THE ENERGY BALANCE OF SOYBEAN OIL BIODIESEL PRODUCTION: A REVIEW OF PAST STUDIES

A. Pradhan, D. S. Shrestha, J. Van Gerpen, J. Duffield

ABSTRACT. *Although several studies have found biodiesel to be a renewable source of energy, there has been a claim that it is not. This article investigates models used to calculate the net energy ratio (NER) of biodiesel production to point out the reasons for the contradictory results, compares their strengths and weaknesses, and proposes a uniform model for interpretation of the final result. Four commonly referenced models were compared for their assumptions and results. The analysis revealed that the most significant factors in altering the results were the proportions of energy allocated between biodiesel and its coproducts. The lack of consistency in defining system boundaries has apparently led to very different results. The definitions of NER used among the models were also found to be different. A unified model is proposed for biodiesel energy analysis to answer the renewability question. Using the unified boundary, a range of probable NERs was calculated using bootstrapping. The mean NER on a mass basis was 2.55 with a standard deviation of 0.38. The economic sustainability ratio (ESR) is defined as the monetary value ratio of biodiesel to biodiesel's share of the energy inputs. The average ESR was found to be 4.43 with a standard deviation of 0.6.*

Keywords. *Biodiesel, Economic analysis, Energy balance, Life cycle analysis, Net energy ratio.*

Biodiesel production in the U.S. is growing rapidly. It has increased from under 1.89 million liters (1/2 million gallons) in 1999 to over 568 million liters (150 million gallons) in 2006 (Methanol Institute, 2007). Despite its rapid growth and several studies showing that it is a renewable energy source, others claim that the use of biodiesel does not reduce petroleum use.

Life cycle analysis (LCA) is a cradle-to-grave analysis for the energy and environmental impacts of making a product. Energy life cycle analysis (ELCA) provides a tool to quantify the total energy from different sources and the overall energy efficiency of processes. Energy balance involves accounting for the amount of energies used in the production and comparing it to the amount of energy contained in the resulting biofuel (Morris, 2005). The result obtained from the energy balance analysis can be expressed as the net energy ratio (NER), which is defined as the total energy produced by the system divided by the total energy consumed by the system (Spath and Mann, 2000). There are several ways the NER can be derived. The final result can be arbitrarily different depending on how the NER was defined. One of the objectives of this article is to compare the NER definitions used in the past according to their merit.

The fossil energy requirement of biodiesel production is a key to understanding the extent to which biodiesel is a renewable energy source. The renewability of biodiesel depends upon the amount of fossil energy required to produce the biodiesel (Sheehan et al., 1998). The renewability can range from completely renewable (if no fossil energy is required) to nonrenewable (if the fossil energy required is as much as or more than the energy content in the biodiesel). It is beneficial to know the renewability of a biofuel for two reasons: (1) to determine to what degree it is renewable, and (2) to compare the renewability of different biofuels.

The NER and the renewability are closely related but are slightly different. These two terms have been used loosely and interchangeably in the literature. Therefore, an attempt was made to distinguish these two terms. Calculation of renewability or the renewability factor (RF) accounts for only the nonrenewable energy used, which is fossil-based energy at this time, whereas the NER accounts for energy inputs from both renewable and nonrenewable sources. The NER is how much energy is produced per unit of energy spent. More precisely, the renewability factor is defined as:

$$\text{Renewability factor (RF)} = \frac{\text{Fuel energy output}}{\text{Nonrenewable energy input}} \quad (1)$$

The RF measures the environmental benefits derived from not having to use fossil-based energy. The higher the RF, the more renewable the biofuel is. The NER is never infinite, but the RF could be infinite. If the NER is greater than one, then theoretically, the biofuel could be used to replace all of the energy used in producing it, and hence the renewability is infinite. Therefore, the renewability analysis must be based on current industry practices (not on theoretical possible value) and strive towards achieving higher renewability for better

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The authors are **Anup Pradhan, ASABE Member Engineer,** Graduate Student, **Dev S. Shrestha, ASABE Member Engineer,** Assistant Professor, and **Jon Van Gerpen, ASABE Member Engineer,** Professor, Department of Biological and Agricultural Engineering, University of Idaho, Moscow, Idaho; and **James Duffield,** Senior Agricultural Economist, USDA, Office of the Chief Economist, Washington D.C. **Corresponding author:** Dev S. Shrestha, Department of Agricultural and Biological Engineering, University of Idaho, P.O. Box 442060, Moscow, ID 83844; phone: 208-885-7545; fax: 208-885-8923; e-mail: devs@uidaho.edu.

environmental benefits. Nevertheless, currently most of the energy used in biodiesel production is fossil based; hence, both RF and NER yield a similar number.

Low RF does not necessarily mean that a biofuel production system is undesirable. Some forms of energy have greater utility (such as liquid transportation fuel because of its higher energy density and suitability for use in internal combustion engines) and higher economic value than some other forms of energy such as coal, biomass, or natural gas. In other words, BTUs from different sources do not have equal utility. Therefore, it may be economically advantageous or functionally desirable to transform the fuel type, even if some energy is lost in the process.

Soybean oil is the primary feedstock used for biodiesel production in the U.S. Soybean biodiesel production is divided into five distinct processes: (1) soybean production (or farm inputs), (2) transport of soybeans to the processing facility, (3) separation of oil and meal, (4) conversion into biodiesel (or transesterification), and (5) transportation of biodiesel for distribution (Sheehan et al., 1998).

Ahmed et al. (1994) concluded that soybean biodiesel was a net energy generator based on a greater than unity NER. They included the energy use in growing and harvesting the crop, extracting the oil, and transesterifying the oil based on three different scenarios. The first scenario used U.S. national average energy use data for soybean farming, oil extraction, refining, and transesterification. The second scenario represented the existing best-case energy efficiency capability for soybean cultivation, oil extraction, refining, and esterification in the U.S. The third scenario was developed to represent future industry potential based on state-of-the-art agricultural practices integrated with the latest technological advances in the extraction and esterification of soy oil. They estimated an NER of 2.51 for the national average, 3.24 for the industry best, and 4.10 for the industry potential (table 1).

The NREL (Sheehan et al., 1998) used TEAM (Ecobalance, Neuilly-sur-Seine, France) as a modeling software for energy analysis. The NREL study showed an overall NER of 3.2 (table 1) and took into account the energy inputs associated with growing soybean, harvesting, transporting, crushing, transesterifying, and finally transporting the biodiesel. The NREL assumed that, on average, soybean processing resulted in about 18% oil and 82% meal on a mass basis. Furthermore, during oil conversion to biodiesel, 82% of the input mass of oil was assigned to biodiesel and 18% to the crude glycerin coproduct.

