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Energy Life-Cycle Assessment of Soybean Biodiesel

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Summary

The first comprehensive life-cycle inventory (LCI) for biodiesel produced in the United States from soybean oil was completed by Sheehan et al. in 1998. 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. One of the most often cited results from Sheehan et al. is that the fossil energy ratio 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. 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 10 years ago.

The LCI of biodiesel in this analysis includes four subsystems: feedstock production, feedstock transportation, soybean processing with biodiesel conversion, and product distribution. 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 requirements to produce materials that are made from energy resources, such as fertilizers, pesticides, and other petrochemicals, are also included in the inventory. 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 result in the production of two important coproducts, soybean meal and crude glycerin, respectively. A mass-based allocation method is used to account for the energy associated with the soybean meal and crude glycerin.

The fossil energy ratio (FER), which is used in this study to measure the energy balance of biodiesel, is defined as the ratio of the energy output of the final biofuel product to the fossil energy required to produce the biofuel. The energy requirements of biodiesel include all the fossil energy in the LCI and do not include any renewable energy, such as solar or hydroelectric energy. The analysis first constructed a base case, in which the inventory was kept basically the same as the inventory used in the Sheehan et al. report. Then additional inputs that were excluded by Sheehan et al., such as agricultural machinery and energy embodied in building materials, were added to study their impact on the FER.

The Sheehan et al. study used data from a U.S. Department of Agriculture (USDA) conducted survey on soybean production in 1990, and this study used data from a 2002 USDA survey. Given the long time period between surveys, the newer data would be expected to reflect some changes in soybean production practices over time. One major change that has occurred is the increased adoption of no-till practices by soybean farmers, which reduces fuel requirements. Another change is the widespread adoption of genetically engineered (GE) soybeans, which have had a major effect on pesticide use. Soybean yields have been improving over time because of new seed varieties, improved fertilizer and pesticide applications, and new management practices. Energy savings have also occurred in the soybean crushing industry because facilities that have been built in recent times are far more energy efficient than the older plants.

The first subsystem constructed for the LCI was soybean production, which is the feedstock source for the biodiesel examined in this study. Energy requirements for producing soybeans were estimated for both direct energy, such as diesel fuel, and gasoline, and indirect energy, such as fertilizers and pesticides. Diesel fuel use required the most energy on the farm, followed by fertilizers, and herbicides. Next, the energy required to transport soybeans from the farm to processing plants was estimated based on information from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. It requires about 6,393 British Thermal Units (Btu) to transport 1 bushel of soybeans to a processing facility.

The model used in this study was designed to represent a processing facility that combines a soybean processing plant with a biodiesel conversion unit 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 soybean crusher 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. Hexane is used for oil extraction. The total amount of energy required for removing the soybean oil is about 23,000 Btu per gallon of biodiesel. The soybean oil is converted into biodiesel using a process called transesterification, which is done by reacting the oil with an alcohol and a catalyst in large reactors. This reaction also results in the production of crude glycerin, which is a valuable coproduct. The conversion of the soybean oil into biodiesel and the treatment of the glycerin requires almost 19,000 Btu per gallon of biodiesel. Energy is also required to ship the biodiesel from the processing plant to marketing outlets. Using the GREET model, it was determined that on average it requires about 1,000 Btu to ship a gallon of biodiesel to its final destination.

Combining the energy input estimates from the four subsystems completed the base case life-cycle assessment for biodiesel. After adjusting the energy inputs by energy efficiency factors and allocating energy by coproducts, the total energy required to produce a gallon of biodiesel was 25,696 Btu. Biodiesel conversion used the most energy, accounting for about 60 percent of the total energy required in the life-cycle inventory. Soybean agriculture accounted for 18 percent of the total energy requirements, followed by soybean crushing, which required almost 15 percent of the total energy. The net energy value (i.e., biodiesel energy output, minus fossil energy input) was about 91,000 Btu per gallon. The estimated FER of biodiesel was 4.56, which is about 42 percent higher than the FER reported by Sheehan et al.

The next step in this analysis was to add secondary energy inputs to the LCI that were not included in Sheehan et al. to determine how they affect the overall results. The secondary inputs added were farm machinery, building materials for a crushing plant, and building materials for a biodiesel conversion plant. When the input energy for both agricultural machinery and building material are added to the inventory, FER declines to 4.40, still considerably higher than the 3.2 FER reported by Sheehan et al. In addition, Sheehan et al. omitted lime from their LCI, whereas this study included lime in the base case LCI. However, lime use only accounted for about 500 Btu per bushel of soybeans, and adding it to the LCI only lowered the FER by 0.22 percent.

The final step in this analysis was to examine the effect of rising soybean yields on the FER of biodiesel. The analysis found that the FER of soybean biodiesel is expected to reach 4.69 when projected soybean yield reaches 45 bushels per acre in 2015. This is about a 3-percent increase compared to the 2002 FER estimate. This result suggests that the FER of biodiesel will continue to improve over time. In addition to higher yields, improvements can be expected to occur in other areas of the life cycle as the agricultural sector, along with the biodiesel industry, continues to make energy efficiency gains in order to lower production costs.

