

# A First Law Thermodynamic Analysis of Biodiesel Production From Soybean

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## Abstract

A proper First Law energy balance of the soybean biodiesel cycle shows that the overall efficiency of biodiesel production is 0.18, i.e., only 1 in 5 parts of the solar energy sequestered as soya beans, plus the fossil energy inputs, becomes biodiesel. Soybean meal is produced with an overall energetic efficiency of 0.38, but it is not a fossil fuel. If both biodiesel and soybean meal were treated as finished fossil fuels, the overall energy efficiency of their production would be 0.56, ~40% higher than the average overall efficiency, 0.4, of producing ethanol and DDGS from corn (Patzek, 2006b; Patzek, 2006a). This difference is caused by the high energy efficiency of producing soybean meal, which is 57% of soya beans by mass. Production of corn ethanol alone, with the average overall efficiency of 0.25, is more energy-efficient than production of biodiesel from soybeans with the overall efficiency of 0.18. The results of the current analysis are compared with those by NREL (Sheehan et al., 1998) and Hill et al. (2006).

KEYWORDS: biofuel, sustainability, energy, mass, balance

## 1 Introduction

Soybean (*soya*) is an important source of high quality, inexpensive protein and oil. With an average protein content of 40% and oil content of ~20%, soybean has the highest protein content of all food crops, and is second only to groundnut in terms of oil content among food legumes.

Cultivation is successful in climates with hot summers, with optimum growing conditions in mean temperatures of 20<sup>0</sup>C to 30<sup>0</sup>C; temperatures below 20<sup>0</sup>C and over 40<sup>0</sup>C retard growth significantly. Soybean plants can grow in a wide range of soils, with optimum growth in moist alluvial soils with a good organic content. Soybeans, like most legumes perform nitrogen fixation by establishing a symbiotic relationship with the bacterium *Bradyrhizobium japonicum*. However, for best results an inoculum of the correct strain of bacteria should be mixed with the soybean (or any legume) seed before planting. Modern crop cultivars generally reach a height of around 1 m (3 ft), and take between 80-120 days from sowing to harvesting. About 370,000 soybean plants per hectare is usually associated with high yields.

According to the FAOSTAT database, in 2005, over 210 million tonnes of soybean was produced worldwide<sup>1</sup> on 91 million hectares. The leading producer was the U.S.A. which accounted for 39% of soybean; Brazil produced 24%, Asia 12%, and Africa 0.5%. The average yield in 2005 was 2300 kg/ha, ranging from about 3500 kg/ha in Western Europe, 2870 kg/ha in the U.S.A. and 2190 kg/ha in Brazil, to 985 kg/ha in Africa. By 2007, global soybean production increased to 216 million tonnes, the U.S.A. produced 33%, Brazil 27%, Asia 13%, and Africa 0.7%.

According to American Soybean Association (ASA), soybeans provide majority of the edible consumption of fats and oils in the United States. Soya beans, which possess high quantities of protein, and soybean products are used in a wide range of food and industrial products. Soya products have three major divisions: soy oil products, whole bean products, and soy protein products. Food products include baby food, cereal, diet foods, imitation meats, processed meats, soy sauce, tofu and miso, salad dressings and margarine, cooking oil, candy, and baked goods. Soybeans are used in pet foods and as the leading source of protein meal for U.S. livestock. Industrial uses for soybeans include wallboard and plywood, medicines, soaps and disinfectants, pesticides, fertilizers, candles, linoleum, varnish, fire extinguisher fluid, and paint.



Figure 1: February 20, 2006. Flight from Manaus to Santarem, Amazon, Brazil. A huge area of 1645 hectares (Gleba do Pacoval area 100 km SE of Santarem) illegally logged to clear land for soya plantations. The President of the Agricultural Producers Association in Santarem, - José Donizetti - is held directly responsible by the Brazilian Environmental Agency IBAMA for this illegal deforestation. ©Greenpeace/Daniel Beltra. Reproduced with the permission of Greenpeace.

