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ENERGY LIFE-CYCLE ASSESSMENT OF SOYBEAN BIODIESEL REVISITED

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ABSTRACT. *The first comprehensive life-cycle assessment (LCA) for soybean biodiesel produced in the U.S. was completed by the National Renewable Energy Laboratory (NREL) in 1998, and the energy inventory for this analysis was updated in 2009 using 2002 data. The continual adoption of new technologies in farming, soybean processing, and for biodiesel conversion affects the life-cycle energy use over time, requiring that LCA practitioners update their models as often as possible. This study uses the most recently available data to update the energy life-cycle of soybean biodiesel and makes comparisons with the two past studies. The updated analysis showed that the fossil energy ratio (FER) of soybean biodiesel was 5.54 using 2006 agricultural data. This is a major improvement over the FER of 3.2 reported in the 1998 NREL study that used 1990 agricultural data and significantly better than the FER of 4.56 reported using 2002 data. The improvements are primarily due to improved soybean yields and more energy-efficient soybean crushing and conversion facilities. The energy input in soybean agriculture was reduced by 52%, in soybean crushing by 58% and in transesterification by 33% per unit volume of biodiesel produced. Overall, the energy input reduction was 42% for the same amount of biodiesel produced. The addition of secondary inputs, such as farm machinery and building materials, did not have a significant effect on the FER. The FER of soybean biodiesel is likely to continue to improve over time because of increases in soybean yields and the development of increasingly energy-efficient technologies.*

Keywords. *Biofuel, Energy balance, Energy life-cycle analysis, Fossil energy ratio, LCA.*

Developing renewable fuels is desirable because these fuels are derived from sustainable sources of energy and have the potential to extend and diversify the world's energy supply. Estimated proven oil reserves in the U.S. are about 19 billion bbl, and the total production of crude oil was 9.2 million bbl/day in 2009 (EIA, 2010b). With this rate of crude production and reserves, the reserves-to-production (R/P) ratio for the U.S. is estimated to be six years. The R/P ratio is the number of years for which the current level of production of fuel can be sustained by reserves and is calculated by dividing proven reserves at the end of the year by the production in that year (Feygin and Satkin, 2004).

The terms "nonrenewable energy" and "fossil energy" are used interchangeably in this article. The production of renewable fuels generally takes in a significant amount of nonrenewable energy (fossil fuel and embedded energy in chemicals). 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 the fuel is renewable. Renewability is a useful measurement that can be used in conjunction with other measurements, such as environmental and economic terms, to assess biofuel benefits. The renewability factor could guide policymakers to evaluate and compare various biofuel options and make judgments to prevent costly mistakes.

Life-cycle analysis (LCA) is a cradle-to-grave analysis of the energy and environmental impacts of making a product. The first comprehensive life-cycle inventory (LCI) of biodiesel produced in the U.S. from soybean oil was published by Sheehan et al. (1998). The inventory and model assumptions were developed by a large stakeholder group and several peer reviewers, including experts from numerous disciplines and institutions. The purpose of that study was to conduct an LCA to quantify and compare the environmental and energy flows associated both with biodiesel and petroleum-based diesel. The LCI flows examined included energy use, greenhouse gases, and other air emissions. Most of the data used in the LCI reported by Sheehan et al. (1998) were from 1990 or earlier. In order to update the energy component of the LCI reported by Sheehan et al. (1998), a report using mostly 2002 data was completed by Pradhan et al. (2009). We are now following up on the 2002 data with recently obtained data from the USDA and other sources. The objective of the study reported in this article is to construct a new biodiesel energy life-cycle with 2006 data that reflects current soybean production and biodiesel plants built after 2002, which constitute the majority of plants producing biodiesel today. In addition, a comparison of the three time periods from the past studies (1990, 2002, and 2006) will be made to show how energy life-cycles change over time.

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Renewability Definition

Although various definitions have been used to measure renewability, fossil energy ratio (FER) is used in this study as suggested by Pradhan et al. (2008) and used by Sheehan et al. (1998) to measure fuel renewability. FER is defined as:

$$\text{FER} = \frac{\text{Renewable fuel energy output}}{\text{Biodiesel share of fossil energy input}} \qquad (1)$$

It is worth noting that only fossil (nonrenewable) energy is included in the denominator. It does not include renewable sources of energy, such as solar and wind. Since the primary goal is to measure renewability, it makes sense not to include renewable sources in the denominator. FER does not measure system efficiency, as fossil fuel can be replaced by other renewable fuel. Net energy ratio (NER), which includes total energy input in the denominator of equation 1, is used to measure system efficiency, rather than FER (Pradhan et al., 2008). While higher FER is desirable to ensure that biofuel is renewable, it does not guarantee that biodiesel will also be economically viable.