Energy Life-Cycle Assessment of Soybean Biodiesel

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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 (U.S. Environmental Protection Agency, 2002; Knothe et al.). In addition, developing renewable fuels 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 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 to which it depends on petroleum fuels. The degree to which biodiesel is renewable is largely a factor of the amount of fossil energy 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-derived energy for its production; the less a biofuel depends on petroleum energy, the more potential it has for diversifying our total fuel supply. Secondly, the renewability factor is one of many criteria that may be used by policymakers and others to evaluate and compare various biofuels. Renewability is a useful measurement that can be used along with other measurements, including environmental, economic, and social criteria, to assess the benefits of biofuels.

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, including 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. and Huo et al.).

One of the most often cited results from Sheehan et al. is that the fossil energy ratio 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. 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 10 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 affect life-cycle energy use.

Methodology

Following Sheehan et al., the formula used in this study to estimate the fossil energy ratio (FER) is defined in equation 1:

$$\mathrm{FER} = \frac{\text{Renewable Fuel Energy Output}}{\text{Fossil Energy Input}}. \qquad (1)$$

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. The FER as defined above only includes fossil energy in the denominator. For example, it does not include the energy value of the soybeans used to make biodiesel, and it does not include any solar or hydroelectric energy because these sources of energy are renewable.

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, is 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 (table A2). 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. About 70 percent of the electricity generated in the United States comes from fossil fuel (Energy Information Administration); hydroelectric and other nonfossil sources provide about 30 percent. 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 result 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, which 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. In general, no allocation method is always applicable, and the appropriate method should be chosen on a case-by-case basis. For more discussion on allocation methods, see Shapouri et al.

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:

$$\text{Energy input allocation for biodiesel} = E_1 f_1 + E_2 f_2 + E_3 \qquad (2)$$

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.

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 (Hill et al.; Huo et al., and Pimentel and Patzek.). A major cause for the contradicting results is 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 yields considerably more meal than oil, as well as more revenue. Clearly, soybean meal is not a byproduct 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. For a detailed comparison and discussion of the different coproducts used in the literature, see Pradhan et al.

Data Description and Trends

At the time of the Sheehan et al. study, the most recent detailed data available on soybean production was from the U.S. Department of Agriculture's (USDA) 1990 Farm Costs and Return Survey (FCRS). The FCRS, which was replaced by the Agricultural Resource Management Survey (ARMS) in 1996, 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 conducted on soybeans in 2006. This study, however, uses the 2002 data, because the 2006 data became available just prior to the release of this study. The ARMS soybean survey only covers major soybean producing States, and detailed data are only reported for a selected number of these States. In 1990, State-level estimates were available for 14 States and the 2002 soybean survey provided detailed State-level data on 20 States. These 20 States are responsible for 98 percent of the soybean production (table 1). The USDA 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. Data from the 2002 ARMS soybean survey on chemicals and fertilizers were not made available at the time of this study, so other USDA data sources were obtained (table 1).

To stay competitive, U.S. farmers are continually minimizing their input costs and increasing productivity. Therefore, soybean data would be expected to reflect some changes in soybean production practices over time. One major change that has occurred is the increased adoption of no-till practices by soybean farmers. No-till use increased in soybean production from about 10 percent of acreage in 1990 to about a third in 2000. Thus, significantly fewer soybean acres required fuel for tilling over this time period (USDA Economic Research Service [ERS], 2003). 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 (includes herbicides, insecticides, and fungicides) 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 (USDA 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). Based on data published in the National Agricultural Statistics Service's (NASS) Agricultural Chemical Usage survey, over the 5-year period from 1990 to 1994; 1995 to1999; and 2000 to 2004, the average herbicide use 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, the insecticide application rate was higher for the years 2005 and 2006, mostly because of higher aphid infestation (Thorson). Some herbicides are also less toxic today. For example, 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 (EPA, 2008). Kovach et al. found that the 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).

