California Environmental Protection Agency

Air Resources Board

California-Modified GREET Fuel Pathways for the Production of Biodiesel from Corn Oil Extracted from Distiller's Grains with Solubles at Dry Mill Ethanol Plants

Staff Report

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Fuels Evaluation Section

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California-Modified GREET Fuel Pathways for the Production of Biodiesel from Corn Oil Extracted from Distiller's Grains with Solubles at Dry Mill Ethanol Plants

1. Pathway Summary

This life cycle analysis calculates the carbon intensity (CI) of a California corn oil biodiesel (BD) pathway in which the corn oil is produced in Midwestern corn ethanol plants and shipped to California for biodiesel production. Air Resources Board (ARB) Staff has developed two pathways for the production of biodiesel from the oil extracted from the thin stillage at such plants: one applies to corn oil extracted in plants where the distiller's grains with solubles co-product (DGS) is dried, and the other applies to corn oil extracted in plants where the DGS remains wet. Both pathways describe the production of biodiesel from corn oil extracted at dry mill ethanol plants where ethanol is the primary product. This analysis finds that the CI of the dry DGS (DDGS) pathway is 5.34 grams of CO_2-equivalent greenhouse gas emissions per mega joule of biodiesel produced (gCO_2e/MJ) while the CI of the wet DGS (WDGS) pathway is 34.03 gCO_2e/MJ. Although the feedstock transport, biodiesel production, finished fuel transport, and finished fuel use components of these two pathways are identical to the corresponding pathway components in the LCFS Soybean-to-Biodiesel Pathway (California Air Resources Board, 2009a), the production of the feedstock is unique to this pathway. Calculation of the CIs 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.

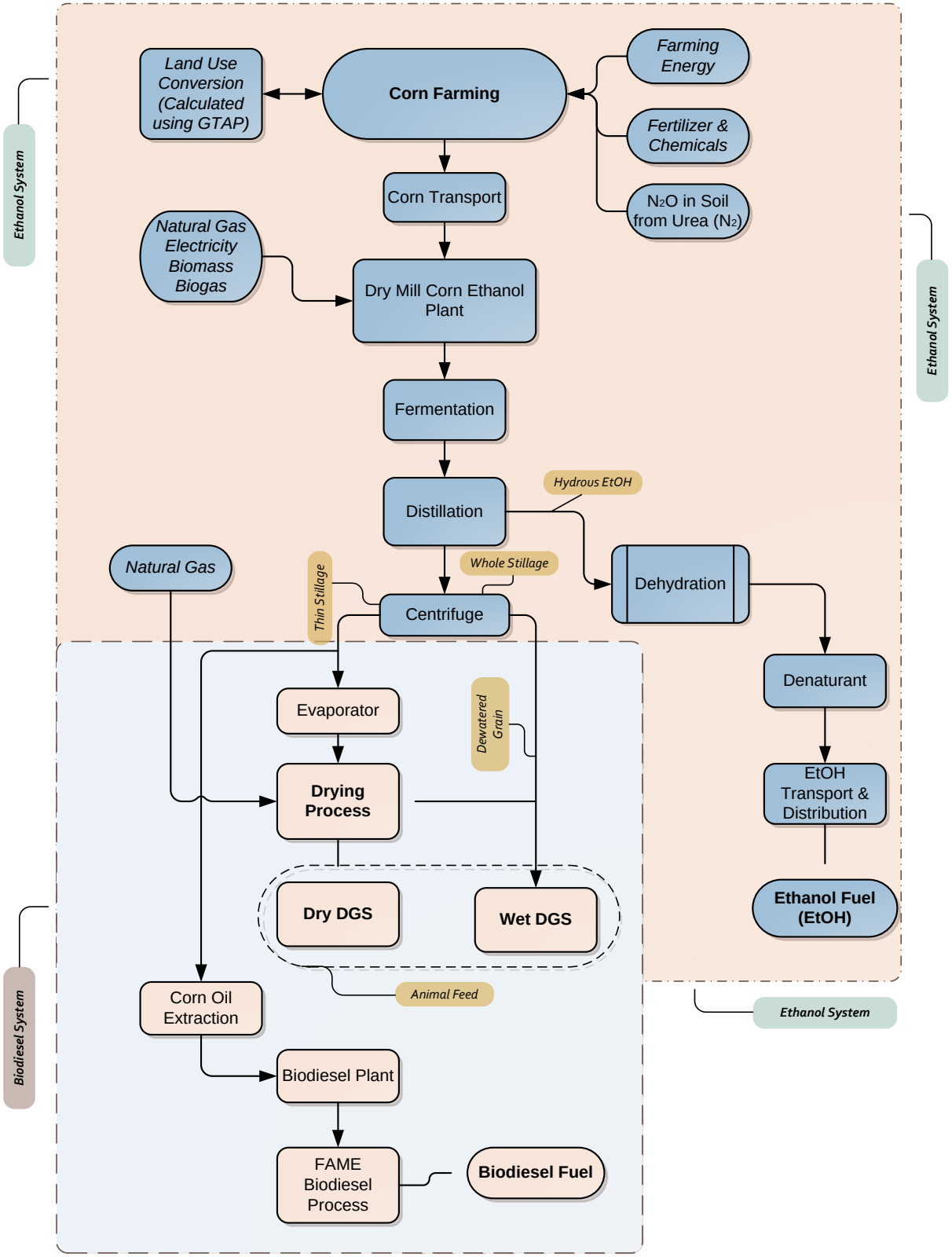
The Well-to-Tank (WTT) portion of this Life Cycle Analysis of the corn oil BD pathway includes all steps from corn farming to final finished 100 percent biodiesel (B100). The Tank-to-Wheels (TTW) portion includes actual combustion of the resulting fuel in a motor vehicle for motive power. Taken together, the WTT and the TTW analyses comprise a total Well-to-Wheel (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 California-specific version known as the CA-GREET model. Changes were restricted mostly to adding California-specific input factors (emission factors, electrical energy generation mix, transportation distances, etc.); no substantial changes were made to the methodology inherent in the original GREET model on which this one is based. The results obtained from the California-modified GREET model (v1.8b, released December 2009) are reported in this document. 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 North American corn ethanol plants. The

pathways assume 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 (2009), staff estimated the energy use and carbon intensity associated with the extraction of corn oil at dry mill ethanol plants, and the energy savings that occurs in the DGS drying process. 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 where all DGS is dried will have a carbon intensity (CI) of 5.34 grams of CO_2-equivalent emissions per mega joule of biodiesel produced (gCO_2e/MJ). The corresponding estimate for plants in which DGS is not dried is 34.03 gCO_2e/MJ. 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. In this scenario, the corn oil produced at ethanol plants that produce either DDGS or WDGS is shipped to a biodiesel plant in California where it is transesterified to fatty acid methyl ester (FAME) biodiesel. Figure 1 illustrates this corn oil biodiesel production process.

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



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

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

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

- Total greenhouse gas emissions are expressed on a CO_2-equivalent, per unit of fuel energy basis, using the gCO_2e/MJ unit. Methane (CH_4) and nitrous oxide (N_2O) are converted to a CO_2-equivalent basis using the Intergovernmental Panel on Climate Change (IPCC) global warming potential values for inclusion in the total pathway carbon intensity (Solomon et al., 2007).[1] 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 IPCC global warming potential indices. 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 and, therefore, includes these pollutants in the total CO_2 value using ratios of the appropriate molecular weights.[2]

- 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:
  Efficiency = energy output / (energy output + energy consumed).

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[1] The 2007 IPCC GHG CO_2-equivalence (CO_2e) values are 1 for CO_2, 25 for CH_4, and 298 for N_2O.
[2] 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.

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

- 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 ethanol plant. 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 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 biodiesel.