Pimentel and Patzek (2005) reported that the energy output from biodiesel is less than the fossil energy inputs. They claimed that the fuel produced using soybean oil required 27% more fossil energy than the energy contained in the biodiesel. The wide disparity between their results and those reported by other researchers has created much controversy. Van Gerpen and Shrestha (2005) pointed out that the biggest discrepancy in the results comes from the fact that Pimentel and Patzek's study assigned only 19.3% of the total input energy to the soybean meal, but in reality 82% of the soybean mass goes into meal. An arithmetic error in the report and an error in proper accounting of lime application that contributed to a discrepancy in the results were also pointed out. Pimentel and Patzek assigned 4,800 kg lime ha^{-1} year^{-1} for the average soybean crop, whereas according to the source they used (Kassel and Tidman, 1999), lime use was recommended for only acidic soil to correct pH once in a several years (usually 5 to 10 years).

Table 1. Net energy ratios reported for soybean biodiesel (SME).

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

Jobe and Duffield (2005) questioned the validity of Pimentel and Patzek's data on agricultural energy input and energy requirements for secondary inputs, such as steel and cement. Morris (2005) also pointed out some of the weaknesses in Pimentel and Patzek's analysis, noting that (1) the study was not clear about the inclusion of energy used to modify the vegetable oil into an ester suitable for use as a diesel fuel, (2) energy appropriated to the soy meal was only about 15% of the total input, and (3) Pimentel and Patzek assumed lime use of 2.2 tons per acre of soybean per year, ignoring the fact that one application can last for up to 10 years.

Hill et al. (2006) concluded that biodiesel would provide greater benefits if its biomass feedstock was producible with low agricultural inputs, producible on land with low agricultural value, and required low input energy to convert the feedstock to biodiesel. They reported that soybean biodiesel yielded 93% more energy than the total energy invested in its production. Their ELCA included energy inputs for soybean agriculture, crop transportation, crushing, oil transportation, transesterification, and transporting biodiesel to its point of end use. Both on-farm and off-farm labor, as well as the energies used for manufacturing agricultural equipment and constructing buildings, were included within the system boundary. Lime input was divided equally between corn and soybean.

In summary, a comparatively wide range of NER results was found in the literature; however, most researchers found a positive NER for biodiesel (table 1).

Another modeling software that has been used extensively to evaluate the energy performance of ethanol and other fuels is the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET V1.6) model developed by Argonne National Laboratory (2006). GREET is available under public license policy free of charge for anyone to use. Although several data used in the GREET model are derived from the NREL study, they are adjusted to reflect some temporal changes. GREET was included in this study for comparison purposes only.

The objective of this study is to find out the causes of discrepancies in the reported NERs by comparing the models used in previous studies. The NER models used for comparison were: Ahmed et al. (1994), Sheehan et al. (1998), Pimentel and Patzek (2005), and the GREET model by Argonne National Laboratory (2006). Henceforth, these models will be referred to as Ahmed's study, the NREL study, Pimentel's study, and GREET, respectively. This study will apply these models to soybean biodiesel, analyze the model discrepancies, recommend a unified system boundary, and re-evaluate the NER along with economic performance using the unified model.

Methodology

The references cited above were carefully evaluated and compared for (1) credibility of data, (2) consistency in energy inputs, (3) energy allocation approaches, and (4) the final conclusions. The results were analyzed for the most sensitive inputs and assumptions. Based on the results, a recommendation was made to unify the definition of the system boundary of the energy analysis studies used to answer renewability questions.

Using the unified model, the NER was recalculated. The data from all models were bootstrapped to get the probability distribution function and variance estimation of the net energy ratio. Bootstrapping is similar to Monte Carlo simulation, except the actual sample values are randomly chosen instead of fitting a probability distribution and then generating a number. Bootstrapping was preferred in this study because the energy used in some categories was reported by only a single researcher, and hence estimation of probability distribution parameters was not possible. Bootstrapping approximates the probability distribution of a statistic (Moore et al., 2003) and estimates the generalization error by resampling (Efron and Tibshirani, 1993). In addition to a simple net energy ratio, the monetary values of input and output energies were used to calculate an economic sustainability ratio (ESR). Bootstrapping was also carried out on the ESR estimate to account for variability in the final results.

Results of Model Comparison and Discussion

Assumptions about the farm inputs, oil extraction, and biodiesel conversion were found to be quite different among the different models. Even for the same input, the amount of embedded energy considered was found to be different. Embedded energy refers to the amount of energy required to produce an input and deliver it to the point of use, including the energy required in building the infrastructure that supports it. Discrepancies were also found in the amount of input required and the inclusion or exclusion of a particular input. For instance, the NREL model did not include the energy required for labor, the embedded energy in machinery, and the energy value of lime, whereas Pimentel's model did not include the energy required for the entire transesterification process. Some inputs were considered in only one model, such as the cement and steel used in the biodiesel plant. Findings from the models varied because of differences in input assumptions, amount of input use, and coproduct evaluation. The analysis was conducted for each stage of production, as described in the following sections.

Soybean Agriculture

The energy input for soybean agriculture varied from 4,032 MJ ha^{-1} in Ahmed's model to 15,506 MJ ha^{-1} in Pimentel's model (table 2). Considering average biodiesel production from soybean agriculture of 497 L ha^{-1} (201.4 L acre^{-1}; Peterson, 2005) and biodiesel energy content of 32.5 MJ L^{-1} (Mittelbach and Remschmidt, 2005), the biodiesel energy produced from 1 ha of soybeans is 16,152.5 MJ. It should be noticed that this is not a unique number and depends on the assumed value of the yield of soybeans per acre. The difference in agricultural energy input alone is about 71% of the energy input to biodiesel. Analysis showed that the main differences came from the assumed energy equivalence for seed, machinery, labor, and lime. These four inputs accounted for 69% of the agricultural energy in Pimentel's model versus 4.13% in the NREL model and 0% in the Ahmed and GREET models. Other energy inputs, such as fuel use and soybean transport, were also significantly different. Although there were large differences in the amounts of the agriculture inputs, the fraction of total energy input assigned to biodiesel (biodiesel share of energy) had the highest impact on the final result (table 2).

Table 2. Energy use in soybean farming (MJ ha^{-1} except for energy allocation).

Inputs	Ahmed	GREET	NREL	Pimentel
Labor	--	--	--	1188.26
Machinery	--	--	--	1506.24
Diesel	2024.52	1933.40	2734.00	1849.33
Gasoline	--	864.48	1467.53	1129.68
LP gas	--	75.93	103.91	104.60
Natural gas	--	--	0.12	--
Nitrogen	263.36	502.04	761.02	246.86
Phosphorus	150.11	439.17	477.39	652.70
Potassium	206.18	460.36	282.61	200.83
Lime	--	--	--	5644.22
Seeds	--	--	315.69	2317.94
Herbicide	520.18[a]	1231.28	1334.77	543.92
Insecticide		14.16	13.48	--
Electricity	--	46.73	160.70	121.34
Others	867.43[b]	--	--	--
Subtotal	4031.78	5567.54	7651.22	15505.90
Biodiesel share of energy (%)	18.80[c]	62.10	18.4	80.36[c]
Soybean transport	63.44	587.77	378.77	167.37

[a] Includes both herbicide and insecticide.