Table 1 – Soybean agriculture system inputs, major States, 2002

State		AR	IL	IN	IA	KS	KY	LA	MD	MI	MN	MS	MO	NE	NC	ND	OH	SD	TN	VA	WI	Weighted Average*
Input																						
Seed	lbs/ac	59.4	69.9	71.7	63.6	59.5	66.1	54.4	67.4	77.4	67.3	51.4	68.6	67.9	54.1	72.3	84.2	65.1	56.9	84.9	79.7	67.9
Fertilizer																						
Nitrogen	lbs/ac	1.76	3.55	3.00	0.89	4.44	7.44	0.13	5.51	11.9	2.24	2.57	2.34	4.91	10.6	16.5	2.97	7.65	12.5	7.5	5.97	4.26
Phosphorus	lbs/ac	19.6	13.6	11.7	4.64	10.4	23.5	6.96	5.92	15.6	4.75	11.0	12.5	17.0	18.4	18.9	13.2	24.0	26.9	15.2	12.3	12.65
Potash	lbs/ac	22.4	40.1	47.6	15.7	2.15	36.1	9.49	14.3	58.1	5.43	17.9	31.3	3.11	37.8	1.24	58.2	5.74	42.0	38.3	35.5	25.52
Direct Energy																						
Gasoline	gal/ac	1.3	0.90	1.60	1.10	1.10	1.40	1.10	2.10	1.50	1.10	1.20	1.40	1.30	1.50	1.40	1.30	1.40	1.30	1.20	2.40	1.26
Diesel	gal/ac	9.90	2.50	2.30	3.40	2.90	2.10	6.50	2.90	4.00	4.00	4.30	4.30	12.9	2.40	3.20	2.00	2.80	2.20	1.90	5.20	4.06
Propane	gal/ac	NR	0.00	NR	0.00	1.80	NR	NR	NR	NR	NR	NR	NR	4.40	NR	NR	NR	0.00	NR	NR	0.00	0.73
Electricity	kWh/ac	11.2	NR	1.30	0.00	9.10	4.50	NR	0.80	NR	NR	3.80	NR	39.4	0.60	0.80	0.00	NR	1.00	NR	NR	6.62
Natural Gas	Cf/ac	NR	0.00	NR	0.00	349	0.00	NR	0.00	0.00	0.00	0.00	0.00	586	0.00	0.00	0.00	0.00	0.00	0.00	0.00	58.41
Chemicals																						
Herbicides	lbs/ac	1.00	1.23	1.35	1.26	1.07	1.15	1.60	1.54	1.22	0.98	1.66	1.17	1.28	1.00	1.26	1.34	1.20	1.29	1.23	0.81	1.21
Insecticides	lbs/ac	0.04	0.00	0.00	0.01	0.00	0.00	0.60	0.34	0.00	0.00	0.02	0.00	0.01	0.07	0.00	0.00	0.02	0.00	0.05	0.00	0.02
Lime	lbs/ac	53.7	595	668.8	286.4	146.7	865.6	70.7	NA	323.3	181.8	120	818.5	123.9	652.9	NR	394.6	NR	828.3	769.7	379.3	357.96
Yield	Bu/ac	33.5	43.0	41.5	48.0	23.0	33.0	32.0	23.0	38.5	43.5	32.0	34.0	38.5	24.0	33.0	32.0	31.0	31.0	23.0	44.0	38.0

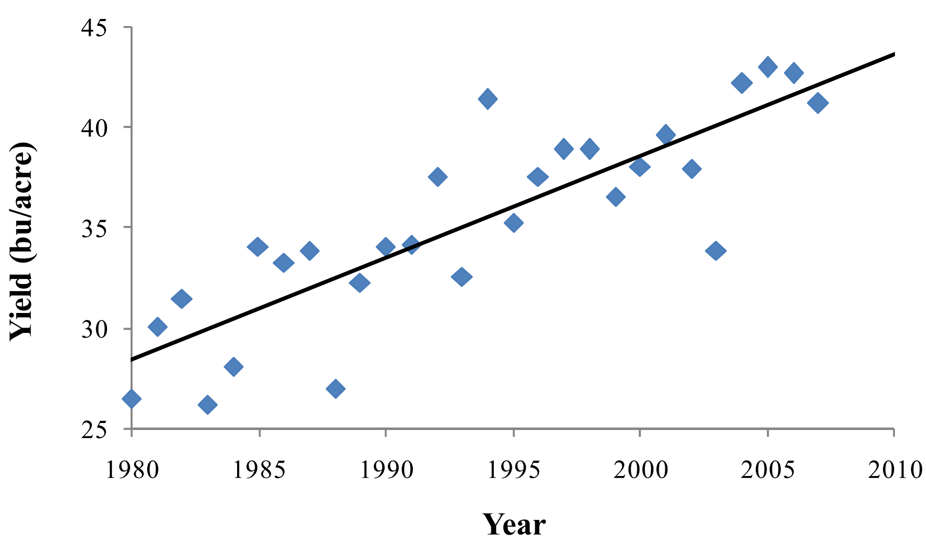
Source: USDA, National Agricultural Statistics Service (NASS), 2005; USDA, Economic Research Service (ERS) (a); USDA, ERS (b); and USDA, NASS, 2003.
*Weighted by area harvested in each State.
NR: Not reported in that State due to small sample size.

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 pounds per acre.

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). The data show a significant increase in soybean yield since 1990 (figure 1). 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). The latest USDA estimate for soybean yield is 41.7 bushels per acre for the 2007 crop year (USDA, Office of the Chief Economist-b). 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.

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 were based on a single facility 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).

