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

An ASABE Meeting Presentation

Paper Number: 084976

An Update on Energy Balance of Soybean Biodiesel Production

Anup Pradhan, Graduate Student

Dev Shrestha, Assistant Professor

James Duffield, OCE – USDA

Hosein Shapouri, OCE – USDA

Michael Haas, ARS - USDA

Andrew McAloon, ARS - USDA

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

Written for presentation at the
2008 ASABE Annual International Meeting
Sponsored by ASABE
Rhode Island Convention Center
Providence, Rhode Island
June 29 – July 2, 2008

Abstract.

Keywords. Soybean, Biodiesel, Energy Balance, Fossil Energy Ratio, Renewability.

Introduction

In 1998 the first comprehensive life cycle inventory for biodiesel produced in the United States from soybean oil was completed (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 study developed a broad-based inventory that included energy use, greenhouse gases, and other air emissions. In addition, a full life-cycle inventory was constructed for petroleum diesel to compare the energy requirements and environmental costs of petroleum diesel versus biodiesel. Other biodiesel studies have been done since Sheehan et al., but none have matched the detailed information or collaborative effort used to produce the original report.

One of the most often cited result from Sheehan et al. is that the fossil energy ratio (or energy balance) 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 0.83 units of energy per unit of fossil energy consumed. The purpose of the following analysis is to update the energy life-cycle of the 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 the life-cycle energy use.

Methodology

Much of the attention directed toward renewable fuels, such as biodiesel, is focused on the perception that they have superior environmental properties compared to their petroleum fuel counterparts (EPA ,2002; Knothe et al. 2005). In addition, developing renewable fuels is desirable because they are derived from sustainable sources of energy, whereas petroleum fuels come from oil, a finite resource that is rapidly being depleted. However, the production of renewable fuels generally involves a significant amount of fossil energy, e.g., petroleum 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 petroleum fuel used for its production.

It is beneficial to know the renewability of a biofuel for two reasons. First, it is useful to know how much a biofuel relies on petroleum energy for its production -- the less a biofuel depends on petroleum energy, the larger contribution it can make to increase and diversify our total fuel supply. Secondly, the renewability of different biofuels can be compared by policymakers and others to determine which biofuels are the most productive in terms of reducing our dependence on petroleum energy.

The Fossil Energy Ratio (FER) of a biofuel is one indication of its renewability. A biofuel's FER is defined as the ratio of the energy output of the final biofuel product to the fossil energy required to produce the biofuel. FER is expressed as:

$$\mathrm{FER} = \frac{\text{Renewable Fuel Energy Output}}{\text{Fossil Energy Input}} \tag{1}$$

Estimating FER begins with defining the entire production system of biodiesel, which includes four subsystems: feedstock production, feedstock transportation, 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 resources used in the system are adjusted by energy efficiency coefficients to take into account the energy used to convert fossil resources into usable energy. These coefficients include the energy required to mine, extract, and manufacture the raw energy materials into the final energy product. Estimates of electricity generation are based on the weighted average of all sources of power, including coal, natural gas, nuclear, and hydroelectric. The electricity used in the system is increased to account for production and transmission loss factor. The overall efficiency of electricity production in the US electricity production increased from 32% as reported in NREL report to 35.28% in 2006 (EIA, 2007). Including the transmission efficiency of 91% (Which was not included in NREL report), the energy used in biodiesel production was multiplied by factor of 3.1 to account for general and distribution losses.

Hexane extraction method is commonly used to extract oil from soybean seed. The most common method used for converting soybean oil into biodiesel is called transesterification, which was the conversion method modeled by Sheehan et al, and also used in this study. 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. In general, no allocation rule is always applicable and the appropriate method should be chosen on a case-by-case basis. For more discussion on allocation rules see Shapouri et al. (2002). The Sheehan et al. study used a mass based allocation method. This method is commonly used because it's 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. In order to provide a consistent comparison of the original Sheehan study, this study also used the mass based allocation method. This allocation rule separates the energy used to produce the soybean oil and biodiesel from the energy used to produce the soybean meal and glycerin respectively in the following manner:

$$\text{Fossil Energy Input} = \mathrm{E}_1 f_1 + E_2 f_2 + E_3 f_3 \tag{2}$$

where E_1 is energy input for agriculture/bean transport, f_1 is mass fraction of oil of harvested crop; E_2 is energy input for oil extraction/oil transport, f_2 is mass fraction of oil production; and E_3 is energy input for transesterification/biodiesel transport and f_3 is biodiesel fraction of the final product.

Over the past several years, the energy balance of soybean biodiesel has been reported by different researchers with considerable variation in results. To better understand the causes behind these differences, Pradhan et al. (2008) compared four different studies that estimated the net energy ratio of biodiesel. They found that the diversity in results among the studies was caused by data differences, conflicting system boundaries, the treatment of labor as an energy input, and differences in energy ratio definitions. By far the largest cause for the contradicting results reported was due to the difference in the method used to allocate the energy between biodiesel and its meal co-product.