- 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):

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

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 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 that staff expects will be installed in corn ethanol plants. Staff expects that, as corn oil becomes an increasingly attractive option for biodiesel fuel production, corn oil extraction equipment will be added to pre-existing corn ethanol plants. However, ethanol will always be the primary product produced at these 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 and emissions associated with the operation of the retrofitted 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, approximately 1,308,588.61 Btu of energy is required when dry DGS is produced and 1,360,459.35 Btu of energy is required when wet DGS is produced.

Table 1. Summary of WTW Energy Consumption and GHG Emissions for Biodiesel Produced from Corn Oil Extracted at Dry Mill Ethanol Plants

Process Parameters	Energy Required for Dry DGS (Btu/MMBtu)	Dry DGS GHG Emissions Carbon Intensity (gCO_2e/MJ)	Energy Required for Wet DGS (Btu/MMBtu)	Wet DGS GHG Emissions Carbon Intensity (gCO_2e/MJ)
Well-to-Tank (WTT)				
Corn Oil Extraction	161,803.17	12.13	161,803.17	12.13
Corn Oil Transport and Distribution	21,258.57	1.64	21,258.57	1.64
Biodiesel Transesterification	159,684.00	4.89	159,684.00	4.89
Biodiesel Transportation and Distribution	10,055.37	0.76	10,055.37	0.76
Reduced DGS Credit due to Reduced DGS[a] mass	7,658.24	10.16	7,658.24	10.16
Subtotal	**360,459.35**	**29.58**	**360,459.35**	**29.58**
Total Energy Savings Credits for Drying DGS to Produce Corn Oil (No Energy Saving Credits for WDGS)	-51,870.74	-28.69	0	0
Total WTT	**308,588.61**	**0.89**	**360,459.35**	**29.58**
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)	**1,308,588.61**	**5.34**	**1,360,459.35**	**34.03**

[a]This credit is given to DGS in dry mill corn ethanol production in the Midwest (ARB, 2009). 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 emits 5.34 gCO_2e when the feedstock is extracted at a plant that produces DDGS and 34.03 gCO_2e when extraction occurs at a plant that produces WDGS. 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 and the subsequent production and use of the biodiesel produced from the resulting corn oil. All land use change emissions, therefore, remain with the production of corn ethanol. The CI of Corn oil biodiesel associated with DDGS includes an energy savings credit reflecting a reduction in DGS drying energy. The CI of Corn oil biodiesel associated with WDGS does not reflect this energy savings credit.

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 the DGS is dried. Corn Oil extraction systems can be added to existing corn ethanol plants to increase plant energy efficiency (when DGS is dried) and to increase the total volume of fuel that is produced per unit of corn processed. The installation of GreenShift-style corn oil extraction equipment in an existing corn ethanol plant will allow a diesel fuel feedstock to be produced 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 and energy savings 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 1, 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 C contains a more detailed discussion of the GreenShift process.

The thin stillage generally contains about 30 percent of the oil available in the corn. Corn Oil Extraction 1 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. The Corn Oil Extraction system 1 can recover about 1.5 million of those gallons.

GreenShift's second corn oil extraction system, referred to as Corn Oil Extraction 2, 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 the wet cake from the thin stillage in a centrifuge. The wet cake, however, contains more than 40 percent of the total oil in the grain. Corn Oil Extraction 2 is a washing technique that frees this oil from the wet cake so that it is recoverable in the Corn Oil Extraction 1 process. The additional oil made available to the Corn Oil Extraction 1 system generally doubles the production of corn oil. Corn Oil Extraction systems 1 and 2 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. The results presented in this analysis are based on the operation of both corn oil extraction systems.

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. Even though the corn oil extraction equipment consumes energy, plants that produce dry DGS will realize a net energy savings when the extraction equipment is operating. Installation of this equipment, therefore, does not require a plant to supply additional process energy. According to GreenShift (2009), operating a Corn Oil Extraction 1 system requires about 0.01 kWhr 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. A Corn Oil Extraction 2 system will use 0.09 kWhr per gallon of ethanol produced, or about 306 Btu per gallon of ethanol produced. The greater electricity use by the Corn Oil Extraction 2 system arises from the operation of much larger centrifuges. Thus, the total additional electricity required for the operation of Corn Oil Extraction systems 1 and 2 would be about 340 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 Dry and Wet DGS

Fuel Production System[b]	Fuel Type	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)	20.34	N/A[c]	290	310.34
	Electricity (Btu/gal)	978.24	33.93	340[d]	1,012.17[d]
	Total Energy (Btu/gal)	998.58	33.93		1,322.51
	Total Energy (Btu/MMBtu)				17,326.23
Biodiesel System	Conversion from Ethanol to BD Basis (Btu/MMBtu)[e]				170,190.95[f]
	Co-product and Loss Factor Adjustments (Btu/MMBtu)[g]				**161,803.17**

[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 (340 Btu) is needed to produce one gallon of corn oil. The total electrical energy (1,012.17 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 0.065 gallon of corn oil per gallon of ethanol produced based on our assumption.
[f]This refers to the corn oil extraction energy required for both dry and wet DGS in Table 1 of this document.
[g]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.

Both Corn Oil Extraction systems 1 and 2 use steam from the ethanol plant's thermal energy system to provide operating heat. System 1 requires about 180 Btu per gallon of ethanol while system 2 requires about 110 Btu per gallon. This energy generally comes from a boiler burning natural gas. The total additional thermal energy requirements for operating Corn Oil Extraction systems 1 and 2 together would be about 290 Btu per gallon of ethanol produced. Thus, the total additional electrical and thermal energy requirements at the ethanol plant for the operation of both Corn Oil Extraction systems would be about 630 (290 + 340) Btu per gallon of ethanol produced. Energy use details are provided in Table 4.

The GHG emissions associated with the energy consumption required for corn oil extraction are summarized in Table 3.

Table 3. Total GHG Emissions from Corn Oil Extraction[a]

GHG Components	GHG Emissions (g/MMBtu) Ethanol	GHG Emissions (gCO_2e/MJ) Biodiesel
VOC	0.14	
CO	1.10	
CH_4	1.94	
N_2O	0.02	
CO_2	1,314.09	
Total GHG Emissions	1,369.97	
Convert to gCO_2e/MJ		1.30
Conversion of Emissions from a per-MJ Ethanol to a per-MJ Biodiesel basis[b]		12.75
Co-product and Loss Factor Adjustments of Biodiesel		**12.13[c]**

[a]GHG emissions were calculated using CA-GREET 1.8b.
[b]Ethanol to Biodiesel conversion detail is shown in Appendix B.
[c]This value applies to the corn oil extraction CIs for both the dry and wet DGS pathways as summarized in Table 1 of this document.

4. Ethanol Plant Energy Savings under the Dry DGS Pathway

Significant energy savings result from the installation of Corn Oil Extraction Systems 1 and 2 at corn ethanol plants that dry their DGS. The sources of these savings are threefold: 1) oil, which acts as a heat insulator, is removed, resulting in improved heat transfer efficiency; 2) Drying efficiency is increased due to a reduced DGS mass flowing through the dryers; 3) DGS flow characteristics are improved following corn oil removal, resulting in reduced drying time. These three effects, according to GreenShift (2009), combine to reduce the energy used by the ethanol plant's DGS dryers by about 3,700 Btu per gallon of ethanol produced. As shown in Table 4, this 3,700 Btu per gallon is adjusted to 3,518.84 due to co-product allocation. This energy savings is discussed in more detail in Appendix C. Subtracting from this energy savings the additional energy consumed by Corn Oil Extraction Systems 1 and 2 (630 Btu per gallon) yields a net ethanol plant energy savings of about 2,888.84 Btu per gallon of ethanol produced. When the upstream feedstock energy uses and savings are accounted for, the total energy savings are reduced to 2,456.33 Btu per gallon of ethanol produced. This is the net energy savings value that would be realized by a dry mill ethanol plant that (a) operates Corn Oil Extraction systems 1 and 2, and (b) produces 100 percent dry DGS. The reduction from 2,888.84 to 2,456.33 Btu in net savings is mostly due to the energy required to produce the additional electricity the plant requires to operate the two corn oil extraction systems. Table 4 summarizes the estimated energy use and savings from the installation of Corn Oil Extraction Systems 1 and 2 at an existing corn ethanol plant producing dry DGS. The calculations behind these energy savings figures are provided in Appendix A.

