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An Update on Life Cycle Study of Soybean Oil Biodiesel Production

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Abstract. The life cycle analysis of soybean oil biodiesel production was performed to estimate the net fossil energy balance of soybean oil biodiesel. The energy inputs were found to be less than the energy contained in the biodiesel. The net energy return of biodiesel was found to be in the range of 2.64 to 2.78 using the NREL energy allocation approach. The addition of labor, farm machinery and soybean transportation energy to this approach didn't show much difference. Pimentel and Patzek energy allocation approach gave the net energy return in the range of 0.85:1 to 0.88:1. However, allocating energy as in NREL study, this method yielded in the net energy return above five folds (5.69 to 5.93), thus giving an energy gain that is even higher than the 3.2 value from the NREL report. The energy allocation approach plays the crucial role in the variation of the net energy return. The net gain in the energy from soybean oil biodiesel showed the effective use of fossil energy resources. This confirms the renewable nature of soybean oil biodiesel.

Keywords. *Biodiesel, Soybean Oil, Life Cycle Analysis, Net Energy Return*

Introduction

Biodiesel production in the United States has shown strong growth in recent years, increasing from under 1 million gallons in 1999 to 75 million gallons in 2005. The production growth from 2004 to 2005 alone is striking with a jump of 25 million gallons to 75 million gallons (NBB, 2006). Soybeans are the primary crop in US for refining into biodiesel.

Biodiesel has become more attractive as an alternative diesel fuel. But, there have been claims that the use of biodiesel does not reduce petroleum use. The energy balance of the biodiesel has been the focus of the researchers. Energy balance is the amount of energy it takes to grow a crop and convert it into biofuels and other products compared to the amount of energy contained in the resulting biofuel and bioproducts (Morris, 2005). It is simply a ratio of the energy of the fuel product to the energy inputs. Life cycle analysis (LCA) is a step by step analysis related to energy and environmental impacts in making a product. Life cycle energy balance provides an opportunity to quantify the total primary energy requirements and the overall energy efficiencies of processes and products. The total primary energy considers the cumulative energy content of all resources extracted from the environment. The overall energy requirement of biodiesel is the key to understand the extent to which the biodiesel is a renewable energy source. The areas of energy analysis considered are (i) soybean production (farm inputs), (ii) transport to processing facility, (iii) separation of oil and meal, (iv) conversion into biodiesel (transesterification) and (v) transportation of biodiesel for distribution.

Several published studies report the energy balances of biodiesel with a considerable amount of variation in the result. The comparatively wide range of results can be explained by the different assumptions about the farm production and biodiesel conversion. Furthermore, the various researchers used data from different time periods. All the studies shown in Fig 1, except for Pimental and Patzek's, have found a positive energy balance.