Data Description and Trends

At the time of the Sheehan et al. study, the most recent detailed data available on soybean production was from USDA's 1990 Agricultural Resource Management Survey (ARMS). The

ARMS (formerly called the Farm Costs and Returns Survey, FCRS) is conducted annually, but to reduce survey costs, USDA does not undertake detailed surveys of every commodity each year. Thus, the ARMS covers a major commodity in detail about every 4 years, with the most recent survey on soybeans occurring in 2002. The ARMS soybean survey only covers major soybean producing states and detailed data is only reported for a selected number of these states. In 1990, state-level estimates were available for fourteen states and the 2002 soybean survey provided detailed state-level data on 20 states. These 20 states are responsible for 98% of the soybean production. The sample size of this state-level data is large enough to provide statistical reliable estimates to represent state averages, but not national averages. The Department of Agriculture uses other versions of the ARMS to gather annual data for national soybean production estimates but they are limited compared to the ARMS soybean survey, which is the only USDA source that provides detailed data on machinery and fuel use.

To stay competitive, U.S. Farmers are continually looking for ways to minimize their input costs and increase productivity. Therefore, the 2002 ARMS soybean data would be expected to reflect some changes in soybean production practices (table 1). The most significant change in U.S. soybean production since 1990 is the use of genetically engineered (GE) soybeans, which have had a major effect on pesticide use. 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 (ERS, 2007). Genetically engineered soybeans with herbicide tolerant and pest management traits increase yields through improved weed and pest control. Using GE soybeans also reduces pesticide use and costs (Heimlich et al., 2000)**Error! Hyperlink reference not valid.**. The fact can also be seen if we compare the average pesticide use over 5 year period from 1990 to 1994 versus 2000 to 2004. The five year average herbicide use from 1990 to 1994 was 1.18 lb/acre/year compared to 1.09 lb/acre/year in year 2000 to 2004. However this decrease in herbicide use may not be realized from year to year comparison as the national pesticide use may vary from year to year depending on the level of infestation. For instance, pesticide application rate was higher for year 2005 and 2006 (figure 1b) mostly because of higher aphid infestation (Thorson, 2008). Moreover, most of the herbicide used in soybean is now in the form of glyphosate which is about 10 times less toxic and more environmentally friendly than traditional herbicide such as Alachlor. A measure of toxicity level of a pesticide is its oral Reference Dose (RfD) established by EPA. Reference dose (RfD) is an estimate of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. RfD for Glyphosate is 0.1 mg/day/kg (EPA 1981) which is ten times higher than 0.01 mg/day/kg for alachlor (EPA 1984). Alachlor was a major herbicide used in year 1990 when in year 2006, 89% of the herbicide used was Glyphosate based.

Table 1: 2002 Soybean Agriculture System Inputs

Item		**Unit**	**20 States* Weighted Average**
Seed[1]		lbs/acre	72.08
Fertilizer:			
	Nitrogen	lbs/acre	4.26
	Phosphorus	lbs/acre	12.65
	Potash	lbs/acre	25.52
Energy:			
	Diesel	gal/acre	4.06
	Gasoline	gal/acre	1.26
	LP	gal/acre	0.73
	Electricity	kWh/acre	6.62
	Natural Gas	C.F/acre	58.41
Ag. Chemical Application:			
	Herbicides	lbs/acre	1.210
	Insecticides	lbs/acre	0.015
	Lime[2]	lbs/acre/yr	758.81
Yield		bu/acre	38.0