Figure 1 – U.S. national average soybean yield 1980-2007 and expected trend to 2010



Source: Ash and Dohlman; and USDA, Office of the Chief Economist (b).

The oil extraction rate for crop year 2002/2003 was 11.39 pounds per bushel and increased to 11.55 pounds 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).

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 wastewater 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, 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 machinery and energy embodied in building materials, were added to study their impact on the FER.

Feedstock Production

The farm input data for soybean production were obtained from ARMS and the National Agricultural Statistics Service (NASS). The direct energy data came from the 2002 ARMS, which were the most recent soybean survey data available at the time of this study (table 1). 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's NASS Agricultural Chemical Survey. The lime-application rates and the seed-application rates shown in table 1 are State averages from the 2002 ARMS (USDA, ERS-a; and USDA ERS-b).

The farm input data in table 1 were weighted by State acreage 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. 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 2). 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 1.

Estimating Energy for Transporting Soybeans to Biodiesel Plant

The amount of energy required to transport soybeans to processing plants came from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Argonne National Laboratory). The energy required for transporting soybeans to processing

Table 2 – Energy equivalents for base case soybean agriculture system inputs before allocating coproduct values, 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
Propane	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.

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.

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. Since actual industry data for soybean crushing and biodiesel production were not available, this study had to develop a generic model to estimate the energy required to crush soybeans and produce biodiesel using transesterification. 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.). 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 were not used.

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 soybeans using chemical hexane extraction (figure 2). 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. Soybeans entering the process are first cleaned and then heated and dried to obtain a 10-percent moisture content (Erickson, 1995). Then the beans are cracked into several pieces by passing them through mechanical rolls. The soybean hulls, which account for about 8 percent of the soybean, are removed by aspiration. The hulls may be blended with the soybean meal that is later extracted in the process or they may be further treated by toasting and grinding and sold as animal feed. The dehulled beans or meats are conditioned by heating, cut into flakes, and fed to the oil extraction unit where the oil from the beans is dissolved with hexane. The oil and hexane mixture is treated with steam to separate the hexane from the oil. Once the hexane is removed, it is recycled for additional processing. Hot air and cooling water are used in the final heating and drying of the oil. The crude soybean oil is degummed and may be deodorized, bleached, and neutralized. The oil-depleted, dried soybeans are ground to a uniform size to make soybean meal, and in some cases, the hulls are blended with the soybean meal. The combined total thermal and electric energy required for preparing the soybeans, extracting the oil from the beans, and drying the soybean meal is 23,151 Btu per gallon of biodiesel (table 3).

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, 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 known as biodiesel (figure 2). The stream of methanol, glycerin, and other impurities is 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 to be used in the production of various other products, including fiberglass 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 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 3).