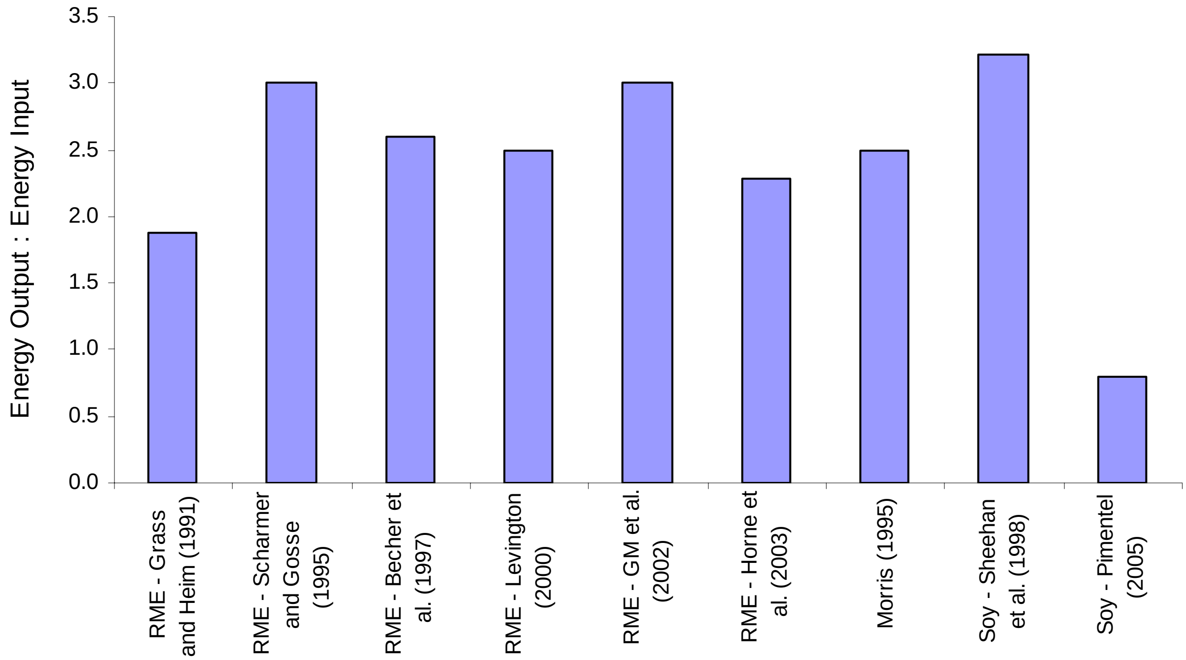

Fig 1: Net Energy Ratios

(Sources: Mittelbach and Remschmidt, 2004; Morris, 2005; and NBB, 2005)

A comprehensive study by Sheehan et al. (1998), also known as NREL study, is the frequently cited fossil energy balance for soybean biodiesel. The fossil energy balance tracks all energy inputs that are from fossil sources such as coal, petroleum, and natural gas. This report shows a positive energy balance of 3.2:1, i.e. for every unit of fossil fuel used to make biodiesel, 3.2 units of energy are gained in energy output, while 0.83 in diesel. This study took into account the energy inputs associated with growing and harvesting soybean, transporting and processing soybean, transporting and producing biodiesel. This study assumes that fossil fuels are used for all inputs. Ahmed et al. (1994) evaluated energy balance of soydiesel for three cases: national average- 2.51:1, industry best- 3.24:1 and industry potential- 4.10:1. They included the credits for process co-products, soy meal and glycerol.

Pimentel and Patzek (2005) reported that the energy output from biodiesel produced is less than the respective fossil energy inputs. They claimed that the biomass produced using soybean and sunflower required 27% and 118% more fossil energy respectively than the biodiesel fuel produced. They considered the energy input by lime which was not mentioned in NREL study.

The wide disparity in Pimentel and Patzek's study about lower net energy return from biofuel has been controversial among the researchers. Jobe and Duffield (2005) stated that Pimentel and Patzek study lacks depth and clarity compared to previous published studies. The study counts calories consumed by farmers as energy inputs for biodiesel, yet it does not give biodiesel credit for the value of glycerin produced as a co-product. While soybeans are approximately 80% protein meal and 20% oil, their study allocates 79% of the energy inputs for growing soybeans to the oil. The study uses energy data for growing soybeans from 15 years ago that does not reflect current soybean production or represent the current biodiesel industry. National Biodiesel Board (NBB, 2005) added that Pimentel and Patzek study does not acknowledge that producing biodiesel also results in the production of glycerin and the study overestimates the energy requirements for secondary inputs, such as steel and cement.

Morris (2005) reported that (i) Pimentel and Patzek are not clear about the inclusion of energy used to modify the vegetable oil into an ester suitable for use as a diesel fuel; (ii) they assumed soy meal only accounts for about 15 percent; (iii) they assumed the lime use of 2.2 tons per acre of soybean per year ignoring the fact that one application lasts for up to 10 years; (iv) they restricted the analysis to fossil energy inputs ignoring solar energy inputs; and (v) they cite no studies, nor press releases or public statements, condemning the energetic of cellulose to ethanol nor biodiesel.

Gerpen and Shrestha (2005) reported that the Pimentel and Patzek's report is based on several critical erroneous analyses and the claim is incorrect. Only 19.3% of total energy was accounted towards soybean meal in Pimentel and Patzek's study, but in reality 82% of soybean mass goes into meal. Inclusion of the energy from this total amount of soybean meal indicates that input energy is only 2% higher than the energy in the biodiesel. The erroneous table in Pimentel and Patzek study led to 8% mark. The authors found the net energy return of 5.3 (higher than 3.2) by applying NREL energy allocation approach to Pimentel and Patzek's energy estimates. Another reason for negative net energy in Pimentel study was that they charged all of the lime (4800 kg/ha) to one year soybean crop, whereas lime use has been recommended for only acidic soil to correct pH once in a several years (Kassel and Tidman, 1999). Correcting lime application by splitting this application to 5 year, the authors found that the energy required to product biodiesel is only 77% of the energy in the fuel.