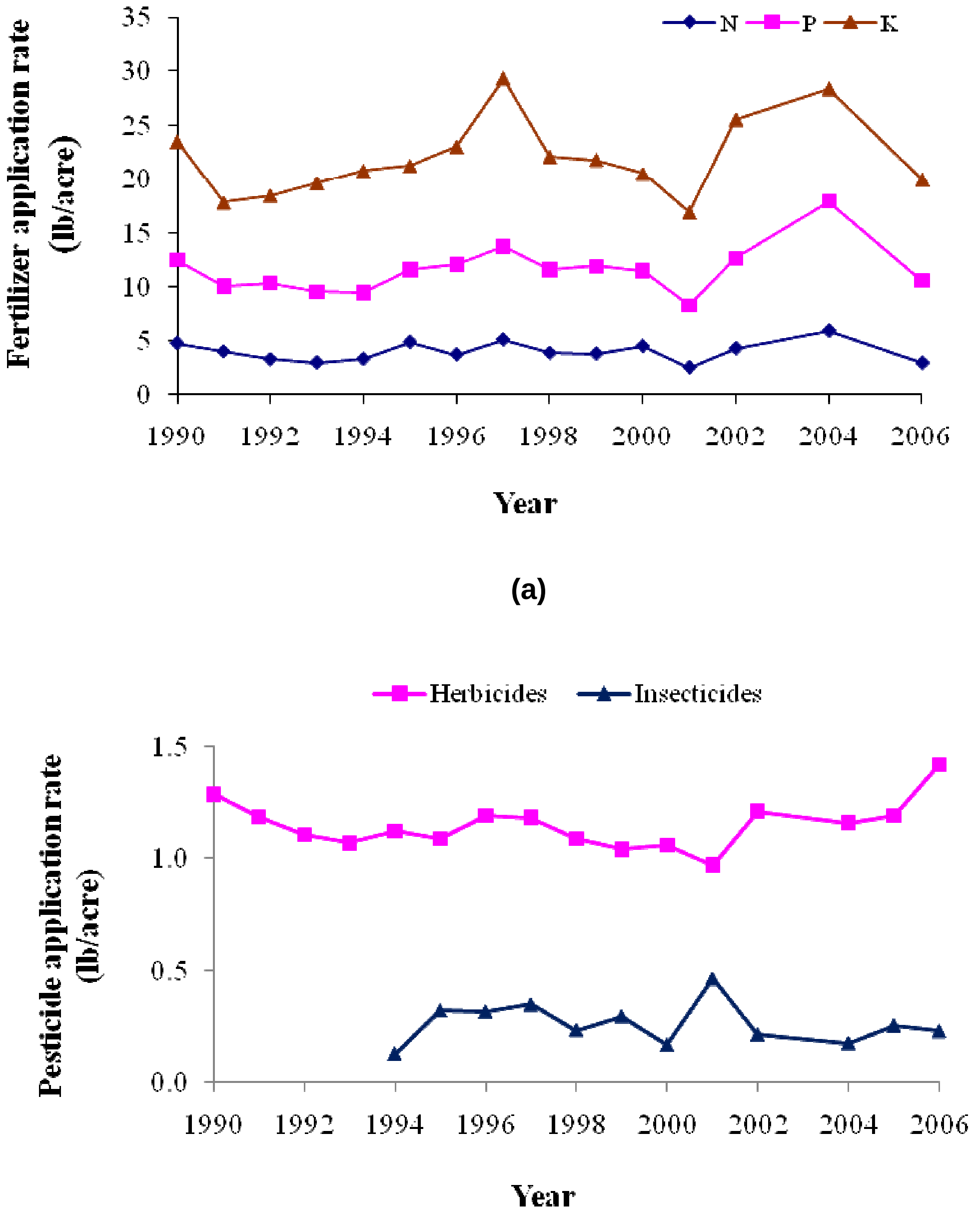
*20 States include AR, IL, IN, IA, KS, KY, LA, MD, MI, MN, MS, MO, NE, NC, ND, OH, SD, TN, VA and WI

[1] Seed average is national average from FAO database

[2] Lime data is made available by Payne, 2006

Source: NASS, USDA

The annual ARMS data shows that the amount of fertilizers and pesticides applied on total soybean acreage varied from year to year (figure 1). The fertilizer usage patterns per acre follows a similar time trend for each fertilizer type. Insecticides were applied in less than one percent of the total acreage during 1990 – 1993, hence the insecticides application rates during this period are omitted in the chart. The total number of states used to estimate the weighted average of the fertilizer and pesticide application rates varied year to year, the lowest being 8 states in the year 2001 and the highest of 29 states in the year 1990.



(a)

(b)

Fig 1: Trend of (a) fertilizer application rate; (b) pesticides application rate for soybean farming (Source: NASS, 2008)

Soybean yields also have been increasing over time because of new seed varieties, improved fertilizer and pesticide applications, and new management practices (Ash et al., 2006). The ARMS data shows a significant increase in soybean yield since 1990 -- soybean yields have increased steadily since 1990 when the U.S. average yield was 34.1 bushels per acre. By 2002, U.S. soybean yield increased to 38 bushels per acre and in 2006 USDA reported an average yield of 42.7 bushels per acre (figure 2).

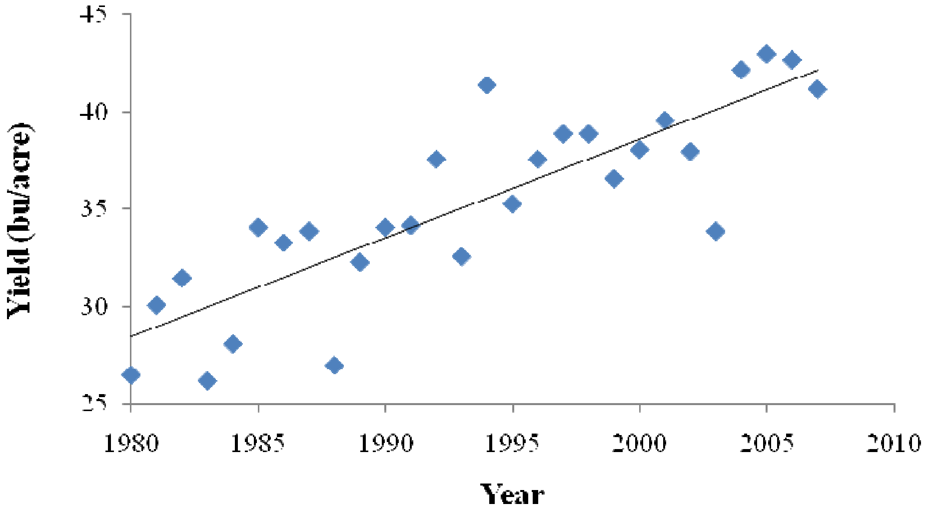


Fig 2: US national average soybean yield (1980-2006)
Source: NASS (2008)

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's 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. Furthermore, these 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, cost reduction, reducing hexane loss, quality of meal and oil, and increased capacity. For instance, the current acceptable level of solvent loss is one-third of 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 the transesterification has decreased over the past decade because producers have adopted energy-saving processing equipment to minimize production costs. The rise of larger biodiesel facilities with corresponding larger energy requirements has prompted greater emphasis on minimizing energy costs. The capital cost of adding energy saving technologies is more than offset by the reduction in 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 has eliminated the need for waste water treatment.