Figure 2 – Soybean crushing and biodiesel conversion

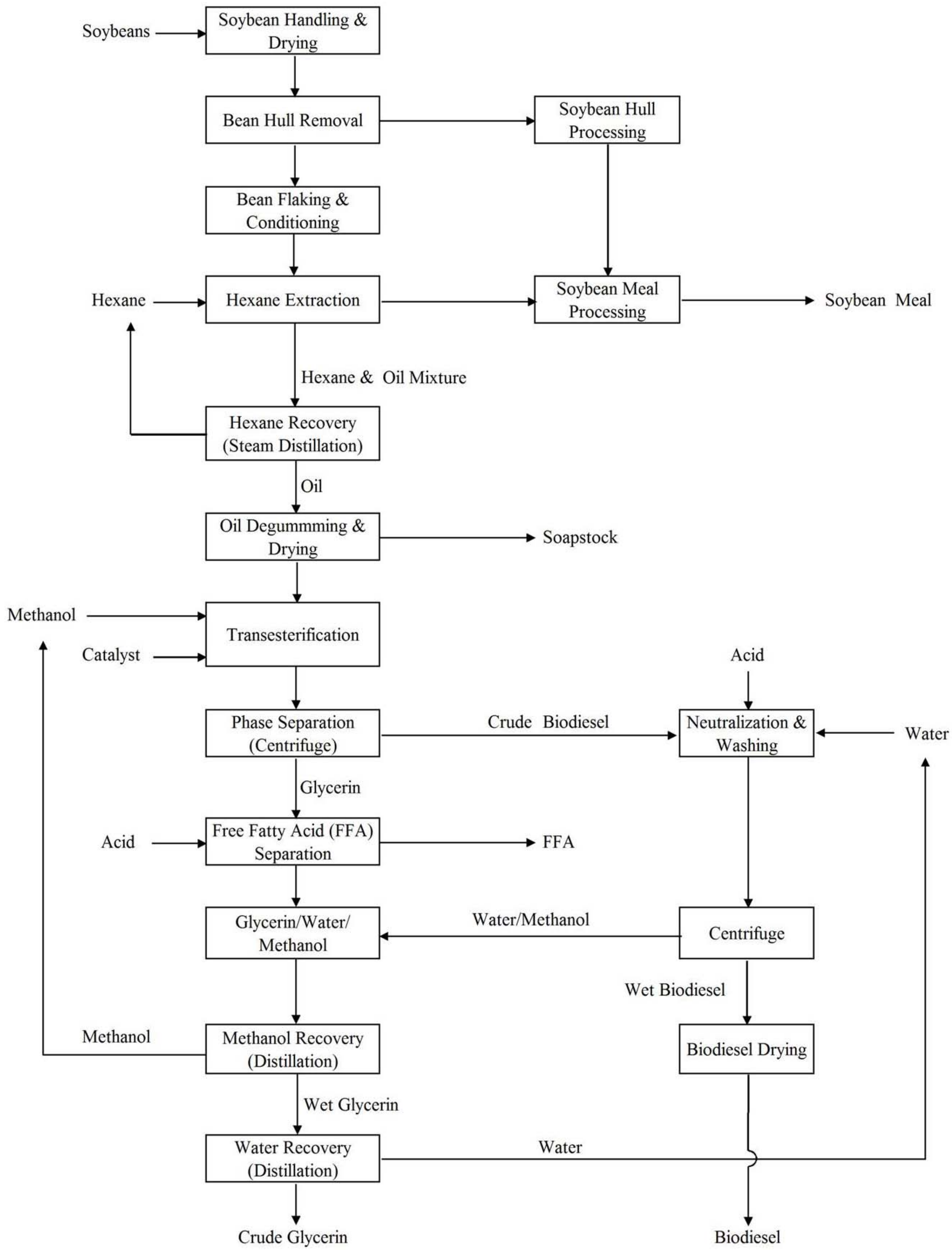


Table 3 – Fossil energy requirements for soybean crushing and conversion before allocating coproduct values, per gallon of biodiesel

Inputs	Equivalent Energy (Btu/gal)	Adjusted Equivalent Energy* (Btu/gal)	Source
Soybean crushing:			
Electricity**	2,738	6,124	ARS
Natural Gas/Steam	14,532	15,460	ARS
Hexane	--	1,567	Huo et al.
Total fossil energy for crushing		23,151	
Biodiesel conversion:			
Electricity	439	981	ARS
NG/Steam	3,551	5,840	ARS
Methanol	7,193	10,633	Huo et al.
Sodium Methoxide	--	1,256	Huo et al.
Sodium Hydroxide	--	24	Huo et al.
Hydrochloric Acid	--	38	Huo et al.
Total fossil energy for conversion		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.

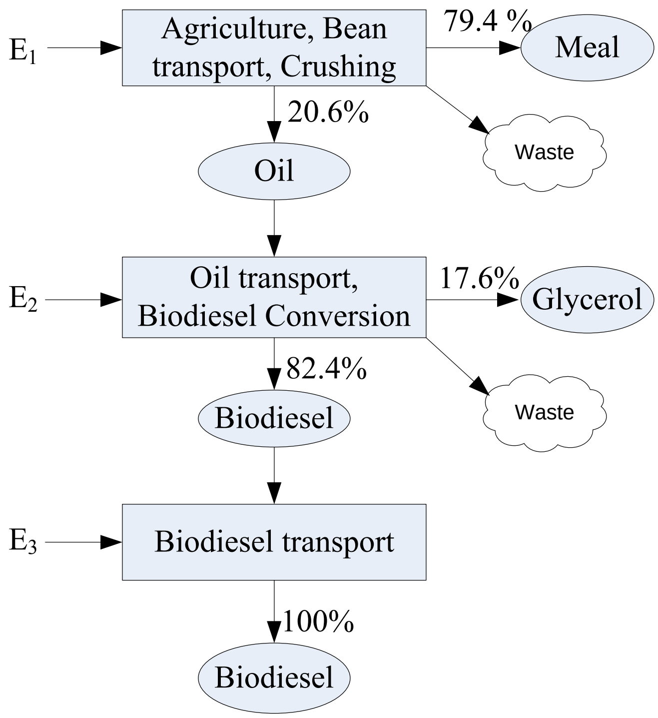
Biodiesel Transport

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 about 32 miles for truck, 42 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.

Calculating Energy Coproduct Values

The energy used to produce the meal portion of the soybean and the crude glycerin that is produced during the transesterification stage must be excluded from the LCI. Several allocation methods can be used to estimate the energy value of coproducts. 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 to the original Sheehan et al. study, we also use the mass-based allocation method (figure 3). Soybean crushing produces oil, meal,

Figure 3 ─ Mass-based energy allocation for biodiesel coproducts



gum, and waste material. USDA ERS (2009) reported a 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 3).

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 (Sheehan et al., pp 145). 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., pp 146). 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 3). 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 (2) = 0.170 = (0.206×0.824), and f_2 = 0.824. All the energy used to transport biodiesel is allocated to biodiesel (figure 3).