Table 4. Energy Use and Savings from the Operation of Corn Oil Extraction Equipment at Dry Mill Ethanol Plants

Sources of Corn Oil Extraction Energy Consumption and Savings	Net Energy Use for Dry DGS (Btu/gal EtOH produced)	Net Energy Use for Wet DGS (Btu/gal EtOH produced)[a]
1. Thermal energy use at the ethanol Plant (natural gas)	290	290
2. Upstream thermal energy consumption (natural gas)	20.34	20.34
3. Electrical energy use at the ethanol plant	340	340
4. Electrical energy, upstream stationary electrical stage feedstock production energy (energy to produce the fuel used to produce electricity)	33.93	33.93
5. Electrical energy, upstream stationary electricity fuel stage energy (energy to produce electricity)	978.24	978.24
6. Energy savings due to reduced DGS drying energy at ethanol plant[b] (natural gas). includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments	-3,518.84	0
7. Energy savings due to reduced DGS drying, upstream natural gas feedstock	-260	0
8. Net energy savings at the ethanol plant[b] due to corn oil production (6 + 1 + 3)	-2,888.84	630
9. Net energy savings due to corn oil production, including upstream energy uses (6 + 7 + 1 + 2 + 4 + 5)	**-2,456.33**	**1,322.51**

[a]The energy consumed for corn oil extraction is identical in the wet and dry DGS scenarios. The difference between the two is that the net energy savings realized in the dry DGS case are not realized in the wet DGS case (see rows 6 through 8).
[b]Savings at the ethanol plant do not include upstream energy savings. Therefore, (-3,700 Btu/gal x 95.1% x 1.000039) = -3,518.84 Btu/gal.

The GHG emissions associated with the energy used to extract corn oil and the energy saved in the DGS drying process are summarized in Table 5. Detailed calculations are provided in Appendix B.

Table 5. Total GHG Emissions from DGS Drying Energy Reduction at Dry Mill Ethanol Plants

GHG Components	GHG Emissions (g/MMBtu) Ethanol	GHG Emissions (gCO_2e/MJ) Ethanol[a]	GHG Emissions (gCO_2e/MJ) Biodiesel
VOC	0.40	0.001	
CO	1.66	0.002	
CH_4	6.30	0.149	
N_2O	0.02	0.005	
CO_2	3074.47	2.915	
Total GHG Emissions	3241.31	3.072	
Convert to gCO_2e/MJ Biodiesel			30.17
Co-product and Loss Factor Adjustments of Biodiesel			**28.69[b]**

[a]Detailed calculations for each GHG component appear in Appendix B. GHG emissions were calculated using CA-GREET 1.8b.
[b]This value applies to the total energy savings credits for drying DGS to produce corn oil as summarized in Table 1 of this document.

5. Carbon Intensity of Corn Oil Extraction

The calculated CIs for the extraction of corn oil using Corn Oil Extraction Systems 1 and 2 are shown in Table 6. The GHG emission factors used to calculate both DDGS and WDGS carbon intensities 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 4, the installation of Corn Oil Extraction Systems 1 and 2 in a corn ethanol plant reduces the total energy consumption at the ethanol plant by about 2,888.84 Btu per gallon of ethanol produced (when DGS is dried), which translates to about an 8.5 percent reduction in the energy used at the ethanol plant (assuming the CA-GREET ethanol plant energy value of 36,000 Btu per gallon of ethanol produced). The net reduction in total energy consumed (at the ethanol plant and upstream) when DGS is dried results in reduced GHG emissions and a corresponding carbon intensity credit of about 1.837 gCO_2 per MJ of ethanol produced. Assuming that about 6.5 gallons of corn oil are produced per 100 gallons of ethanol, and taking into account the energy differences between corn oil and ethanol, this credit translates to net reduction of about 18.04 gCO_2 per MJ of corn oil produced in the DGS case. Without a savings credit from drying, the energy consumption and resulting emissions from corn oil extraction accrue in full to the corn oil biodiesel. Table 6 shows the net CI for WDGS which is equivalent to 12.13 gCO_2 per MJ of ethanol produced. The details behind these calculations are shown in Appendix B.

Table 6. Greenhouse Gas Emission Factors and Net Carbon Intensities for Corn Oil Extraction

Sources of Energy Use	GHG Emissions Factor (gCO_2/MMBtu)[a]	Carbon Intensity (gCO_2e/MJ of EtOH)	Dry DGS Carbon Intensity (gCO_2e/MJ of Biodiesel)	Wet DGS Carbon Intensity (gCO_2e/MJ of Biodiesel)
1. Thermal Energy Use at the Ethanol Plant, Natural Gas, (CO_2 emissions)	58,198	0.200	1.97	1.97
2. Thermal Energy, Upstream Feedstock, Natural Gas, (CO_2 emissions)	5,245	0.018	0.18	0.18
3. Electrical Energy, Upstream Stationary Electricity Feedstock Stage Energy, (Energy to Produce the Fuel Used to Produce Electricity), (CO_2 emissions)[b]	7,794	0.031	0.30	0.30
4. Electrical Energy, Upstream Stationary Electricity Fuel Stage Energy (Energy to Produce Electricity), (CO_2 emissions)[b]	233,154	0.936	9.19	9.19
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]	0.050	0.49	0.49
6. Total Carbon Intensity for Corn Oil Extraction (1 + 2 + 3 + 4 + 5)	N/A	1.235	12.13	12.13
7. Carbon Intensity of Energy Savings Due to Reduced DGS Drying Energy at Ethanol Plant, Natural Gas, (CO_2 emissions)	58,198	-2.674	-26.26	0
8. Carbon Intensity of Energy Savings Due to Reduced DGS Drying at the Ethanol Plant, Upstream Natural Gas Feedstock, (CO_2 emissions)	5,245	-0.241	-2.36	0
9. Carbon Intensity of Energy Savings Due to Reduced DGS Drying at the Ethanol Plant, Direct and Upstream Energy Use, (CH_4, VOC, CO, N_2O emissions)	Detailed CO_2e Calculations are in Table B-1 of Appendix B[c]	-0.157	-1.54	0
10. Carbon Intensity of Total Energy Savings Due to Reduced DGS Drying (7 + 8 + 9)	N/A	-3.072	-30.17	0
11. Net Carbon Intensity for Corn Oil Extraction Including Energy Savings (6 + 10)	N/A	**-1.837**	**-18.04**	**12.13**

[a]The emission factor for natural gas is expressed in units of gCO_2 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 290 Btu per gallon. The emission factor for electricity is expressed in units of gCO_2 upstream emissions per Btu downstream electricity use. Therefore, the CO_2 emissions for electricity are calculated by taking the product of this emission factor and the downstream energy use of 340 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.

6. Effect of Corn Oil Extraction on DGS Production

As shown in Section 2, the use of both Corn Oil Extraction Systems 1 and 2 would remove about six to seven gallons of corn oil per 100 gallons of corn ethanol produced. This equates to about 0.50 pounds of corn oil per gallon of ethanol produced. 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 (which is the yield value used in CA-GREET), a reduction of 0.50 pounds per gallon of ethanol represents about a 9.4 percent reduction in the DGS yield. This 9.4 percent reduction in DGS yield would translate into a 9.4 percent reduction in the DGS co-product credit. Because the DGS co-product credit for corn ethanol without corn oil extraction is about 11.62 gCO_2e per MJ of ethanol produced, a 9.4 percent reduction in the credit due to corn oil extraction would translate into a reduction in the co-product credit of about 1.09 gCO_2e per 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 1.09 gCO_2e credit reduction per MJ of ethanol to a gCO_2e per MJ of biodiesel basis gives a credit reduction of 10.16 gCO_2 per MJ of biodiesel. This credit applies to both the DDGS and the WDGS pathway. 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.