System Boundary

Analysis of the life-cycle of biodiesel was divided into four subsystems in this analysis: feedstock production, feedstock transportation, soybean processing with biodiesel conversion, and product distribution. An inventory of material and energy was then developed that quantifies all fossil energy inputs used in each subsystem. All direct and indirect sources of energy were 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 were made from energy resources, such as fertilizers, pesticides, and other petrochemicals, is also included in the inventory. The effect of adding energy used for building biodiesel plants and agricultural machinery was studied separately and not included in the base case to be consistent with Sheehan et al. (1998). As suggested by Pradhan et al. (2008), the energy consumed by labor was not included or studied.

Energy Conversion Factors

All materials used in the inventory list were converted to their equivalent life-cycle energy content (table 1). The life-cycle energy of a material is defined as the total nonrenewable energy embedded and incurred during extraction, processing, and transport of that material. Renewable energy, such as solar energy entrapped during photosynthesis, is not included in life-cycle energy. The embedded energy fraction of life-cycle energy for materials used for fuel, such as diesel, gasoline, and natural gas, was taken to be the same as the low heating value (LHV) of that material. LHV is the amount of heat released during combustion of fuel when water vapor from the combustion process is still in the gaseous phase. The life-cycle energy of those materials was calculated by dividing the LHV by the life-cycle efficiency. Life-cycle efficiency is the ratio of embedded energy to the total energy, including extraction, processing, and transport, of that material as well as the embedded energy in the material. High heating value was used for non-fuel inputs such as methanol.

The life-cycle energy of fossil fuels was calculated by dividing embedded energy by life-cycle efficiency. The life-cycle efficiency factors adjust for energy required to mine, extract, manufacture, and transport the product. Estimates of electricity generation used throughout the life-cycle are based on the U.S. weighted average. About 67% of the electricity generated in the U.S. comes from fossil fuel (EIA, 2010a). Based on data from the Energy Information Administration, the efficiency of electricity generation in the U.S. increased from 32.0% as reported by Sheehan et al. (1998) to 36.7% in 2009. In addition to generation loss, there is also a distribution lines loss. Inclusion of distribution loss reduces the overall efficiency of electricity to 32.5%.

Table 1. Life-cycle energy equivalents of various inputs.

Input	Embedded Energy	Life-Cycle Efficiency (%)	Life-Cycle Energy Equivalent
Fuel inputs			
Diesel	35.9 MJ/L[a]	84.3[b]	42.5 MJ/L
Gasoline	32.4 MJ/L[a]	80.5[b]	40.2 MJ/L
Propane (LP gas)	23.7 MJ/L[a]	89.8[b]	26.4 MJ/L
Natural gas	36.6 MJ/m^{3}[a]	94.0[b]	38.9 MJ/m^{3}
Electricity	3.6 MJ/kWh[c]	32.5[d]	7.4 MJ/kWh[e]
Steam at 10.3 bar (150 psi)	2.0 MJ/kg[f]	60.8[g]	3.3 MJ/kg
Material inputs			
Nitrogen	--	--	51.5 MJ/kg[h]
Phosphorus	--	--	9.2 MJ/kg[h]
Potassium	--	--	6.0 MJ/kg[h]
Herbicide	--	--	319 MJ/kg[h]
Insecticide	--	--	325 MJ/kg[h]
Lime	--	--	0.1 MJ/kg[i]
Seeds	--	--	4.7 MJ/kg[j]
Methanol	22.7 MJ/kg[k]	67.7[l]	33.5 MJ/kg
Sodium methoxide	--	--	31.7 MJ/kg[j]
Sodium hydroxide	--	--	1.5 MJ/kg[j]
Hydrochloric acid	--	--	1.7 MJ/kg[j]
Hexane	--	--	0.5 MJ/kg oil[a]

[a] Source: Huo et al. (2008).
[b] Source: Shapouri et al. (2002).
[c] Direct unit conversion.
[d] Source: EIA (2010a).
[e] Only 70% was included to account for fossil energy.
[f] Source: steam table data.
[g] Estimated from the USDA-ARS model.
[h] Source: Hill et al. (2006).
[i] Source: Graboski (2002).
[j] Source: Sheehan et al. (1998).
[k] Source: AMI (2009).
[l] Source: Wang and Huang (1999).

