2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Life Cycle Analysis of Soybean Biodiesel Production

Anup Pradhan, Graduate Student

Dev Shrestha, Assistant Professor

Department of Biological and Agricultural Engineering, P. O. Box 442060, University of Idaho, Moscow, ID 83844, Email: devs@uidaho.edu.

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Abstract. *Developing renewable fuels, such as biodiesel, is desirable because they are derived from sustainable sources of energy, whereas petroleum fuels come from a finite resource that is rapidly being depleted. However, the production of renewable fuels generally involves a significant amout of fossil energy. The renewability of biofuel is largely a factor of the amount of fossil energy used for its production, hence it is essential to estimate the amount of fossil energy used over the entire life cycle of the biodiesel production. The comprehensive Life Cycle Analysis (LCA) of soybean biodiesel production was conducted by National Renewable Energy Laboratory (NREL) in 1998. Because of increasing changes in land use and production process, the LCA conducted few years ago is no longer representative of current practices. This research updated the Energy Life Cycle Analysis (ELCA) of the NREL model and estimated the Fossil Energy Ratio (FER) to be 4.56 based on data from 2002 soybean production in the United States. This is a significant improvement (43%) over the 1998 NREL study that reported a FER of 3.2. The United States Department of Agriculture (USDA) projects soybean yield to increase annually by 0.4 to 0.5 bushel/acre through the year 2017. For every one bushel increase in soybean yield, FER increases by about 0.45 percent. Holding all other variables constant, the FER of soybean biodiesel is estimated to reach 4.69 in the year 2015 when soybean yield is projected to increase to 45.3 bushels per acre. The FER will continue to improve overtime with increasing trend of soybean yield and improvement in the energy efficiency of the crushing and biodiesel plants. In addition to ELCA, four commonly referenced models were compared for the GHG emission savings. The analysis revealed that the most significant factors in altering the results in GHG emissions were differences in data citations, system boundaries, and coproduct allocations.*

Keywords. Soybean, Biodiesel, Renewability, Fossil Energy Ratio, Greenhouse Gas.

Introduction

The development of renewable biofuels is desirable because they are derived from biological materials and hence can be replaced in a relatively short period of time compared to petroleum fuels which come from oil, a finite resource that is depleting rapidly. The 2008 estimates of proved oil reserves in the United States is about 21 billion bbl and the total production of crude oil is 8.5 million bbl per day (Energy Information Administration, 2009). With today's rate of crude production and reserves, the reserves-to-production (R/P) ratio for US is estimated to be 7 years. The R/P ratio is the number of years for which the current level of production of fuel can be sustained by its reserves and is calculated by dividing proved reserves at the end by the production in that year (Feygin and Satkin, 2004). Compared to 8.5 million bbl of daily production, US consume about 20 million bbl of crude petroleum. The deficit is fulfilled through petroleum import from foreign countries. Biofuels have potential to reduce the nation's dependence on imported fuels and conserve limited fossil fuel supplies for the alternative uses, which is one of a key driver to the energy security. In addition, biofuels have superior environmental attributes compared to their petroleum counterparts (US EPA, 2002; Knothe et al., 2005).

While biofuels themselves consist solely of energy photosynthesized with sunlight, producing them requires outside energy resources. The production of renewable fuels generally involves a significant amount of fossil energy, e.g., petroleum derived diesel fuel is used to cultivate and harvest the soybeans used to make biodiesel. The amount of fossil energy used for biodiesel must be measured over the entire life-cycle of biodiesel production to determine the extent in which it depends on petroleum fuels. The degree in which biodiesel is renewable is largely a factor of the amount of fossil energy used for its production. Some feedstocks are more efficient and easier to process than others, and some farming and refining methods are more energetically frugal than others. Therefore, there is a need of defining ways of measuring the energy and environmental performance of biofuels (Worldwatch Institute, 2007).

Life Cycle Analysis (LCA)

Life cycle analysis or Life cycle assessment (LCA) is an established technique widely used to quantitatively assess the environmental impact and the energy requirements of a product or service from original resources to its final disposal. The aim of a LCA is to compare certain ecological impact categories of a renewable energy source (e.g. biodiesel) and the finite energy source that can be replaced (e.g. fossil diesel fuel in diesel vehicles) (Mittelbach and Remschmidt, 2004).

LCA of biofuels, such as ethanol and biodiesel, is being popular among the producers, users and researchers to compare the environmental performance of the biofuels with petroleum fuels. The other important aspect of biofuel LCA is to evaluate its renewability, i.e. whether the ratio of energy content in biofuel to the total energy required to produce the biofuel is positive or more than one or not. LCA can help policy makers compare all major environmental impacts and select the product or process that results in the least burden to the environment. In addition, cost of product or process can be incorporated in LCA to evaluate the economic sustainability of the system.

International Standardization Organization standards (ISO 14040, 2006; ISO 14044, 2006) provide guidelines for conducting LCA. According to these ISO standards, LCA is conducted in four phases. The first phase, goal and scope definition requires a precisely defined system boundary and level of detail of an LCA study which depends primarily on the subject and the intended use. The second phase, inventory analysis is the detailed accounting of inventory that enters and leaves the system boundary. The input and output data for each individual process are collected to meet the goals of the defined study. The third phase, impact assessment evaluates the environmental impacts from each individual process and provides assessment of a product's life cycle inventory results. The fourth and the final phase is interpretation in which the results of the study are interpreted and significant issues are identified in accordance with the goal and scope definition. Even though ISO standards have been set forth to standardize the procedures, energy and emission estimations are still very difficult to compare as experts use different system boundaries, data citation and assumptions on the basis of their specific objective.

In 1998, the first comprehensive life cycle inventory (LCI) for biodiesel produced in the United States from soybean oil was completed by Sheehan et al. The inventory and model assumptions were developed by a large stakeholders group and several peer reviewers that included experts from numerous disciplines and institutions. The purpose of the study was to conduct a life-cycle assessment (LCA) to quantify and compare the environmental and energy flows associated both with biodiesel and petroleum based diesel. The LCI flows examined included greenhouse gases, energy use, and other air emissions. Other biodiesel LCAs have been done since Sheehan et al., but none have matched the detailed information or collaborative effort used to produce the original report (Hill et al., 2006; and Huo et al., 2008).