7. Corn Oil Transport and Distribution

Because feedstock transportation is within the system boundaries of both of the pathways 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 Midwest dry mill ethanol plants is assumed to be transported 1,400 miles by rail to California rail yards, then 50 miles by heavy-duty-diesel truck (HDDT) from the destination rail yards to biodiesel production facilities. The energy consumption associated with corn oil transport applies to both the DDGS and the WDGS pathway and is shown in Table 7.

Table 7. Total Energy Required for Corn Oil Transport from the Midwest to California

Corn Oil Transport	Energy Use (Btu/MMBtu)	With 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (Btu/MMBtu)
Transported by Rail, 1400 miles	18,653.04	17,739.73
Transported 50 miles by Heavy-Duty-Diesel Truck	3,700	3,518.84
Total Energy	**22,353.04**	**21,258.57[a]**

[a]This value applies to the energy required for corn oil transport and distribution for both dry and wet DGS as summarized in Table 1 of this document.

The GHG emissions generated by the consumption of this transport energy are summarized in Table 8. The results apply equally to the DDGS and the WDGS pathways developed in this document. The calculations behind the values appearing in Table 8 are performed using the CA-GREET model.

Table 8. Total GHG Emissions from Corn Oil Transportation

GHG Components	GHG Emissions (Btu/MMBtu)
VOC	1.21
CO	4.28
CH_4	1.96
N_2O	0.04
CO_2	1,751.60
Convert to Total gCO_2e/MMBtu	1,823.61
Convert to gCO_2e/MJ	1.73
Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (gCO_2e/MJ)	**1.64[a]**

[a]This value applies to the GHG emissions from corn oil transport and distribution for both the dry and wet DGS pathways as summarized in Table 1 of this document.

8. Biodiesel Production

This life cycle analysis calculates the CI of corn oil biodiesel produced in California from feedstock that originates in the Midwest. The electrical energy consumed in the biodiesel production process was therefore estimated using the California marginal electrical energy generation mix option in the CA-GREET model.

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. The filtered 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 159,684 Btu/MMBtu for the transesterification step (California Air Resources Board, 2009a). This energy consumption value and the GHG emissions it produces applies equally to both of the pathways developed in this document. Tables 9 and 10 summarize the energy use and the GHG emissions generated by the biodiesel production process and are calculated using the CA-GREET model.

Table 9. Total Energy Required for Biodiesel Production via Transesterification

Source of Energy Use	Energy Use (Btu/lb)
Natural Gas	949.92
Electricity	92.94
Methanol	1354.21
Sodium Hydroxide	42.32
Sodium Methoxide	209.48
Hydrochloric Acid	63.00
Total Energy Use	2712.36
Total Energy Use (Btu/MMBtu)	167,961.00
Total Energy Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (Btu/MMBtu)	**159,684.00[a]**

[a]This value applies to the biodiesel transesterification energy for both the dry and wet DGS pathways as summarized in Table 1 of this document.

Table 10. Total GHG Emissions from Biodiesel Transesterification

GHG Components	GHG Emissions ($gCO_2e/MMBtu$)
VOC	1.86
CO	3.84
CH_4	18.08
N_2O	0.06
CO_2	4,954
Convert to Total $gCO_2e/MMBtu$	5,422.57
Convert to gCO_2e/MJ	5.14
Includes 95.1% Co-production Allocation and 1.000039 Loss Factor Adjustments (gCO_2e/MJ)	**4.89[a]**

[a]This value applies to the GHG emissions from biodiesel transesterification for the both dry and wet DGS pathways as summarized in Table 1 of this document.

9. 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. When the finished biodiesel is transported 50 miles from the production plant to the bulk terminal, and then 90 miles to refueling stations by HDD truck, as this analysis assumes, CA-GREET calculates the energy expenditure to be 10,055.37 Btu/MMBtu, based on the consumption of California marginal electricity. This result applies equally to the DDGS and the WDGS pathways developed in this document. Table 11 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 Table A-1 of Appendix A.

Table 11. Energy Consumption for Biodiesel Transport and Distribution (T&D)

Biodiesel Transport	Total Energy (Btu/MMBtu)
Transported 50 miles by Heavy-Duty-Diesel Truck to Bulk Terminal	8,272.38
Transported 90 miles by Heavy-Duty-Diesel Truck to Distribution Centers	1,782.99
Total T&D Energy	**10,055.37[a]**

[a]This value applies to the energy required for biodiesel transportation and distribution for both the dry and wet DGS pathways as summarized in Table 1 of this document.

The GHG emissions generated by the energy consumed to transport biodiesel are summarized in Table 12. These results apply to both pathways. The calculations behind the values appearing in Table 12 are provided in Table B-2 of Appendix B.

Table 12. Total GHG Emissions from Biodiesel Transport and Distribution

GHG Components	GHG Emissions ($gCO_2e/MMBtu$)
VOC	1.41
CO	1.48
CH_4	0.95
N_2O	0.02
CO_2	769.72
Convert to Total $gCO_2e/MMBtu$	802.40
Convert to gCO_2e/MJ	**0.76**[a]

[a]This value applies to the GHG emissions from biodiesel transportation and distribution for both the dry and wet DGS pathways as summarized in Table 1 of this document.

10. 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).

Because no emissions data exists for the combustion of biodiesel in a HDD engine, these emissions are assumed to be equal to the combustion emissions from a ULSD-powered HDD engine: As described in the ULSD pathway document (California Air Resources Board, 2009c), the N_20 and CH_4 generated by the combustion of ULSD create GHG emissions that sum to 0.78 gCO_2e/MJ.

The GHG emissions from the fossil carbon in corn oil biodiesel and the combustion of that fuel in an HDD engine are included in TTW portion as summarized in Table 1 of this document. The details on how these emissions are calculated can be found in Section 14 of Appendix B.

These two categories of tailpipe emissions are summarized and totaled in Table 13. This total applies to biodiesel produced from corn oil associated with both the dry and wet DGS pathways.

Table 13. 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**[a]

[a]This value applies to the GHG emissions from biodiesel used in vehicles from tank-to-wheel for both the dry and wet DGS pathways as summarized in Table 1 of this document.

11. Complete Pathway Carbon Intensities

This section summarizes the overall CIs for the dry and wet DGS pathways which 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 CIs are shown in Table 14. The calculations behind these carbon intensity values are also provided in Appendix B.

Table 14. Corn-Oil-to-Biodiesel Pathways Carbon Intensity for Dry and Wet DGS

Component	Dry DGS Carbon Intensity (gCO_2e/MJ of Biodiesel)	Wet DGS Carbon Intensity (gCO_2e/MJ of Biodiesel)
Corn Oil Extraction	12.13	12.13
Corn Oil Transport	1.64	1.64
Biodiesel Transesterification[a]	4.89	4.89
Biodiesel Transportation and Distribution[a]	0.76	0.76
Fossil Carbon in Fuel[a]	3.67	3.67
Vehicle CH_4 and N_2O[a]	0.78	0.78
DGS Co-Product Credit Reduction	10.16	10.16
Total CI for Corn Oil Biodiesel (without credits)	34.03	34.03
Credit for Reduced DGS Drying Energy	-28.69	0
Total CI for Corn Oil Biodiesel for Dry and Wet DGS	**5.34[b]**	**34.03[b]**

[a]California Air Resources Board, 2009a. December 14, 2009. California-Modified GREET Pathway for Conversion of Midwest Soybeans to FAME Biodiesel.
[b]These values apply to the total well-to-wheel GHG emissions carbon intensities for both the dry and wet DGS pathways as summarized in Table 1 of this document.