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. Hexane extraction is fairly common for large-scale oil extraction from soybean and was also used by Sheehan et al. (1998). 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. Several allocation methods 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. (1998) used a mass-based allocation method; 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 (Shapouri et al., 2002).

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

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

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

ENERGY LIFE-CYCLE INVENTORY

Life-cycle inventory (LCI) is the accounting of all inputs and outputs of processes that occur during the life-cycle of a product. LCI for biodiesel includes all four subsystems mentioned earlier. For the purposes of comparison and sensitivity analysis, this study first constructed a base case in which the LCI was kept the same as the inventory reported by Sheehan et al. (1998) except for lime, which was added to the base case. Then the inputs that were not included by Sheehan et al. (1998), such as agricultural machinery and energy embodied in building materials, were added to study their sensitivity on the FER calculation.

DATA ON FEEDSTOCK PRODUCTION

Since U.S. agriculture has a tendency to become more energy efficient over time, it is important to use the most recent set of data available when conducting life-cycle analysis. In order to eliminate the error from temporal variation in agricultural production, the LCA reported in this study used the 2006 Agricultural Resource Management Survey (ARMS) and National Agricultural Statistics Service (NASS) data, as it was the most recent complete data set available. At the time of the Sheehan et al. (1998) study, the most recent detailed agricultural data available on soybean production was from the 1990 USDA Farm Costs and Return Survey (FCRS), which is now known as ARMS. The analysis by Pradhan et al. (2009) used 2002 ARMS data. The state soybean yield data are USDA estimates reported by the National Agricultural Statistics Service (NASS, 2010). The fertilizer and chemical data for 2006 soybeans are also from the National Agricultural Statistics Service (NASS, 2007). The lime application rates and the seed application rates are state averages from the 2006 ARMS (ERS, 2009a).

The farm input data from 19 major soybean-growing states were averaged weighted by harvested acreage to derive energy used for soybean agriculture (table 2). The weighted average yield equaled 2906.7 kg/ha (43.2 bu/ac) in 2006. This is equivalent to a yield of 598.6 L/ha (64.1 gal/ac) of biodiesel. The weighted average energy input use and the weighted average yield were used to estimate the energy required for soybean production in the U.S. (table 2).

Table 2. Soybean agriculture system inputs, weighted averages of 19 major soybean-growing states, 2006 (source: ERS, 2009a; NASS, 2007; NASS, 2010).

Inventory	Quantity Used (per ha)[a]	Life-Cycle Energy Equivalent (MJ/ha)[b]
Diesel	33.3 L	1417.6
Gasoline	12.8 L	515.7
LP gas	2.0 L	52.7
Natural gas	4.1 m^3	161.4
Nitrogen	3.3 kg	168.2
Phosphorus	12.1 kg	111.2
Potassium	22.4 kg	133.4
Lime	463.7 kg	57.9
Seeds	68.9 kg	324.4
Herbicide	1.6 kg	507.7
Insecticide	0.04 kg	13.2
Electricity	17.1 kWh	127.1
Total		3590.5

[a] Weighted average by area harvested in each state.

[b] Calculated using table 1. Equivalent average biodiesel production was 598.6 L/ha (64.1 gal/ac) for 19 major soybean-growing states.

Lime use was not reported by Sheehan et al. (1998); however, in some acidic fields, farmers apply lime periodically to increase soybean yield. In 2006, the average lime application for soybean production was 463.7 kg/ha (table 2). Total Life-cycle energy input in soybean agriculture was 3590.5 MJ/ha, or equivalently 6.0 MJ/L of biodiesel produced. Comparing the 2006 soybean inputs with the estimates reported in the past verifies that soybean producers have been decreasing their total energy use over time (fig. 1). Moreover, as energy input use has been declining, soybean yields have been increasing. The most significant change in U.S. soybean production since 1990 is the use of genetically engineered (GE) soybeans. Use of GE soybeans has not only increased yields but also helped reduce pesticide use (including herbicides, insecticides, and fungicides).

