0.030 gallon of corn oil per gallon of ethanol produced based on GreenShift information.
[f]The BD process yields BD and glycerin. Of the total energy contained in these two products, 95.1 percent is contained in the BD and the remaining 4.9 percent is contained in the glycerin. The 95.1 percent of the energy consumed in the extraction process is therefore allocated to BD and the remaining 4.9 percent to the glycerin. Thus, the Loss Factor of 1.000039 is applied to the final value.
[g]This refers to the corn oil extraction energy required for Wet DGS in Table 1 of this document.

The COES I system uses steam from the ethanol plant's thermal energy system to provide operating heat. This system requires about 180 Btu per gallon of ethanol produced. This energy generally comes from a boiler burning natural gas. Table 3 provides additional detail on the sources of the energy consumption values given in the first three rows of Table 2.

Table 3. Energy Use from the Operation of Corn Oil Extraction Equipment at Dry Mill Ethanol Plants

Sources of Corn Oil Extraction Energy Consumption	Energy Use for Wet DGS (Btu/gal EtOH Produced)
1. Thermal energy use at the ethanol Plant (natural gas)	180
2. Upstream thermal energy consumption (natural gas)	12.64
3. Electrical energy use at the ethanol plant	34
4. Electrical energy, upstream stationary electrical stage feedstock production energy (energy to produce the fuel used to produce electricity)	2.65
5. Electrical energy, upstream stationary electricity fuel stage energy (energy to produce electricity)	105.18
6. Energy use at the ethanol plant due to corn oil production (1 + 3)	214
7. Energy use due to corn oil production, including upstream energy uses (1 + 2 + 4 + 5)	**297.82**

4. Carbon Intensity of Corn Oil Extraction

The calculated CI for the extraction of corn oil using the COES I system is shown in Table 4. The GHG emission factors are the same as those used in staff's pathway for the production of ethanol from corn (California Air Resources Board, 2009b). As shown in Table 3, the installation of COES I in a corn ethanol plant increases the total energy consumption at the ethanol plant by 297.82 Btu per gallon of ethanol produced. Assuming that 3.0 gallons of corn oil are produced per 100 gallons of ethanol, and taking into account the energy differences between corn oil and ethanol, this translates to an increase of 5.76 gCO_2e/MJ of corn oil extracted when DGS remains wet. Table 4 shows a net CI of 5.75 gCO_2e/MJ for corn oil extraction. The slight difference between this and the value reported in Table 1 is due to rounding. The details behind these calculations are shown in Appendix B.

Table 4. Greenhouse Gas Emission Factors and Net Carbon Intensities for Corn Oil Extraction at Dry Mill Ethanol Plants that Produce Wet DGS

Sources of Energy Use	GHG Emissions Factor ($gCO_2e/MMBtu$)[a]	Carbon Intensity (gCO_2e/MJ of EtOH)	Wet DGS Carbon Intensity (gCO_2e/MJ of Biodiesel)
1. Thermal Energy Use at the Ethanol Plant, Natural Gas, (CO_2 emissions)	58,187	0.137	2.912
2. Thermal Energy, Upstream Feedstock, Natural Gas, (CO_2 emissions)	5,245	0.012	0.262
3. Electrical Energy, Upstream Stationary Electricity Feedstock Stage Energy, (Energy to Produce the Fuel Used to Produce Electricity), (CO_2 emissions)[b]	7,794	0.003	0.074
4. Electrical Energy, Upstream Stationary Electricity Fuel Stage Energy (Energy to Produce Electricity), (CO_2 emissions)[b]	233,154	0.104	2.204
5. Electrical Energy and Thermal Energy, Direct and Upstream Use of Natural Gas and Electricity (CH_4, VOC, CO, N_2O emissions)[b]	Detailed CO_2e Calculations are in Table B-1 of Appendix B[c]	0.012	0.245
6. Total Carbon Intensity for Corn Oil Extraction (1 + 2 + 3 + 4 + 5)	N/A	**0.27**	**5.75**[d]

[a]The emission factor for natural gas is expressed in units of gCO_2e upstream emissions per Btu downstream energy use. Therefore, the total greenhouse gas emissions are calculated by taking the product of the emission factor and the downstream energy use of 180 Btu per gallon. The emission factor for electricity is expressed in units of gCO_2e upstream emissions per Btu downstream electricity use. Therefore, the CO_2e emissions for electricity are calculated by taking the product of this emission factor and the downstream energy use of 34 Btu per gallon.
[b]Although natural gas use produces emissions both upstream and in the plant, electricity use produces emissions only upstream. The use of electricity in the plant produces no additional emissions.
[c]The upstream and direct energy use calculations (natural gas and electricity basis) for all pollutants (VOC, CO, CH_4, and N_2O) are rather lengthy, therefore, they are placed in Appendix B, Table B-1.
[d]Numbers do not add up exactly due to rounding. No rounding was performed when calculating the final number. Due to a slightly different calculation methodology, this number does not match the value in Table 1.

5. Effect of Corn Oil Extraction on DGS Production

As shown in Section 2, the use of COES I results in the extraction of about three gallons of corn oil per 100 gallons of corn ethanol produced. This equates to about 0.23 pounds of corn oil per gallon of ethanol produced, assuming corn oil weighs 7.7 pounds per gallon[3] (U.S. Department of Agricultural, 1992). The removal of the corn oil from DGS reduces the DGS co-product credit for corn ethanol. Because DGS yields without the use of corn oil extraction are typically 5.34 pounds per gallon of ethanol produced (CA-GREET default), a reduction of 0.23 pounds per gallon of ethanol represents about a 4.3 percent reduction in the DGS yield. This 4.3 percent reduction in DGS yield translates to a 4.3 percent reduction in the DGS co-product credit. Because

[3]Calculations: (3 lbs of corn oil/100 gals of EtOH produced) x 7.70 lbs/gal = 0.231 lb of corn oil/gal EtOH produced.

the DGS co-product credit for corn ethanol without corn oil extraction is 11.62 gCO_2e/MJ of ethanol produced, a 4.3 percent reduction in the credit due to corn oil extraction translates to a reduction in the co-product credit of 0.50 gCO_2e/MJ of ethanol produced. This reduction in the credit can be considered as an increase in the carbon intensity of corn-oil-based biodiesel. Converting this 0.50 gCO_2e credit reduction per MJ of ethanol to a gCO_2e/MJ of biodiesel basis gives a credit reduction of 10.16 gCO_2 per MJ of biodiesel. The details of this calculation are shown in Appendix B. This co-product credit reduction is included in the WTW carbon intensity of the biodiesel.

Removal of corn oil reduces the fat and energy content and increases the protein content of the DGS. For some livestock species, higher fat and energy content is desirable, while for others higher protein content is needed. Staff has not attempted to estimate the net effects of these nutritional changes on the extent to which DGS displaces other feeds in the marketplace, nor on the carbon intensity associated with this displacement change. It has instead assumed that the effects described in this paragraph offset each other, and left the CA-GREET DGS-to-other-feed displacement ratio unchanged at 1:1.

6. Corn Oil Transportation

Because feedstock transportation is within the system boundary of the pathway covered by this analysis, staff used the CA-GREET model to calculate the energy consumed and the GHG emissions generated during the transport of the corn oil extracted from the ethanol process stream.

Corn oil from dry mill ethanol plants is assumed to be transported 50 miles by heavy-duty-diesel truck (HDDT) to biodiesel production facilities.

The energy consumption associated with corn oil transport is shown in Table 5. All transportation emissions calculations are performed using the CA-GREET model.

Table 5. Total Energy Required for Corn Oil Transport

Corn Oil Transport	Energy Use (Btu/MMBtu)	With 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (Btu/MMBtu)
Transported by HDDT to Production Facility, 50 miles	3,861.60	3,671.28
Total Energy	**3,861.60**	**3,671.28**

The GHG emissions generated by the consumption of this transport energy are summarized in Table 6.

Table 6. Total GHG Emissions from Corn Oil Transportation

GHG Components	GHG Emissions (g/MMBtu)
VOC	0.16
CO	0.52
CH_4	0.38
N_2O	0.01
CO_2	316.94
Conversion to gCO_2e/MMBtu	330.74
Total Emissions Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (gCO_2e/MJ)	**0.31**

7. Biodiesel Production

The interaction of FFAs in feedstock with the sodium methoxide catalyst may form emulsions which make separation of the biodiesel more difficult, possibly leading to

reduced yields. At over 12 percent, corn oil extracted from distiller's grains at corn ethanol plants contains more FFAs than most other feedstocks. To prevent emulsion formation, FFAs must be removed prior to transesterification (Sanford, et al., 2009). The total energy required for this pre-treatment is 13,304.85 Btu/MMBtu (i.e., direct 10,588.89 Btu/MMBtu and upstream 2,715.96 Btu/MMBtu). The emissions associated with the FFA pre-treatment steps are shown in Table 7.

Table 7. Total GHG Emissions from Corn Oil Free-Fatty Acids Pre-treatment

GHG Components	GHG Emissions (gCO_2e/MMBtu)
VOC	0.11
CO	0.60
CH_4	1.61
N_2O	0.01
CO_2	913.28
Conversion to Total gCO_2e/MMBtu	956.51
Conversion to gCO_2e/MJ	**0.86**

The process of producing biodiesel from corn oil is known as fatty acid methyl ester (FAME) transesterification. Prior to transesterification, the feedstock is filtered to remove water and contaminants, and then pre-treated to reduce the free fatty-acid content of the oil. The filtered pre-treated oil is then mixed with methanol and a catalyst in a closed reactor system at low temperature and pressure. After the mixture settles in the reactor vessel, the glycerin and crude biodiesel are separated. The majority of the methanol is recovered from the glycerin co-product and recycled back into the system. The biodiesel is then washed to remove residual contaminants.