Energy Life Cycle Analysis (ELCA)

Energy Life Cycle Analysis (ELCA) is a branch of general life cycle analysis (LCA) which accounts for all the energy that goes into making a biofuel and compares it with energy contained in the produced fuel. ELCA is relevant for the products that is used as a fuel or used for energy. Net Energy Ratio (NER) is a measure of the efficiency of making a biofuel and generally expressed as:

$$\mathrm{NER} = \frac{\text{Biofuel energy output}}{\text{Biofuel share of total energy input}} \tag{1}$$

Biofuel is usually produced in conjunction with other co-products such as soybean meal and glycerol in case of biodiesel. Therefore, only a portion of total energy attributed to biofuel is used in denominator of equation 1.

A significant amount of nonrenewable energy is being used in farm operations and transportation to produce biological materials and to convert them into biofuels. The fossil energy requirement for biofuel production is a key to understand the extent to which the biofuel is a renewable energy source. The amount of fossil energy used is measured over the entire life-cycle of biofuel to determine the extent to which it is renewable. The renewable qualities of biofuel can range from completely renewable (if no fossil energy input is needed), to nonrenewable (if the fossil energy required is as much or more than the energy content in the biofuel). The more fossil energy is required in its production, the less renewable the biofuel becomes.

It is important to know the renewability of a biofuel for two reasons. Firstly, it is useful to know how much a biofuel relies on fossil energy for its production. The less a biofuel depends on fossil energy, the larger is the contribution it can make towards energy security. Secondly, the renewability of different biofuels can be compared by policymakers and others to make go/ no-go decisions.

This raises an important question on how to define the degree of renewability of a specific biofuel. One way is to express the result obtained from the ELCA as the Fossil Energy Ratio

(FER), which is defined as the ratio of the energy output from the final biofuel to the fossil energy required to produce the biofuel (Spath and Mann, 2000). According to Sheehan et al. (1998), FER is expressed as:

$$\text{FER} = \frac{\text{Biofuel energy output}}{\text{Biofuel share of fossil energy input}} \tag{2}$$

If no renewable fuel is used in biofuel production, FER is equal to NER defined in eq (1). FER is commonly used to measure and compare the advantages of different biofuels. There is, however, a potential pitfall in using absolute value of FER as a measure of renewability. One is that fossil energy input can be partially or entirely replaced by using renewable sources such as corn stover, bagasse or DDGS from ethanol plant, which can increase the FER value. To offset this pitfall, the definition of FER has been modified by researchers to include not only the final biofuel product, but also the energy of co-products.

Over the past several years the FER, also called energy balance, of soybean biodiesel has been reported by different researchers with considerable variation in results (table 1). The variation in results published by different researchers is attributed to data differences, conflicting system boundaries, and differences in energy ratio definitions (Pradhan et al., 2008). A major cause for the contradicting results is due to the difference in the amount of energy allocated between the soybean oil used to make biodiesel and the soybean meal. Historically, soybean demand is driven by the demand for soybean meal, which is used as a high protein animal feed. Crushing soybeans yield considerably more meal than oil, as well as more revenue. Clearly, soybean meal is not a by-product of biodiesel production. Rather, soybean meal and oil are jointly produced and sold in separate markets. Therefore, an allocation method must be used to determine how the energy used for crushing soybeans should be divided between the two products. Unfortunately, different allocation methods can produce significantly different coproduct energy values.

One of the most often cited results from Sheehan et al. (1998) is that the FER of biodiesel is equal to 3.2. In other words biodiesel yields 3.2 units of energy for every unit of fossil energy consumed over its life cycle. By contrast, it was found that petroleum diesel's life cycle yielded only about 0.84 units of energy per unit of fossil energy consumed.

Table 1: Net energy ratios reported for soybean biodiesel

FER	Source
2.51	Ahmed et al. (1994)
3.20	Sheehan et al. (1998)
0.79	Pimentel and Patzek (2005)
1.93	Hill et al. (2006)

Life Cycle GHG Emissions

During the lifecycle of biofuels, emissions arise during biomass feedstock production, transport of the raw material and products, conversion of the feedstock into the biofuel, and use of the fuel in vehicles. These emissions can have various impacts on environmental themes, such as greenhouse gas (GHG) effect, acidification, eutrofication, toxication, ozone layer depletion and photochemical smog. Farming is the primary source of GHG emissions associated with biofuels production because of emissions of nitrous oxide (N_2O). These emissions are not very large in mass terms but the very high GHG effect of this gas (about 300 times more than CO_2 on mass basis) makes their impact significant (GAVE, 2005). N_2O emissions from farming are dominated by two sources: nitrogen fertilizer production and its application on the field (Edwards et al., 2004).

Basically, biofuels releases the same amount of carbon that the feedstock takes out of the air during its cultivation. Therefore, biofuels have the theoretical potential to reduce GHG emissions. Sheehan et al. (1998) reported a 78% reduction of fossil carbon dioxide (CO_2) from soybean biodiesel production compared to that of petroleum diesel (table 2). They reported that about 18,193 gm of CO_2 was emitted per GJ of biodiesel compared to 84,437 gm of CO_2 per GJ of diesel fuel. The emission of fossil CO_2 during all the biodiesel production (soybean agriculture, bean crushing and oil conversion processes) processes and end use combustion of biodiesel were reported to be around 21% each. Biodiesel combustion emits larger quantities of CO_2, but most of the fraction comes from renewable carbon which is subtracted from the final GHG emissions. Compared to petroleum diesel fuel, biodiesel life cycle emissions of methane (CH_4), carbon monoxide (CO), particulate materials (PM_{10}), sulfur oxides (SOx) and hydrogen fluoride (HF) were reported to be lowered by 2.6%, 34.5%, 44.5%, 8.03% and 15.5% respectively. However, biodiesel production increased the life cycle emissions of nitrogen oxide (NOx) and hydrochloric acid (HCl) by 13% each.

Like Sheehan et al., other models also reported a significant reduction in GHG emission from biodiesel production and combustion compared to that of petroleum fuel (Table 2). However, some researchers argue that biofuel production causes a net increase in GHG emissions when undisturbed land is used to cultivate the growing demand of feedstock. Land use change by converting forest or grassland to soybean farm releases carbon stored in the plants and soil to the atmosphere through decomposition or burning. In addition to this, the loss of carbon sequestration as plants grow each year is the equivalent of additional emissions (Searchinger et al., 2008; Fargione et al., 2008). The GHG emission due to land use change is out of scope of this study.