The 1990 ARMS soybean production data used by Sheehan et al. (1998) did not include any GE soybeans because they

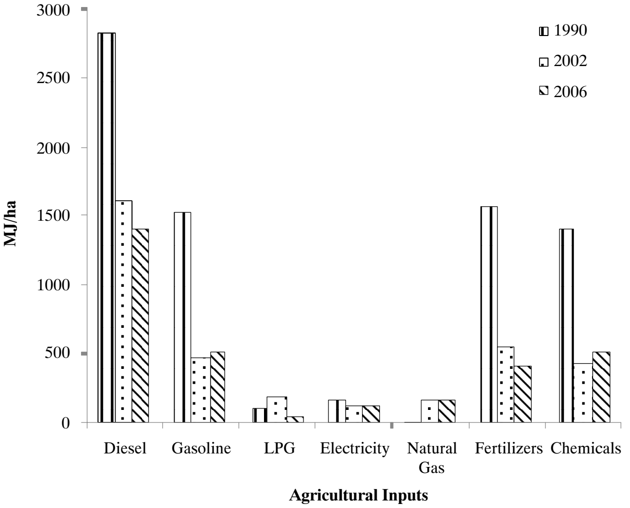

Figure 1. Comparison of major agricultural inputs from 1990, 2002, and 2006.

had not been introduced into U.S. agriculture yet. However, by 2002, the rapid rise in GE soybeans had reached 75% of all soybeans planted, and today almost all soybeans in the U.S. are GE varieties (ERS, 2010). Another major change is the increased adoption of no-till practices by soybean farmers. No-till use increased in soybean production from about 10% of acreage in 1990 to 45% in 2006 (Horowitz et al., 2010). Thus, significantly fewer soybean acres required fuel for tilling.

ENERGY FOR TRANSPORTING SOYBEANS TO BIODIESEL PLANTS

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 (ANL, 2010). The energy required for transporting soybeans to processing plants was estimated to be about 720.1 MJ/ha (1.2 MJ/L of biodiesel). The estimation was based on a distance of 80 km (50 mi) for trucking soybeans from a distribution center to the soybean crusher and biodiesel plant.

ENERGY FOR OIL CRUSHING AND BIODIESEL CONVERSION

The energy input data for oil crushing and biodiesel conversion was obtained from a model developed by the USDA-ARS. The USDA model was prepared by the authors from process designs, equipment specifications, costs, and energy consumptions that were provided by technical experts and equipment suppliers to the soybean crushing and biodiesel industry. This information was then modeled in the process simulation program Superpro Designer (Intelligen, Inc., Scotch Plains, N.J.), and total energy consumptions were calculated for each step in the process. Copies of this model are available upon request from the authors.

In the model, the energy requirements for soybean crushing and transesterification were estimated using chemical process engineering and cost engineering technology developed by the USDA-ARS (Haas et al., 2006). The model measures the electrical and thermal energy inputs required for a joint facility that combines a soybean processing plant with a biodiesel conversion plant producing 38.6 million L (10.2 million gal) of biodiesel, 137,491 MT of soybean meal, 8,167 MT of soybean hulls, and 3,975 MT of crude glycerin. The model provides a blueprint of a modern biodiesel plant based on the best information available from equipment manufacturers and communication with the industry. The model does not represent an industry average but rather a case study of a plant with the specifications cited earlier.

MODEL DESCRIPTION

Separation of the soybean into oil and soybean meal, which is generally referred to as crushing, can be done using mechanical extruders, but more commonly the oil is extracted from the soybeans using hexane extraction (fig. 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 life-cycle efficiency of 60.8%. Thus, the energy value for steam is incorporated into the energy value of the natural gas used to generate the required steam. Soybeans entering the process are first cleaned and then heated and dried to 10% (wet basis) moisture content (Erickson, 1995). The beans are cracked into several pieces by passing them through mechanical rolls. The soybean hulls, which account for about 8% 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 oil from the hexane. The crude soybean oil is degummed and deodorized, bleached, and neutralized. Hot air and cooling water are used in the final heating and drying of the oil. More details about the processing can be found in Anderson (2005).