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, biodiesel conversion, and product distribution.

Feedstock Production

The farm input data for soybean production was obtained from several sources, including the Economic Research Service (ERS) of USDA, the Food and Agriculture Organization (FAO) and USDA's National Agricultural Statistics Service (NASS). NASS's Agricultural Resource Management Survey (ARMS) last conducted the soybean survey in 2002, which is the source of the energy data shown in table 1. The ARMS soybean survey only covers major soybean producing states, however, the 20 states covered by the survey accounts for about 98 percent of the U.S. soybean production in 2002. The state yield data and the fertilizer data for soybeans are also from NASS. The herbicide and insecticide use data are from NASS's agricultural chemical survey. The lime application rates are from Payne (2006). The seed application rate shown in table 1 is a U.S. national average from the Food and Agricultural Organization (FAO, 2007)

The farm input data in table 1 were weighted by state production to derive average energy used for U.S. soybean production. The weighted average soybean yield for the state data equaled 38 bushels per acre in year 2002 (table 1). 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. The direct energy inputs were converted to British thermal units (BTU) using low-energy heat values (table 2). It was assumed that electricity generation came from a combination of coal, natural gas, nuclear, and hydropower at the same proportion as national average. The energy equivalents of hexane and methanol used in NREL study differ significantly than those used in this study from new results. Hexane energy used in NREL study is one-half and methanol energy is twice than the updated values considered in this study.

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 (table 1). The fuel required to haul soybeans to a local biodiesel plant or distribution center is also included. The estimates in table 1 do not include the energy used to mine, extract, and manufacture the raw materials into the final energy product. The sum of these energy values must be added to the values in table 1 to estimate the total energy associated with each farm input required to produce a bushel of soybeans. This final calculation will be performed in the result section.

Table 2: British thermal units (BTU) equivalent of energy inputs

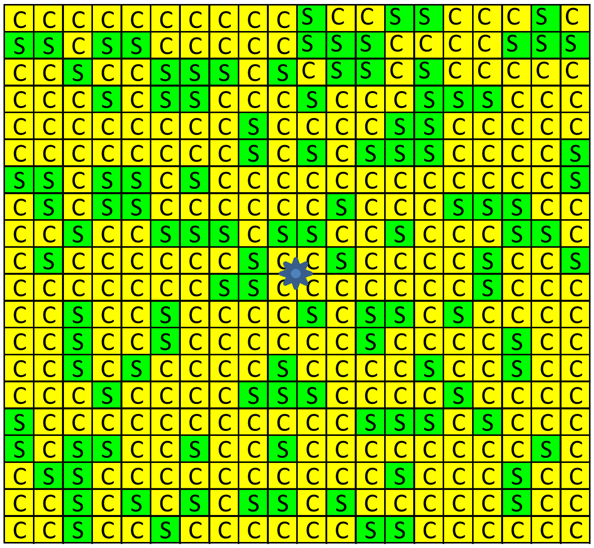
Inputs	**NREL Study**	**This Study**	
		Energy	**Sources**
Diesel (BTU/gal)	131,295	128,450	Huo et al. (2008)
Gasoline (BTU/gal)	115,500	116,090	Huo et al. (2008)
LP Gas (BTU/gal)	90,387	84,950	Huo et al. (2008)
Natural Gas (BTU/cft)	996	983	Huo et al. (2008)
Nitrogen (BTU/lb)	31,033	22,147	Hill et al. (2006)
Phosphorus (BTU/lb)	6,303	3,946	Hill et al. (2006)
Potassium (BTU/lb)	2,200	2,565	Hill et al. (2006)
Lime (BTU/lb)	-	53.72	Graboski (2002)
Seeds (BTU/lb)	1,954	1,954	NREL (1998)
Herbicide (BTU/lb)	137,146	137,263	Hill et al. (2006)

Insecticide (BTU/lb)	137,146	139,845	Hill et al. (2006)
Electricity (BTU/kWh)	3,412	3,412	Huo et al. (2008)
Hexane (BTU/lb)	9,845	19,230	Chevron (2006)
Methanol (BTU/lb)	17,283	9,768	Elert (2008)

Estimating Energy for Transporting Soybeans to Biodiesel Plant

Based on the rectilinear transportation system developed as the grid plan for the physical development of US cities, it is more realistic to assume the biodiesel plants to be located at the center of a square field. Assuming a regular corn-corn-soybean crop rotation only one third of the field will be planted with soybean on any given year.