Appendix A

Energy Use Estimates

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, 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 290 Btu per gallon of ethanol produced, the upstream natural gas use is:

$$= \frac{\left(70{,}154\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(290\,\frac{Btu}{gal\ EtOH}\right) = \left(20.34\,\frac{Btu}{gal\ EtOH}\right)$$

2. Corn Oil Extraction, Electrical Energy, 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 340 Btu per gallon of ethanol produced, the upstream stationary electricity feedstock stage energy is:

$$= \frac{\left(99{,}790\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(340\,\frac{Btu}{gal\ EtOH}\right) = \left(33.93\,\frac{Btu}{gal\ EtOH}\right)$$

3. Corn Oil Extraction, Electrical Energy, 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 340 Btu per gallon of ethanol produced, the upstream stationary electricity fuel stage energy is:

$$= \frac{\left(2{,}877{,}173\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(340\,\frac{Btu}{gal\ EtOH}\right) = \left(978.24\,\frac{Btu}{gal\ EtOH}\right)$$

4. Corn Oil Extraction, Energy Savings Due to Reduced DGS Drying, Upstream Natural Gas Feedstock Use

The upstream natural gas energy use is 70,154 Btu/MMBtu of natural gas produced. Therefore, this is also the savings for the use of less fuel natural gas downstream. For a natural gas energy savings of 3,700 Btu/gal of ethanol produced at the ethanol plant, the upstream natural gas savings is:

$$= \frac{\left(70{,}154\,\frac{Btu}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \left(3{,}700\,\frac{Btu}{gal\ EtOH}\right) = \left(260\,\frac{Btu}{gal\ EtOH}\right)$$

5. Biodiesel Transport and Distribution

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 10,055.37 Btu/MMBtu based on Midwest regional analysis. Table A-1 summarizes the transport assumptions and resulting energy consumption in the finished fuel transport step.

All of the Biodiesel is transported by heavy-duty-diesel truck 50 miles from the plant to bulk terminal and, then another 90 miles by heavy-duty-diesel truck 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. The energy values are converted from Btu/ton-mile to total energy as follows. The energy and emissions are calculated same here as for corn transport and corn oil BD transport. Btu/ton-mile is converted to Btu/ton, which is converted to Btu/MMBtu fuel for both legs of the trip. Next, the upstream Btu/MMBtu for each mode of transport is calculated the same way using the Btu/ton-mile values. Finally, the energy for each mode is multiplied by the mode share to yield the total energy for its transport.

Table A-1. Energy Use for Biodiesel Transport and Distribution[a]

Parameter	Plant to Bulk Terminal	Distribution	Total Energy
Mode	HDD Truck	HDD Truck	
Shares (%)	80%	100%	
Distance (miles)	50	90	
Payload (tons)	25	25	
Fuel Economy (mi/gal)	5	5	
Fuel	Diesel	Diesel	
Fuel LHV (Btu/gal)	128,450	128,450	
Energy Intensity (Btu/ton-mile)[b]	1,028	1,028	
Direct Energy (Btu/MMBtu)[c]	2,545.35	5,727.03	8,272.38
Upstream Energy (Btu/MMBtu)[c]	548.61	1,234.38	1,782.99
Total BD T&D Energy (Btu/MMBtu)	**3,093.96**	**6,961.41**	**10,055.37**

[a]The CA-GREET calculation is based on CA-Marginal (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 take into account for round trip energy.
[c]Since the distance traveled is small, therefore, the return trip energy intensity is assumed to be the same as from origin to destination.

Appendix B

Emissions Factors and Carbon Intensity Estimates

This appendix shows how the CA-GREET model calculated 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, Natural Gas (CO_2 emissions)

We will use the average emission factors of large and small boiler. Therefore, (58,198 + 58,176)/2 gCO_2/MMBtu = 58,187 gCO_2/MMBtu represents direct emissions per Btu downstream energy use. Therefore, the total direct greenhouse gas emission carbon intensity from natural gas feedstock use is calculated by taking the product of the emission factor and the downstream energy use of 290 Btu/gal ethanol).

$$= \frac{\left[\frac{\left(290\,\frac{Btu}{gal\ ethanol}\right) \times \left(58{,}187\,\frac{gCO_2}{mmBtu}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{MJ}{MMBtu}\right)} = \left(0.210\ \frac{gCO_2}{MJ\ EtOH}\right)$$

An adjustment to this carbon intensity must be made to account for the glycerin co-product credit. The adjustment is made by multiplying the carbon intensity by 95.1% co-product allocation, as was done in the ARB's soybean-to-biodiesel pathway analysis (California Air Resources Board, 2009a). Doing this multiplication gives a carbon intensity of 0.200 gCO_2/MJ ethanol.

2. Corn Oil Extraction Carbon Intensity, 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 emissions greenhouse gas carbon intensity from natural gas feedstock use is calculated by taking the product of the emission factor and the downstream energy use of 290 Btu/gal ethanol).

$$= \frac{\left[\frac{\left(290\,\frac{Btu}{gal\ ethanol}\right) \times \left(5{,}245\,\frac{gCO_2}{MMBtu}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{MJ}{MMBtu}\right)} = \left(0.019\ \frac{gCO_2}{MJ\ EtOH}\right)$$

Multiplying 0.019 gCO_2/MJ ethanol by the glycerin co-product adjustment factor of 0.951 gives a carbon intensity of 0.018 gCO_2/MJ ethanol.

3. Corn Oil Extraction, Carbon Intensity of Electrical Energy, 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:

$$= \frac{\left[\frac{\left(7{,}794\,\frac{gCO_2}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(340\,\frac{Btu}{gal\ EtOH}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) = \left(0.033\,\frac{gCO_2}{MJ\ EtOH}\right)$$

Multiplying 0.033 gCO_2/MJ ethanol by the glycerin co-product adjustment factor of 0.951 gives a carbon intensity of 0.031 gCO_2/MJ ethanol.

4. Corn Oil Extraction, Carbon Intensity of Electrical Energy, 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:

$$= \frac{\left[\frac{\left(233{,}154\,\frac{gCO_2}{MMBtu}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(340\,\frac{Btu}{gal\ EtOH}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) = \left(0.984\,\frac{gCO_2}{MJ\ EtOH}\right)$$

Multiplying 0.984 gCO_2/MJ ethanol by the glycerin co-product adjustment factor of 0.951 gives a carbon intensity of 0.936 gCO_2/MJ ethanol.

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

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

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

Pollutant (g/MMBtu)	Natural Gas[a]			Electricity[a]		
	Direct[b]	Upstream	Total	Direct	Upstream	Total
VOC	1.987	6.283	8.27	18.855	4.762	23.62
CO	22.621	11.611	34.23	17.691	200.550	218.24
CH_4	1.100	128.837	129.94	317.44	7.261	324.70
N_2O	0.315	0.067	0.382	0.303	3.308	3.61

[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 direct and upstream 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, Direct: EF Tab, Cells B6:B14; Natural Gas, Upstream: NG Tab, Cells B129:B137; Electricity, Direct: Electric tab, Cells B89:B97.
The emissions factors are for the CA-GREET Midwest electricity profile.
[b]50 percent use of each large and small size of natural gas boiler.