[b] Includes seed, on-farm electricity, and lime.

[c] Back-calculated from presented results for comparison.

The energy equivalent of different agricultural inputs used in the estimation of the NER varied among the models (table 3). For instance, the energy value of seed in Pimentel's model is almost eight times higher than that assumed in the NREL model. The conversion factor used by the NREL model reflects consideration of life cycle energy. It is interesting to see that hardly any conversion factors exactly match

Table 3. Farm inputs energy equivalent (dashed lines indicate a value either not considered or not reported).

Inputs	Ahmed	GREET	NREL	Pimentel
Labor (MJ h^{-1})	--	--	--	167.36
Machinery (MJ kg^{-1})	--	--	--	75.31
Diesel (MJ L^{-1})	38.44	35.78	51.12	47.66
Gasoline (MJ L^{-1})	--	32.34	52.85	31.64
LP gas (MJ L^{-1})	--	23.66	30.63	31.70
Natural gas (MJ L^{-1})	--	-	0.05	--
Nitrogen (MJ kg^{-1})	72.29	47.74	71.91	66.72
Phosphorus (MJ kg^{-1})	12.92	13.36	14.38	17.27
Potassium (MJ kg^{-1})	9.95	8.17	5.00	13.57
Lime (MJ kg^{-1})	--	-	--	1.18
Seeds (MJ kg^{-1})	--	-	4.71	33.45
Herbicide (MJ kg^{-1})	418.02	274.32	310.35	418.40
Insecticide (MJ kg^{-1})		314.98	310.35	--
Electricity (MJ kWh^{-1})	--	--	14.81	10.79
Soybean transport (MJ tonne^{-1} km^{-1})	0.28	--	1.29	1.09

among the models, even for a standard input such as electricity.

Seed Energy

The seed energy refers to the energy equivalence of soybean seed. There are two ways to assign energy equivalence to an input. One is to consider the absolute chemical or physical energy contributed by an input and is referred to as "calorific value." For instance, diesel fuel has a calorific value of about 36 MJ L^{-1} of fuel, which is taken as the energy input from diesel. The Ahmed and GREET models used this value (table 3) for energy conversion. Even though this approach is simple and direct, it does not reflect renewability and environmental impacts. The second method uses the energy consumed in producing a specific input as an energy equivalence of that input and is referred to as "life cycle energy." For instance, it takes some energy to extract and refine mineral oil into diesel fuel. That is why the energy equivalent of diesel fuel is considerably higher in the NREL and Pimentel models. The disadvantage of using this second approach is that it can be extremely complex and create ambiguity in defining the system boundary. For instance, accounting for the energy content in the seed may be quite complex and variable if it were to include the energy consumed by the seed company.

Usually, the life cycle energy of an input is higher than its calorific value, with seed as an exception. According to the NREL study, 3.16 MJ of total fossil energy is required per kg of soybean seed production, whereas soybeans contain 16.8 MJ kg^{-1} (estimated from the equivalent energy of the protein, carbohydrate, and fat in the seed). The rest of the energy in the seed comes from renewable solar energy trapped by the crop. Renewable energy input is not counted in calculating the total nonrenewable energy use. The NREL study modified the life cycle energy (3.16 MJ) of the seed by a multiplication factor of 1.5 to account for the energy requirement of handling and processing. The Pimentel study assumed that the energy requirement for seed was twice as much (33.45 MJ) as the calorific value of the soybean, which was almost equal to the calorific value of diesel fuel itself (table 3).

ISO standard 14041 (ISO, 1998) for life cycle analysis requires careful definition of the goal and scope of every LCA study. If the purpose of the study is to assess the renewability of biodiesel fuel production, then it makes sense to consider the life cycle energy of all inputs. However, if the objective of the model is to calculate the system efficiency, then it is not incorrect to consider either the calorific value or the life cycle energy, whichever is larger. However, it should be kept in mind that, according to the second law of thermodynamics, system efficiency is less than unity for all practical fuel production systems. Since life cycle energy was used for the agricultural inputs, if not for any other reason than for the sake of consistency, then life cycle energy should be considered for the seed as well.

Labor

The labor and machinery inputs were used only in Pimentel's model and were cited from previous work (Pimentel and Pimentel, 1996). Looking at the original source of these numbers, it was found that the energy for machinery was only an estimate from an unknown source. In the same table from which the machinery data were taken, the labor use for soybean agriculture was listed as 10 h ha^{-1} with a corresponding energy input of 19.5 MJ ha^{-1} (4,650 kcal ha^{-1}). This corresponds to human power output of 540 W (0.72 hp). This value is higher than the 75 W (0.1 hp) average physical power output from an average person (Lakomy, 1993). However, Pimentel's study used 7.1 h ha^{-1} from Ali and McBride (1990) instead of 10 h ha^{-1}. For the average human power output, the energy consumed by an average person during an entire year was considered, which is equivalent to a human power output of 46.5 kW (62.3 hp).

Calculating labor energy in this manner has some drawbacks. First, the average per capita energy consumption may not represent a person living on a farm compared to a person who commutes 80 km (50 miles) daily to work. Second, consideration of annual energy consumption by human laborers does not aid in evaluating the renewability of biodiesel, as human food consumption is independent of soybean agriculture. Third, people from other sectors of the economy use the service provided by people involved in biodiesel production through use of the biodiesel, thus reducing the consumption of services from the competitive fuel industry (i.e., regular diesel fuel). This makes the accounting very ambiguous and makes it difficult to track how much net labor was incurred or saved. Fourth, people are hired primarily for their ability to perform a task and not for their energy output. The physical energy input from human labor makes up a negligible fraction of the total energy input. Finally, the labor is not considered in other ELCA analyses (Shapouri et al., 2006; Wu et al., 2006). Therefore, it is recommended not to include labor as an energy input in biodiesel ELCA.

Lime

Pimentel's model has an error in interpreting lime use data from their original source. Pimentel's model included all of the lime (4,800 kg ha^{-1}) applied to one year's soybean crop, which accounted for 36% of the total agricultural energy input. The data were taken from Kassel and Tidman (1999), in which lime was recommended for acidic soil only once in several years (usually 5 to 10 years). Since lime is applied on average every 5 to 10 years, the total application amount should be spread out on a per year basis. Crop rotation does not affect the lime allocation when the lime consumption per year is used in the calculation.

Energy Allocation to Coproducts

While different energy input values are major factors causing the results to vary among the studies, the biggest difference, which can completely reverse the final result, is the method used to allocate the energy use for coproducts. Since more than one final product comes out of the process, each product should share the input energy in some way. The most common method of energy allocation is a mass fraction basis.