The theoretical minimum distance to supply soybeans for a 100 million gallon/year oil production plant located at the center of a square grid assuming only one third of the area planted with soybean at random is about 48 miles with average yield (38 bu/ac) and oil content (18% oil). The theoretical minimum distance for soybean transport increased to 152 miles when estimated for a 1000 million gallon oil production plant. Individual field size is not relevant to this calculation.



C	C	C	C	C	C	C	C	C	C	S	C	C	S	S	C	C	C	S	C
S	S	C	S	S	C	C	C	C	C	S	S	S	C	C	C	C	S	S	S
C	C	S	C	C	S	S	S	C	S	C	S	S	C	S	C	C	C	C	C
C	C	C	S	C	S	S	C	C	C	S	C	C	C	S	S	S	C	C	C
C	C	C	C	C	C	C	C	S	C	C	C	C	S	S	C	C	C	C	C
C	C	C	C	C	C	C	C	S	C	S	C	S	S	S	C	C	C	C	S
S	S	C	S	S	C	S	C	C	C	C	C	C	C	C	C	C	C	C	S
C	S	C	S	S	C	C	C	C	C	C	S	C	C	C	S	S	S	C	C
C	C	S	C	C	S	S	S	C	S	S	C	C	S	C	C	C	S	S	C
C	S	C	C	C	C	C	C	S	C	C	S	C	C	C	C	S	C	C	S
C	C	C	C	C	C	C	S	S	C	C	C	C	C	C	C	S	C	C	C
C	C	S	C	C	S	C	C	C	C	S	C	S	S	C	S	C	C	C	C
C	C	S	C	C	S	C	C	C	C	C	C	S	C	C	C	C	S	C	C
C	C	S	C	S	C	C	C	C	S	C	C	C	C	S	C	C	S	C	C
C	C	C	S	C	C	C	C	S	S	S	C	C	C	C	S	C	C	C	C
S	C	C	C	C	C	C	C	C	C	C	C	S	S	S	C	S	C	C	C
S	C	S	S	C	C	S	C	C	S	C	C	C	C	C	C	C	C	S	C
C	S	S	C	C	C	C	C	C	C	C	C	C	S	C	C	C	S	C	C
C	C	S	C	S	C	S	C	S	S	C	S	C	C	C	C	C	S	C	C
C	C	S	C	C	S	C	C	C	C	C	C	S	S	C	C	C	C	C	C

Figure 3: A hypothetical farm area with corn-corn-soybean rotation. Soybean acres denoted by letter "S" are randomly distributed to 1/3rd of the planted acres. The crushing plant is assumed to be located at the middle of the field.

Argonne National Laboratory (2006) estimated the energy involved in soybean transportation using GREET model. The energy required in transporting soybeans from farms to processing plants was estimated to be 213,927 BTU/ton. The estimation was based on the total distance of 800 miles and the modes of transportation used were barge, truck, and rails. Since this distance is adequately larger to account for much larger than 1000 million gallon/year production plants, the value from GREET model was used for this transportation calculation.

Estimating Energy for Oil Crushing and Biodiesel Conversion

The production of biodiesel from soybeans occurs in two stages; the soybeans are first treated to remove the oil and then the soybean oil is converted into biodiesel. The first stage, the removal of the oil from the soybean is often called crushing and the most common method used to convert the oil into biodiesel is a process known as transesterification.

Oil Extraction from Soybeans

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 soybean using the chemical process hexane extraction (figure 4). Soybeans are cleaned, dried to a required moisture level, tempered and then typically cracked and the hulls removed. The hulls may then be further treated by heating (toasting) and grinding and are either sold as soybean hulls or blended with the soybean meal that is later extracted in the process. The dehulled beans are then conditioned and flaked prior to hexane extraction where the beans are mixed with hexane, a solvent which separates the oil from the remaining portion of the bean (figure 4). The oil and hexane mixture are treated in a recovery system where the hexane is removed and recycled for additional processing. The crude soybean oil is degummed and may be deodorized, bleached and neutralized. The oil depleted beans are then treated to remove any remaining solvent, dried, cooled , ground and sometimes mixed with the soybean hulls to produce soybean meal, an important livestock feed (figure 4).

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. Soybeans entering the process are first dried to obtain a 10% moisture content (Erickson, 1995). Then the beans are processed thru mechanical rolls to loosen the hulls which are then heated in a hull toaster. The hulls are ground and mixed with the soybean meal or they may be sold as a separate product. The dehulled beans are conditioned by heating, cut into flakes and fed to the oil extraction unit where the oil in the beans are dissolved with hexane. Steam is then introduced into the system to separate the hexane from the oil. Hot air and cooling water are used in the final heating and drying of the oil. The oil depleted, dried soybean meal from the extraction process is then ground to a uniform size and in some cases blended with the soybean hulls to produce soybean meal.