Carbon Intensity Calculations for Direct and Upstream:

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

$$= \frac{\left[\dfrac{\left(8.27\,\dfrac{gVOC}{MMBtu}\right)\times\left(290\,\dfrac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\dfrac{Btu}{MMBtu}\right)}\times\dfrac{\left(\dfrac{0.85\ \dfrac{gCarbon}{gVOC}}{0.27\ \dfrac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\,\dfrac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\dfrac{J}{Btu}\right)}\times\left(1{,}000{,}000\,\dfrac{J}{MJ}\right)\times(0.951)$$

$$= \left(0.000089\,\frac{gCO_2e}{MJ}\right)$$

Natural Gas CO

$$= \frac{\left[\frac{\left(34.23\,\frac{gCO}{MMBtu}\right) \times \left(290\,\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(\frac{0.43\,\frac{gCarbon}{gCO}}{0.27\,\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times (0.951)$$

$$= \left(0.000187\,\frac{gCO_2e}{MJ}\right)$$

Natural Gas CH_4

$$= \frac{\left[\frac{\left(129.94\,\frac{gCH_4}{MMBtu}\right) \times \left(290\,\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(25\,\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times (0.951)$$

$$= \left(0.011125\,\frac{gCO_2e}{MJ}\right)$$

Natural Gas N_2O

$$\frac{\left[\frac{\left(0.382\,\frac{gN_2O}{MMBtu}\right) \times \left(290\,\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\,\frac{Btu}{MMBtu}\right)} \times \frac{\left(298\,\frac{gCO_2e}{gN_2O}\right)}{\left(76{,}330\,\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\,\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\,\frac{J}{MJ}\right) \times (0.951)$$

$$= \left(0.000390\,\frac{gCO_2e}{MJ}\right)$$

Electricity VOC

$$= \frac{\left[\frac{\left(23.62\frac{gVOC}{MMBtu}\right)\times\left(340\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(\frac{0.85\frac{gCarbon}{gVOC}}{0.27\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right) \times (0.951)$$

$$= \left(0.000299\frac{gCO_2e}{MJ}\right)$$

Electricity CO

$$= \frac{\left[\frac{\left(218.24\frac{gCO}{MMBtu}\right)\times\left(340\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(\frac{0.43\frac{gCarbon}{gCO}}{0.27\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right) \times (0.951)$$

$$= \left(0.001396\frac{gCO_2e}{MJ}\right)$$

Electricity CH_4

$$\frac{\left[\frac{\left(324.70\frac{gCH_4}{MMBtu}\right)\times\left(340\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(25\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right) \times (0.951)$$

$$= \left(0.032594\frac{gCO_2e}{MJ}\right)$$

$\boldsymbol{Electricity\ N_2O}$

$$\frac{\left[\frac{\left(3.61\frac{gN_2O}{MMBtu}\right)\times\left(340\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)}\times\frac{\left(298\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)}\times\left(1{,}000{,}000\frac{J}{MJ}\right)\times(0.951)$$

$$=\left(0.004320\frac{gCO_2e}{MJ}\right)$$

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

$$(0.000089+0.000187+0.011125+0.000390+0.000299+0.001396+0.032594+0.004320)=0.050400\frac{gCO_2e}{MJ}\approx\left(0.050\frac{gCO_2e}{MJ}\right)$$

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:

$$(0.200+0.018+0.031+0.936+0.050)=\left(1.235\frac{gCO_2e}{MJ\ EtOH}\right)$$

Therefore, gCO_2e/MJ Biodiesel =

$$\left(1.235\frac{gCO_2e}{MJ\ EtOH}\right)\times\left(76{,}330\frac{Btu\ EtOH}{gal\ EtOH}\right)\times\left(\frac{1\ gal\ EtOH}{0.065\ gal\ corn\ oil}\right)$$

$$\times\left(\frac{1gal\ corn\ oil}{1gal\ biodiesel}\right)\times\left(\frac{1gal\ biodiesel}{119{,}550\ Btu\ biodiesel}\right)=\mathbf{12.13}\frac{\boldsymbol{gCO_2e}}{\boldsymbol{MJ\ Biodiesel}}$$

7. Carbon Intensity of Energy Savings Due to Reduced DGS Drying Energy at Ethanol Plant, Direct Energy Use (Natural Gas) (CO_2 emissions)

The emission factor of 58,198 gCO_2/MMBtu for the natural gas savings is the same as the emission factor for the natural gas use shown in Calculation 1 above. The carbon intensity of these savings is as follows:

$$= \frac{\left[\frac{\left(3{,}700\,\frac{Btu}{gal\ EtOH}\right) \times \left(58{,}198\,\frac{gCO_2}{MMBtu}\right)}{\left(76{,}330\,\frac{Btu}{gal\ EtOH}\right)}\right]}{\left(1{,}055\,\frac{MJ}{MMBtu}\right)} = \left(2.674\,\frac{gCO_2e}{MJ}\right)$$

8. Carbon Intensity of Energy Savings Due to Reduced DGS Drying Energy, Upstream Natural Gas Feedstock (CO_2 emissions)

The emission factor of 5,245 gCO_2/MMBtu for the natural gas savings is the same as the emission factor for the natural gas use shown in Calculation 2 above. The carbon intensity of these savings is as follows:

$$= \frac{\left[\frac{\left(3{,}700\,\frac{Btu}{gal\ EtOH}\right) \times \left(5{,}245\,\frac{gCO_2}{MMBtu}\right)}{\left(76{,}330\,\frac{Btu}{gal\ EtOH}\right)}\right]}{\left(1{,}055\,\frac{MJ}{MMBtu}\right)} = \left(0.241\,\frac{gCO_2e}{MJ}\right)$$

9. Carbon Intensity of Energy Savings Due to Reduced DGS Drying Energy at Ethanol Plant, Direct and Upstream Energy Use (CH_4, VOC, CO, N_2O Emissions)

These calculations are performed the same way as in calculation 5, but for natural gas only, using the same emission factors and the ethanol plant thermal energy savings of 3,700 Btu/gal.

Carbon Intensity Calculations for Direct and Upstream:

$\boldsymbol{Natural\ Gas\ VOC}$

$$\frac{\left[=\frac{\left(7.84\frac{gVOC}{MMBtu}\right)\times\left(3{,}700\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)}\times\frac{\left(\frac{0.85\frac{gCarbon}{gVOC}}{0.27\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)}\times\left(1{,}000{,}000\frac{J}{MJ}\right)$$

$$=\left(0.001134\frac{gCO_2e}{MJ}\right)$$

$\boldsymbol{Natural\ Gas\ CO}$

$$=\frac{\left[\frac{\left(28.13\frac{gCO}{MMBtu}\right)\times\left(3{,}700\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)}\times\frac{\left(\frac{0.43\frac{gCarbon}{gCO}}{0.27\frac{gCarbon}{gCO_2}}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)}\times\left(1{,}000{,}000\frac{J}{MJ}\right)$$

$$=\left(0.002058\frac{gCO_2e}{MJ}\right)$$

$\boldsymbol{Natural\ Gas\ CH_4}$

$$\frac{\left[\frac{\left(129.94\frac{gCH_4}{MMBtu}\right)\times\left(3{,}700\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)}\times\frac{\left(25\frac{gCO_2e}{gCH_4}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)}\times\left(1{,}000{,}000\frac{J}{MJ}\right)$$

$$=\left(0.149258\frac{gCO_2e}{MJ}\right)$$

$\boldsymbol{Natural\ Gas\ N_2\ O}$

$$= \frac{\left[\frac{\left(0.382\frac{gN_2O}{MMBtu}\right)\times\left(3{,}700\frac{Btu}{gal}\right)}{\left(1{,}000{,}000\frac{Btu}{MMBtu}\right)} \times \frac{\left(298\frac{gCO_2e}{gN_2O}\right)}{\left(76{,}330\frac{Btu}{gal}\right)}\right]}{\left(1{,}055\frac{J}{Btu}\right)} \times \left(1{,}000{,}000\frac{J}{MJ}\right)$$

$$= \left(0.005231\frac{gCO_2e}{MJ}\right)$$

$Therefore, the\ total\ Carbon\ Intensity\ from\ VOC, CO, CH_{4,}\ and\ N_2O$

$$= (0.001 + 0.002 + 0.149 + 0.005) = \left(0.157\frac{gCO_2e}{MJ}\right)$$

10. Total Carbon Intensity of Energy Savings Due to Reduced DGS Drying Energy (CO_2, VOC, CO, CH_4, N_2O emissions)

The total carbon intensity of the energy savings due to reduced DGS drying energy is the sum of the carbon intensities in calculations 7, 8, and 9.