Table 2: GHG emissions reported for soybean biodiesel

GHG Emissions (gm CO_2 equiv./GJ of fuel)	**GHG Reduction (%)**	**Source**
18,193	78	Sheehan et al. (1998)
29,674	65	GHGenius ((S & T)^2, 2008)
33,740	60	GREET ((S & T)^2, 2008)
49,113	40	Hill et al. (2006)

Objectives

The purpose of this study is to update the ELCA of the Sheehan et al. model to determine if any significant changes in the original inventory have occurred since the model was first developed ten years ago. For example, the adoption of new technologies in the farm sector, the soybean processing sector, and in the biodiesel industry are expected to effect life-cycle energy use. The study also reviews and compares the life cycle GHG emissions estimated by various models, such as Sheehan et al., Argonne GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model, GHGenius, and Hill et al. This study will apply these models to GHG emissions from soybean biodiesel production and analyze the model discrepancies.

Methodology

Following Sheehan et al, the formula used in this study to estimate the fossil energy ratio (FER) is defined in equation 2.Estimating FER begins with defining the entire production system of biodiesel, which includes four subsystems in this analysis: feedstock production, feedstock transportation, soybean processing with biodiesel conversion, and product distribution. An inventory is then developed that identifies and quantifies all the fossil energy inputs used in each subsystem. All significant sources of energy are included in the inventory, such as the liquid fuel and electricity used to directly power equipment in the system. The energy content of materials that are made from energy resources, such as fertilizers, pesticides, and other petrochemicals are also included in the inventory. The energy values of all fossil energy used in the system are adjusted by energy efficiency factors to take into account the energy used to convert fossil resources into usable energy (Appendix table A.1). The energy efficiency factors also adjust for any energy required to mine, extract, and manufacture the raw energy sources. Estimates of electricity generation used throughout the life-cycle are based on the U.S. weighted average of all sources of power, including coal, natural gas, nuclear, and hydroelectric. When excluding hydroelectric and other non-fossil sources of energy, about 70 percent of the electricity generated in the United States comes from fossil fuel (Energy Information Administration, 2007). The efficiency of electricity generation in the U.S. increased from 32 percent as reported in Sheehan et al. to 33.71 percent in 2007 based on data from the Energy Information Administration. In addition to generation loss, there is also a loss of electricity over the distribution lines, which reduces the overall efficiency of electricity to 31.29 percent. Therefore, all electricity used over the life-cycle is increased by a factor of 3.2 to account for generation and distribution losses.

Similarly to Sheehan et al. the soybean crushing model in this analysis uses the hexane extraction method to extract oil from soybean seed and transesterification is used to convert soybean oil into biodiesel. Oil extraction and transesterification results in the production of two important coproducts, soybean meal and crude glycerin respectively. Since this energy life-cycle focuses exclusively on biodiesel, the energy associated with the production of the other two coproducts must be estimated and excluded from the inventory. Since detailed information is often not available to measure the exact energy requirements of the individual coproducts, an allocation method can be used to assign coproduct values. There are several allocation methods that can be used to estimate the energy value of coproducts. For example, the energy method uses the energy content of each coproduct to allocate energy. Another example is the economic method that uses the relative market value of each coproduct to allocate energy. Sheehan et al. used a mass based allocation method and to be consistent with their analysis, this study also uses the mass based allocation method (figure 1). In general, no allocation method is always applicable and the appropriate method should be chosen on a case-by-case basis.

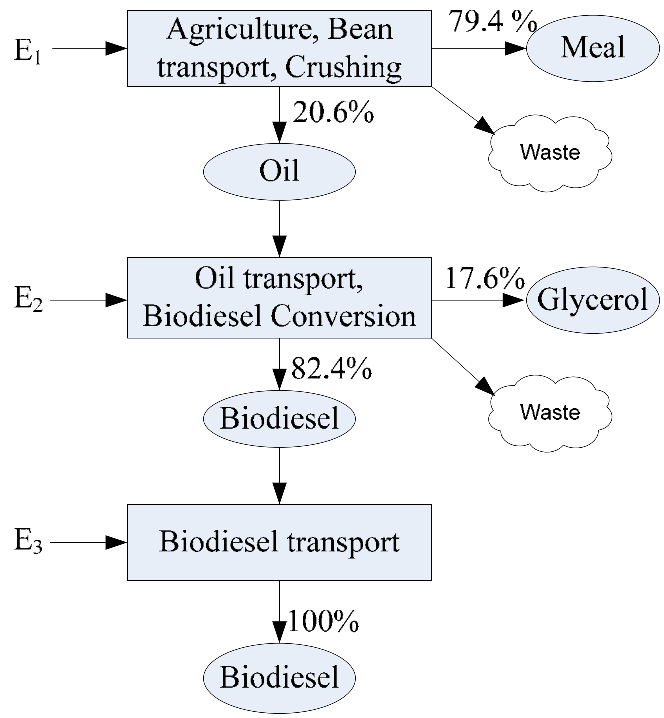

Figure 1: Mass based energy allocation for biodiesel coproducts

The mass based allocation method is commonly used because it is easy to apply and provides very reasonable results (Vigon et al., 1993). This method simply allocates energy to the various coproducts by their relative weights. This allocation rule separates the energy used to produce the soybean oil from the energy used to produce the soybean meal and glycerin in the following manner:

Energy input allocation for biodiesel = $E_1 f_1 + E_2 f_2 + E_3$ (3)

where E_1 is energy input for agriculture, soybean transport and soybean crushing, f_1 is the mass fraction of soybean oil used to produce biodiesel; E_2 is the energy used during transesterification and the transport of the soybean oil, and f_2 is mass fraction of the transesterified oil used to produce biodiesel. E_3 is energy input for biodiesel transport.

USDA ERS (2009) reported an U.S. average oil yield of 11.39 pounds per bushel of soybeans, a soybean meal yield of 43.9 pounds per bushel, and a hull yield of 3.27 pounds per bushel in 2002/2003. Excluding the hulls and waste material, 20.6 percent of the total energy used for soybean agriculture, soybean transport, and crushing is allocated to the oil used to make biodiesel, and 79.4 percent is allocated to the meal (figure 1).