The CA-GREET corn oil biodiesel model calculates a total energy consumption value of 162,752.58 Btu/MMBtu for the transesterification step. Tables 8 and 9 summarize the energy use and the GHG emissions generated by the biodiesel production process calculated using the CA-GREET model.

Table 8. Total Energy Required for Biodiesel Production via Transesterification

Source of Energy Use	Energy Use (Btu/lb)
Natural Gas	951.15
Electricity	143.98
Methanol	1,354.07
Sodium Hydroxide	42.32
Sodium Methoxide	209.48
Hydrochloric Acid	63.48
Total Energy Use	2,764.49
Total Energy Use (Btu/MMBtu)	171,189.58
Total Energy Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (Btu/MMBtu)	**162,752.58**

Table 9. Total GHG Emissions from Biodiesel Transesterification

GHG Components	GHG Emissions (gCO_2e/MMBtu)
VOC	1.91
CO	4.50
CH_4	18.47
N_2O	0.04
CO_2	5,568.05
Conversion to Total gCO_2e/MMBtu	6,053.98
Convert to gCO_2e/MJ	5.74
Total Emissions Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (gCO_2e/MJ)	**5.46**

8. Biodiesel Transport and Distribution

The next step in the biodiesel pathway is the transport of finished biodiesel fuel from the production plant to the retail station. To account for the fact that any biodiesel blend, up to and including B100, could be transported from the bulk terminal to refueling stations, this analysis assumes that B100 is transported.

In this analysis, the finished biodiesel is assumed to be transported 50 miles by HDDT to the rail yard, 1,400 miles by rail to the California rail yard, and then 90 miles by HDDT to refueling stations. The energy expenditure is calculated using CA-GREET to be 29,152.40 Btu/MMBtu.

Table 10 summarizes the transport assumptions and resulting energy consumption in the finished fuel transport step. Details of energy consumption for biodiesel transport and distribution are provided in Appendix A.

Table 10. Energy Consumption for Biodiesel Transport and Distribution (T&D)

Biodiesel Transport	Energy Use (Btu/MMBtu)
Transported by HDDT to Rail Yard, 50 miles	3,713.07
Transported by Rail to California Rail Yard, 1,400 miles	18,717.13
Transported by HDDT to Refueling Station, 90 miles	6,683.53
Hydrochloric acid adjustments for de-soaping biodiesel during transport	38.67
Total Energy	**29,152.40**

The GHG emissions generated by the energy consumed to transport biodiesel are summarized in Table 11. The detailed calculations behind the values appearing in Table 11 are provided in Appendix B.

Table 11. Total GHG Emissions from Biodiesel Transport and Distribution (T&D)

GHG Components	GHG Emissions ($gCO_2e/MMBtu$)
VOC	2.53
CO	5.34
CH_4	2.67
N_2O	0.06
CO_2	2,300.98
Conversion to Total $gCO_2e/MMBtu$	2,400.40
Conversion to gCO_2e/MJ	**2.27**

9. GHG Emissions from Biodiesel-Fueled Vehicles

Tailpipe GHG emissions from biodiesel-fueled vehicles are calculated using the same approach that was used to calculate ultra-low sulfur diesel (ULSD) tailpipe emissions (California Air Resources Board, 2009c). This approach accounts for two categories of emissions: those resulting from the fossil carbon in the fuel, and those generated by the combustion of the fuel in a heavy-duty-diesel (HDD) engine.

As with soy oil biodiesel, the only source of fossil carbon in corn oil biodiesel is a trace of residual methanol. While the methanol used to produce soy and corn oil biodiesel is typically derived from natural gas, the remainder of the carbon in the fuel is biogenic. Carbon from biogenic sources is assumed to produce no net greenhouse gas emissions in LCFS fuel pathways. The amount of residual methanol present, and the emissions produced by that methanol—3.67 gCO_2e/MJ—are assumed to be equal for soy and corn oil biodiesel. Please see the soy biodiesel pathway document (California Air Resources Board, 2009a).

Biodiesel emissions of methane and N_2O from an HDDT are assumed to be equal to the combustion emissions from an ULSD-powered HDD engine: As described in the ULSD pathway document (California Air Resources Board, 2009c), the N_2O and CH_4 generated by the combustion of ULSD create GHG emissions that sum to 0.78 gCO_2e/MJ.

As shown in Table 1, the combustion-related N_2O, CH_4, and fossil carbon emissions from corn oil biodiesel are included in the TTW portion of the corn oil biodiesel CI. Details on the calculations of these emissions can be found in Section 9 of Appendix B.

These two categories of tailpipe emissions are summarized and totaled in Table 12.

Table 12. Total GHG Emissions from Biodiesel Used in a Heavy-Duty Vehicle

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

10. Complete Pathway Carbon Intensity

This section summarizes the overall CI for biodiesel produced from corn oil extracted in ethanol plants that produce a wet DGS co-product. This CI is available for use by plants located in the western and midwestern states. The overall CI of this pathway consist of the sum of the CIs of each of the process components discussed in the previous sections of this document (which, in turn, correspond to entries in Table 1).

Individual corn oil biodiesel pathway component CIs, along with overall pathway CI for wet DGS, are shown in Table 13. The calculations behind these carbon intensity values are also provided in Appendix B.

Table 13. Pathway Carbon Intensity for Biodiesel Produced from Corn Oil Extracted at Dry Mill Ethanol Plants that Produce Wet DGS

Process Parameters	Carbon Intensity (gCO_2e/MJ of Biodiesel)
Corn Oil Extraction	5.76
Corn Oil Transport	0.31
Corn-Oil Free-fatty Acids Pre-treatment	0.86
Biodiesel Transesterification	5.46
Biodiesel Transportation and Distribution	2.27
Fossil Carbon in Fuel	3.67
Vehicle CH_4 and N_2O	0.78
DGS Co-Product Credit Reduction	10.16
Total CIs for Corn Oil Biodiesel for Wet DGS	**29.27**

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APPENDIX A

Energy Use Estimates: Corn Oil Extraction and Biodiesel Transport

This appendix shows how the CA-GREET model calculated the energy use estimates on which pathway GHG emissions and final carbon intensities are based. Please see ARB's corn ethanol pathway document for additional information on energy use calculations (California Air Resources Board, 2009b).

1. Corn Oil Extraction and Upstream Well-to-Tank Natural Gas Feedstock Use

Upstream natural gas energy use is 70,154 Btu/MMBtu of natural gas produced. At an ethanol plant consuming 180 Btu/gal of ethanol produced, the upstream natural gas use is:

$$= \frac{\left(70{,}154\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(180\,\frac{Btu}{gal\ EtOH}\right) = \left(12.63\,\frac{Btu}{gal\ EtOH}\right)$$

2. Corn Oil Extraction, Electrical Energy, and Upstream Stationary Electricity Feedstock Stage Energy Use (Energy to Produce the Fuel Used to Produce Electricity)

The stationary electricity feedstock energy is 99,790 Btu/MMBtu. For a total electrical energy use at the ethanol plant of 34 Btu/gal of ethanol produced, the upstream stationary electricity feedstock stage energy is:

$$= \frac{\left(99{,}790\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(34\,\frac{Btu}{gal\ EtOH}\right) = \left(3.39\,\frac{Btu}{gal\ EtOH}\right)$$

3. Corn Oil Extraction, Electrical Energy, and Upstream Stationary Electricity Fuel Stage Energy (Energy to Produce Electricity)

The stationary electricity fuel stage energy is 2,877,173 Btu/MMBtu. For a total electrical energy use at the ethanol plant of 34 Btu/gal of ethanol produced, the upstream stationary electricity fuel stage energy is:

$$= \frac{\left(2{,}877{,}173\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(34\,\frac{Btu}{gal\ EtOH}\right) = \left(97.82\,\frac{Btu}{gal\ EtOH}\right)$$

4. Biodiesel Transport and Distribution

Finished corn oil biodiesel is transport 1,400 miles via railcar to California. CA-GREET calculates the energy expenditure to be 18,717.13 Btu/MMBtu. Table A-1 summarizes the transport assumptions and resulting total energy consumption in the finished fuel transport step.

All of the Biodiesel is transported by heavy-duty-diesel truck (HDDT) 50 miles from the plant to bulk terminal and, then another 90 miles by HDDT from the bulk terminal to refueling or distributing stations. The trucking distance input in CA-GREET includes hauling biodiesel to a petroleum terminal for blending followed by distribution to a fueling station as a blended fuel. Since any blend up to and including B100 could be transported from the petroleum terminal to refueling stations, this analysis is based on the transport of B100. The resulting transport CI covers all possible blends. Transport energy use and emissions are calculated identically for corn oil and finished biodiesel: Btu/ton-mile is converted to Btu/ton, which, in turn, is converted to Btu/MMBtu. Upstream transport energy use is calculated in the same way. Finally, the energy consumed during each transport mode is multiplied by its respective mode share and the results summed to yield total transport energy consumption.