This study updates on the life cycle analysis of soybean oil biodiesel production. The energy balance of soybean biodiesel will be estimated using the most recent available data.

Methodology

The recently available farm input data were collected and entered in the excel spreadsheet for analysis. The most current source of farm input data for soybean production is from Farm Costs and Returns Surveys (FRCS, USDA, 2006), National Agricultural Statistics Service (NASS, 2006) and FAO statistics (FAO, 2006). Lime use data was collected through personal contact.

The total energy inputs of soybean production were estimated for five different years. Lime use data were split to five years and more to get the accurate energy input by lime. Missing data for some years were assumed from the previous studies. Energy inputs for soybean crushing, oil transport, transesterification and biodiesel transport were assumed from the previous studies. The energy allocation approaches of NREL and Pimentel & Patzek were used to estimate the total energy input in biodiesel production. The NREL approach assigned the energy on weight basis as 18% soybean oil versus 82% soy meal (oil extraction) and 82% biodiesel versus 18% crude glycerin (transesterification), while Pimentel and Patzek approach assigned the 79% of the energy inputs for growing soybeans to the oil. The net energy return was then calculated as the ratio of the energy contained in the fuel product and the total energy input required to produce it.

Results and Discussion

The soybean yield in US showed variation over the years. It declined from 0.266 to 0.227 kg/m^2 between the years 2001 to 2003 and again increased to 0.291 kg/m^2 from 2003 to 2005.

Calculations with NREL approach, the fossil energy balance of soy-biodiesel resulted in the range of 2.64:1 to 2.78:1. This is quite near to NREL value of 3.2:1. When labor, machinery and soybean transportation energy inputs from Pimentel and Patzek were included in NREL approach, the energy balance were slightly reduced. The results thus obtained were in the range of 2.31:1 to 2.42:1. The inclusion of these energies doesn't have much impact on net energy return. The energy inputs and energy ratios obtained from the analysis are given in Table 1. The detail on the amount of farm inputs and computation of farm energy input and total energy input involved in the soybean oil biodiesel production for 2002 is illustrated in Table 2.

Table 1: Energy inputs and energy ratios (NREL approach)

Year	**Labor, Machinery and Soybean transportation excluded**		**Labor, Machinery and Soybean transportation included**	
	Energy Inputs (MJ/kg of BD)	**Energy Ratio**	**Energy Inputs (MJ/kg of BD)**	**Energy Ratio**
1999	13.94	2.64	15.96	2.31
2000	13.95	2.64	15.89	2.32
2001	13.71	2.68	15.57	2.36
2002	13.26	2.78	15.20	2.42
2004	13.70	2.69	15.43	2.38

Table 2: Energy inputs for soybean production in 2002 (NREL approach)

	Amount	Unit	Energy (MJ/m^2)	
			Primary	**Fossil**
Labor*			0.1188	0.1188
Machinery*			0.1506	0.1506
Diesel	3.76E-06	m^3/m^2	0.1837	0.1835
Gasoline	1.09E-06	m^3/m^2	0.0553	0.0552
LP Gas	6.83E-07	m^3/m^2	0.0200	0.0200
Natural Gas	4.09E-04	m^3/m^2	0.0180	0.0102
Nitrogen	2.37E-03	kg/ m^2	0.1629	0.1624
Phosphorus	2.37E-03	kg/ m^2	0.0765	0.0751
Potassium	2.37E-03	kg/ m^2	0.0490	0.0479
Lime	2.37E-03	kg/ m^2	0.0405	0.0405
Seeds	2.37E-03	kg/ m^2	0.0365	0.0363
Herbicide	2.37E-03	kg/ m^2	0.0415	0.0408
Insecticide	2.37E-03	kg/ m^2	0.0081	0.0080
Electricity	2.38E-03	MJ/ m^2	0.0236	0.0231
Transport			0.0672	0.0672
Total			1.0522	0.9724
Agricultural Energy Input excluding labor, machinery and soybean transport (MJ/kg of BD)			17.93	15.93
Agricultural Energy Input including labor, machinery and soybean transport (MJ/kg of BD)			26.36	24.36
Total Energy Input (Agriculture inputs and biodiesel preparation) excluding labor, machinery and soybean transport (MJ/kg of BD)			47.95	13.26
Total Energy Input (Agriculture inputs and biodiesel preparation) including labor, machinery and soybean transport (MJ/kg of BD)			49.89	15.20