Crude degummed soybean oil contains a small amount of unsaponifiable matter and free fatty acids that must be removed because they are detrimental to the transesterification process. The free fatty acids can turn into soap when transesterified, resulting in more difficult phase separation of the methyl ester and glycerin. The crude degummed oil is treated with sodium hydroxide to obtain dry refined oil, with a yield of about 96 percent (Sheehan et al., 1998). The other 4 percent is considered waste. Following transesterification, the proportion of refined biodiesel to crude glycerin (with a purity of about 80 percent) is 82.4 percent biodiesel and 17.6 percent crude glycerin. Therefore, 82.4 percent of the total energy used to convert degummed soybean oil into biodiesel is allocated to biodiesel and 17.6 percent is allocated to crude glycerin (figure 1). In addition, the coproduct energy value of crude glycerin must be deducted from soybean agriculture, crushing, and soybean transport, so that f_1 in equation (3) = 0.170 (0.206×0.824), and f_2 = 0.824. All the energy used to transport biodiesel is allocated to biodiesel (figure 1).

Energy Life Cycle Inventory

This section describes the inventory and data used to construct the four subsystems of the biodiesel life-cycle; feedstock production, feedstock transportation, soybean processing with biodiesel conversion, and product distribution. The analysis first constructs a base case, in which the inventory was kept basically the same as the inventory in the Sheehan et al. report. Then additional inputs that were not included in Sheehan et al., such as agricultural lime use, agricultural machinery and energy embodied in building materials were added to study their impact on FER.

Feedstock Production

The farm input data for soybean production was obtained from USDA ERS, USDA Agricultural Resource Management Survey (ARMS), and USDA's National Agricultural Statistics Service (NASS). The direct energy data came from the 2002 ARMS, which was the most recent soybean survey data available at the time of this study. The state soybean yield data are USDA estimates reported by NASS (USDA NASS, 2005). The fertilizer and chemical data for year 2002 soybeans are from the USDA, NASS Agricultural Chemical Survey. The seed application rates is a state average from the 2002 ARMS (USDA, ERS-a).

The weighted average soybean yield for the state data equaled 38 bushels per harvested acre in year 2002. The weighted average energy input use and the weighted average yield were used to estimate the energy required to produce a bushel of soybeans in the United States (table 3). The direct energy inputs were converted to British thermal units (Btu) using low-energy heating values, assuming that electricity generation came from a combination of coal, natural gas, nuclear, and hydropower at the same proportion as the national average. Electricity use only includes electricity generated from fossil sources, which on a national average equals 70 percent. The energy used for planting the seed and other farm activities such as land preparation, plowing, weeding, fertilizer, and pesticide application, irrigating, harvesting and drying is included in total farm fuels and electricity estimates. The fuel required for hauling the soybeans from the field to the first destination point, either farm storage or local market, is also included in the fuel estimates. The conversion factors used to convert farm energy inputs into Btus are listed in appendix table A.2.

Table 3: Energy equivalents for base case soybean agriculture system inputs, 2002

Inputs*	20 States Weighted Average	
	Btu/bu	Btu/gal
Seed	3,617	2,428
Fertilizer:		
Nitrogen	2,482	1,666
Phosphorus	1,313	881
Potash	1,721	1,155

Direct Energy:		
Diesel	16,280	10,928
Gasoline	4,782	3,210
LP	1,817	1,220
Electricity**	1,330	893
Natural Gas	1,607	1,079
Ag. Chemical Application:		
Herbicides	4,368	2,932
Insecticides	55	37
Lime	506	340
Total Fossil Energy for Agriculture	39,878	26,769

* Inputs are adjusted by energy efficiency factors.

**Assumes 70 percent of electricity generated from fossil sources.

Feedstock Transportation

The amount of energy required to transport soybeans to processing plants came from the GREET model developed by Argonne National Laboratory. The energy required for transporting soybeans to processing plants was estimated to be 6,393 Btu/bushel, which is equivalent to about 4,291 Btu per gallon of biodiesel. The estimation was based on a distance of 50 miles for trucking soybeans from a distribution center to the soybean crusher/biodiesel plant.

Oil Crushing and Biodiesel Conversion

The energy requirements for soybean crushing and transesterification were estimated using a computer model utilizing chemical process engineering and cost engineering technology that were developed by USDA's Agricultural Research Service (Haas et al., 2006). The model measures the electrical and thermal energy inputs required for a joint facility that combines a soybean processing plant with a biodiesel conversion plant producing 9.8 million gallons of biodiesel, 151,515 tons of soybean meal, 9,000 tons of soybean hulls and 4,380 tons of crude glycerin. The model provides a blueprint of a biodiesel plant based on the best information available, but it does not represent an actual plant, since actual industry data was not used.

The separation of the soybean into oil and soybean meal, which is generally referred to as crushing, can be done by crushing using mechanical extruders, but more commonly the oil is extracted from the soybeans using chemical hexane extraction. A soybean processing facility uses energy in the form of electricity to power motors and provide lighting. Natural gas and process steam are used to provide heat for drying. The model used in this analysis allows the plant to generate its own steam from natural gas with a boiler efficiency of 80 percent. Thus, the energy value for steam is incorporated in the energy value of natural gas used to generate the required steam. The combined total thermal and electric energy required for preparing the soybeans, extracting the oil from the beans, and drying the soybean meal requires 23,151 Btu per gallon of biodiesel (table 4).

The conversion of soybean oil into biodiesel is done by reacting the oil with an alcohol, usually methanol, and a catalyst, such as sodium hydroxide in large reactors. After the soybean oil, methanol, and catalyst have reacted the resulting mixture is centrifuged to remove excess methanol, glycerin and other impurities. After the centrifuge step, the mixture is then washed with a water acid solution, and dried to become a methyl ester, which is commercially know as biodiesel. Electrical energy is used to drive the pumps, centrifuges, and mixers, while thermal energy is needed in the distillation column to recover the excess methanol and remove the final rinse water from the biodiesel. Thermal energy is also used to heat the soybean oil to accelerate the conversion process. The conversion of the soybean oil into biodiesel, the recovery of the excess methanol and the treatment of the glycerin requires 18,772 Btu per gallon of biodiesel (table 4).