Table A-1. Energy Use for Biodiesel Transport and Distribution[a] from Primary Corn-Oil-Producing States to California

Parameters	Biodiesel Transport to CA	Plant to Bulk Terminal	Distribution to Refueling Station	Total Energy
Mode	Rail	HDD Truck	HDD Truck	
Shares (%)	100%	100%	100%	
Distance (miles)	1400	50	90	
Truck Payload (tons)	N/A	25	25	
Railcar Payload (gallons)	25,000			
Truck Fuel Economy (mi/gal)	N/A	5	5	
Railcar Fuel Economy (ton-mile/gal diesel)	476	N/A	N/A	
Fuel	Diesel	Diesel	Diesel	
Fuel LHV (Btu/gal)	128,450	128,450	128,450	
Energy Intensity (Btu/ton-mile)[b]	370	1,028	1,028	
Direct Energy (Btu/MMBtu)[c]	16,038.47	3,181.68	5,727.03	24,947.18
Upstream Energy (Btu/MMBtu)[c]	2,678.66	531.39	956.50	4,166.55
Total BD T&D Energy (Btu/MMBtu)	**18,717.13**	**3,713.07**	**6,683.53**	**29,152.40[d]**

[a]The CA-GREET calculation is based on eGRID subregion energy generation mix (Regional LT Tab) because of the finished fuel. In addition, no co-product allocation and loss factor adjustment is made for finished fuel transport.
[b]Energy Intensity = LHV/fuel economy/payload = 1,028 Btu/ton-mile for truck and 370 Btu/ton-mile for railcar. Direct truck energy doubles the miles to take into account for round trip energy, but not for the railcar.
[c]Since the distance traveled is relatively short, the return trip energy intensity is assumed to be the same as from origin to destination. Energy intensity usage by railcar is one way to transport biodiesel to California assuming railcar returns with goods movement.
[d]Hydrochloric acid factor is added to the biodiesel to prevent soap formation in the biodiesel tank of the truck and railcar due to continuous movement of the fluids during the traveling period.

For California, the next step in the biodiesel pathway is transport of finished biodiesel fuel from the production plant to the retail station. When transported 50 miles from plant to bulk terminal and, then 90 miles to refueling stations by HDDT, as this analysis assumes, CA-GREET calculates the energy expenditure to be 10,880.07 Btu/MMBtu based on using the eGRID subregion electrical energy mix in California. Table A-2 summarizes the transport assumptions and resulting energy consumption in the finished fuel transport step.

Table A-2. Energy Use for Biodiesel Transport and Distribution[a] within California

Parameters	Plant to Bulk Terminal	Distribution to Refueling Station	Total Energy
Mode	HDD Truck	HDD Truck	
Shares (%)	100%	100%	
Distance (miles)	50	90	
Payload (tons)	25	25	
Fuel Economy (mi/gal)	5	5	
Fuel	Diesel	Diesel	
Fuel LHV (Btu/gal)	128,450	128,450	
Energy Intensity (Btu/ton-mile)[b]	1,028	1,028	
Direct Energy (Btu/MMBtu)[c]	3,181.68	5,727.03	8,908.72
Upstream Energy (Btu/MMBtu)[c]	690.25	1,242.44	1,932.69
Total BD T&D Energy (Btu/MMBtu)	**3,871.93**	**6,969.48**	**10,880.07[d]**

[a]The CA-GREET calculation is based on using the eGRID subregion energy mix (Regional LT Tab) because of the finished fuel. In addition, no co-product allocation and loss factor adjustment is made for finished fuel transport.
[b]Energy Intensity = LHV/fuel economy/payload = 1,028 Btu/mile-ton. Direct truck energy doubles the miles to account for round trip energy.
[c]Since the distance traveled is relatively short, the return trip energy intensity is assumed to be the same as from origin to destination.
[d]Hydrochloric acid factor is added to the final biodiesel to prevent soap formation in the biodiesel tank of the truck due to continuous movement of the fluids during the traveling period.

APPENDIX B

Emission Factors and Carbon Intensity Estimates

This appendix shows how the CA-GREET model was used to calculate carbon intensities for the corn oil biodiesel pathway and also provides the GHG emission factors on which those carbon intensities are based. Please see ARB's corn ethanol pathway document for additional information on emission factors and carbon intensity calculation (California Air Resources Board, 2009b).

1. Corn Oil Extraction Carbon Intensity, Direct Emissions, Thermal Energy, and Natural Gas (CO_2 emissions)

We use the average emission factors for large and small boilers. Therefore, (58,198 + 58,176)/2 gCO_2/MMBtu = 58,187 gCO_2/MMBtu represents direct emissions per Btu of downstream energy use. Therefore, the total direct carbon intensity from natural gas feedstock use is calculated by taking the product of the emission factor and the downstream energy use of 180 Btu/gal ethanol).

$$= \frac{\left[\frac{\left(180\,\frac{Btu}{gal\ ethanol}\right) \times \left(58{,}187\,\frac{gCO_2}{mmBtu}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{MJ}{MMBtu}\right)} \times 0.951\ \times 1.000039 = \left(0.1368\ \frac{gCO_2}{MJ\ EtOH}\right)$$

An adjustment to this carbon intensity must be made to account for the loss factor and the glycerin co-product credit. The adjustment is made by multiplying the carbon intensity by 95.1 percent co-product and 1.000039 loss factor allocation. Conducting this multiplication gives a carbon intensity of 0.1368 gCO_2/MJ ethanol. Similar calculations and adjustments were made from the following step 2 to step 4.

2. Corn Oil Extraction Carbon Intensity and Upstream Well-to-Tank Natural Gas Feedstock Energy Use (CO_2 emissions)

The emission factor of 5,245 gCO_2/MMBtu represents upstream emissions per Btu of downstream energy use. Therefore, the total upstream carbon intensity from natural gas feedstock use is calculated by taking the product of the emission factor and the downstream energy use of 180 Btu/gal ethanol.

$$= \frac{\left[\frac{\left(180\,\frac{Btu}{gal\ ethanol}\right) \times \left(5{,}245\,\frac{gCO_2}{MMBtu}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{MJ}{MMBtu}\right)} \times 0.951 \times 1.000039 = \left(0.0123\ \frac{gCO_2}{MJ\ EtOH}\right)$$

3. Corn Oil Extraction, Carbon Intensity of Electrical Energy, and Upstream Stationary Electricity Feedstock Stage Energy (Energy Used to Produce the Fuel Used to Produce Electricity) (CO_2 emissions)

The emission factor of 7,794 gCO_2/MMBtu represents the upstream emissions per Btu of downstream electricity use. Therefore, the upstream stationary electricity feedstock carbon intensity is:

$$= \frac{\left[\frac{\left(7{,}794\,\frac{gCO_2}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(34\,\frac{Btu}{gal\ EtOH}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times 0.951 \times 1.000039$$

$$= \left(0.0035\,\frac{gCO_2}{MJ\ EtOH}\right)$$

4. Corn Oil Extraction, Carbon Intensity of Electrical Energy, and Upstream Stationary Electricity Fuel Stage Energy (Energy to Produce Electricity) (CO_2 emissions)

The emission factor of 233,154 gCO_2/MMBtu represents the emissions from the natural gas fuel burned to generate electricity. The carbon intensity value is:

$$= \frac{\left[\frac{\left(233{,}154\,\frac{gCO_2}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(34\,\frac{Btu}{gal\ EtOH}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times 0.951 \times 1.000039$$

$$= \left(0.1035\,\frac{gCO_2}{MJ\ EtOH}\right)$$

5. Corn Oil Extraction, Carbon Intensity of Electrical Energy and Thermal Energy, and Direct Use of Natural Gas and Electricity (CH_4, VOC, CO, and N_2O Emissions)

Table B-1 shows the CA-GREET emissions factors for upstream and direct use of natural gas and electricity.

Table B-1. Upstream and Direct Emissions Factors for Natural Gas and Electricity

Pollutant (g/MMBtu)	Natural Gas[a]			Electricity[a]		
	Upstream	Direct[b]	Total	Upstream	Direct	Total
VOC	6.288	1.987	8.28	22.460	4.250	26.71
CO	11.702	22.621	34.32	14.249	265.809	280.06
CH_4	128.850	1.100	129.95	363.575	4.967	368.54
N_2O	0.065	0.315	0.38	0.104	2.134	2.54

[a]Direct emission factors are in units of direct emissions per unit direct energy use. Upstream emission factors are in units of upstream emissions per unit direct energy use. Because both upstream and direct emission factors are in units of emissions per direct energy use, they can be added.
These emission factors can be found on the following tabs and cells in the CA-GREET spreadsheet: Natural Gas, Upstream: NG Tab, Cells B129:B136; Direct: EF Tab, Cells B6:B13; Electricity, Upstream: Electric tab, Cells B89:B96; Direct: Electric tab, Cells C89:C96. The emissions factors are for the CA-GREET eGRID subregion energy generation mix.
[b]50 percent use of each large and small size of natural gas boiler.