On October 30, 2002, Brazil launched the Probiodiesel Program, with Portaria MCT Number 702, Directive #702 of the Ministry of Science and Technology (MCT). The program aims to develop technology for the production, industrialization, and use of biodiesel, including its use in

<sup>1</sup>In comparison, the U.S.A. alone produced 300 million tonnes of corn grain in 2004.

mixtures, with diesel using pure and residual vegetable oils. In 2008, a 2 percent mix of biodiesel became mandatory in all nationally sold diesel. Much of the biodiesel is produced from soya.

According to Greenpeace (Greenpeace, 2006), since January 2003, nearly 70,000 km<sup>2</sup> of the Amazon rainforest has been destroyed. Between August 2003 and August 2004, 27,200 km<sup>2</sup> - an area the size of Belgium - was lost. In 2004-05 around 12,000 km<sup>2</sup> of soybean (5% of the national total) was planted in the Brazilian Amazon rainforest, see **Figure 1**. Some 8,000 km<sup>2</sup> of the Amazon forest were destroyed between August 2007 and August 2008 - a 69 percent increase over the 4,800 km<sup>2</sup> felled in the previous 12 months, according to the National Institute for Space Research, or INPE, which monitors destruction of the Amazon. Based on an independent analysis of the same satellite images, another source<sup>2</sup> puts the total Amazon deforestation in 2007 and 2008, at roughly 12,000 km<sup>2</sup> per year.

Three U.S.-based agricultural commodities giants Archer Daniels Midland (ADM), Bunge and Cargill are responsible for about 60% of the total financing of soybean production in Brazil<sup>3</sup>. With an estimated 13 silos and an illegal port facility already built into the Amazon rainforest, Cargill is leading soybean's invasion of the region - spurring the incursion of illegal farms and building infrastructure to deliver Amazon soybean to global markets<sup>4</sup>. Bunge and ADM are following Cargill's lead, with an estimated six and four silos respectively in the Amazon.