$Therefore, the\ total\ Carbon\ Intensity$

$$= (2.674 + 0.241 + 0.157) = \left(3.072\frac{gCO_2e}{MJ\ Ethanol}\right)$$

The carbon intensity is then converted from a gCO_2e/MJ of ethanol basis to a gCO_2e/MJ of biodiesel fuel.

$Therefore, \frac{gCO_{2e}}{MJ} Biodiesel$

$$= \left(3.072\frac{gCO_2e}{MJ\ EtOH}\right)\times\left(76{,}330\frac{Btu\ EtOH}{gal\ EtOH}\right)\times\left(\frac{1\ gal\ EtOH}{0.065\ gal\ corn\ oil}\right)$$

$$\times\left(\frac{1gal\ corn\ oil}{1gal\ biodiesel}\right)\times\left(\frac{1gal\ biodiesel}{119{,}550\ Btu\ biodiesel}\right) = \left(30.17\frac{gCO_2e}{MJ\ Biodiesel}\right)$$

$$Co - Product\ and\ Loss\ Factor\ Adjustment\ of\ Biodiesel$$

$$= \left(30.17 \frac{gCO_2e}{MJ\ Biodiesel}\right) \times 95.1\% \times 1.000039\ = \mathbf{28.69} \frac{\boldsymbol{gCO_{2e}}}{\boldsymbol{MJ\ Biodiesel}}$$

11. Net Carbon Intensity Due to Corn Oil Extraction (Including Energy Savings)

The net carbon intensity of corn oil extraction, including the energy savings, can be converted from the -1.837 gCO_2e/MJ of ethanol produced value shown in Table 6 to an equivalent gCO_2e/MJ of biodiesel produced as follows:

$$Therefore, \frac{gCO_{2e}}{MJ} of\ Biodiesel$$

$$= \left(-1.837 \frac{gCO_2e}{MJ\ EtOH}\right) \times \left(76{,}330 \frac{Btu\ EtOH}{gal\ EtOH}\right) \times \left(\frac{1\ gal\ EtOH}{0.065\ gal\ corn\ oil}\right)$$

$$\times \left(\frac{1gal\ corn\ oil}{1gal\ biodiesel}\right) \times \left(\frac{1gal\ biodiesel}{119{,}550\ Btu\ biodiesel}\right) = \mathbf{-18.04} \frac{\boldsymbol{gCO_2e}}{\boldsymbol{MJ\ Biodiesel}}$$

This is equivalent to a credit of 18.04 gCO_2e/MJ of biodiesel produced.

12. Carbon Intensity Due to Reduction in Corn Ethanol DDGS Co-product Credit

This carbon intensity is due to the reduction in the DDGS co-product credit for corn ethanol due to the addition of a corn oil extraction process. As mentioned above, the DDGS co-product for corn oil is reduced by about 9.4 percent when corn oil is extracted. The DDGS co-product credit for corn ethanol without the use of corn oil extraction is about 11.62 gCO_2e per MJ of ethanol produced (9.4% x 11.62=1.09 gCO_2e/MJ), as discussed in the ARB's corn ethanol pathway document (California Air Resources Board, 2009b). A reduction of this credit by about 9.4 percent is a reduction of about 1.09 gCO_2e per MJ of ethanol produced. This value is converted to a gCO_2e per MJ of biodiesel produced.

$$Therefore, \frac{gCO_{2e}}{MJ} of\ Biodiesel\ include\ Loss\ Factor\ Adjustment$$

$$= \left(1.09 \frac{gCO_2e}{MJ\ EtOH}\right) \times \left(76{,}330 \frac{Btu\ EtOH}{gal\ EtOH}\right) \times \left(\frac{1\ gal\ EtOH}{0.065\ gal\ corn\ oil}\right)$$

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

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

13. GHG Calculations for Biodiesel Transport to Retail Stations

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

- 80% transported 50 miles by heavy-duty-diesel truck (HDDT) from plants in CA to bulk terminal
- 100% distributed 90 miles by heavy duty truck

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

Table B-2. GHG Emissions from Biodiesel Transport and Distribution[a]

Parameters	Plant to Bulk Terminal	Fuel Distribution	Total Transport
Mode	HDD Truck	HDD Truck	
Mode Share	80%	100%	
Distance (miles)	50	90	
Fuel	Diesel	Diesel	
Direct CO_2 Emission (gCO_2/MMBtu)	77,809 (77,912)[b]	77,809 (77,912)[b]	
Upstream CO_2 Emission (gCO_2/MMBtu)	15,186[c]	15,186[c]	
Energy Intensity (Btu/ton-mile)	1,028	1,028	
Direct Emissions (g/MMBtu)			
VOC	0.076	1.052	1.128
CO	0.390	0.877	1.266
CH_4	0.004	0.009	0.013
N_2O	0.005	0.012	0.017
CO_2	**198.18**	**445.91**	**644.09**
Upstream Emissions (g/MMBtu)			
VOC	0.024	0.054	0.078
CO	0.065	0.146	0.211
CH_4	0.287	0.647	0.934
N_2O	0.000	0.001	0.002
CO_2	**38.65**	**86.97**	**125.62**
Total Emissions (g/MMBtu)			
VOC	0.101	1.106	1.207
CO	0.455	1.023	1.478
CH_4	0.291	0.656	0.947
N_2O	0.006	0.013	0.019
CO_2	236.84	532.88	769.72
GHG Emissions (gCO_2e/MMBtu)	246.89	558.25	805.14
GHG Emissions (gCO_2e/MJ)	**0.23**	**0.53**	**0.76**

[a]The CA-GREET calculation is based on CA-Marginal (Regional LT Tab) because of the finished fuel. 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 Table B-2 above.

14. GHG Emissions from Biodiesel-Fueled Vehicle

14.1 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 fuels derived from non-fossil biological sources is the atmosphere, the return of that carbon to the atmosphere as the fuel is combusted completes a cycle which 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-3 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. As shown in Table B-3, CA-GREET uses the values in the top 9 rows of the table below to calculate the fuel carbon CI shown in the row 10. In addition, the CA-GREET default values under Biodiesel (B100) column are identified by 'Tab and Cell' numbers in the last column of this table. The biodiesel

production energy and methanol energy share for production shown in rows 1 and 5 of Table B-3 are CA-GREET default values and the remaining values in the table are fuel properties.

The total BD processing energy of 2,116 Btu/lb BD 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 BD. The GHG emissions are calculated based on the fraction of methanol energy in BD.

Table B-3. 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.

14.2 Detailed Calculation of Fossil Carbon in Biodiesel

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

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

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

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

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

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

14.3 Vehicle CH_4 and N_2O emissions

The tailpipe CH_4 and N_2O emissions from all LCFS BD pathways and from ULSD are assumed to be equivalent. 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-4.

Table B-4. 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

Energy Use Reduction in the Production of Corn Ethanol from Adding Corn Oil Extraction by GreenShift Corporation

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.