Carbon Intensity Calculations for Upstream and Direct:

$$\boldsymbol{Natural\ Gas\ VOC}$$

$$= \frac{\left[\dfrac{\left(8.28\,\dfrac{gVOC}{MMBtu}\right)\times\left(180\,\dfrac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\dfrac{Btu}{MMBtu}\right)} \times \dfrac{\left(\dfrac{0.85\ \dfrac{gCarbon}{gVOC}}{0.27\ \dfrac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\,\dfrac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\dfrac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\dfrac{J}{MJ}\right)$$

$$\times\,(0.951)\ \times\ 1.000039$$

$$= \left(0.00005488\,\frac{gCO_2e}{MJ}\right)$$

Natural Gas CO

$$= \frac{\left[\frac{\left(34.32\,\frac{gCO}{MMBtu}\right) \times \left(180\,\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(\frac{0.43\,\frac{gCarbon}{gCO}}{0.27\,\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right)$$

$$\times (0.951) \times 1.000039$$

$$= \left(0.00011454\,\frac{gCO_2e}{MJ}\right)$$

Natural Gas CH_4

$$= \frac{\left[\frac{\left(129.95\,\frac{gCH_4}{MMBtu}\right) \times \left(180\,\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(25\,\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times (0.951)$$

$$\times 1.000039$$

$$= \left(0.00690565\,\frac{gCO_2e}{MJ}\right)$$

Natural Gas N_2O

$$\frac{\left[\frac{\left(0.38\,\frac{gN_2O}{MMBtu}\right) \times \left(180\,\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(298\,\frac{gCO_2e}{gN_2O}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times (0.951) \times 1.000039$$

$$= \left(0.00024080\,\frac{gCO_2e}{MJ}\right)$$

Electricity VOC

$$= \frac{\left[\frac{\left(26.71\frac{gVOC}{MMBtu}\right)\times\left(34\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(\frac{0.85\frac{gCarbon}{gVOC}}{0.27\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right) = 0.0000355$$

$$(0.0000355 \times 0.951 \ \times 1.000039) = \left(0.00003347\frac{gCO_2e}{MJ}\right)$$

Electricity CO

$$= \frac{\left[\frac{\left(280.06\frac{gCO}{MMBtu}\right)\times\left(34\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(\frac{0.43\frac{gCarbon}{gCO}}{0.27\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right) = 0.000188$$

$$(0.000188 \times 0.951 \ \times 1.000039) = \left(0.00017658\frac{gCO_2e}{MJ}\right)$$

Electricity CH_4

$$\frac{\left[\frac{\left(368.54\frac{gCH_4}{MMBtu}\right)\times\left(34\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(25\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right) = 0.00389$$

$$(0.003389 \times 0.951 \ \times 1.000039) = \left(0.00370010\frac{gCO_2e}{MJ}\right)$$

$\boldsymbol{Electricity\ N_2O}$

$$\frac{\left[\frac{\left(2.24\frac{gN_2O}{MMBtu}\right)\times\left(34\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)}\times\frac{\left(298\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)}\times\left(1{,}000{,}000\frac{J}{MJ}\right)=0.0002818$$

$$(0.0002818\times 0.951\ \times 1.000039)=\left(0.00026782\frac{gCO_2e}{MJ}\right)$$

Therefore, the total carbon intensity (gCO_2e/MJ) =

$$(0.00005488+0.00011454+0.00690565+0.00024080+0.00003347+0.00017658 \\ +0.00370010+0.00026782)=0.01149384\frac{gCO_2e}{MJ}\approx\left(0.0115\frac{gCO_2e}{MJ}\right)$$

6. Total Carbon Intensity of Corn Oil Extraction (CO_2e emissions)

Carbon intensity of corn oil extraction is the sum of the above components (from Section 1 through 5), which is equal to:

$$(0.1368+0.0123+0.0035+0.1035+0.0115)=0.2667\ \approx\left(0.27\frac{gCO_2e}{MJ\ EtOH}\right)$$

Therefore, gCO_2e/MJ Biodiesel =

$$\left(0.27\frac{gCO_2e}{MJ\ EtOH}\right)\times\left(76{,}330\frac{Btu\ EtOH}{gal\ EtOH}\right)\times\left(\frac{1\ gal\ EtOH}{0.030\ gal\ corn\ oil}\right)$$

$$\times\left(\frac{1gal\ corn\ oil}{1gal\ biodiesel}\right)\times\left(\frac{1gal\ biodiesel}{119{,}550\ Btu\ biodiesel}\right)\ =\mathbf{5.75}\frac{\boldsymbol{gCO_2e}}{\boldsymbol{MJ\ Biodiesel}}$$

However, the CA-GREET calculations on corn oil extraction in Table 1 of this report shows 5.76 gCO_2e/MJ of biodiesel because the value in Table 1 of this report did not include rounding. Hence, the difference between the two numbers is insignificant.

7. Carbon Intensity Due to Reduction in Corn Ethanol DGS Co-product Credit

This carbon intensity reduction is due to the reduction in the DGS co-product credit for corn ethanol due to the addition of a corn oil extraction process. The DGS co-product for corn oil is reduced by about 4.3 percent when corn oil is extracted. This value reflects the 4.3 percent reduction in mass due to corn oil extraction. The DGS co-product credit for corn ethanol without the use of corn oil extraction is about

11.62 gCO_2e/MJ of ethanol produced, as discussed in the ARB's corn ethanol pathway document (California Air Resources Board, 2009b). A reduction of this credit by about 4.3 percent is a reduction of about 0.50 gCO_2e/MJ of ethanol produced. This value is converted to a gCO_2e/MJ of biodiesel basis.

Therefore, gCO_2e/MJ of biodiesel, including loss factor and glycerine co-product credit adjustments

$$= \left(0.50\frac{gCO_2e}{MJ\ EtOH}\right) \times \left(76{,}330\frac{Btu\ EtOH}{gal\ EtOH}\right) \times \left(\frac{1\ gal\ EtOH}{0.030\ gal\ corn\ oil}\right)$$

$$\times \left(\frac{1gal\ corn\ oil}{1gal\ biodiesel}\right) \times \left(\frac{1gal\ biodiesel}{119{,}550\ Btu\ biodiesel}\right) \times 95.1\% \times 1.000039$$

$$\approx \mathbf{10.16}\frac{\boldsymbol{gCO_2e}}{\boldsymbol{MJ\ Biodiesel}}$$

8. GHG Calculations for Biodiesel Transport to Retail Stations

COPS:

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

- 100% transported 1,400 miles by rail from corn-oil-producing states (COPS) to California
- 100% transported 50 miles by heavy-duty-diesel truck (HDDT) from rail yard in California to bulk terminal
- 100% of the blended product distributed 90 miles by HDDT from bulk terminal to refueling stations in California. Since blends could range from less than B5 to B100, staff based the analysis on B100 to insure that all the possibilities of blend in these pathways are covered

Table B-2 shows the direct emissions, upstream emissions, and total emissions including mode share for GHG calculations.

California:

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

- 100% transported 50 miles by HDDT from plants in California to bulk terminal
- 100% of the blended product distributed 90 miles by HDDT from bulk terminal to refueling stations in California. Since blends could range from less than B5 to B100, staff based the analysis on B100 to insure that all the possibilities of blends in these pathways are covered

Table B-3 shows the direct emissions, upstream emissions, and total emissions including mode share used in the GHG calculations.

Table B-2. GHG Emissions from Biodiesel Transport and Distribution[a] from Corn-Oil-Producing States

Parameters	Biodiesel[a] Transport to CA from COPS	CA Railyard[b] to Bulk Terminal	Distribution[b] to Refueling Station, CA	Total Transport Emissions
Mode	Rail	HDD Truck	HDD Truck	
Mode Share	100%	100%	100%	
Distance (miles)	1,400	50	90	
Fuel	Diesel	Diesel	Diesel	
Direct CO_2 Emission (gCO_2/MMBtu)[c]	77,809 (77,712)	77,809 (77,912)	77,809 (77,912)	
Upstream CO_2 Emission (gCO_2/MMBtu)[d]	15,186	15,186	15,186	
Energy Intensity (Btu/ton-mile)	370	1,028	1,028	
Direct Emissions (g/MMBtu)				
VOC	0.957	0.096	1.259	2.312
CO	3.448	0.487	0.877	4.812
CH_4	0.063	0.005	0.009	0.077
N_2O	0.032	0.007	0.012	0.051
CO_2	**1,245.62**	**247.73**	**445.91**	**1,939.26**
Upstream Emissions (g/MMBtu)				
VOC	0.133	0.030	0.054	0.218
CO	0.294	0.082	0.147	0.523
CH_4	1.586	0.360	0.648	2.594
N_2O	0.002	0.001	0.001	0.004
CO_2	**225.11**	**48.79**	**87.82**	**361.72**
Total Emissions (g/MMBtu)				
VOC	1.091	0.126	1.313	2.530
CO	3.743	0.569	1.024	5.335
CH_4	1.649	0.365	0.657	2.671
N_2O	0.034	0.007	0.013	0.055
CO_2	1,470.73	296.52	533.73	2,300.98
GHG Emissions (gCO_2e/MMBtu)	1,531.51	309.11	559.78	2,400.40
GHG Emissions (gCO_2e/MJ)	**1.45**	**0.29**	**0.53**	**2.27**

[a]CA-GREET calculation is based on eGRID subregion energy generation mix (Regional LT Tab) because of the finished fuel transported to California from COPS. In addition, co-product allocation and loss factor adjustment is not required for finished fuel.
[b]CA-GREET calculations is based on eGRID subregion energy mix (Regional LT Tab) because of the finished fuel transported within CA.
[c]Return Trip from destination to origin emissions in parenthesis (CA-GREET calculation, cells AD41 and AD54 of the EF Tab)
[d]Upstream energy of diesel from CA-GREET calculation (cell B184, T&D Tab of the CA-GREET 1.8b).