Table 4: Fossil energy requirements for soybean crushing and conversion, per gallon of biodiesel

Inputs	**Equivalent Energy (Btu/gal)**	**Adjusted Equivalent Energy* (Btu/gal)**	**Source**
Soybean crushing:			
Electricity**	2,738	6,124	ARS
NG/Steam	14,532	15,460	ARS
Hexane	1,567	1,567	Huo et al.
Total fossil energy for crushing	18,837	23,151	
Biodiesel conversion:			
Electricity	439	981	ARS
NG/Steam	3,550	5,840	ARS
Methanol	7,193	10,633	Huo et al.
Sodium Methoxide	1,256	1,256	Huo et al.
Sodium Hydroxide	24	24	Huo et al.
Hydrochloric Acid	38	38	Huo et al.
Total fossil energy for conversion	12,500	18,772	

* Inputs are adjusted by energy efficiency factors.

**Assumes 70 percent of electricity generated from fossil sources, which is adjusted for generation and line losses.

Biodiesel Transport

The GREET model was used to estimate the energy required for transporting biodiesel. Transporting biodiesel to marketing outlets requires 8,767 Btu per million Btu of biodiesel. This is equivalent to 1,027 Btu per gallon of biodiesel transported. The estimation was based on the total distance of 335 miles using a combination of truck, barge, and rail. It required a distance of 31.5 miles for truck, 41.6 miles for barge, and 232 miles for rail to transport biodiesel from the plant to a distribution center, and another 30 miles by truck to get it to its final destination.

Data Trends

Soybean yields also have been improving over time because of new seed varieties, improved fertilizer, and pesticide applications, and new management practices (Ash et al., 2006). Genetically engineered soybeans with herbicide tolerant and pest management traits increase yields through improved weed and pest control. The 1990 ARMS soybean production data used in the Sheehan et al. report did not include any GE soybeans, because they had not been introduced into U.S. agriculture yet. However, by 2002 the rapid rise in GE soybeans had reached 75 percent of the soybeans planted and today almost all soybeans in the United States are GE varieties (USDA ERS, 2007). Using GE soybeans also reduces pesticide use and costs (Heimlich et al., 2000)**Error! Hyperlink reference not valid.**. When comparing the average herbicide use from the data published from the NASS Agricultural Chemical Usage survey, over the 5-year period from 1990-994; 1995-1999; and 2000-2004, the average was 1.18, 1.11 and 1.09 lb/acre/year respectively (USDA, NASS, 1990-2005). However this average decrease in herbicide use may not be realized from year to year because annual pesticide use depends on the level of infestation. For instance, pesticide application rate was higher for the years 2005 and 2006 mostly because of higher aphid infestation (Thorson, 2008). Some herbicides are also less toxic today, e.g., most of the herbicide used on soybeans is now in the form of glyphosate, which is about 10 times less toxic in terms of the oral Reference Dose (RfD) established by the Environmental Protection Agency (EPA) than herbicides used in the past, such as Alachlor (US EPA, 2008). Kovach et al. (2007) found environmental impact quotient (EIQ), which encompasses 11 different types of toxicity measurements and environmental impacts was found more favorable for glyphosate (EIQ =15.3) than for alachlor (EIQ = 18.3).

The data shows a significant increase in soybean yield since 1990 (figure 2). Soybean yields have increased steadily since 1990 when the U.S. average yield was 34.1 bushels per acre and by 2002, U.S. soybean yield increased to 38 bushels per acre (Ash and Dohlman, 2007). The latest USDA estimate for soybean yield is 41.7 bushels per acre for the 2007 crop year (USDA, Office of the Chief Economist, 2008). The data trend shows a continuous increase in yield but there was no significant increase in other agricultural inputs. Consequently, as shown later in this report, the FER increases with crop productivity.

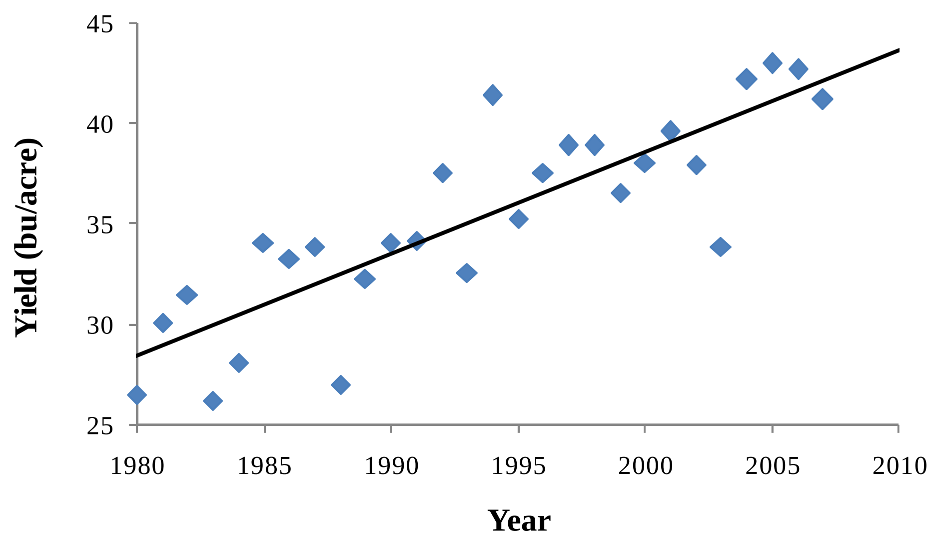

Figure 2: U.S national average soybean yield 1980-2007 and expected trend to 2010

Source: Ash and Dohlman; and USDA, Office of the Chief Economist

There have also been major changes in the soybean crushing industry that are expected to reduce the energy requirements of biodiesel. Unfortunately, the best data available to Sheehan et al. on oil crushing was based on a single plant that was 17 years old at the time of the study. Although adjustments were made to the model to modernize the plant, it is unlikely that it was a good representative of a typical crusher of the time. Thus, the typical plant in operation today is much newer than the plant modeled by Sheehan et al. For example, the oil extraction rate has increased since the Sheehan et al. study, which used 10.16 pounds per bushel (Table 79, pp 134). The oil extraction rate for crop year 2002/2003 was 11.39 pounds per bushel and increased to 11.55 lbs per bushel in crop year 2007/2008 (USDA ERS, 2009). Even though the oil extraction rate for year 2007/2008 was higher, the oil extraction rate of 2002/2003 was used in this report to be consistent with the 2002 ARMS agricultural input data. Furthermore, newer plants are more energy efficient due to the adoption of energy saving technologies that reduce production costs. Process improvement in extraction plants has continued with increasing emphasis on energy efficiency, reducing hexane loss, and increasing capacity. For instance, the current acceptable level of solvent loss is one-third the level used by U.S. extraction plants in 1970 (Woerfel, 1995).