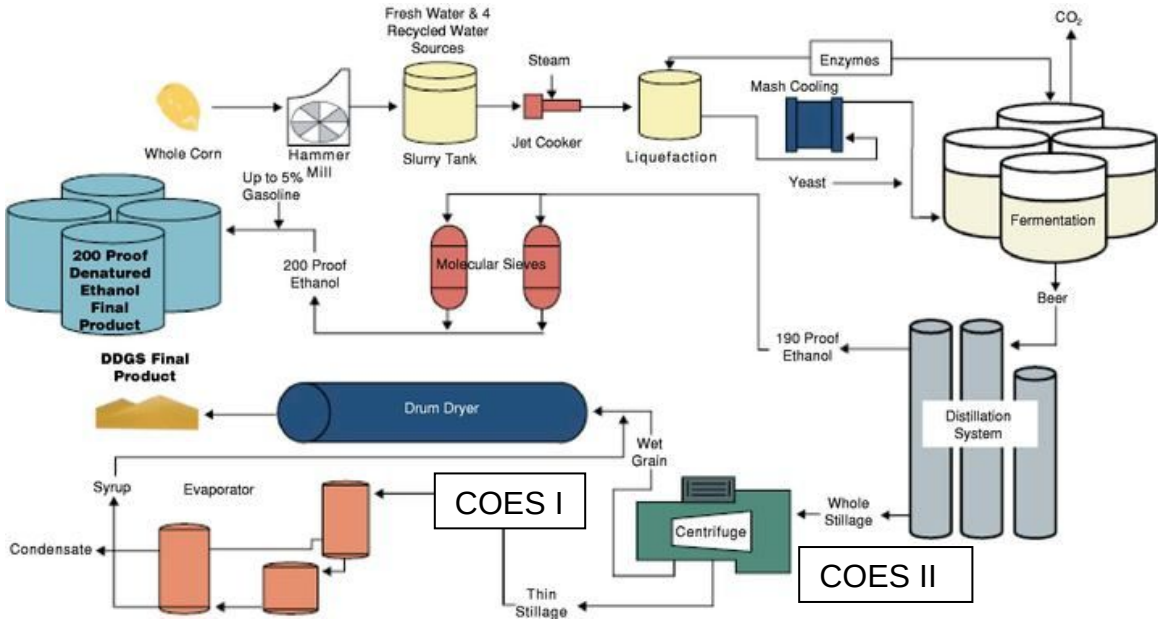
Second: Corn oil extraction after fermentation allows a dry mill ethanol plant to produce 11 percent more total fuel energy by manufacturing additional renewable biofuels from its corn oil byproduct. Corn oil is an excellent feedstock for biodiesel and renewable diesel.

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.



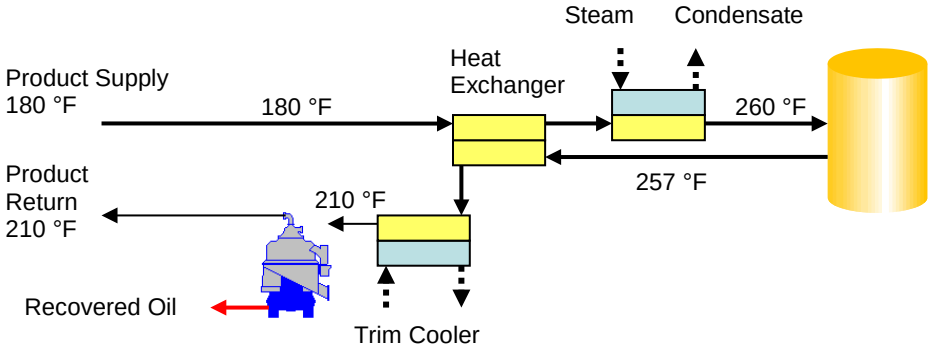
The COES placed in the ethanol plants are of two types. The first system, referred to as COES I, extracts corn oil from the thin stillage as it works its way through the evaporators. GreenShift has been awarded three patents on its COES I technology. The thin stillage generally contains about 30 percent 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°C (68°F)). Its flash point is greater than 290°C (550°F), 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:

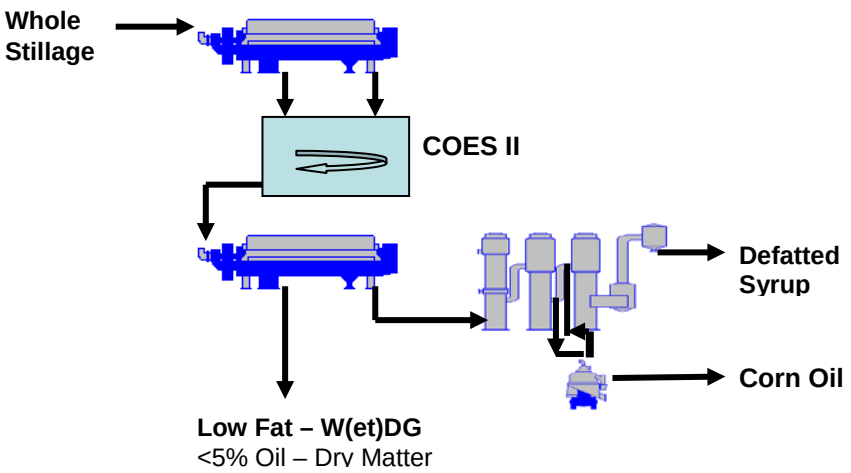


The main process is to heat the partially concentrated thin stillage and extract the corn oil by separation in a centrifuge. Steam is used in heat exchangers to raise the temperature of the thin stillage for extraction. As the temperature is reduced prior to returning the defatted stillage to the evaporators 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, 24 hours a day, that is 1.8 X 10^{12} Joules/year, or 3.6 X 10^{4} Joules/ethanol gallon. 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).

REFERENCES

Argonne National Laboratory and Life Cycle Associates LLC, 2009. California-Modified Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (CA-GREET), Version 1.8b. Systems Assessment Section, Center for Transportation Research, Argonne National Laboratory. http://www.arb.ca.gov/fuels/lcfs/ca_greet1.8b_dec09.xls

Argonne National Laboratory, 2008. Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels. Energy Systems Division. ANL/ESD/08-2. http://www.transportation.anl.gov/pdfs/AF/467.pdf.

California Air Resources Board, 2009a. Detailed California-Modified GREET Pathway for Conversion of Midwest Soybeans to Biodiesel (Fatty Acid Methyl Esters-FAME). December 14, 2009; version 3.0: http://www.arb.ca.gov/fuels/lcfs/121409lcfs_soybd.pdf. California Air Resources Board.

California Air Resources Board, 2009b. Detailed Modified-California GREET Pathway for Corn Ethanol, February 27, 2009; version 2.1: http://www.arb.ca.gov/fuels/lcfs/o22709lcfs_cornetoh.pdf. California Air Resources Board.

California Air Resources Board, 2009c. Detailed California-Modified GREET Pathway for Ultra Low Sulfur Diesel (ULSD) for Average Crude Refined in California, February 28, 2009; version 2.1: http://www.arb.ca.gov/fuels/lcfs/022709lcfs_ulsd.pdf. California Air Resources Board. Please see page 43, Table 5.02 for Emissions Factor Model and page 44 for information on emission factors and the calculation of carbon intensities at corn ethanol plants.

GreenShift Corporation, 2009. Energy Use Reduction in the Production of Corn Ethanol from Adding Corn Oil Extraction. February, 2009. GreenShift Corporation submitted this document 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.

Intergovernmental Panel on Climate Change, 2007. Climate Change 2007: Working Group I: The Physical Science Basis. (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html).

Solomon, S., Qin, D., Manning, M., Alley, R.B., Berntsen, T., Bindoff, N.L., Chen, Z., Chidthaisong, A., Gregory, J.M., Hegerl, G.C., Heimann, M., Hewitson, B., Hoskins, B.J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T.F., Whetton, P., Wood, R.A., and Wratt, D, 2007. "Climate Change 2007: The Physical Science Basis," Technical Summary, .Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Cambridge University Press, Cambridge, UK, and New York, USA, 2007. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html.