Table B-3. GHG Emissions from Biodiesel Transport and Distribution[a] within California

Parameters	CA Plant to Bulk Terminal	Distribution to Refueling Station, CA	Total Transport Emissions
Mode	HDD Truck	HDD Truck	
Mode Share	100%	100%	
Distance (miles)	50	90	
Fuel	Diesel	Diesel	
Direct CO_2 Emission (gCO_2/MMBtu)[b]	77,809 (77,912)	77,809 (77,912)	
Upstream CO_2 Emission (gCO_2/MMBtu)[c]	15,186	15,186	
Energy Intensity (Btu/ton-mile)	1,028	1,028	
Direct Emissions (g/MMBtu)			
VOC	0.096	1.259	1.355
CO	0.487	0.877	1.364
CH_4	0.005	0.009	0.014
N_2O	0.007	0.012	0.019
CO_2	**247.73**	**445.91**	**693.64**
Upstream Emissions (g/MMBtu)			
VOC	0.030	0.054	0.084
CO	0.082	0.147	0.229
CH_4	0.360	0.648	1.008
N_2O	0.001	0.001	0.002
CO_2	**48.79**	**87.82**	**136.61**
Total Emissions (g/MMBtu)			
VOC	0.126	1.313	1.439
CO	0.569	1.024	1.593
CH_4	0.365	0.657	1.021
N_2O	0.007	0.013	0.021
CO_2	296.52	533.73	830.25
GHG Emissions (gCO_2e/MMBtu)	309.11	559.78	868.89
GHG Emissions (gCO_2e/MJ)	**0.29**	**0.53**	**0.82**

[a]CA-GREET calculation is based on eGRID subregion energy generation mix (Regional LT Tab) because of the finished fuel in California. In addition, co-product allocation and loss factor adjustment is not required for finished fuel.
[b]Return Trip from destination to origin emissions in parenthesis (CA-GREET calculation, cells AD41 and AD54 of the EF tab of the CA-GREET 1.8b).
[c]Upstream energy of diesel from CA-GREET calculation (cell B184, T&D tab of the CA-GREET 1.8b).

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

$$Direct\ Emissions$$

$$= \frac{\left(3{,}361\frac{g}{gal}\right) \times (77{,}809 + 77{,}912)\left(\frac{gCO_2}{MMBtu}\right) \times \left(1{,}028\frac{Btu}{ton - mile}\right) \times (90\ miles)}{\left(119{,}550\frac{Btu}{gal}\right) \times \left(454\frac{g}{lb}\right) \times \left(2{,}000\frac{lb}{ton}\right)}$$

$$= \mathbf{445.91}\ \left(\frac{\mathbf{g}\boldsymbol{CO_2}}{\mathbf{MMBtu}}\right)$$

$$Upstream\ Emissions$$

$$= \frac{\left(3{,}361\frac{g}{gal}\right) \times (15{,}186 + 15{,}186)\left(\frac{gCO_2}{MMBtu}\right) \times \left(1{,}028\frac{Btu}{ton - mile}\right) \times (90\ miles)}{\left(119{,}550\frac{Btu}{gal}\right) \times \left(454\frac{g}{lb}\right) \times \left(2{,}000\frac{lb}{ton}\right)}$$

$$= \mathbf{87.00}\ \left(\frac{\mathbf{g}\boldsymbol{CO_2}}{\mathbf{MMBtu}}\right)$$

$$Therefore, Total\ Emissions = 445.91\ \left(\frac{\mathrm{g}CO_2}{\mathrm{MMBtu}}\right) + 87.00\ \left(\frac{\mathrm{g}CO_2}{\mathrm{MMBtu}}\right) = \mathbf{532.91}\ \left(\frac{\mathbf{g}\boldsymbol{CO_2}}{\mathbf{mmBtu}}\right)$$

Note: Similar calculations for VOC, CO, CH_4, and N_2O to generate results shown in Tables B-2 and B-3 above.

9. GHG Emissions from Biodiesel-Fueled Vehicle

9.1 Vehicle CO_2 (Carbon in Fuel)

The CA-GREET model uses the fossil carbon content in the fuel (expressed as fully oxidized, gCO_2/MMBtu fuel) to calculate the GHG emissions. Since the source of the carbon in biodiesel is derived from non-fossil biological sources that fix atmospheric CO_2, the return of that carbon to the atmosphere as the fuel is combusted completes a cycle that involves no net increase in atmospheric carbon. The only fossil carbon in biodiesel originates from the methanol (produced from natural gas) used in the transesterification process. Table B-4 shows the fossil CO_2 emissions per MMBtu and MJ of fuel. This table summarizes the values used in the CA-GREET fuel carbon calculations and also shows the results from those calculations. The CA-GREET uses the values in the top 9 rows of Table B-4 to calculate the fuel carbon CI shown in row 10. In addition, the CA-GREET default values under the Biodiesel (B100) column are identified by tab and cell coordinates in the last column of the table. The biodiesel

production energy and methanol energy share for production shown in rows 1 and 5 of Table B-4 are CA-GREET default values and the remaining values in the table are fuel properties.

The total biodiesel processing energy of 2,116 Btu/lb biodiesel is a CA-GREET default value. Esterification requires a methanol input that corresponds to 10 percent of the biodiesel mass. This methanol energy is input to CA-GREET as fuel shares of 40.9 percent of the 2,116 Btu of energy input, which is equal to 865 Btu/lb of biodiesel. The GHG emissions are calculated based on the fraction of methanol energy in biodiesel.

Table B-4. GHG Emissions from Fossil Carbon in Biodiesel[a]

Parameters	Biodiesel (B100)	CA-GREET Default and Other Details
1. BD Production Energy Input (Btu/lb. BD)	2,116	Tab BD, Cell B12
2. BD Lower Heating Value (Btu/gal)	119,550	Tab Fuel_Specs, Cell B29
3. BD Density (g/gal)	3,361	Tab Fuel_Specs, Cell E29
4. BD Carbon Ratio (wt.%)	77.6	Tab Fuel_Specs, Cell F29
5. Methanol Fuel Production Share	40.9	Tab BD, Cell M177
6. Methanol Lower Heating Value (Btu/gal)	57,250	Tab Fuel_Specs, Cell B20
7. Methanol Density (g/gal)	3,006	Tab Fuel_Specs, Cell E20
8. Methanol Carbon Ratio (wt.%)	37.5	Tab Fuel_Specs, Cell F20
9. Mass Ratio, CO_2/C (wt.%)	44.0095/ 12.011	Molecular Weight of CO_2 Molecular Weight of Carbon
10. Fossil Carbon in Fuel (gCO_2e/MJ)	**3.67**	

[a]California Air Resources Board, 2009a. Detailed calculations can be found in the California-Modified GREET Pathway for Conversion of Midwest Soybeans to FAME Biodiesel.

9.2 Detailed Calculation of Fossil Carbon in Biodiesel

$$The\ Energy\ share\ of\ Methanol\ (MeOH)\ Production$$

$$= \frac{\left(2{,}116\,\frac{Btu}{lb\ BD}\right) \times (40.9\%)\ \times \left(3{,}361\,\frac{g}{gal}\right)}{\left(454\,\frac{g}{lb}\right) \times \left(119{,}550\,\frac{Btu}{gal}\right)} = 5.4\%\ Energy$$

$$Therefore, CO_2\ in\ Methanol\ Production$$

$$= \frac{\left(3{,}006\,\frac{gMeOH}{gal}\right) \times (37.5\%) \times (44\ gCO_2)}{\left(57{,}250\,\frac{Btu}{gal}\right) \times (12\ gC) \times \left(1{,}055\,\frac{MJ}{MMBtu}\right)} \times 1{,}000{,}000\,\frac{Btu}{MMBtu}$$

$$= \left(68.4\,\frac{gCO_2}{MJ}\,Methanol\right)$$

$$Finally, the\ Fossil\ Carbon = (5.4\%) \times \left(68.4 \frac{gCO_2}{MJ}\right) = \mathbf{3.67 \frac{gCO_2}{MJ}}$$

9.3 *Vehicle CH_4 and N_2O emissions*

The tailpipe CH_4 and N_2O emissions from biodiesel under all LCFS biodiesel pathways are assumed to be equivalent to ULSD CH_4 and N_2O emissions. ULSD emission factors for heavy duty trucks were provided in the ULSD Pathway document (California Air Resources Board, 2009c). The vehicle energy use, CH_4 and N_2O emission rates, and final GHG emissions are shown in Table B-5.

Table B-5. Vehicle CH_4 and N_2O Emissions[a]

Parameters	2010 Emission Factor (g/mi)	GWP	GHG (gCO_2e/MJ)
N_2O	0.048	298	0.735
CH_4	0.035	25	0.045
Vehicle Energy Efficiency	**6.1 mi/gal**		**0.78**

[a]California Air Resources Board, 2009a. Detailed calculations can be found in the California-Modified GREET Pathway for Conversion of Midwest Soybeans to FAME Biodiesel.

APPENDIX C

Comparative Analyses of Carbon Intensity Values for California and the Corn-Oil-Producing States

This appendix shows how staff used the CA-GREET model to calculate separate CIs for California and COPS regions. The results of these calculations were CIs that differed by less than one gCO_2e/MJ. This is not a significant difference and cannot serve as the basis for separate California and COPS CIs. The following tables and short narratives summarize the derivation of these two CIs.

1. Corn Oil Transportation

For corn oil biodiesel produced in California, corn oil from COPS dry mill ethanol plants is assumed to be transported 50 miles to rail yards in the COPS, 1,400 miles by rail to California rail yards, then 50 miles by heavy-duty-diesel truck (HDDT) to California biodiesel production facilities.

For corn oil biodiesel produced in the COPS, corn oil from COPS dry mill ethanol plants is assumed to be transported 50 miles by HDDT to COPS biodiesel production facilities.

The energy consumption associated with corn oil transport is shown in Table C-1 for both the California and COPS pathways. All transportation emissions calculations were performed using the CA-GREET model.