Continuous changes in the soybean crushing industry are expected to reduce the energy requirement for biodiesel production. The best data available to Sheehan et al. (1998) on oil crushing were based on a single facility that was 17 years old at the time of the study. Thus, a typical plant in operation today is likely more efficient than the plant modeled by Sheehan et al. (1998). For example, the industry average oil extraction rate has increased from 0.169 kg/kg (10.16 lb/bu) of soybeans as reported by Sheehan et al. (1998) to 0.189 kg/kg (11.34 lb/bu) of soybeans in 2006/2007 (ERS, 2009b). The oil yield has further increased to 0.193 kg/kg (11.55 lb /bu) of soybeans in crop year 2007/2008. Even though the oil extraction rate for the later years was higher, the oil extraction rate for 2006/2007 was used in this study to be consistent with the 2006 ARMS agricultural input data. Furthermore, newer plants are more energy efficient due to the adoption of energy-saving technologies that reduce production costs. Process improvement in extraction plants has continued, with increasing emphasis on energy efficiency, reducing hexane loss, and increasing capacity. For instance, the current acceptable level of solvent loss is one-third the level used by U.S. extraction plants in 1970 (Woerfel, 1995).

CONVERSION OF SOYBEAN OIL INTO BIODIESEL

Conversion of soybean oil into biodiesel is done by reacting the oil with an alcohol (mostly methanol) and catalyst (mostly sodium hydroxide or sodium methylate) 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 biodiesel (fig. 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 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 data presented in table 3 for biodiesel conversion were obtained from the USDA-ARS model. The model assumes recovery of the catalyst and hydrochloric acid and reports steam as an input for biodiesel conversion. Space heat-

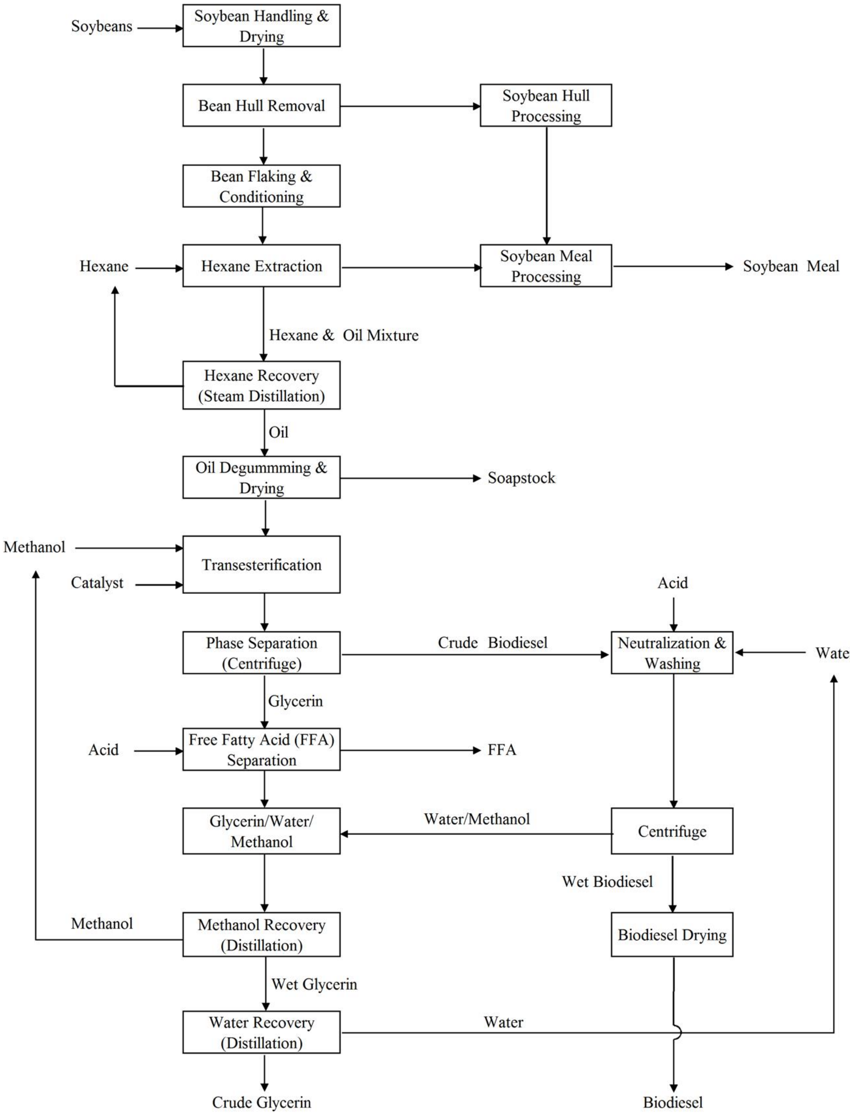

Figure 2. Process diagram for soybean crushing and biodiesel conversion.