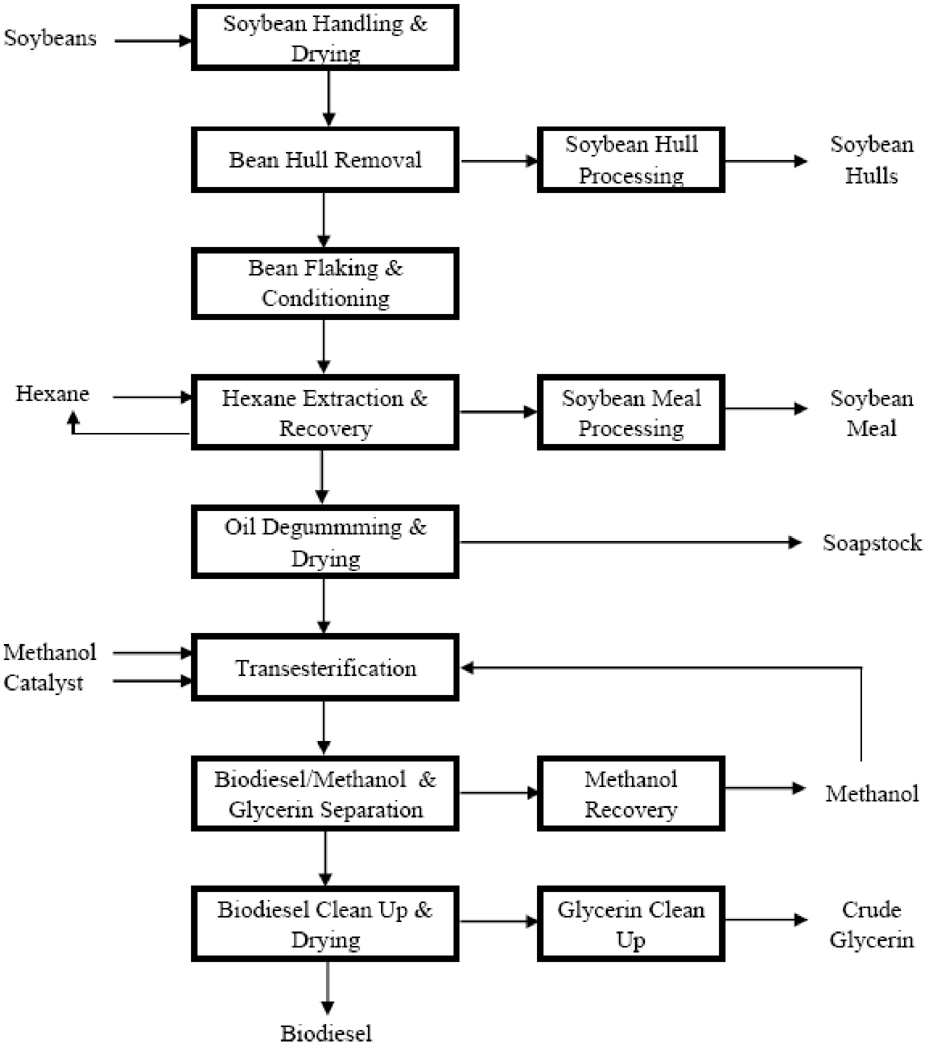


Figure 4. Soybeans to biodiesel conversion process

Conversion of Soybean Oil into Biodiesel

The conversion of soybean oil into biodiesel is done by reacting the oil with an alcohol, usually methanol, and a catalyst, normally sodium hydroxide in large reactors. After the soyoil, 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 water and dried to become biodiesel (figure 4). The stream of methanol, glycerin and other impurities are then treated with a small amount of acids and bases to remove any remaining fatty acids. The remaining material is then distilled to recover the methanol and most of the water. The excess methanol and water are recovered and reused to avoid waste and reduce input costs. The crude glycerin is often sold to companies that refine the glycerin so it can be used in the production of a variety of other products, including fiber glass resin, cosmetics, pharmaceuticals, liquid laundry detergents, soaps, deicers, and antifreeze. 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 soyoil to accelerate the conversion process.

Soy Oil Transportation

Most of the biodiesel plants have oil extraction and biodiesel conversion facilities co-located together, which saves the energy spent in transporting oil. The energy involved in transporting soy oil is hence excluded in this study. This is a reasonable assumption as larger oil cruising plants are now also making biodiesel at the crushing location such as Cargill and Bunge in Midwest.

Biodiesel Production Model

The energy requirements for soybean crushing and transesterification were estimated using technical models utilizing chemical process engineering and cost engineering technology that were developed by USDA's Agricultural Research Service (table 3). These models measure 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 combined total thermal and electric energy required for preparing the soybeans, extracting the oil from the beans, and drying the soybean meal requires 17,272 British thermal units (BTU) per gallon of biodiesel. The conversion of the soybean oil into biodiesel, the recovery of the excess methanol and the treatment of the biodiesel coproducts requires another 5,449 BTU's per gallon of biodiesel.

Table 3: Soybean oil crushing and biodiesel conversion inputs

Inputs	Units	Amount
Oil crushing:		
Electricity	kWh/gal of BD	0.8023
NG	BTU/gal of BD	14,532
Biodiesel conversion:		
Electricity	kWh/gal of BD	0.1286
Steam	BTU/gal of BD	5,029

Source: ARS, USDA (2007)

Biodiesel Transport

In GREET model, the energy required in transporting and distributing biodiesel was estimated to be 8,768 BTU/mmBTU of biodiesel. The estimation was based on the total distance of 1,750 miles and the modes of transportation used were barge, truck, and rails. (Biodiesel plants are being contacted to get more realistic data. We are waiting for the response.)