Likewise the amount of energy required to convert soybean oil into biodiesel using transesterification may have decreased over the past decade if producers have adopted energy-saving processing equipment to minimize production costs. The rise in larger biodiesel facilities with corresponding larger energy requirements has prompted greater emphasis on minimizing energy costs. The capital cost of adding energy saving technologies would be justified if the investment cost is less than the savings from lower energy costs. For example, heat integration technologies have resulted in the capture and reuse of heat that was previously discharged. Improvements in the catalytic technology used to produce biodiesel have resulted in higher conversion efficiencies of soybean oil into biodiesel. Reclaiming and reusing the wash water stream used to purify biodiesel eliminates the need for waste water treatment.

Life Cycle GHG Emissions

The four commonly referenced studies (Sheehan et al., GREET, GHGenius and Hill et al.) were compared for the variation in the GHG savings reported by these studies. The models were carefully evaluated for (1) data credibility, (2) assumptions, (3) input consistency, (4) allocation approaches, and (5) the final conclusions. The results from the comparison were analyzed for the most sensitive inputs and assumptions to address the cause of discrepancies in the outputs reported by the referenced studies.

Results

Combining the energy input estimates from the four subsystems completes the base case life-cycle assessment for biodiesel (table 5). As discussed above the energy requirements for producing the biodiesel coproducts, i.e., soybean meal and crude glycerin have been removed from the biodiesel inventory. The energy use estimates in table 5 are adjusted by energy efficiency factors (appendix table A.1). All estimates of electricity generation were based on weighted average of all sources of power used in the United States, including coal, natural gas, nuclear, and hydroelectric. Electricity use only includes electricity generated from fossil sources, which on a natural average equals 70 percent.

Table 5: Base case energy use for biodiesel and FER adjusted for coproduct allocation and energy efficiency factors

Life-Cycle Inventory	Fossil Energy Use (BTU/gal of BD)	
	Total	Biodiesel fraction[1]
Agriculture	26,769	4,544
Soybean transport	4,291	728
Soybean crushing	23,151	3,930
Biodiesel conversion	18,772	15,467
Biodiesel transport	1,027	1,027
Total Energy Input for biodiesel adjusted for coproducts		25,696
BD Total Energy Output		117,093
Net Energy Value		91,397
Fossil Energy Ratio (FER)		4.56

[1] Coproducts are allocated as shown in figure 3.

After adjusting the inputs by energy efficiencies and allocating energy by coproducts, the total energy required to produce a gallon of biodiesel is 25,696 Btu (table 4). Biodiesel conversion uses the most energy, accounting for about 60 percent of the total energy required in the life-cycle inventory. Soybean agriculture accounts for 18 percent of the total energy requirements, followed by soybean crushing, which requires almost 15 percent of the total energy. The net energy value, i.e., biodiesel energy output, minus fossil energy input is about 91 thousand Btu per gallon. The estimated FER of biodiesel is 4.56, which is about 42 percent higher than the FER reported by Sheehan et al.

A major reason for this improvement is that the soybean crusher modeled for this study more accurately measured the energy used by a modern facility. Soybean crushing facilities that have been built in recent times are far more energy efficient than the older plant used by Sheehan et al. In addition, since 2002, EPA has required soybean plants to limit their hexane use, thus the amount of hexane reported by Sheehan et al. had to be adjusted to reflect the new industry standard (US EPA, 2001). The new hexane energy value that was used in this study is one-half of that reported by Sheehan et al. Overall, the energy required for crushing fell from 9,321 Btu to 3,930 Btu per gallon of biodiesel, about a 58 percent reduction (figure 3). The reduction in the crushing energy is primarily due to a reduction in the electricity and natural gas/steam inputs.

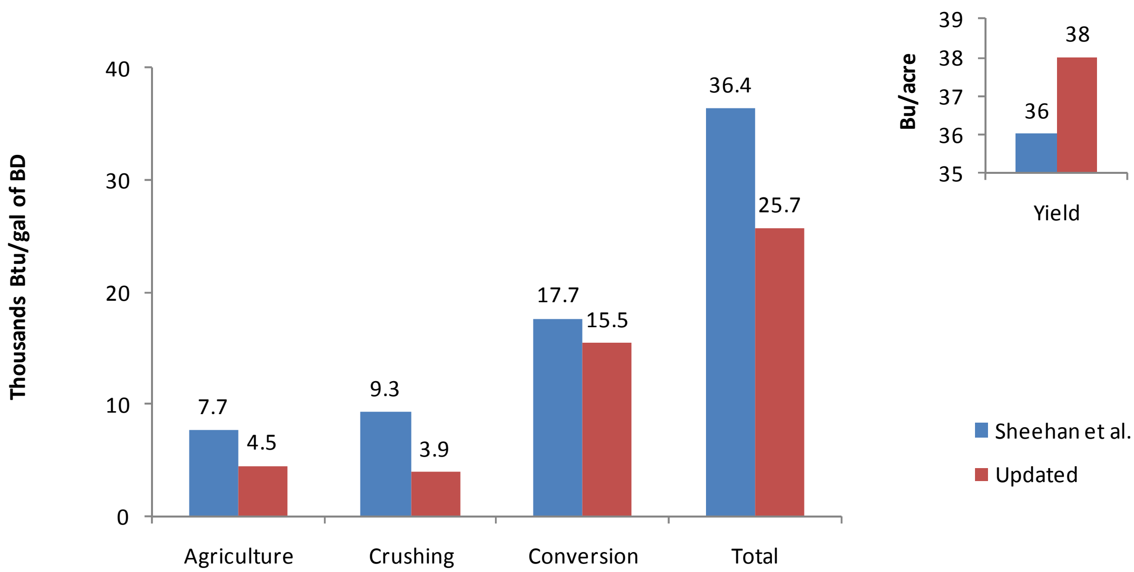

Figure 3: Comparing energy requirements for selected biodiesel subsystems and total life-cycle energy requirements between this study and Sheehan et al.