When all coproducts have a food value, their calorific value can be used to allocate energy credits (Shapouri et al., 2006). Calorific value would also be a good way to assign energy credits if all coproducts were used for energy. However, in the case of biodiesel, soybean meal is not used as an energy source but as animal feed; hence, it has a higher market price than biodiesel for an equivalent caloric value. The NREL and GREET models assigned the energy in proportion to the mass fraction of output, whereas the Pimentel model subtracted the energy contained in the meal from the total input energy. Hill et al. (2006) also used the calorific value of meal as an energy credit.

Another logical way to allocate energy for different products would be according to the market value of each product.

From a producer's point of view, the input cost must be justified by the economic value of the end-product. A high-value product should absorb a bigger portion of the input cost than a low-value product. One of the costs in biodiesel production is the purchase of input energy, and fractions of this input energy can be assigned to different end-products according to their economic value. The market value of a product can serve as a way to evaluate the quality of the energy contained in the product. This approach would measure biofuel's economic sustainability. One drawback of this approach is that market dynamics can change the allocation factor, and a good energy balance today can turn out to be a poor energy balance tomorrow.

Shapouri et al. (2006) pointed out another method of energy allocation based on the replacement value of the primary product. For biodiesel, the replacement value is based on the energy required to produce a substitute for each coproduct. Even though this is one of the scientifically preferred methods (Kim and Dale, 2002; Farell et al., 2006), the difficulty with this method is to find an exact substitute for soybean meal. For example, dried distillers grain (DDG) or canola meals are animal feed products similar to soybean meal, but they are not exact substitutes. Even if they were comparable substitutes, it may be impossible to calculate a precise replacement energy value.

Even though the NREL study indicated that the total energy was assigned to the final products according to the mass fraction of the output stream, there seems to be some error in the agricultural energy allocated to soybean meal and oil. The energy allocation for soybean oil was found to be only 13.7% of the total energy used in soybean agriculture, whereas soybean contains 18.4% oil. The NREL study does not specifically mention a 13.7% energy allocation to oil; however, this value can be estimated from the presented results of 3.13795 MJ kg^{-1} of soybean in the original report (table 62, p. 116), soybean oil content (table 64, p. 121), biodiesel conversion rate (p. 143), biodiesel energy content (p. 181), and final consideration of fossil energy of 0.0656 MJ MJ^{-1} of fuel (table 6, p. 17) for agriculture as:

$$\frac{3.13795\ \text{MJ}}{\text{kg soybean}} \times \frac{1\ \text{kg soybean}}{0.184\ \text{kg oil}} \times \frac{1\ \text{kg oil}}{0.964\ \text{kg biodiesel}} \times \frac{1\ \text{kg biodiesel}}{36.95\ \text{MJ}} = 0.4788\ \text{MJ}\ \text{MJ}^{-1}\ \text{of fuel} \tag{2}$$

Therefore, the soybean agriculture energy allocation = 0.0656 / 0.4788 × 100% = 13.7%. This discrepancy might have been due to an error in the report. If the error is corrected to allocate energy according to mass, then the final NER would be reduced from 3.2, as stated in the report, to 3.0.

SOYBEAN TRANSPORT

There was a significant variation in soybean transport energy among the models. Ahmed's model estimated the transportation energy based on 80 km (50 miles) of crop transport distance by truck. The NREL study assumed that the soybeans were moved by trucks from the field to a crushing plant located at a 120 km (75 mile) radius. In Pimentel's study, the soybean transportation included transportation of machinery, fuel, and seed at an estimated distance of 1,000 km (621 miles). The other models did not assume any energy for transportation. Despite the longer distance included for soybean transport in Pimentel's model, it was interesting to see that the actual energy allocated to soybean transport was smaller (table 2).

Assuming that the crushing plant is at the center of a circular field, the theoretical minimum distance needed to supply soybeans for a 189 ML (50 million gallon) oil production plant is about 24 km (15 miles) with average yield and oil content. Even after considering inefficiencies, 1,000 km transportation of soybeans, as assumed by Pimentel, for crushing is hard to justify. Since soybean transportation is only a small fraction of the total energy input in all cases, it is not a major factor leading to the differing conclusions.

SOY OIL EXTRACTION AND OIL TRANSPORT

The energy input for oil extraction varied from the lowest estimate of 4,611 MJ ha^{-1} in Ahmed's study to 7,938 MJ ha^{-1} in the NREL study (table 4). The difference was about 21% of the energy in the biodiesel. The energy per hectare was chosen for unit consistency from the analysis for soybean agriculture. Fuel use (including electricity) was the major energy input for soybean oil extraction. The NREL model assumed the highest amount of fuel used. All studies reported fuel inputs of more than 4,300 MJ ha^{-1}. The soybean crushing data reported by the NREL study were from a single performance study conducted in 1981. There have been many improvements in oil extraction technology since then. For instance, currently acceptable levels of hexane loss are less than 1/3 of the level reported in the NREL study (Woerfel, 1995). The data used in Pimentel's study originated from industry interviews from 1979. The data used in Ahmed's model were from 1993 and were collected through personal communication.

Only Pimentel's model included secondary energy inputs, such as cement, steel, space heat, losses, and other materials associated with equipment and construction, which alone totaled 2,254 MJ ha^{-1} (about 1/3 of the oil extraction energy input). Compared to this value, Hill et al. (2006) reported energy input for the production facility as 30 MJ ha^{-1} (0.06 MJ L^{-1}). Pimentel included energy for secondary inputs to account for the energy required for building the infrastructure used specifically for crushing soybeans into oil and meal and for converting the oil into biodiesel. Researchers

Table 4. Energy use in oil extraction (MJ ha^{-1} except for energy allocation).

Inputs	Ahmed	GREET	NREL	Pimentel
Electricity	1016.71	607.56	2037.78	1400.39
Steam production	3375.40	--	2940.28	2712.37
Natural gas	--	5653.50	2846.72	884.03
Hexane	219.12	200.09	112.72	--
Space heat	--	--	--	305.39
Losses	--	--	--	602.75
Cleanup water	--	--	--	321.47
Stainless steel	--	--	--	317.45
Steel	--	--	--	494.25
Cement	--	--	--	212.97
Subtotal	4611.23	6461.14	7937.50	7251.07
Biodiesel share of energy (%)	18.80[a]	62.10	18.00	80.40[a]
Oil transport	--	--	717.28	--

[a] Value represents calculated equivalent for comparison.

Table 5. Oil extraction input energy equivalent.

Inputs	Ahmed	GREET	NREL	Pimentel
Electricity (MJ kWh^{-1})	11.24	--	12.98	10.79
Steam (MJ kg^{-1} BD)	7.66	--	7.35	5.65
Natural gas (MJ kg^{-1} BD)	--	13.11	7.12	1.84
Hexane (MJ kg^{-1})	44.76	--	22.88	--
Space heat (MJ kg^{-1} BD)	--	--	--	0.64
Losses(MJ kg^{-1} BD)	--	--	--	1.26
Cleanup water (MJ kg^{-1} BD)	--	--	--	0.67
Stainless steel (MJ kg^{-1})	--	--	--	60.10
Steel (MJ kg^{-1})	--	--	--	49.01
Cement (MJ kg^{-1})	--	--	--	7.92
Oil transport (MJ tonne^{-1} km^{-1})	--	--	2.04	--

who do not include secondary inputs in their analyses argue that the energy required for these inputs is very small in proportion to the total energy required, and that adding this complex step to the analysis takes a considerable amount of additional work and is not justified (Delucchi, 1993).