Table 3. Fossil energy requirements for soybean crushing and conversion before allocating coproduct values (from USDA-ARS model).

Inventory	Quantity Used (per L biodiesel)	Equivalent Energy (MJ/L of biodiesel)[a]
Soybean crushing		
Electricity	212.3 Wh	1.6
Natural gas	106.8 L	4.2
Hexane	11.1 g	0.5
Biodiesel conversion		
Electricity	44.6 Wh	0.3
Steam from natural gas	124.1 g	0.4
Methanol	96.7 g	3.2
Sodium methylate	2.7 g	0.1
Hydrochloric acid	0.5 g	0.83×10^{-3}

[a] Calculated using table 1.

ing of the facility was not included in the model as it varies greatly depending on location and time of year. The model data showed that soybean crushing required a total of 6.3 MJ of fossil fuel, and reconversion of the soybean oil into biodiesel, recovery of the excess methanol, and treatment of the glycerin required 4.0 MJ/L of biodiesel produced.

The amount of energy required to convert soybean oil into biodiesel using transesterification may have decreased over the past decade. The rise in larger biodiesel facilities has prompted greater emphasis on minimizing energy costs. The capital cost of adding energy-saving technologies would be justified for larger plants, where the investment cost is less than the savings from lower energy costs. For example, heat-integration technologies have resulted in the capture and re-use 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 washwater stream used to purify biodiesel eliminates the need for wastewater treatment.

BIODIESEL TRANSPORT

Data from the GREET model were used to estimate the energy required for transporting biodiesel. Transporting biodiesel to marketing outlets requires 0.3 MJ/L of biodiesel. The

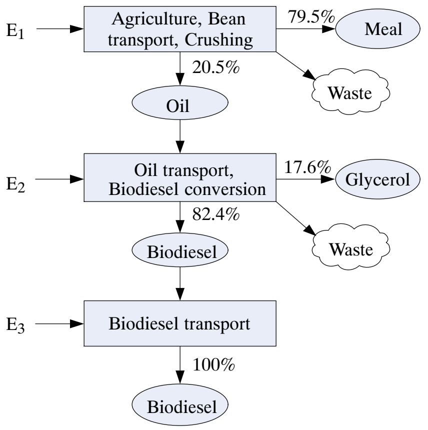

Figure 3. Mass-based energy allocation for biodiesel coproducts.

estimation was based on a total distance of 540 km (335 mi) using a combination of truck, barge, and rail, which included a distance of about 50 km (32 mi) for truck, 68 km (42 mi) for barge, and 374 km (232 mi) for rail to transport biodiesel from a plant to a distribution center, and another 48 km (30 mi) by truck to transport it to its final destination.

Energy Allocation for Coproducts

One of the major causes of the discrepancies in energy LCA report is the difference in the way the energy is allocated among the coproducts (Pradhan et al., 2008). 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. The energy used to produce the meal portion of the soybean and the crude glycerin that is produced during the transesterification stage must be discounted from biodiesel LCI. A mass-based allocation method was used to determine how the energy used is attributed among these coproducts (fig. 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., 1998). 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%. The other 4% is considered waste. Following transesterification, the proportion of refined biodiesel to crude glycerin (with a purity of about 80%) is 82.4% biodiesel and 17.6% crude glycerin. Therefore, 82.4% of the total energy used to convert degummed soybean oil into biodiesel is allocated to biodiesel (fig. 3). Therefore, in equation 2, $f_1 = 20.5\% \times 82.4\% = 16.9\%$, and $f_2 = 82.4\%$. All the energy used to transport biodiesel is allocated to biodiesel.

Results and Discussion

Combining the energy input estimates from the four subsystems completes the base case life-cycle assessment for biodiesel (table 4). As discussed earlier, 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 3 have been adjusted by energy efficiency factors. All estimates of electricity generation were based on weighted averages of all sources of power used in the U.S., including coal, natural gas, nuclear, and hydroelectric. Electricity use includes electricity generated from fossil sources, which on a national average equals 67%.