Calculating Energy Coproduct Values

The two coproducts, soybean meal and crude glycerin, produced during the production of biodiesel needs to be excluded from the inventory. Several allocation methods can be used to estimate the energy value of coproducts; the appropriate method is chosen on case-by-case basis. The most commonly used methods are the displacement method and the allocation method. The Sheehan et al. study used a mass based allocation method, which simply allocates energy to the various coproducts by their relative weights. In order to provide a consistent comparison of the original Sheehan et al.'s study, this study also used the mass based allocation method. In mass based allocation method, energy contents of the primary product and coproducts are used to split the energy input.

Results

Combining the energy input estimates from the four subsystems completes the life-cycle inventory for biodiesel (table 4). 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. In addition, estimates in table 4 also include the energy used to mine, extract, and manufacture the raw materials used to produce the final energy product. The sum of these energy values was included in the estimates to derive the total energy associated with each farm input required to produce a bushel of soybeans. Input efficiencies for fossil energy sources which were estimated with Argonne's GREET model were used to calculate these additional energy input values. In particular, GREET estimated the energy efficiency of gasoline at 80.5 percent; 84.3 percent for diesel fuel; 89.8 percent for LPG; 94.0 percent for natural gas; and 98.0 percent for coal (Shapouri et al., 2002). Boiler efficiency of 80 percent was used for the steam production (Ahmed et al., 1994) and the conversion efficiency of 70 percent was used for methanol production from natural gas (Kiso and Arashi, 1998). 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. The electricity used in the system is increased to account for general and distribution loss by a factor of 3.1.

After adjusting the inputs by these energy efficiencies, the total energy required to produce a bushel soybeans in 2002 was 39,980 BTU (table 4). The total energy required for soybean transport equaled 6,418 BTU, the crushing and conversion steps required 61,281 BTU. The fossil energy ratio, i.e., the ratio of the energy output of biodiesel 163,149 BTU, to the total fossil energy required to produce the biofuel 41,823 BTU was equal to 3.90.

Table 4: Energy balance with 2002 agriculture data

Inputs		Energy Use[1] (BTU/acre)	Sources
Agriculture	Diesel	618,632	ERS/ USDA (2003)
	Gasoline	181,706	ERS/ USDA (2003)
	LP Gas	69,057	ERS/ USDA (2003)
	Natural Gas	61,082	ERS/ USDA (2003)
	Nitrogen	94,346	NASS/USDA (2003)
	Phosphorus	49,917	NASS/USDA (2003)
	Potassium	65,459	NASS/USDA (2003)
	Seeds	140,844	FAO (2003)
	Herbicide	166,088	NASS/USDA (2003)
	Insecticide	2,098	NASS/USDA (2003)
	Electricity	70,021	ERS/ USDA (2003)
	Sub Total	1,519,251	
Soybean transport		243,877	ANL (2006)
Crushing	Hexane	82,000	Huo et al. (2008)
	Electricity	432,487	ARS/USDA (2007)
	NG	787,885	ARS/USDA (2007)

	Sub total	1,302,371	
Conversion	Electricity	693,23	ARS/USDA (2007)
	Steam	320,374	ARS/USDA (2007)
	Methanol	522,520	Huo et al. (2008)
	Sodium Methoxide	3,741	ANL (2006)
	Sodium Hydroxide	98,382	ANL (2006)
	Hydrochloric Acid	11,971	ANL (2006)
	Sub total	1,026,310	
Biodiesel transport		52,479	ANL (2006)
Total Energy Input[2]		1,589,257	
BD Energy Output		6,199,675	
Energy Ratio		3.90	

[1] Energy use indicates the final energy use after adjustment for energy efficiencies and losses.

[2] Coproducts are allocated as: soy meal = 80% and glycerin = 10%.

Sensitivity Analysis

Lime use energy was not included in the original Sheehan et al. report. The addition of 2002 lime use data to the soybean agriculture in the analysis slightly decreased the FER to 3.88.

Hill et al. (2006) estimated the energy associated with manufacturing machinery to be 404,702 BTU/acre. Including this energy to the analysis in table 4 resulted in the FER of 3.71. The impact of adding machinery energy on FER is 4.87 percent. Hill et al. also estimated the energies associated with the building materials (7,515 BTU/acre for crushing plant and 3,904 BTU/acre for biodiesel conversion plant). The addition of building energies to the analysis resulted in the FER of 3.89 and hence showed no impact on FER.

Conclusion

The renewability factor was averaged to be around 3.90 using 2002 data. The energy use for growing soybean and extracting oil were observed to be reduced by 48% and 57% respectively. Reduction in pesticide energy (67.5%), fertilizer energy (64%) and fossil fuel energy (42%) contributed to the energy reduction observed in the soybean farming. The reduction in the electricity (45%) and natural gas energy (28%) contributed in the reduction of total oil crushing energy.

The addition of lime use energy in the soybean farming has no significant effect on FER. Likewise, no significant effect was observed for adding energy associated with building materials. However, addition of machinery use energy reduced FER by 5%.