The fossil energy inputs for soybean agriculture fell from 7,681 Btu to 4,544 Btu (41 percent reduction) per gallon of biodiesel (figure 3). This reduction is primarily due to less diesel, gasoline, fertilizer and chemical usage. A likely reason for the decrease in fuel use is the increased adoption of less intensive tilling practices by soybean farmers. The lower chemical use in 2002 is partially related to the adoption of GE soybeans, however, differences in weather and other factors unrelated to energy efficiency can cause annual variation in chemical use. The energy required for transesterification estimated in this study was about 12 percent lower than the estimate reported by Sheehan et al (figure 3). The fossil energy for electricity decreased and methanol usage decreased, however natural gas and steam usage slightly increased. Overall, the total life-cycle energy required for biodiesel fell from 36,416 Btu to 25,696 Btu per gallon.

The Effects of Adding Inputs to the LCI

Figure 4 shows the effects of adding secondary energy inputs to the LCI that were not included in Sheehan et al. to determine how they affect the overall results. Hill et al. estimated the energy associated with manufacturing farm machinery to be 7,547 Btu per bushel (5,066 Btu/gal of biodiesel). Adding biodiesel share of this energy to soybean production reduces the base case FER of 4.56 to 4.41. Hill et al. also estimated the energies associated with building materials – 193 Btu per bushel (129 Btu/gal of biodiesel) for a crushing plant and 100 Btu per bushel (67 Btu/gal of biodiesel) for a biodiesel conversion plant. Adding the biodiesel share of energy related to building materials lowered the FER to 4.54. If the input energy for both agricultural machinery and building material were added to the inventory, FER would decline to 4.40, still considerably higher than the 3.2 FER reported by Sheehan et al.

The Effect of Adding Lime to the LCI

Lime use was not reported by Sheehan et al, however farmers apply lime periodically to increase soybean yield. In 2002, the average lime application for soybean production was 2 tons per treated acre (USDA, ERS b). About 52 percent of the total planted acres were treated with lime and the lime was applied on average every 5.9 years. Adjusting for the soybean planted acres and the annual rate, the lime application rate was estimated to be 358 lbs per acre per year.

Our base case LCI did not include lime in order to be consistent with the Sheehan et al. inventory that omitted lime. Lime is added to soil periodically and the annual lime application rates reported in table 1 are adjusted by average years between applications. Since farmers do not apply lime every year and some acreage never receives lime, the adjusted annual average lime application rate is relatively small. Lime use only accounts for 506 Btu per bushel of soybeans and lowers the FER by only about 0.22 percent. Therefore, including lime in the Sheehan et al, inventory would not have changed the results significantly.

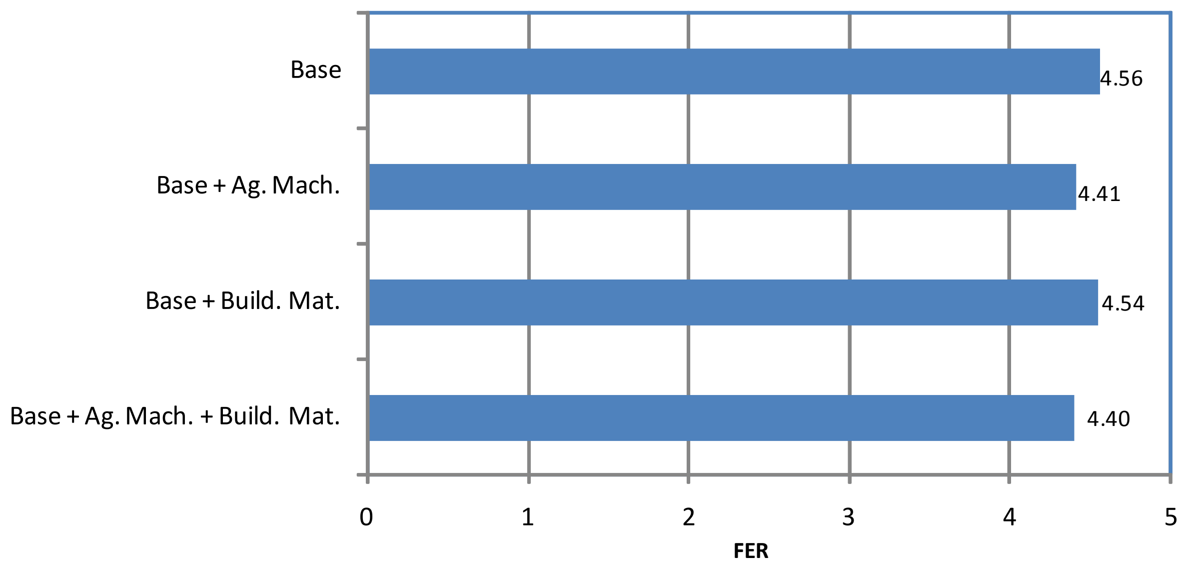

Figure 4: Effect on FER from adding the energy from secondary energy inputs to the LCI

Effect of Oil Transport

The generic biodiesel plant modeled in this study combined an oil crushing facility with a biodiesel conversion plant at the same location. Soybeans are shipped to the plant, crushed into oil that is converted to biodiesel on site; hence oil transport was not included in the baseline inventory. There are many biodiesel plants in the industry that do not have crushing capability, so they must purchase oil and have it transported to their plant. The model used by Sheehan et al. separated the crusher from the biodiesel conversion facility; so their inventory included the energy required to transport the oil to the biodiesel plant, which was 843 Btu per gallon of biodiesel for 571 miles. When adding this energy to our inventory, the FER declines to 4.41 compared to the baseline result of 4.56.