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

	Fossil Energy Use (MJ/L of biodiesel)	
Subsystems	Total Used	Biodiesel Fraction[a]
Soybean production	6.0	1.0
Soybean transport	1.2	0.2
Soybean crushing	6.3	1.1
Biodiesel conversion	4.0	3.3
Biodiesel transport	0.3	0.3
Total	17.8	5.9
Biodiesel total energy output		32.7
Fossil energy ratio (FER)		5.5

[a] Coproducts were allocated as shown in figure 3.

After adjusting the inputs by energy efficiencies and allocating energy by coproducts, the total energy required to produce a liter of biodiesel was 5.9 MJ (table 4). Biodiesel conversion uses the most energy, accounting for about 56% of the total energy required in the life-cycle inventory. Soybean crushing accounts for about 19%, followed by soybean agriculture, which requires almost 17% of the total energy. The net energy value (i.e., biodiesel energy output minus fossil energy input) is about 26.8 MJ/L of biodiesel (6.2 million Btu/ac). The estimated FER of biodiesel is 5.54, which is about 73% higher than the original FER reported by Sheehan et al. (1998) using 1990 data and 21% higher than that reported by Pradhan et al. (2009), which used 2002 data.

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. The soybean crushing facilities that have been built in recent times are far more energy efficient than the older plant used by Sheehan et al. (1998). In addition, since 2002, the U.S. EPA has required soybean plants to limit their hexane use; thus, the amount of hexane reported by Sheehan et al. (1998) had to be adjusted to reflect the new industry standard (EPA, 2004). The new hexane energy value that was used in this study is one-half of that reported by Sheehan et al. (1998). Overall, the energy required for crushing fell from 2.6 to 1.1 MJ/L of biodiesel, about a 58% reduction (fig. 4). This reduction in 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 2.1 to 1.0 MJ/L of biodiesel, about a 52% reduction (fig. 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 2006 is partially related to the adoption of GE soybeans; however, differences in weather and other factors unrelated to energy efficiency can cause annual variation in chemical use.

The energy required for transesterification estimated in this study was about 33% lower than the estimate reported by

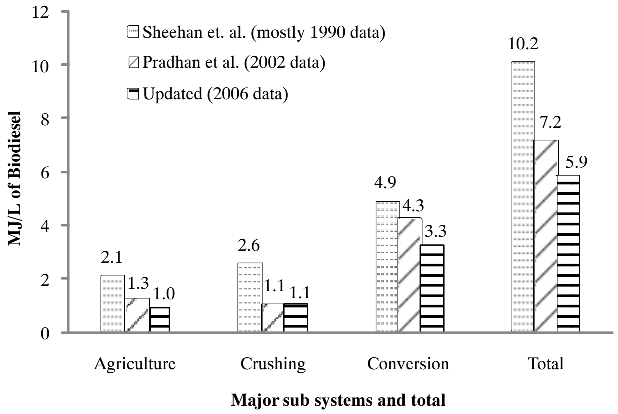

Figure 4. Comparing energy requirements for major biodiesel subsystems and total life-cycle energy requirements between this study, Pradhan et al. (2009), and Sheehan et al. (1998).

Sheehan et al. (1998) (fig. 4). The fossil energy for electricity and methanol usage decreased; however, natural gas and steam usage slightly increased. Overall, the total life-cycle energy required for biodiesel fell from 10.2 to 5.9 MJ/L of biodiesel.

Effects of Adding Inputs to the LCI

Figure 5 shows the effects of adding secondary energy inputs to the LCI that were not included by Sheehan et al. (1998) to determine how they affect the overall results. Hill et al. (2006) estimated the energy associated with manufacturing farm machinery to be 1.4 MJ (biodiesel share = 0.2 MJ) per L of biodiesel. Adding the biodiesel share of this energy to soybean production reduces the base case FER of 5.54 to 5.36. Hill et al. (2006) also estimated the energies associated with building materials to be 0.04 MJ (biodiesel share = 6.11 kJ) per L of biodiesel for a crushing plant and 0.02 MJ (biodiesel share = 15.4 kJ) per L of biodiesel for a biodiesel conversion plant. Adding the biodiesel share of energy related to building materials lowered the FER to 5.52. If the input energy for both agricultural machinery and building material were added to the inventory, FER would decline to 5.34.