Results

Combining the energy input estimates from the four subsystems completes the base case life-cycle assessment 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. The energy use estimates in table 4 are adjusted by energy efficiency factors (appendix table 2). 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.

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 91,000 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.

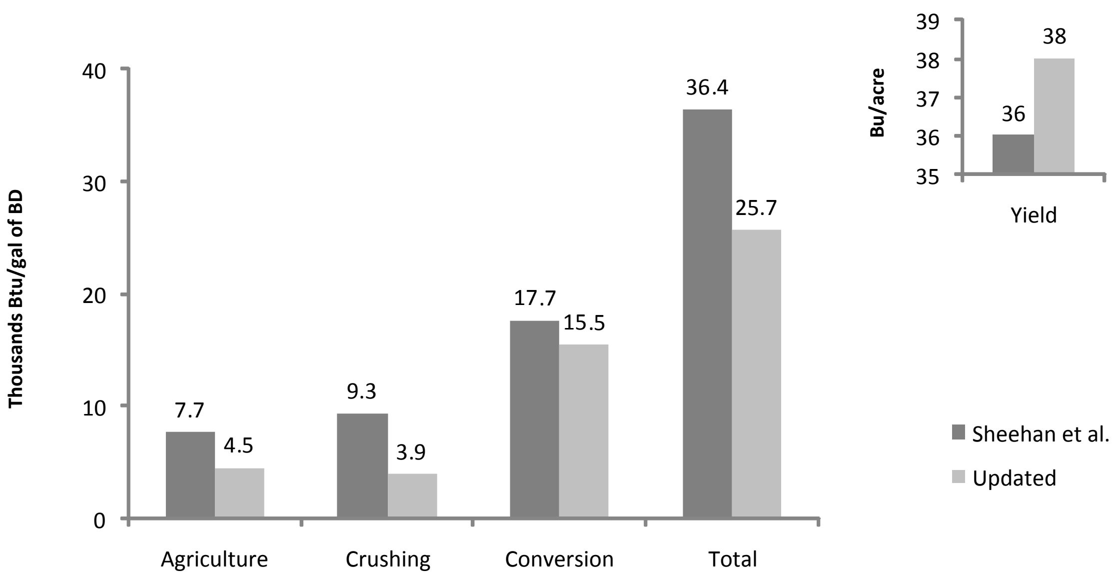
Table 4 – Base case energy use for biodiesel and FER with coproduct allocation and adjusted by energy efficiency factors

Life-Cycle Inventory	Fossil Energy Use (Btu/gal of Biodiesel)	
	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
Biodiesel 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.

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 (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 4). The reduction in the crushing energy is primarily due to a reduction in the electricity and natural gas/steam inputs. The fossil energy inputs for soybean agriculture fell from 7,681 Btu to 4,544 Btu (41 percent reduction) per gallon of biodiesel (figure 4). 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.

Figure 4 – Comparing energy requirements for selected biodiesel subsystems and total life-cycle energy requirements between this study and Sheehan et al.



The energy required for transesterification estimated in this study was about 12 percent lower than the estimate reported by Sheehan et al. (figure 4). 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.

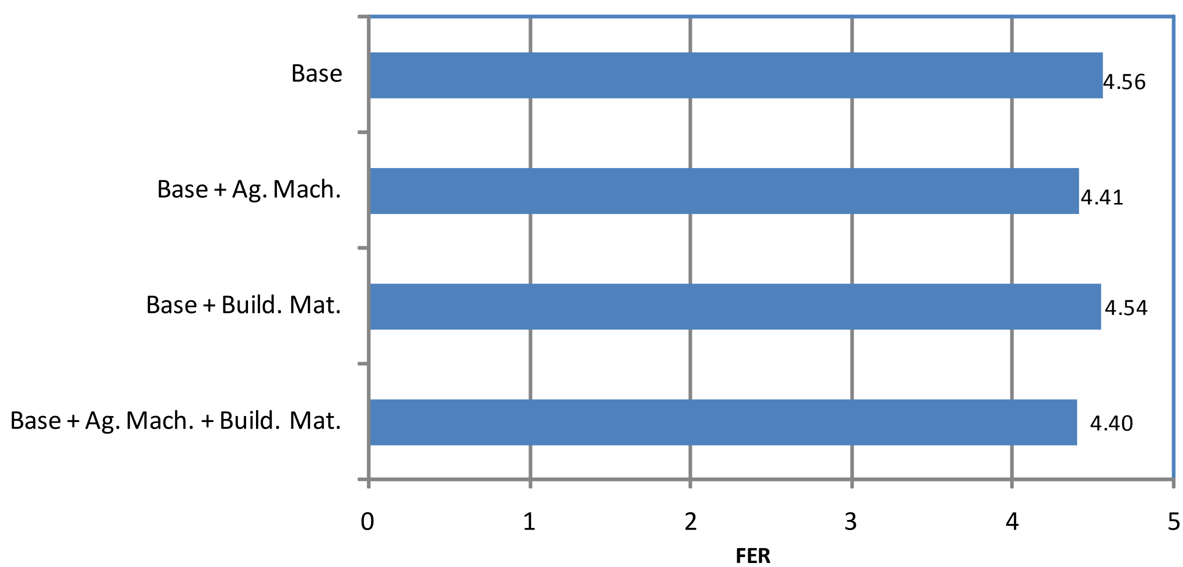
The Effects of Adding Inputs to the LCI

Figure 5 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 the 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

Our base case LCI included lime unlike 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.