The energy equivalence of different inputs used in the estimation of the NER of the oil extraction phase showed significant variation among the models (table 5). The energy value of electricity used by the NREL model was about 84% lower than that used by the other models. The NREL model used only half the energy value of hexane compared to that used by Ahmed. The actual energy content of hexane is 44.73 MJ kg^{-1} (ASTM, 1991), which is closer to the number used by Ahmed.

The NREL study estimated soybean oil transportation for an average radius of 920 km (571 miles). The NREL estimation was based on a calculated average distance from the soybean crushers to 14 major metropolitan areas in the U.S. using trains as a mode of transportation. The other models did not include soybean oil transport.

TRANSESTERIFICATION AND BIODIESEL TRANSPORT

The energy input for transesterification varied from 2,477 MJ in the NREL model to 4,050 MJ per hectare of production in Ahmed. The difference is 9.7% of the energy provided from the biodiesel (table 6). The significant difference was observed to be the steam input equivalent of 2,535 MJ in Ahmed, compared to none in GREET and Pimentel. The GREET model reported natural gas use that alone accounted for 56% of the transesterification energy input in the model.

The NREL study used a transesterification model from an older commercial transesterification facility located in Kansas City in 1994. Apparently, Pimentel's model did not assign any energy value for processing soybean oil into biodiesel or for transportation. The Pimentel study offers no explanation for excluding the transesterification phase, which is a major component of the biodiesel production process. The energy estimates for the transesterification procedure in Ahmed's model were based on data from 1993, which were collected through personal communication. The NREL model assumed biodiesel transportation for a maximum distance of 160 km (100 miles) using trucks from the production facility to the point of end use. Biodiesel transport energy values for the GREET and Ahmed models are shown in table 6.

Table 6. Energy use in transesterification (MJ ha^{-1} except for energy allocation).

Inputs	Ahmed	GREET	NREL	Pimentel
Electricity	370.90	341.69	124.91	--
Steam	2535.51	--	651.18	--
Natural gas	--	1867.80	--	--
Methanol	1018.38	801.63	1289.74	--
Sodium methoxide	--	10.02	339.18	--
Sodium hydroxide	125.49	263.54	15.93	--
Hydrochloric acid	--	32.07	55.96	--
Subtotal	4050.29	3316.74	2476.90	--
Biodiesel share of energy (%)	90.20[a]	79.60	90.00	--
Biodiesel transport	31.72	143.35	71.89	--

[a] Value represents calculated equivalent for comparison.

Table 7. Transesterification input energy equivalent.

Inputs	Ahmed	GREET	NREL	Pimentel
Electricity (MJ kg^{-1} BD)	0.84	0.79	0.31	--
Steam (MJ kg^{-1} BD)	5.76	--	1.63	--
Natural gas (MJ kg^{-1} BD)	--	4.33	--	--
Methanol (MJ L^{-1} methanol)	18.54	15.95	31.73	--
Sodium methoxide (MJ kg^{-1} BD)	-	0.02	0.85	--
Sodium hydroxide (MJ kg^{-1} NaOH)	26.21	--	0.04	--
Hydrochloric acid (MJ kg^{-1} BD)	--	0.07	0.14	--
Biodiesel transport (MJ kg^{-1} BD)	0.07	0.34	0.18	--

It is interesting to see the extreme variability in energy values used for some of the inputs. For instance, the energy equivalent of sodium hydroxide used in Ahmed's model was over 650 times higher than that used in the NREL model (table 7).

DEFINITION OF THE NET ENERGY RATIO

Not only did the values of energy inputs differ among the studies, as discussed in the previous sections, but the definition of the net energy ratio used to measure the renewability of biodiesel was also found to be different. The NREL and GREET models estimated the NER as the ratio of the energy content in biodiesel to the fossil energy required to produce the biodiesel (eq. 3). The energy required to produce biodiesel was the fraction of the total energy assigned to biodiesel in proportion to the mass fraction of the biodiesel output stream; E_1, E_2, and E_3 are the energy inputs for agricultural production and soybean transport, crushing and oil transport, and transesterification and biodiesel transport, respectively (fig. 1). To estimate the total energy going into biodiesel, the NREL model multiplied these energies by the fractions f_1, f_2, and f_3 depending on the mass fraction of biodiesel after that

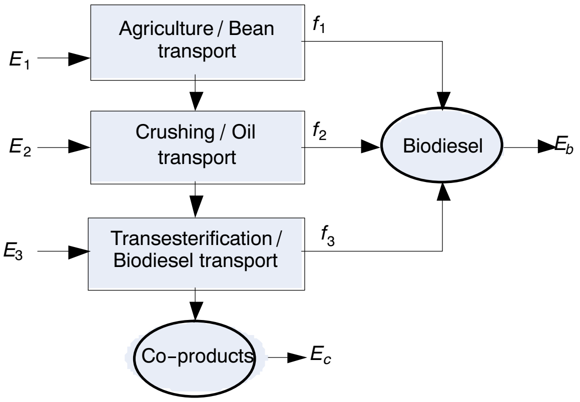

Figure 1. Energy allocation model: $E_{1...3}$ are the total energy inputs, $f_{1..3}$ are the fractions of the total energy inputs attributed to biodiesel, and E_b and E_c are the calorific values of biodiesel and the coproduct(s).

process. According to the NREL model, the net energy ratio is defined as:

$$\text{NER}_{\text{NREL}} = \frac{E_b}{E_1 f_1 + E_2 f_2 + E_3 f_3} \tag{3}$$

where E_b is the calorific value of biodiesel.

Pimentel's model defined the NER differently. Pimentel subtracted the energy contained in the meal (calorific value of meal) from the total input energy and divided the biodiesel energy content by this amount to get the net energy ratio (eq. 4):

$$\text{NER}_{\text{Pimentel}} = \frac{E_b}{E_1 + E_2 + E_3 - E_c} \tag{4}$$

where E_c is the calorific value of the meal.