Table C-1. Corn Oil Transport Energy Difference between California and Corn-Oil-Producing States Biodiesel Production Facility

Corn Oil Transport	Energy Use (Btu/MMBtu)	With 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (Btu/MMBtu)
COPS Ethanol Plants to California Biodiesel Production Facility		
Transported by HDDT to Rail Yard, 50 miles	3,861.60	3,671.28
Transported by Rail to California Rail Yard, 1,400 miles	19,465.83	18,506.46
Transported by HDDT to Production Facility, 50 miles	4,026.81	3,823.35
Total Energy	**27,354.23**	**26,006.09**
COPS Ethanol Plant to COPS Biodiesel Production Facility		
Transported by HDDT to Production Facility, 50 miles	3,861.60	3,671.28
Total Energy	**3,861.60**	**3,671.28**

The different modes and distances summarized in Table C-1 result in different GHG emissions for the California and the COPS pathways. These differences are summarized in Table C-2.

Table C-2. GHG Emissions Difference between Corn Oil Transportation in California and in the Corn-oil-Producing States

GHG Components	CA GHG Emissions (g/MMBtu)	COPS GHG Emissions (g/MMBtu)
VOC	1.52	0.16
CO	5.32	0.52
CH_4	2.73	0.38
N_2O	0.06	0.01
CO_2	2,223.87	316.94
Conversion to gCO_2e/MMBtu	2,323.10	330.74
Total Emissions Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (gCO_2e/MJ)	**2.20**	**0.31**

2. Biodiesel Production

The energy use and GHG emissions associated with the production of corn oil biodiesel are shown in Tables C-3 and C-4. As shown, production in the COPS consumes 2,235 Btu/MMBtu more energy than does production in California. Although in-plant energy consumption is equal in these regions, more energy is used in the COPS to generate the energy delivered to the production facilities. This difference results in a difference of about 0.50 gCO_2e/MJ in GHG emissions between the two regions.

Table C-3. Energy Consumption Difference for Biodiesel Production via Transesterification between Pathways

Source of Energy Use	CA Energy Use (Btu/lb)	COPS Energy Use (Btu/lb)
Natural Gas	950.29	951.15
Electricity	106.36	143.98
Methanol	1,354.59	1,354.07
Sodium Hydroxide	42.32	42.32
Sodium Methoxide	209.48	209.48
Hydrochloric Acid	63.48	63.48
Total Energy Use	2,726.53	2,764.49
Total Energy Use (Btu/MMBtu)	168,838.92	171,189.58
Total Energy Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (Btu/MMBtu)	**160,517.77**	**162,752.58**

Table C-4. GHG Emissions Difference for Biodiesel Transesterification between Pathways

GHG Components	CA GHG Emissions ($gCO_2e/MMBtu$)	COPS GHG Emissions ($gCO_2e/MMBtu$)
VOC	1.89	1.91
CO	3.95	4.50
CH_4	18.18	18.47
N_2O	0.04	0.04
CO_2	5,040.93	5,568.05
Conversion to Total $gCO_2e/MMBtu$	5,519.81	6,053.98
Convert to gCO_2e/MJ	5.23	5.74
Total Emissions Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (gCO_2e/MJ)	**4.97**	**5.46**

3. Biodiesel Transport and Distribution

For California biodiesel production, the finished biodiesel is assumed to be transported 50 miles by HDDT from the production plant to the bulk terminal, and then 90 miles by HDDT to refueling stations. The resulting energy expenditure, as calculated using CA-GREET, is 10,880.07 Btu/MMBtu.

For COPS biodiesel production, the finished biodiesel is assumed to be transported 50 miles by HDDT to the rail yard, 1,400 miles by rail to the California rail yard, and then

90 miles by HDDT to refueling stations. The energy expenditure, as calculated using CA-GREET, is 29,152.40 Btu/MMBtu.

Details on the energy consumed during the transport of finished corn oil biodiesel are reported in Table C-5. As shown, 18,272 Btu/MMBtu more energy is consumed for fuel transport from the COPS.

Table C-5. Energy Consumption Difference for Biodiesel Transport and Distribution (T&D)[a] between Pathways

Biodiesel Transport	Energy Use (Btu/MMBtu)
California Production Facility to Refueling Station	
Transported by HDDT to Bulk Terminal, 50 miles	3,871.93
Transported by HDDT to Refueling Station, 90 miles	6,969.48
Hydrochloric acid adjustments for de-soaping biodiesel during transport	38.66
Total Energy	**10,880.07**
COPS Production Facility to Refueling Station	
Transported by HDDT to Rail Yard, 50 miles	3,713.07
Transported by Rail to California Rail Yard, 1,400 miles	18,717.13
Transported by HDDT to Refueling Station, 90 miles	6,683.53
Hydrochloric acid adjustments for de-soaping biodiesel during transport	38.67
Total Energy	**29,152.40**

[a]Details of energy consumption for biodiesel transport and distribution are provided in Tables A-1 and A-2 of Appendix A.

Similarly, the difference in the GHG emissions generated by the energy consumed to transport biodiesel is summarized in Table C-6.

Table C-6. GHG Emissions Difference for Biodiesel Transport and Distribution (T&D)[a] between Pathways

GHG Components	CA GHG Emissions ($gCO_2e/MMBtu$)	COPS GHG Emissions ($gCO_2e/MMBtu$)
VOC	1.44	2.53
CO	1.59	5.34
CH_4	1.02	2.67
N_2O	0.02	0.06
CO_2	830.25	2,300.98
Conversion to Total $gCO_2e/MMBtu$	868.89	2,400.40
Conversion to gCO_2e/MJ	**0.82**	**2.27**

[a]Details on the GHG emissions from biodiesel transport and distribution are provided in Tables B-2 and B-3 of Appendix B.

The emissions associated with the pre-treatment of corn oil to remove FFAs are shown in Table C-7. Although identical processes are assumed for California and COPS plants, more energy is consumed in the COPS to produce the energy that is delivered to the biodiesel production plants in these two regions. The result is that life cycle GHG emissions from the FFA-removal process are 0.16 gCO_2e/MJ higher in the COPS than in California.

Table C-7. GHG Emissions Difference due to Corn Oil Free-Fatty Acids Pre-treatment between Pathways

GHG Components	CA GHG Emissions ($gCO_2e/MMBtu$)	COPS GHG Emissions ($gCO_2e/MMBtu$)
VOC	0.10	0.11
CO	0.42	0.60
CH_4	1.50	1.61
N_2O	0.01	0.01
CO_2	739.97	913.28
Conversion to Total $gCO_2e/MMBtu$	780.60	956.51
Conversion to gCO_2e/MJ	**0.70**	**0.86**

4. Biodiesel Pathway Carbon Intensities

Table C-8 summarizes each process component and compares the overall CIs for biodiesel produced in California and the COPS from corn oil extracted in ethanol plants that produce a wet DGS co-product.

Table C-8. Carbon Intensity Difference between Pathways for Biodiesel Produced from Corn Oil Extracted at Dry Mill Ethanol Plants that Produce Wet DGS[a]

Process Parameters	CA Carbon Intensity (gCO_2e/MJ of Biodiesel)	COPS Carbon Intensity (gCO_2e/MJ of Biodiesel)
Corn Oil Extraction	5.76	5.76
Corn Oil Transport	2.20	0.31
Corn-Oil Free-fatty Acid Pre-treatment	0.70	0.86
Biodiesel Transesterification	4.97	5.46
Biodiesel Transportation and Distribution	0.82	2.27
Fossil Carbon in Fuel	3.67	3.67
Vehicle CH_4 and N_2O	0.78	0.78
DGS Co-Product Credit Reduction	10.16	10.16
Total CIs for Corn Oil Biodiesel for Wet DGS	**29.06**	**29.27**

[a]Details behind these carbon intensity values are also provided in Appendix B.

Because the difference between the California and COPS CI values is not significant, the COPS value of 29.27 gCO_2e/MJ will serve as the single CI for WDGS-associated corn oil biodiesel in the COPS and the western U.S**.**

APPENDIX D

Description of the GreenShift Corn Oil Extraction System

GreenShift Corporation submitted the following narrative to the U.S. Environmental Protection Agency during the Renewable Fuel Standard rulemaking process in 2009. GreenShift provided a copy to the Air Resources Board in February of 2010 for inclusion in this pathway report (GreenShift Corporation, 2009).

GreenShift Corporation (GreenShift) is a company that develops and commercializes clean technologies that facilitate the efficient use of natural resources. As a particular focus, we are using innovative technologies to produce biofuel and other biomass-derived products by extracting and refining raw materials that other producers cannot access or process. A prime example of fundamental importance to the increased availability of renewable fuels is using the extracted corn oil from dry mill corn ethanol plants as a feedstock for biofuels, such as biodiesel. The technology also substantially decreases the energy and production costs of corn ethanol, thereby simultaneously reducing greenhouse gas (GHG) emissions associated with corn ethanol and improving the economic viability of ethanol plants. Corn oil extraction systems, dubbed (COES) by GreenShift, thereby add even more to the renewable energy value of corn ethanol.

GreenShift presented testimony at the Public Hearing on the federal Renewable Fuel Standard Program (RFS2) held in Washington DC on June 9, 2009, and submitted comments on the RFS2 rulemaking. GreenShift spoke of three of the most significant effects of extracting corn oil from any ethanol plant:

First: The energy savings from installing corn oil extraction are substantial, reducing energy use to manufacture ethanol by as much as 25 percent. As a result, GHG emissions are actually 29 percent less than gasoline.