Figure 5 – Effect on fossil energy ratio from adding the energy from secondary energy inputs to the life-cycle inventory



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.

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 and crushed into oil that is converted to biodiesel onsite; 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 were 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 over time, 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 Economist-a). For every 1 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 a 3- percent increase compared to the 2002 FER estimate.

Summary and 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 2 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.

Finally, the results from this research suggest that the FER of biodiesel will continue to improve over time. 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 over time.

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Appendix

Appendix Table 1 – 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.
Propane(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)	22,136	Hill et al
Phosphorus (Btu/lb)	3,944	Hill et al.
Potassium (Btu/lb)	2,563	Hill et al.
Lime (Btu/lb)	53.72	Graboski
Seeds (Btu/lb)	2,024	Sheehan et al.
Herbicide (Btu/lb)	137,191	Hill et al.
Insecticide (Btu/lb)	139,772	Hill et al.
Methanol (Btu/lb)	9,750	American Methanol Institute

Appendix Table 2 -- Life-cycle energy efficiency factors for fossil fuels and electricity

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

Source: Shapouri et al.; Energy Information Administration; United State Department of Agriculture, Agricultural Research Service; and Wang and Huang.

Glossary

Allocation Method — Rules to determine the fraction of total input energy that is assigned to each coproduct. For example, both biodiesel and glycerin are produced during the transesterification process, but the energy used to produce the two products cannot be easily delineated. Therefore an allocation method has to be used, such as a mass-based rule that allocates energy to the various coproducts by their relative weights.

ARMS — USDA's Agricultural Resource Management Survey (ARMS) is sponsored jointly by the Economic Research Service (ERS) and the National Agricultural Statistics Service (NASS). ARMS began in 1996 as a synthesis of the former USDA cropping practice, chemical use, and farm costs and returns surveys, which dated back to 1975. It is USDA's primary source of information on the financial condition, production practices, resource use, and economic well-being of America's farm households. http://www.ers.usda.gov/data/arms/GlobalAbout.htm#Use

British Thermal Units (Btu) — British thermal units are widely used in the United States to describe the heat value or energy content of fuels and other types of energy. One Btu is equivalent to 1,055 joules, which is an energy unit in the international system of weights and measures.

Catalyst — A substance that enables a chemical reaction to proceed usually at a faster rate or under different conditions (as at a lower temperature) than otherwise possible.

Centrifuge — A process of separating liquids with different specific gravities by rotating the fluid at high speed.

Coproduct — When a production process results in two or more products, the products are called coproducts. For example, a soybean processing plant crushes soybeans to obtain two marketable coproducts (i.e., soybean oil and soybean meal).

Degummed Soybean Oil — Soybean oil after removing phosphotides and some unsaponifiable matter commonly known as gums.

Dehulled Beans or Meats — That part of the soybean remaining after removing the hull. The hull is the skin of the soybean, which is removed to facilitate solvent extraction of the oil and improve protein content of the meal.

Direct Energy Inputs — Inputs in the form of energy, such as gasoline, diesel, natural gas, and electricity. Inputs that depend on energy for their production, such as fertilizers and pesticides, are indirect energy inputs.

Energy Balance of a Biofuel — An energy life-cycle assessment that measures the fossil energy required to produce a biofuel relative to its energy output value.

Energy Efficiency Factor — A coefficient used to account for the energy required to bring a raw energy resource from the environment to its final useable form. For example, for every unit of electrical energy produced, it takes on average 3.2 units of energy to get that energy into its final form and transport it to its final destination. Therefore, 3.2 is the energy efficiency factor for electricity, and the electrical energy used to produce a product must be multiplied by this factor to account for the total energy associated with electricity use.

Energy Life-Cycle Assessment — A life-cycle assessment that focuses just on the energy inputs and outputs of a product.

Environmental Impact Quotient (EIQ) — A measurement that estimates the environmental impacts of a pesticide taking into account several environmental variables, including fish toxicity, bird toxicity, bee toxicity, and leaching potential.

Fatty Acids — Fats or triglycerides, which are the primary constituents of vegetable oils and animal fats. When using transesterification, the triglycerides are transformed to esters and crude glycerin. The esters become biodiesel and the glycerin can be further processed to make other products.