Effect of Soybean Yield

Even though yields have been higher in recent years, yield data for year 2002 was used to calculate FER in this study to correspond to the 2002 ARMS agricultural input data. Yield plays a critical role in the FER calculation because as soybean yields increase overtime, the FER of biodiesel is also expected to increase. The USDA projects soybean yield to increase annually by 0.4 to 0.5 bushel/acre through the year 2017 (USDA Office of the Chief Encomiast, 2008). For every one bushel increase in soybean yield, FER increases by about 0.45 percent. Holding all other variables constant, the FER of soybean biodiesel is estimated to reach 4.69 in the year 2015 when soybean yield is projected to increase to 45.3 bushels per acre. This is about 3 percent increase compared to the 2002 FER estimate.

Life Cycle GHG Emissions

The saving of GHG emission ranged from 40 – 78% among the models considered in the study (Table 2). The GHG contribution of soybean farming and bean transportation were found to be 22, 29 and 37% of the total GHG emissions for Sheehan et al., GHGenius and GREET models respectively. Biodiesel production accounted for 51, 67 and 61% of the total GHG emission for Sheehan et al., GHGenius and GREET models respectively. GHG emissions from the vehicle use is reported higher in Sheehan et al. which accounts for 22% of the total. GHGenius and GREET models have lower GHG emissions from combustion accounting about 4 and 2% of the total GHG emissions respectively.

The range of the outputs from the models relates to the varying system boundary, data sources, assumptions and coproduct allocation methods used by the models. The system boundary of GHGenius and Hill et al. includes inputs for manufacturing farm machinery, but Sheehan et al. and GREET does not. GREET does not include emissions from the production of seeds.

The data used for GHG emissions are inconsistent among the models. For instance, Sheehan et al. study used data from 1990 US FCRS, GHGenius and GREET used data from 2002 US average, and Hill et al. used data from 2002-2004 US averages for soybean farming inputs. Likewise, different sources were cited for the oil extraction and biodiesel conversion inputs.

Sheehan et al. and Hill et al. used mass based allocation method while GHGenius and GREET uses displacement based allocation method. Sheehan et al. allocated 18% to soybean oil and 82.4% to biodiesel; Hill et al. allocated 18% to soybean oil and 90.4% to biodiesel; GREET allocated 62.1% to soybean oil and 79% to biodiesel; and GHGenius allocated 38% to soybean oil. Even though both GHGenius and GREET models use displacement method for coproduct allocation, the process of displacement differs between two. GREET applies displacement ratio to the energy use and emissions to allocate energy between the two coproducts so that the emissions from the sum of the product and coproduct equals the total resulting from the use of the energy in the system. GHGenius calculates the coproduct emissions by subtracting the emissions from the displaced product from the total emissions.

Conclusion

The fossil energy ratio (FER) of biodiesel is 4.56 based on data from 2002 soybean production. This is a significant improvement over the 1998 Sheehan et al study that reported a FER of 3.2. A major reason for this improvement is that the soybean crusher modeled for this study more accurately measured the energy used by a modern facility. Soybean crushing facilities that have been built in recent times are far more energy efficient than the older plant used by Sheehan et al. In addition, improved soybean yields and overall less energy used on the farm helped increase the energy balance of biodiesel. When comparing the two study years (1990 and 2002) less fertilizers and pesticides were applied in the latter year. The lower chemical use in 2002 can partially be explained by the adoption of GE soybeans that resulted in reduced pesticide use. However, differences in weather and other factors unrelated to energy efficiency may have also partially been responsible for the lower farm energy estimates in 2002.

The life-cycle inventory used for this study was constructed to resemble the Sheehan et al. study in order to make comparisons between the two time periods. To be consistent with

Sheehan et al., secondary inputs such as building materials and farm machinery were not included in the base case inventory. However, the results show that the FER of biodiesel changes very little when adding secondary inputs to the life-cycle inventory. The model used to estimate the energy required to convert soybean oil into biodiesel represents a soybean processing plant combined with a transesterification unit with an annual capacity of 9.8 million gallons per year. Although plants under 10 million gallons are quite common, there has been a recent trend in the industry towards larger plants. Larger plants with more capital investment would be expected to be more energy efficient.

The results from this research suggest that the FER of biodiesel will continue to improve overtime. This improvement will occur because increases in soybean yields are expected to continue and for every one bushel per acre increase in soybean yield, the FER increases by 0.45 percent. In addition, the agricultural sector, along with the biodiesel industry will likely continue to make energy efficiency gains in order to lower production costs. In the future, as the United States develops its renewable energy resources, more non-fossil energy will be included in the biodiesel life-cycle inventory, for example, more electricity may be generated from biomass, wind, and solar power and more farm equipment may use biofuels. Replacing fossil energy with renewable energy over the life cycle could also significantly increase the energy balance of biodiesel overtime.

The reduction in GHG emissions reported by different models (Sheehan et al., GHGenius, GREET, and Hill et al.) varied in the range 40 – 78%. A deeper look at these models revealed that the models varied by system boundary, data citations, assumptions, and the coproduct allocations. All models reported a positive reduction in GHG emission compared to the petroleum fuel.

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Appendix A.

Table A.1 -- Life cycle energy efficiency factors for fossil fuels and electricity

Inputs	Life Cycle Efficiency percent
Diesel	84.3
Gasoline	80.5
LP Gas	89.8
Natural Gas	94.0
Steam	60.8
Electricity	31.3
Methanol	67.7

Source: Shapouri et al., 2002 except for Electricity (EIA, 2007), Steam (USDA ARS, 2008) and Methanol (Wang and Huang, 1999)

Table A.2 – Energy Coefficients used to convert inputs into British thermal units (Btu).

Inputs	Energy Value	Sources
Fuel Inputs	**Low heating value**	
Diesel (Btu/gal)	128,450	Huo et al.
Gasoline (Btu/gal)	116,090	Huo et al.
LP Gas (Btu/gal)	84,950	Huo et al.
Natural Gas (Btu/cft)	983	Huo et al.
Electricity (Btu/kWh)	3,412	Huo et al.
Material Inputs		
Nitrogen (Btu/lb)	22,147	Hill et al
Phosphorus (Btu/lb)	3,946	Hill et al.
Potassium (Btu/lb)	2,565	Hill et al.
Lime (Btu/lb)	53.72	Graboski
Seeds (Btu/lb)	1,954	Sheehan et al.
Herbicide (Btu/lb)	137,263	Hill et al.
Insecticide (Btu/lb)	139,845	Hill et al.

Methanol (Btu/lb)	9,750	American Methanol Institute