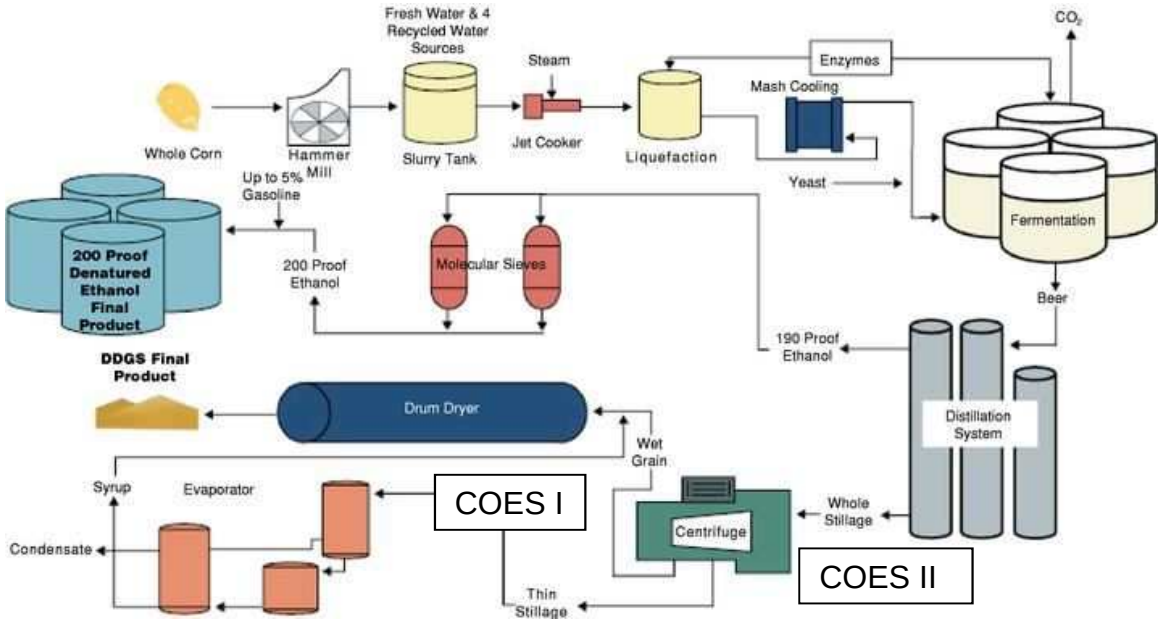
Second: Corn oil extraction after fermentation allows a dry mill ethanol plant to produce 11 percent more total fuel energy by manufacturing additional renewable biofuels from its corn oil byproduct. Corn oil is an excellent feedstock for biodiesel and renewable diesel.

Third: Success is just beginning. Additional corn oil extraction efficiency, coupled with corn varieties now available that have higher corn oil content (and the same starch content), have the potential to more than double these benefits.

In this report, GreenShift will focus on the first point, the significant reduction in energy needed by an ethanol plant to produce ethanol from a bushel of corn, when corn oil is extracted following fermentation and before drying of the ethanol plant's co-product, distillers dried grains with solubles (DDGS). EPA has predicted a 70 percent penetration of corn oil extraction in ethanol production facilities.

COES Technology

COES are built to extract corn oil in the most efficient manner possible, keyed to each ethanol plant's specific design and operational characteristics, which vary from site to site. The exact configuration depends on the ethanol plant design vendor chosen by the ethanol company and the operating characteristics proven at the plant to optimize ethanol production. A general flow sheet is pictured on the next page.



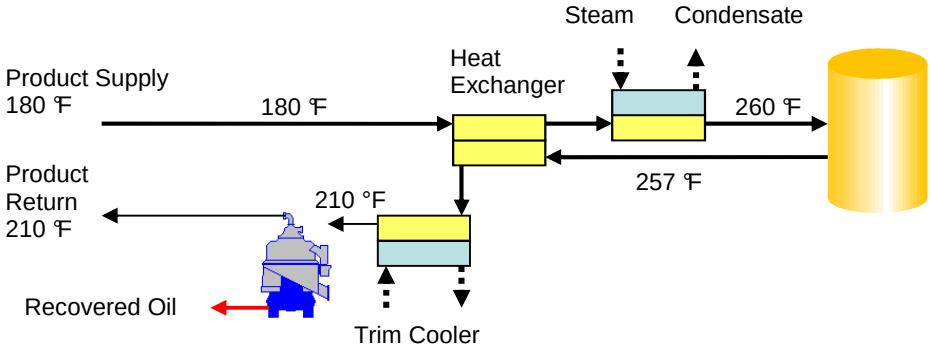
The COES placed in the ethanol plants are of two types. The first system, referred to as COES I, extracts corn oil from the thin stillage as it works its way through the evaporators. GreenShift has been awarded three patents on its COES I technology. The thin stillage generally contains about 30 percent of the oil available in the corn. COES I can recover most of that corn oil, depending on site-specific conditions. A typical ethanol plant uses corn that contains approximately 4 percent by weight corn oil, which in the absence of corn oil extraction, passes through the process to the DDGS. For a 50-million gallon per year (MGY) ethanol plant, the corn oil incoming is about 5 MGY and COES I can recover about 1.5 MGY.

Patent-pending COES II is an extraction extension that frees another 30 percent of the corn oil that is bound in the whole stillage, prior to the separation of wet grain and thin stillage. The unbound oil is thus made available to COES I and generally increases production of corn oil by nearly 100 percent. COES I and II together therefore can extract on the order of 60 percent (up to 75 percent) of the corn oil passing through the plant, or about 3.0 MGY to 3.8 MGY of corn oil from a 50 MGY ethanol plant.

COES installations are similar from plant to plant. They consist of skid mounted equipment placed in the ethanol plant so as to become part of its operation, but in a manner transparent to the production of ethanol – except, that is, for the dramatic decrease in energy use at the ethanol plant.

An installed COES, either COES I or II, adds no new materials to the ethanol circuit and uses or consumes no reagents, solvents, or other chemicals. Both COES I and COES II are sealed processes. Only corn oil is taken out and no materials are added. Corn oil (CAS #: 8001-30-7) is a stable vegetable oil, with a very low vapor pressure (< 1.0 mmHg @ 20℃ (68℉)). Its flash point is gre ater than 290℃ (550℉), with a specific gravity of about 0.95 and negligible solubility in water. It is relatively viscous and biodegradable. Corn oil is a light to dark red with a mild corn odor.

COES I extracts the corn oil from the thin stillage. The entire flow of thin stillage is passed through the COES and returned, minus the extracted corn oil, just downstream of the extraction point in the evaporator circuit of the ethanol plant. A COES I consists of the equipment shown in the following Process Flow Diagram:

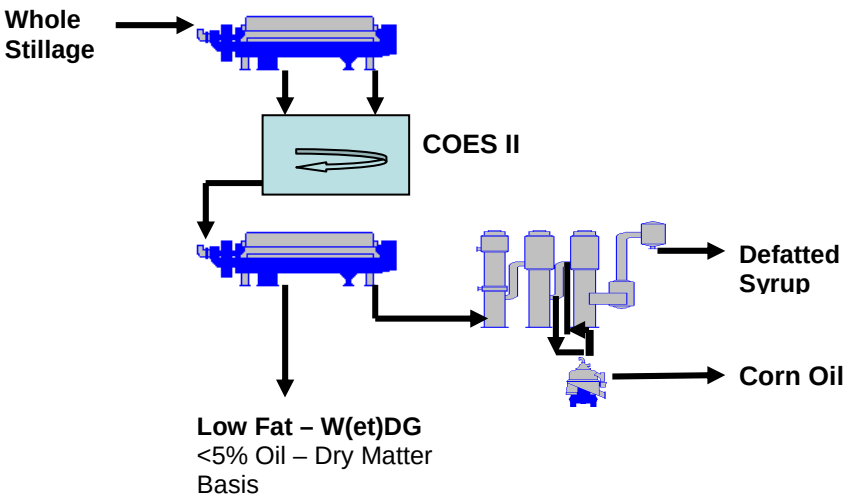


The main process is to heat the partially concentrated thin stillage and extract the corn oil by separation in a centrifuge. Steam is used in heat exchangers to raise the temperature of the thin stillage for extraction. As the temperature is reduced prior to returning the defatted stillage to the evaporators in the ethanol plant, energy is recovered in the heat exchangers to preheat the incoming thin stillage.

The COES I equipment is mounted on three skids placed in the ethanol plant near the evaporators as shown in the photograph of a typical installation. The skids are manufactured offsite according to standard specifications and shipped to the ethanol plant as sub-systems to be interconnected and coupled to the evaporator circuit. Electric power and steam are supplied to the COES from the ethanol plant utilities. Since the COES operation reduces the ethanol facilities energy demand for drying the syrup (the concentrated thin stillage from the evaporators), the steam used is not additional to the demand for steam without the COES installation. Therefore, no increase in boiler size or boiler fuel consumption results from the COES. Instead, the ethanol plant experiences a decrease in energy demand, as mass (corn oil) has been removed from the process and in addition the defatted syrup dries more efficiently in the ethanol plant's drying system, as corn oil is an insulator.

GreenShift's patent-pending COES II is used to free additional oil from the wet cake so that it is able to exit with the thin stillage for final recovery via COES I. As more than 40 percent of the total oil within the corn is trapped within the wet cake, GreenShift developed a washing technique to free this oil from the cake so that it is recoverable by the already proven COES I. The COES I recovery system is not inhibited by oil volumetric flow rate and therefore no adjustments or additional hardware would be required by COES I to recover higher concentrations of oil.

An additional line of horizontal centrifuges is placed prior to the existing horizontal centrifuges as shown in the following diagram. One hundred percent of the whole stillage is routed to the additional line of horizontal centrifuges where the wet cake and thin stillage exit the centrifuges and are mixed again back into solution prior to being pumped to the currently installed horizontal centrifuges. The result of this practice is a reduction of oil within the wet cake by roughly 50 percent. The oil removed from the wet cake is now present in the thin stillage and available for COES I recovery.