Free Fatty Acids — Fatty acid groups that have broken off from the vegetable oil triglyceride molecule. Unless properly accounted for, free fatty acids consume catalyst needed for transesterification, lowering yield, increasing the reaction time, or potentially stopping the reaction altogether. Feedstocks with high free fatty acid levels will often be pretreated to remove free fatty acids before transesterification.

Feedstock — Raw material used in making an energy product. For example, biodiesel can be made from various feedstocks, including soybean oil, animal fat, and recycled cooking oil.

Fossil Energy — Energy derived from fossil fuel, which includes petroleum oil, coal, and natural gas.

Fossil Energy Ratio (FER) — The energy output of a biofuel divided by the life-cycle energy required to produce the product. The FER only includes fossil energy in the denominator, and it is often the measurement used to quantify the energy balance of a biofuel.

Genetically Engineered (GE) Soybeans — A soybean variety that has been genetically modified to make it more resistant to herbicide applications, primarily glyphosate, commercially known as Roundup. GE soybeans were developed to survive the application of glyphosate that previously would have destroyed the crop along with the targeted weeds.

Glycerin or Glycerol — An organic compound present in all animal and vegetable fats that is produced along with biodiesel when using the transesterification production process. Historically, refined glycerin has been a product of the commercial soap industry; however, a synthetic glycerin is also produced on a commercial scale by the petroleum industry. Commercial glycerin is found in many products, including solvents, sweeteners, cosmetics, liquid soaps, candy, liqueurs, and dynamite**.**

GREET Model — The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model was developed by Argonne National Laboratory, U.S. Department of Energy. It fully evaluates life-cycle energy and emission impacts of advanced vehicle technologies and new transportation fuels.
http://www.transportation.anl.gov/modeling_simulation/GREET/index.html

Life Cycle — Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO 14040). The life cycle of soybean biodiesel is assumed to start from the beginning of the soybean production and end with the delivery of the biodiesel to a gas station or the point of the final use.

Life-Cycle Assessment (LCA) — Also known as life-cycle analysis, it is a technique to assess or measure certain aspects of a product over its entire life cycle. Life-cycle assessments are most often used to assess the environmental aspects of a product, but LCAs can also be used to measure the social impacts of a product.

Life-Cycle Inventory (LCI) — The database that contains the amounts of all inputs and outputs of processes that occur during the life cycle of a product. The LCI is typically organized by a set of subsystems (e.g., biodiesel includes a feedstock subsystem and a conversion subsystem). The LCI sets boundaries for each subsystem to avoid unnecessary data collection.

Methyl Ester — Biodiesel is called a methyl ester if the alcohol used for transesterification is methanol.

Net Energy Value (NEV) — The energy content of 1 gallon of biodiesel minus the life-cycle fossil energy required to produce 1 gallon of biodiesel. A biofuel has a positive energy balance if its NEV is greater than one, and a negative energy balance if the NEV is less than one.

No-Till — A crop residue management (CRM) system that maintains additional crop residue on the soil surface through fewer and/or less intensive tillage operations. CRM is generally cost effective in protecting soil and water resources and can lead to higher farm economic returns by reducing fuel, machinery, and labor costs while maintaining or increasing crop yields.

Pest Management — A set of techniques used to reduce pest populations or prevent their detrimental effect on crops and livestock. A pest is any noxious and damaging organism, including mites, insects, plant pathogens, and weeds. Pest management techniques can be broadly classified into chemical, cultural, and biological.

Renewability — The degree in which a biofuel is renewable. The fossil energy ratio (FER), which is the ratio of renewable energy output to fossil energy input, is a measure of renewability. Biofuels that use less fossil energy per unit of renewable energy output have a higher degree of renewability.

Secondary Inputs — Secondary inputs have no energy value per se, but it requires energy to produce them (e.g., building materials used to construct processing plants and farm vehicles used for cultivation). These inputs are often excluded from the LCI because they do not provide direct energy to the system and they're difficult to quantify. Energy estimates for secondary inputs are generally very small, so their exclusion from the inventory has little effect on the LCA.

Soybean Crusher — A generic term used for a plant that primarily processes soybeans into two products: soybean meal and soybean oil.

System Boundaries — Limits set in the life-cycle inventory (LCI) to prevent boundless production systems and unnecessary data collection. Whether to include or exclude energy used beyond direct inputs, such as energy embodied in labor, building materials, and manufacturing equipment, depends on several factors, including goal and scope of the LCA, availability of data, reliability of data, time and cost of collecting the data, and the extent to which the inclusion will make difference in the final result.

Thermal Energy — The energy required for heating, for example, the heat generated from natural gas to dry soybeans.

Transesterification — A process for producing alkyl esters (biodiesel) by reacting a vegetable oil or animal fat with an alcohol, usually ethanol or methanol. This reaction also results in the production of crude glycerin.

Unsaponifiable Matter — Non-triglyceride part of oil and fat that does not convert into soap. It is removed from the oil because it is detrimental to the transesterification process.