Increase in soybean yield and improvements in the biodiesel process technology have reduced the total energy consumption which in turn has increased the FER.

References

Ahmed, I., J. Decker, and D. Morris. 1994. How much energy does it take to make a gallon of soydiesel? Jefferson City, Mo.: National Soydiesel Development Board.

Argonne National Laboratory. 2006. The greenhouse gases, regulated emissions, and energy use in transportation (GREET) model. Version 1.6. Argonne, Ill.: Argonne National Laboratory. Available at: www.transportation.anl.gov/software/GREET/.

Ash, M., J. Livezey and E. Dohlman. 2006. Soybean backgrounder. ERS, USDA. OCS-2006-01. Available at: http://www.ers.usda.gov/publications/OCS/apr06/OCS200601/OCS200601_lowres.pdf. Accessed on: 05.28.08.

Chevron. 2006. Aviation fuels technical review. Available at: http://www.chevron.com/products/ourfuels/prodserv/fuels/documents/aviation_fuels.pdf. Accessed on: 06.04.08.

EIA. 2007. Electricity flow, 2006. Annual energy review, 2006. DOE/EIA-0384(2006). Energy Information Administration, U.S. Department of Energy. Available at: http://www.eia.doe.gov/emeu/aer/pdf/pages/sec8_3.pdf. Accessed on: 05.21.08.

Elert, G. 2008. Chemical potential energy. The physics hypertextbook. Available at: http://hypertextbook.com/physics/matter/energy-chemical/. Accessed on: 06.04.08.

EPA. 2002. A comprehensive analysis of biodiesel impacts on exhaust emissions. Report no. EPA420-P-02-001

Erickson, D R. 1995. Overview of modern soybean processing and link between processes. In Practical handbook of soybean processing and utilization, 56-64.Erickson, D. R. ed. Champaign,IL: AOCS Press and United Soybean Board.

ERS. 2007. Agricultural biotechnology: Adoption of biotechnology and its production impacts. Economic Research Service, USDA. Available at: http://www.ers.usda.gov/Briefing/biotechnology/chapter1.htm. Accessed on: 05.28.08

FAO. 2007. FAOStat. Available at: http://faostat.fao.org/site/408/default.aspx.

Graboski, M. 2002. Fossil energy use in the manufacture of corn ethanol. Prepared for National Corn Growers Association. Available at: http://www.ncga.com/ethanol/pdfs/energy_balance_report_final_R1.PDF. Accessed on: 06.04.08.

Heimlich, R. E., Cornejo, F., McBride, W., Klotz-Ingram, C., J. Sharon and N. Brooks. 2000. Changing pesticide use: Impact also matters. Agricultural Outlook, AGO-273/August 2000. Economic Research Service, USDA. Available at: http://usda.mannlib.cornell.edu/reports/erssor/economics/ao-bb/2000/ao273.pdf. Accessed on: 05.28.08.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tifanny. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNSS. 103(30): 11206-11210.

Huo, H., Wang, M., C. Bloyd and V. Putsche. 2008. Life-cycle assessment of energy and greenhouse gas effects of soybean-derived biodiesel and renewable fuels. USDA, Office of Energy Efficiency and Renewable Energy. ANL/ESD/08-2.

Kiso, F. and N. Arashi. 1998. Hybrid methanol-production process. Applied Energy, Vol. 59, pp. 215-228.

Knothe, G, J. H. Van Gerpen, and J. Krahl. 2005. The biodiesel handbook. Champaign, Ill: AOCS Press.

NASS. 2003. Agricultural chemical usage: 2003 field crops summary. National Agricultural Statistics Service, USDA, May 2003.

NASS. 2008. National Agricultural Statistics Field Crop Data. Available at www.nass.gov. Accessed on 6/15/2008.

Payne, 2006. Nutrient use and practices on Soybeans, major producing states. USDA.

Pimentel, D., and T. W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Natural Resources Res. 14(1): 65-76.

Pradhan, A., Shrestha, D. S., J. V. Gerpen, and J. Duffield. 2008. The energy balance of soybean oil biodiesel production: a review of past studies. Transactions of the ASABE. 51(1): 185-194.

Shapouri, H., J. A. Duffield and M. Wang. 2002. The energy balance of corn ethanol: An update. Agricultural Economic Report No. 813, USDA.

Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri. 1998. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. NREL/SR-580-24089 Golden, CO: National Renewable Energy Laboratory. U.S. Department of Energy.

Thorson, T. 2008. Personal communication. National Agricultural Statistics Service – U.S. Department of Agriculture.

Vigon, B. W., Tolle, D. A., Cornaby, B. W., Latham, H. C., Harrison, C. L., Boguski, T. L., R. G. Hunt and J. D. Sellers. 1993. Life cycle assessment: Inventory guidelines and principles. Washington D.C. & Cincinnati: United States Environmental Protection Agency, Office of Research and Development. (EPA/600/R-92/245).

Woerfel, J. B. 1995. Extraction. In Practical handbook of soybean processing and utilization, 65-92.Erickson, D. R. ed. Champaign,IL: AOCS Press and United Soybean Board.