In Ahmed's model, the coproduct energy was calculated by multiplying the total energy input by the mass fraction of the coproducts, and its value was added with E_b in the numerator instead of subtracting it from denominator, as Pimentel did. Mathematically, the net energy ratio was defined as:

$$\text{NER}_{\text{Ahmed}} = \frac{E_b + E_c}{E_1 + E_2 + E_3} \tag{5}$$

and the energy credit for meal was defined as:

$$E_c = E_1(1 - f_1) + E_2(1 - f_2) + E_3(1 - f_3) \tag{6}$$

Pimentel's model did not use equation 6 to calculate coproduct credit. Instead, it used the energy value of soybean meal. Note that if equation 6 is used to calculate coproduct credit, then equations 3 and 4 become equivalent. The disadvantage of not using equation 6 to calculate coproduct credit is that the definition of the NER can be problematic. As E_c approaches the sum of the total energy inputs, the ratio approaches infinity. Furthermore, since E_c may contain stored solar energy that is not included as an energy input, it may actually be greater than the sum of the energy inputs. As pointed out by Van Gerpen and Shrestha (2005), if a proper calorific value is assigned, then E_c may actually be larger than the total energy input, giving a negative NER.

Ahmed's definition of the NER is logical if the coproducts are also used for fuel. The total energy output in this model is the energy content in biodiesel and its coproducts. Since soybean meal is not generally used for energy purposes, this definition carries less meaning in evaluating the renewability of the fuel. Hill et al. (2006) defined the NER as a combination of Pimentel's definition and Ahmed's definition. They calculated E_c as the calorific value of the coproducts following Pimentel, but added it to the numerator as Ahmed did.

Each NER defined above provides a unique result, even for the same data set. For example, for the NREL model: E_1 = 8,030 MJ ha^{-1} (from table 2, including soybean transport) and f_1 = 0.14; E_2 = 8,655 MJ ha^{-1} (from table 4) and f_2 = 0.18; E_3 = 2,549 MJ ha^{-1} (from table 6) and f_3 = 0.9; and E_b was taken as 16,000 MJ ha^{-1}. The value of E_c for equation 4 was taken as 4,420 MJ ha^{-1} (2.2 million kcal per 1000 kg of biodiesel) from Pimentel's study, as Pimentel did not use equation 6 to calculate coproduct credit. Using the above numbers:

NER from NREL and GREET (eq. 3) = 3.21

NER from Pimentel's definition (eq. 4) = 1.08

NER from Ahmed's definition (eq. 5) = 1.57

The variation in the results clearly shows that the reported numbers should be interpreted carefully, as they do not mean the same thing. Which definition to use depends on the research question that is being answered.

Soybean meal coproduct is not used for energy, and using the calorific value of the coproduct would make the number harder to interpret. If a coproduct such as glycerol is used as a source of energy in the process, it reduces the use of nonrenewable energy and should be accounted for in the calculation of RF. Therefore, for the NER, we found equation 3 to be most appropriate.

If equation 3 (the NREL equation) is used to define the NER with the Ahmed, GREET, and Pimentel data without any adjustments, then the NERs would be 3.15, 3.11, and 4.80, respectively. It is interesting to note that the Pimentel data yielded the highest NER because this model apparently left out the transesterification energy.

PROPOSED SYSTEM BOUNDARY, ENERGY ALLOCATION, AND NER DEFINITION

The system boundary defines what is included and excluded in a model. It is almost impossible to track all the energy used over the life cycle of a product because each input has a life cycle of its own, and in turn the inputs required to produce each input all have unique life cycles. Therefore, a researcher must limit the system boundary used in the analysis and still provide a meaningful ELCA. Considerable discrepancies were observed among the four models in their system boundary definitions. A reasonable system boundary should be defined and justified in LCA based on the objectives of the study (ISO, 1998).

This study develops a new system boundary based on the merits and shortcomings of the earlier models to answer the biodiesel renewability question. The following observations were made when carefully examining each of the four system boundaries:

- As discussed earlier in the Labor section, human food consumption should not be included as an energy input because it does not aid in answering the renewability question and creates a circular reference within the system boundary. In any case, since the calorific value provided by human labor accounts for a negligible fraction of the total energy, this input can be excluded without introducing much error.
- As discussed in the Seed Energy section, life cycle energy (not calorific value) should be assigned as the equivalent energy for an input.
- Energy associated with inputs, including machinery, fertilizer, pesticides, lime, chemicals, liquid fuel, electricity, and other fuels used in production and transportation and processing, should be included.
- Energy required for building and maintaining the biodiesel infrastructure, such as a biodiesel plant, should be included and amortized per unit of biofuel production.
- Each coproduct should share a portion of the energy input according to its mass fraction or economic value. The choice depends on the type of research question being answered. For a renewability analysis, mass

fraction of the coproduct energy is helpful in determining the NER. On the other hand, the economic value of the coproduct energy is suitable for analyzing the economic viability of the energy production system.
- Equation 3 should be used as the definition of NER because it considers only the fuel production system and allocates energy to biofuel as a portion of the total energy used.

REVISED ANALYSIS

Along with this new system boundary, a statistical procedure known as bootstrapping (Mathworks, 2007) was incorporated into the model to estimate a range of NERs. Bootstrapping is used to estimate the most likely NER when there is uncertainty in the model inputs and significant variation among models. Since some models combined certain inputs, such as insecticide and herbicide in Ahmed's model, and some models reported natural gas instead of steam as the process heat source, the energy inputs were aggregated into three categories: fuel input, material input, and input from infrastructure overhead. Fuel inputs are direct energy inputs in the form of electricity, natural gas, and liquid petroleum fuels. Material inputs are the direct energy inputs that are consumed in the biofuel production process, such as fertilizer, chemicals, and hexane. Infrastructure overhead is the energy required to build the infrastructure that is relatively permanent, such as machinery, cement, and steel. In this study, diesel, gasoline, LP gas, natural gas, steam, electricity, space heat, and energy losses are categorized as fuel inputs. Nitrogen, phosphorus, potassium, lime, seed, herbicide, insecticide, hexane, cleanup water, methanol, catalyst, and acid are categorized as material inputs. Machinery, stainless steel, steel, and cement are classified as infrastructure inputs. Table 8 summarizes the categorized energy inputs reported by the different studies.

Table 8. Categorized sum of energy inputs reported in all models (MJ ha^{-1} soybean production).

					Biodiesel Fraction Based on:	
Input	Ahmed	GREET	NREL	Pimentel	Mass	Economic Value
Agriculture						
Fuel	2024.5	2920.5	4466.3	3205.0		
Material	2007.3	2647.0	3185.0	4903.0[a]		
Infrastructure	--	--	--	1506.2		
Soybean transport	63.4	587.8	378.8	167.4	0.18	0.32
Crushing						
Fuel	4392.1	6261.1	7824.8	5904.9		
Material	219.1	200.1	112.7	321.5		
Infrastructure	--	--	--	317.5		
Oil transport	--	--	717.3	--	0.90	0.88
Transesterification						
Fuel	2906.4	2209.5	776.1	--		
Material	1143.9	1107.3	1700.8	--		
Biodiesel transport	31.7	143.4	71.9	--	1.00	1.00

[a] Lime application was assumed to be once every 6 years.