*values taken from Pimentel and Patzek

Calculating with Pimentel and Patzek approach, the fossil energy balance of soy-biodiesel resulted in the range of 0.85:1 to 0.88:1. The net energy ratios were slightly reduced in the range of 0.84:1 to 0.87:1 when insecticides and natural gas were considered in Pimentel and Patzek approach. The inclusion of these energies didn't show much impact on net energy return. The results obtained are slightly higher than the value 0.79 (27 % loss in energy) reported by the Pimentel and Patzek result. The energy inputs and energy ratios obtained from the analysis are given in Table 3. The detail of the computation of farm energy input in soybean agriculture and total energy involved in biodiesel production for 2002 is illustrated in Table 4.

Table 3: Energy inputs and energy ratios (Pimentel and Patzek approach)

Year	Insecticides and Natural gas excluded		Insecticides and Natural gas included	
	Input energy (MJ/kg of BD)	Energy Ratio	Input Energy (MJ/kg of BD)	Energy Ratio
1999	42.64	0.88	43.05	0.87
2000	43.30	0.87	43.66	0.86
2001	42.73	0.88	43.27	0.87
2002	43.38	0.87	43.76	0.86
2004	44.52	0.85	44.87	0.84

Table 4: Energy inputs for soybean production in 2002 (Pimentel and Patzek approach)

	Energy (MJ/m^2)	
	Insecticides and Natural gas excluded	**Insecticides and Natural gas included**
Agricultural Phase		
Nitrogen	0.16	0.16
Phosphorus	0.09	0.09
Potassium	0.14	0.14
Lime	0.10	0.10
Herbicide	0.06	0.06
Insecticide		0.01*
Seed	0.27	0.27
Transport	0.02	0.02
Gasoline	0.03	0.03
Diesel	0.18	0.18
Natural gas		0.01*
LPG	0.02	0.02
Electricity	0.02	0.02
Farm labor	0.12	0.12
Farm machinery	0.15	0.15
Sub - Total	**1.36**	**1.38**
Biodiesel Production Phase	**0.73**	**0.73**
Total Energy Input	**2.08**	**2.10**
Energy content in BD	1.81	1.81
Coproduct credits (Soy meal)	0.44	0.44
Output Energy	2.25	2.25
Net Energy Ratio	0.87:1	0.86:1

* Values taken from NREL

Allocating energy as in NREL study, the Pimentel and Patzek approach showed the energy balance in the range of 5.73:1 to 5.98:1. The similar allocation analysis with insecticides and natural gas slightly reduced the net energy in the range 5.69:1 to 5.93:1. These inputs didn't show much impact on the net energy return. The energy inputs and energy ratios obtained from the analysis are summarized in Table 5.

Table 5: Energy inputs and energy ratios (Pimentel and Patzek approach)

Year	Insecticides and Natural gas excluded		Insecticides and Natural gas included	
	Input Energy (MJ/kg of BD)	Energy Ratio	Input Energy (MJ/kg of BD)	Energy Ratio
1999	6.29	5.98	6.35	5.93
2000	6.39	5.89	6.44	5.84
2001	6.31	5.97	6.39	5.90
2002	6.40	5.88	6.46	5.83
2004	6.57	5.73	6.62	5.69

Conclusion

The fossil energy inputs are less than the energy contained in the soybean oil biodiesel. The NREL energy allocation approach yielded in the positive net energy return. The inclusion of labor, machinery and soybean transportation energy to this approach has no significant effect on the net energy return. The results obtained in both cases are comparable to the stated value (3.2) of NREL report.

The Pimentel and Patzek approach results showed slight improvement with the updated farm input data. The correction in lime use energy and the inclusion of insecticides and natural gas energy to this approach showed no significant effect on the net energy return. However, allocating energy as in NREL study, this method yielded in the net energy return above five folds, thus giving an energy gain that is even higher than the 3.2 value from the NREL study. Hence, the allocation of energy use is the most important factor in the variation of the net energy return.

The soybean biodiesel showed the positive fossil energy balance. There is a net gain in energy from soybean oil biodiesel. It showed the effective use of fossil energy resources, which confirms the renewable nature of biodiesel.

Incomplete data are the rule rather than the exception. The life cycle energy balance of soybean biodiesel production can be more comprehensive with the updated data of soybean crushing, oil transport, transesterification, and biodiesel transport. More detailed analysis on energy, environmental, and socio-economic implications of biodiesel production are important.

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