Effect of Adding Lime to the LCI

Our base case LCI included lime, unlike the Sheehan et al. (1998) inventory that omitted lime. Lime is added to soil periodically, and the annual lime application rates are adjusted by average years between applications. Since farmers do not apply lime every year and some acreage never receives lime, the adjusted annual average lime application rate is relatively small. Lime use only accounts for 57.9 MJ/ha and lowers the FER by only about 0.3%. Therefore, including lime in the Sheehan et al. (1998) inventory would not have changed the results significantly.

Effect of Adding 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. However, many biodiesel plants do not have crushing capability, so they must purchase oil and have it transported to their plant. The model used by Sheehan et al. (1998) 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 0.21 MJ/L of biodiesel (biodiesel share = 0.17 MJ) for 920 km (571 mi). When adding this energy to our inventory, the FER declines to 5.39 (fig. 5).

Effect of Soybean Yield

Soybean yields have been improving over time because of new seed varieties, improved fertilizer and pesticide applications, and new management practices (Ash et al., 2006). In addition, the 1990 ARMS soybean production data used by Sheehan et al. (1998) did not include genetically engineered (GE) soybeans because they had not been introduced into U.S. agriculture yet. However, today almost all soybeans in the U.S. are GE varieties (ERS, 2010). 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 USDA-NASS Agricultural Chemical Usage survey, over the five-year periods 1990 to 1994, 1995 to 1999, and 2000 to 2004, the average herbicide use was 1.32, 1.24, 1.22 kg/ha (1.18, 1.11, and 1.09 lb/ac) per year, respectively (NASS, 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 2005 and 2006, mostly because of higher aphid infestation (T. Thorson, personal communication, 2008). 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 U.S. EPA than herbicides used in the past, such as alachlor (EPA, 1990). Kovach et al. (2007) found that the environ-

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

mental impact quotient (EIQ), which encompasses eleven different types of toxicity measurements and environmental impacts, was more favorable for glyphosate (EIQ =15.3) than for alachlor (EIQ = 18.3).

The U.S. annual soybean yield data show a significant increase in yields since 1980. Soybean yields have increased steadily since 1990, when the U.S. average yield was 2293 kg/ha (34.1 bu/ac); by 2006, the U.S. soybean yield had increased to 2885 kg/ha (42.9 bu/ac) (NASS, 2010). The data trend shows a continuous increase in yield of 33.6 kg/ha (0.5 bu/acre) per year without a significant increase in other agricultural inputs.

Even though yields have been higher in recent years, yield data for 2006 were used to calculate FER to correspond to the 2006 ARMS agricultural 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 yields to increase annually by 27 to 34 kg/ha (0.4 to 0.5 bu/ac) through 2017 (USDA, 2008). For every 100 kg/ha (1.5 bu/ac) increase in soybean yield, FER increases by about 0.76%.

SUMMARY AND CONCLUSION

The fossil energy ratio (FER) of biodiesel was 5.54 based on 2006 soybean production data. This is a significant improvement over the study by Sheehan et al. (1998), which reported an FER of 3.2, and even notably better than the FER of 4.56 that was found by Pradhan et al. (2009), which was based on 2002 data. The soybean crushing and transesterification facilities that have been built in recent times are more energy efficient than older plants. In addition, the continued improvement in soybean yields and reduced overall energy usage on the farm helped increase the energy balance of biodiesel. The lower chemical uses in recent years can partially be explained by the adoption of GE soybeans, which resulted in reduced pesticide use. Five-year average chemical use data showed a general decline in the amount of pesticide use.

The effects of adding secondary energy inputs to the calculations, such as those for agricultural machinery and building materials for a biodiesel plant, were also studied. The FER of biodiesel changed very little upon adding such secondary inputs. When the life-cycle energy for agricultural machinery fabrication and building materials were added, the FER decreased to 5.34 (3.6% reduction). 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 38.6 million L (10.2 million gal) per year.

The results from this research suggest a likely improvement of the biodiesel FER over time. All other factors being constant, for every 100 kg/ha (1.5 bu/ac) increase in soybean yield, the FER increases by 0.76%. In addition, the agricultural sector and the biodiesel industry are likely to continue to make energy efficiency gains in order to lower production costs, eventually achieving an even higher FER.

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