During bootstrapping, an energy value from one of the models is randomly chosen for each input category from table 8. However, for the agriculture infrastructure category, Pimentel's number was used because the other models did not include this quantity. Every iteration used a complete set of energy inputs to calculate the renewability. A large number of iterations was performed to ensure that the energy inputs from each model were included in each category. Coproduct values were given according to the mass fraction to estimate NER (table 8).

A probability distribution function was computed for the NER (eq. 3) from 10,000 iterations of bootstrapping. It was found to be a slightly bimodal distribution, with a major peak at an NER of 2.3 and minor peak at 3. This is reflected in the cumulative distribution curve (fig. 2a) having its highest slope at an NER 2.3. The bimodality resulted primarily from Pimentel's data set being considerably different from the others. The mean NER was found to be 2.55 with a standard deviation of 0.38. Note that this is higher than the average NERs shown in table 1. This is primarily because of the use of equation 3 as the definition of NER for all models and the correction of some obvious errors in the reported data. The median NER was found to be 2.44, and the NER corresponding to a 5% probability was found to be 2.08.

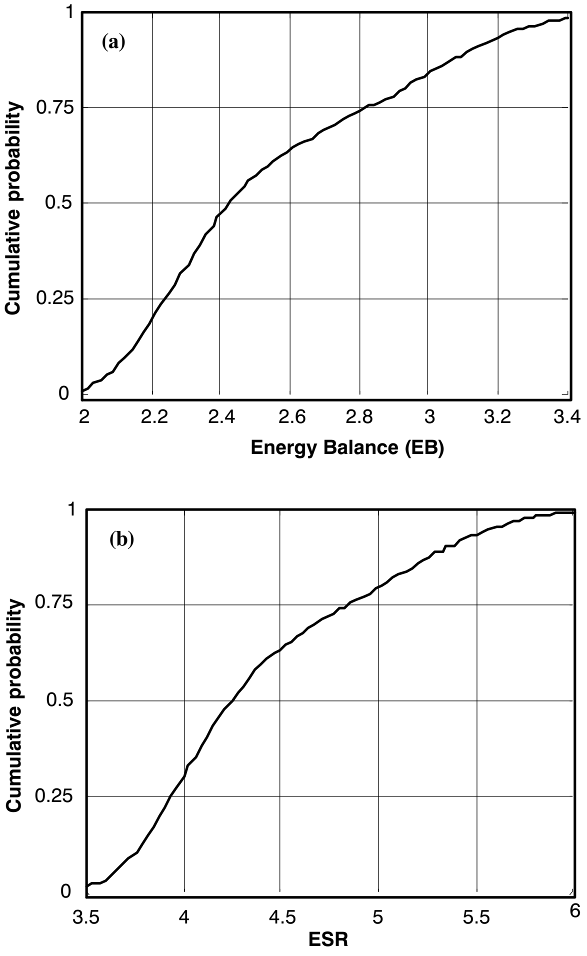

Figure 2. Cumulative probability plot from bootstrapping: (a) the probability of NER being less than the value on the *x*-axis, and (b) the probability of ESR being less than the value on the *x*-axis.

MEASURE OF THE ECONOMIC SUSTAINABILITY

While the NER can be helpful in calculating the extent of renewability, it does not provide a complete picture of whether an energy production system would be economically viable. Not all energy sources have equal economic value. Energy from coal or natural gas is cheaper than electricity or liquid petroleum for the same amount of energy (table 9). Since biodiesel is a substitute for diesel fuel for transportation with additional environmental benefits, biodiesel has more useful energy than the energy used to make it.

A parameter that incorporates the energy requirement along with the market value of that energy would be helpful in determining the viability of a fuel. This parameter will be referred to as the economic sustainability ratio (ESR). The ESR is defined as the ratio of the economic value of the output energy to its share of the economic value of the input energies. Mathematically:

$$\text{ESR} = \frac{E_b . C_b}{\sum f_i E_{ai} C_i + \sum f_i E_{oi} C_i + \sum f_i E_{ti} C_i} \tag{7}$$

where E_b is the energy in biodiesel, C_b is the unit energy price for biodiesel, E_{ai} is the energy input in agriculture and soybean transport from energy source i, C_i is the per unit energy cost from source i, E_{oi} is the energy input in oil extraction and oil transport from source i, E_{ti} is the energy for transesterification and biodiesel transport from source i, and f_i is the fraction of the biodiesel revenue from the process coproducts according to their fair market value. The ESR gives an estimate of whether a bioenergy system can be self-sustaining for given market prices for different energy sources.

Notice that equation 7 is comparable to equation 3; the only difference is that the monetary value of energy is used instead of energy itself to calculate the ESR. It is important to understand that the ESR is based only on energy values and does not represent overall return on investment. The ESR gives only a guideline on how a biodiesel industry will perform at various fuel prices. The energy fraction in the economic analysis was determined using the current market values of the biodiesel and its coproducts. The present market price of soybean oil, soy meal, biodiesel, and glycerin are \$0.60 kg^{-1} (\$0.273 lb^{-1}), \$0.20 kg (\$0.09 lb^{-1}), \$0.90 kg^{-1} (\$3 gal^{-1}) and \$0.11 kg^{-1} (\$0.05 lb^{-1}), respectively (CBOT, 2006). Therefore, 65% of the energy fraction was assigned to the meal and only 3% was assigned to glycerin. We recognize that the price of glycerin is volatile and some producers may not receive any payment for their glycerol, but the calculation uses only the market average.

Diesel fuel was used as the transportation fuel. For the energy used in the material and infrastructure inputs, the weighted average unit energy price was calculated using the national average fossil fuel use (EIA, 2006). The average energy cost was estimated as \$0.012 MJ^{-1}, which was a little higher than the unit energy price for natural gas (table 9).

A cumulative probability distribution function of the ESR (from eq. 7) was also computed from 10,000 iterations of bootstrapping (fig. 2b). The mean ESR was found to be 4.43 with a standard deviation of 0.61. The median ESR was found to be 4.26. The NER corresponding to 5% probability was found to be 3.65.

Table 9. Energy price comparison (EIA, 2007).

Fuel	2006 Average Price		Energy Content		Unit Energy Price (\$ MJ^{-1})
Coal	\$48.95	short ton^{-1}	21347	MJ short ton^{-1}	0.0023
Natural gas	\$0.011	cft^{-1}	1.05	MJ cft^{-1}	0.0105
Diesel	\$2.5	gal^{-1}	138	MJ gal^{-1}	0.0181
Gasoline	\$2.24	gal^{-1}	122	MJ gal^{-1}	0.0184
LP gas	\$1.9	gal^{-1}	95.3	MJ gal^{-1}	0.0199
Biodiesel	\$3.00	gal^{-1}	125	MJ gal^{-1}	0.0240
Electricity	\$0.0939	kWh^{-1}	3.6	MJ kWh^{-1}	0.0261

SUMMARY AND CONCLUSION

To better understand the source of discrepancies in biodiesel energy balance reports, four frequently cited models (Ahmed, GREET, NREL, and Pimentel) were compared. A deeper look at these models revealed that the models varied by system boundary, input amounts, assumed energy equivalence, and even in the definition of NER. However, the contradictory results were mainly due to differences in the proportion of energy allocated to biodiesel and its meal coproduct. All models except Pimentel reported a positive NER.