COES Energy Use -- Electrical

An installed COES is not energy-intensive. By calculation, operating a COES I requires about 0.01 kWh per gallon of ethanol produced, which is not much more than a one percent increase in the electricity demand in a typical dry mill ethanol plant. The electrical energy used is mostly to run motors, on the centrifuge and the pumps.

At a 50 MMGY ethanol plant, a COES I consumes about 60 kW. Running 350 days a year, it's about 0.01kW/gal. Expressed in Btu, that is approximately 34 Btu/ethanol gallon as electricity used by COES I. For comparison, ethanol contains about 78,000 Btu/ethanol gallon and a corn ethanol plant uses about 2,700 Btu/ethanol gallon in electrical energy.

To confirm the electrical demand calculations, a refereed COES performance test was run at a system in Indiana in October 2008. During the three-day test, the COES operated at capacity on the 50 MMGY ethanol plant, consuming about 63 kW, very close to the calculated rate of electrical energy usage.

A COES II system has not been available to corroborate similar calculations. It is estimated from electrical demand, however, that a COES II will require about 540 kW, again primarily for motors, since for a 50 MMGY ethanol plant, a COES II has two much larger centrifuges. COES I and II together will thus use about 340 Btu/ethanol gallon as electricity, which represents about a 12 percent increase in electrical energy for a 50 MMGY ethanol plant recovering from 60 percent to 75 percent of its corn oil.

COES Energy Use – Thermal

Both COES I and II use steam from the ethanol plant's utility system to provide operating heat. Heat exchangers balance the load so as to maximize the use of energy and return syrup, minus the corn oil, to the ethanol circuit at approximately the same temperature as it was when diverted to COES. Consumed energy as heat is therefore limited to waste heat lost and heat retained in the extracted corn oil.

GreenShift has calculated the heat energy needed to run a COES I on a 50 MMGY ethanol plant to be about 1 million Btu/hr, obtained by using 900 lb/hr of steam. That is about 180 Btu/ethanol gallon. In most ethanol plants, as assumed here, this energy comes from a boiler burning natural gas. In the performance test mentioned above, the COES I consumed approximately 450 lbs/hr of steam, one half this rate at that particular plant.

The steam demand for a COES II is estimated by GreenShift to be about 550 lb/hr of steam, or 110 Btu/ethanol gallon. Taken together, the total thermal energy demand for operating COES I and II is just under 300 Btu/ethanol gallon produced.

Adding the electrical and thermal energy uses for COES I results in 34 plus 180, or about 210 Btu/gal ethanol. COES I and II require 640 Btu/ethanol gallon.

Ethanol Plant Energy Use Reduction

While electrical demand, which increases with COES installation, is a small component of an ethanol plant's energy use, large savings in the use of thermal energy result from the effects of extracting corn oil. First, corn oil is removed from the syrup stream in the evaporators, which increases their performance by improving heat transfer, since oil is an insulator and is hard to heat. Second, corn oil extraction improves the drying efficiency of the DDGS, as there is less mass passing through the dryers. Third, corn oil extraction improves the flow-ability and handling of DDGS, such that less drying is needed to produce a quality feed product.

To calculate the ethanol plant energy reductions resulting from COES, GreenShift has performed a mass balance on a typical 50 MMGY ethanol plant, with and without COES. COES I reduces the energy use in the ethanol plant dryers by about 3,700 Btu/ethanol gallon, due to the combined effects listed above. Subtracting the COES I consumption of energy from this reduction, the net energy savings produced by a COES I is 3,700 minus 210, or about 3,500 Btu/ethanol gallon.

EPA estimates that a total ethanol plant energy use is about 35,700 Btu/gal, as noted in the draft Regulatory Impact Analysis (DRIA) of the Renewable Fuel Standard (Reference is made here to the DRIA instead of the final RIA to be conservative, since energy efficiencies are included in the final that lower the total energy demand, which will increase the value of COES in reducing energy use.). Installation of a COES I therefore represents a 9.8 percent total energy savings (3,500/35,700). GreenShift

feels these numbers are the expected savings in energy and should be considered along with the conservative 5.4 percent figure in the FRIA.

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).

APPENDIX E

CA-GREET Terminology and Conventions

The analysis appearing in this fuel pathway document uses conventions and technical terms with specific meanings that are defined here:

- Emissions from the generation of electricity depend upon the mix of energy sources used to generate that electricity. Electrical energy generation mixes are determined in CA-GREET using the U.S. Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID) (U.S. Environmental Protection Agency, 2014). The CA-GREET uses eGRID subregional energy mixes. The average energy mixes reported in the eGRID database must be converted to marginal mixes for purposes of CI calculation under the LCFS. Average mixes are typically converted to marginal mixes by reallocating nuclear and large hydroelectric generation to natural gas generation. Marginal mixes include energy sources most likely to be used to meet the new electrical demand.

- Some emission values in CA-GREET are calculated recursively. This happens when a fuel is used in the process that produces that same fuel. Diesel fuel, for example, is used to extract and transport crude oil. This means that the CI of diesel contributes to the CI of crude oil. Since diesel is refined from crude, the CI of diesel plays a role in its own CI. The CIs of crude oil and diesel fuel are recursively calculated in CA-GREET. If a new CI for diesel is entered into the model, that CI will be used to calculate a new CI for crude oil. The result of that calculation will be used to calculate a new CI for diesel. This iterative recalculation process will continued a fixed number of times.

- The British thermal unit (Btu) per million Btu (Btu/MMBtu) is the energy input necessary in Btu to produce one million Btu of a finished (or intermediate) product. This description is used consistently in CA-GREET for all energy calculations.

- In order to calculate a single aggregate carbon intensity value for all greenhouse gas emissions occurring throughout the WTW life cycle, the atmospheric heat-trapping potential of all greenhouse gases must be expressed in standardized additive units. Under the LCFS, all greenhouse gas species other than CO_2 are converted to CO_2-equivalent (CO_2e) values. These conversions are accomplished by using the Intergovernmental Panel on Climate Change (IPCC) global warming potential indices. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2-equivalent basis using (IPCC) global warming potential values for inclusion in the total pathway carbon

intensity (Solomon et al., 2007).[4] The IPCC Global Warming Potential (GWP) indices function as multipliers: CH_4 emissions, for example, are multiplied by 25.

- CA-GREET assumes that VOC and CO are converted to CO_2 in the atmosphere. It therefore, includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.[5]

- The input values extracted from reference material may have been in units that differ from the units used in this document. For example, if a fertilizer value was in kilograms per hectare (kg/ha), ARB staff would apply the standard conversion factors to convert this value to grams per acre (g/ac).

- Process efficiency for any step in CA-GREET is defined as the ratio of energy output to the sum of the energy output and energy consumed. (Efficiency = energy output/(energy output + energy consumed)).

- As used in this document, the term "upstream" refers to the energy use and emissions associated with the inputs supplied to the fuel production process. Upstream energy is produced from natural gas, nuclear power, renewables, etc. to generate the electrical and thermal energy consumed by the feedstock and fuel production processes. In the case of most fuels, including corn oil biodiesel, the two upstream processes considered in the WTT analysis are the production of natural gas and the generation of electricity. In the case of natural gas, the energy used to extract, process, and transport the gas is quantified. In the case of electrical generation, the energy needed to produce and transport the fuels used to generate the electrical energy is considered. In both cases, the consumption of this energy results in GHG emissions. Details on how upstream energy consumption from various sources is calculated are provided in Appendix A.

- The fuel production process can yield what are known as co-products. The biodiesel production process, for example, yields glycerin as a co-product. If that glycerin is sold, it displaces glycerin from other sources. The GHGs associated with the production of glycerin from those other sources could be greater than the GHGs associated with the biodiesel co-product. Glycerin from the production of biodiesel sometimes displaces glycerin produced from petrochemicals, for example. This indicates that biodiesel should be credited for the GHG reduction associated with this displacement. Because the amounts and types of displaced glycerin are difficult to measure, however, the emissions associated with the production of both the biodiesel and the

[4] The 2007 IPCC GHG CO_2-equivalence (CO_2e) values are 1 for CO_2, 25 for CH_4, and 298 for N_2O.
[5] For other GHGs, CA-GREET uses molecular weight ratios to calculate the amount of carbon present relative to the carbon in CO_2. The ratio of the molecular weight of carbon to the molecular weight of CO_2, for example is 12/44 = 0.273. The CO_2e values of VOCs and CO are, therefore, 0.85/0.273 = 3.12, and 0.43/0.273 = 1.57, respectively.

glycerin are allocated over the two products according the relative energy content of each. This results in an allocation of 4.9 percent of total emissions to glycerin, leaving 95.1 percent of total process emissions for the biodiesel. This 4.9 percent reduction in the CI of biodiesel comprises what is known as a co-product credit for glycerin.

- Fuel and feedstock production emissions are also adjusted to reflect material losses incurred during the production process. These are accounted for through the use of a loss factor. In this analysis, a 1.000039 loss factor is applied. It is calculated as follows in CA-GREET (California Air Resources Board, 2009a):

$$\text{Loss Factor} = 1 + \left[\frac{\left(0.207 \frac{\text{gVOC}}{\text{MMBtu BD}}\right) + \left(0.880 \frac{\text{gVOC}}{\text{MMBtu BD}}\right)}{\frac{\left(3{,}361 \frac{\text{g BD}}{\text{gal}}\right)}{\left(119{,}550 \frac{\text{Btu BD}}{\text{gal}}\right)} \times 10^6} \right] = 1.000039$$