The discrepancies in the models pointed towards a necessity of a definite system boundary and standard definition of NER. Based on the research question on assessing the renewability of biodiesel, a unified system boundary was developed that excluded labor energy, arguing that it does not aid in answering the renewability question and causes the analysis to enter into a circular reference. Since the physical human power output contributes a negligible fraction of the total energy, eliminating it from the analysis has no effect on the final results for all practical purposes. It was argued that the coproducts should share the energy input according to their economic value or mass fraction. A specific guideline was presented to define the system boundary of the biodiesel production system.

The economic sustainability ratio (ESR) was introduced to calculate the economic sustainability of the biodiesel production system. The ESR was the ratio of the revenue from biodiesel to the cost of the biodiesel's share of the energy inputs. Based on the unified system boundary, the NER and ESR ranges were recalculated using bootstrapping. The NER on a mass basis resulted in a mean value of 2.55. Based on the bootstrapping results, there was a 95% probability that the NER was at least 2.08. This is a very strong indication that the biodiesel from soybean has a favorable NER of greater than 2.08. Because of the higher economic value of the energy from biodiesel, the ESR was higher than the RF. The analysis resulted in a mean ESR of 4.43. This indicates that making biodiesel on average returns 4.43 times the cost of the energy input. The results indicated that soybean biodiesel is both renewable and economically sustainable.

Incomplete data are the rule rather than the exception in ELCA. The life cycle energy balance of soybean biodiesel production could be more comprehensive with updated data for soybean crushing, oil transport, transesterification, and biodiesel transport. Furthermore, with the continuous development of new technologies, current input data are critical for the accuracy of the energy balance analysis of biodiesel. Since the data currently used for crushing, transportation, and transesterification are old, it is suggested that updating these data be a high priority.

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REFERENCES

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

Ali, M. B., and W. D. McBride. 1990. Soybeans: State level production costs, characteristics, and input use. Washington, D.C.: USDA-ERS.

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

ASTM. 1991. *Physical Constants of Hydrocarbon and Non-hydrocarbon Compounds*. ASTM Data Series DS 4B. West Conshohocken, Pa.: ASTM.

CBOT. 2006. Soybeans futures settlement. Chicago, Ill.: Chicago Board of Trade. Available at: www.cbot.com/cbot/pub/page/0,3181,959,00.html. Accessed 28 December 2006.

Delucchi, M. A. 1993. Emissions of greenhouse gases from the use of transportation fuels and electricity. ANL/ESD/TM-22. Argonne, Ill.: Argonne National Laboratory, Center for Transportation Research.

Efron, B., and R. J. Tibshirani. 1993. *An Introduction to the Bootstrap*. London, U.K.: CRC Press.

EIA. 2006. Annual energy review 2005. DOE/EIA-0384(2006) Washington D.C.: U.S. Department of Energy, Energy Information Administration.

EIA. 2007. Short-term energy outlook. Available at: www.eia.doe.gov/pub/forecasting/steo/oldsteos/mar07.pdf. Accessed 1 January 2008.

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare, and D. M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311(5760): 506-508.

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

ISO. 1998. Environmental management – Life cycle assessment: Goal and scope definition and inventory analysis. ISO 14041. Geneva, Switzerland: ISO.

Jobe, J., and J. Duffield. 2005. NBB and USDA statements on Pimentel energy balance paper. Jefferson City, Mo.: National Biodiesel Board.

Kassel, P., and M. Tidman. 1999. Ag lime impact on yield in several tillage systems. Ames, Iowa: Iowa State University, Integrated Crop Management.

Kim, S., and B. E. Dale. 2002. Allocation procedure in ethanol production system from corn grain. *Intl. J. Life Cycle Assessment* 7(4): 237-243.

Lakomy, H. K. A. 1993. Laboratory measurement of human power output during maximum-intensity exercise. *Physics Edu*. 28(6): 376-379.

Methanol Institute. 2007. A biodiesel primer: Market and public policy developments, quality, standards and handling. Methanol institute and International fuel quality center. Available at: http://www.methanol.org/pdfFrame.cfm?pdf=BiodieselPrimer2007.pdf. Accessed 10 February 2008.

Mathworks. 2007. *Statistics Toolbox 6 User's Guide*. Natick, Mass.: The Mathworks, Inc.

Mittelbach, M., and C. Remschmidt. 2005. *Biodiesel: The Comprehensive Handbook*. 2nd ed. Vienna, Austria: Boersedruck.

Moore, D. S., G. McCabe, W. Duckworth, and S. Sclove. 2003. Chapter 18: Bootstrap methods and permutation tests. In *The Practice of Business Statistics: Using Data for Decisions*, 18.1-18.74. New York, N.Y.: W. H. Freeman. Available at: bcs.whfreeman.com/pbs/cat_140/chap18.pdf. Accessed 14 September 2007.

Morris, D. 2005. The carbohydrate economy, biofuels and the net energy debate. Minneapolis, Minn.: Institute for Local Self-Reliance. Available at: www.newrules.org/agri/netenergyresponse.pdf.

Peterson, C. 2005. Potential production of biodiesel. In *The Biodiesel Handbook*, 231-238. G. Knothe, J. Krahl, and J. Van Gerpen, eds. Champaign, Ill.: AOCS Press.

Pimentel, D., and M. Pimentel. 1996. Energy use in grain and legume production. In *Food Energy and Society*, 107-130. Boulder, Colo.: University Press of Colorado.

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

Shapouri, H, M. Wang, and J. Duffield. 2006. Net energy balance and fuel-cycle analysis. In *Renewables-Based Technology*, 73-86. J. Dewulf and H. Van Langenhove, eds. Chichester, U.K.: John Wiley and Sons.

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

Spath, P. L., and M. K. Mann. 2000. Life cycle assessment of a natural gas combined-cycle power generation system. NREL/TP-570-27715. Golden, Colo.: National Renewable Energy Laboratory.

Van Gerpen, J., and D. Shrestha. 2005. Biodiesel energy balance. Moscow, Idaho: University of Idaho, Department of Biological and Agricultural Engineering. Available at: www.uidaho.edu/bioenergy/NewsReleases/Biodiesel%20Energy%20Balance_v2a.pdf.

Woerfel, J. B. 1995. Extraction. In *Practical Handbook of Soybean Processing and Utilization*, 65-92. D. R. Erickson, ed. Champaign, Ill.: AOCS Press and United Soybean Board.

Wu, M., M. Wang, and H. Huo. 2006. Fuel-cycle assessment of selected bioethanol production pathways in the United States. Reference No. ANL/ESD/06-7. Argonne, Ill.: Argonne National Laboratory.