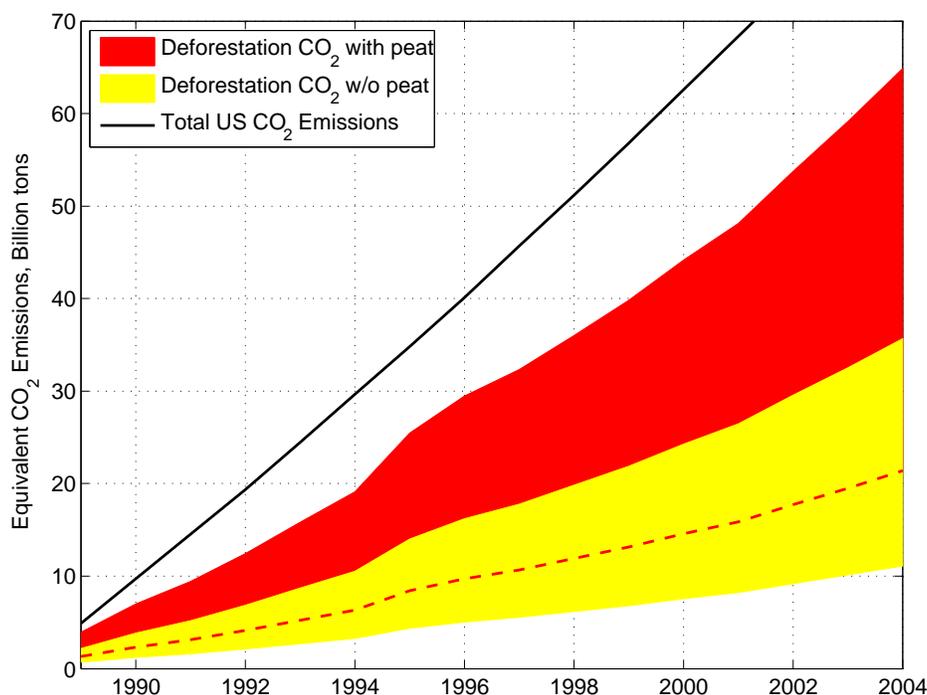


Figure 2: The cumulative CO<sub>2</sub> emissions from Amazon deforestation rival those of the U.S. The range of values depends on the thickness of peat. This thickness is usually larger in Asian tropical forests. Sources: Brazilian National Institute for Space Research (INPE), ORNL, J. Germer and J. Souerborn.

<sup>2</sup>[www.mongabay.com/brazil.html](http://www.mongabay.com/brazil.html), accessed on Feb. 17, 2009.

<sup>3</sup>Note that as the corn-for-ethanol acreage is expanded in the U.S., corn encroaches on the next two largest crops, soya and wheat. Some of the U.S. soybean farming will then move to Brazil's Amazon forest.

<sup>4</sup>The Green Peace Report was independently corroborated by Mr. DANIEL HOWDEN, a reporter for *The Independent*, who published "Environment Eating the Amazon: The fight to curb corporate destruction," July 21, 2006. In March 2007, the illegal Cargill port was taken over by the Brazilian military and shut down.

Deforestation has been responsible for up to 75% of Brazil's emissions, with 59% coming from Amazon deforestation, see **Figure 2**. By 2050, current trends in agricultural expansion will eliminate a total of 40% of Amazon forests, including at least two thirds of the forest cover of six major watersheds and 12 ecoregions, releasing carbon into the atmosphere equivalent to four years of current annual emissions worldwide.



Figure 3: A soybean field (left) and soybean varieties (right).

Table 1: Soybean mass composition and heating values

Soybean Component	LHV <sup>a</sup> MJ/kg	HHV <sup>a</sup> MJ/kg	Mass <sup>b</sup> %	HHV %	Heating Value Data Source
Oil	37.0	39.6	18.4	40.3	(Domalski et al., 1987), p. 237
Dirt	0.0	0.0	0.8	0.0	Estimated, (Domalski et al., 1987), p. 9-29 <a href="http://www.gnb.ca/0170/01700003-e.asp">http://www.gnb.ca/0170/01700003-e.asp</a>
Hulls <sup>c</sup>	17.1	18.2	7.4	7.5	
Water	0.0	0.0	16.0	0.0	
Meal <sup>d</sup>	15.4	16.5	57.4	52.3	
<b>Total</b>	16.9	18.1	100.0	100.0	

<sup>a</sup> LHV = Low (Net) Heating Value, HHV = High (Gross) heating Value

<sup>b</sup> (Sheehan et al., 1998), Table 82, p. 136

<sup>c</sup> Estimated from heating values of various nut hulls

<sup>d</sup> The high heating value is assumed to be  $1.07 \times \text{LHV}$

## 2 Soybean Characterization

The average mass composition of soybean, *Glycine max* in **Figure 3**, reported in (Sheehan et al., 1998) is summarized in **Table 1**.

The soybean oil is only 18% of the soybean mass. It is a liquid consisting of up to 3 fatty acids 16 – 18 carbon atoms long, see **Table 2**, linked to a glycerine molecule with ester bonds, see **Figure 4**. The average molecular weight of the fatty acids is 278 kg/kmol, and the average molecular weight of soybean oil is 920 kg/kmol ( $\sim 900$  kg/kmol). The oil density is 0.9138 kg/L at room temperature.

Table 2: Typical composition of fatty acids in soybean oil<sup>a</sup>

Component	Weight Percent	Molecular Weight	Chemical Formula
Palmitic Acid	12.0	256.42	$C_{15}H_{31}COOH$
Stearic Acid	5.0	284.48	$C_{17}H_{35}COOH$
Oleic Acid	25.0	282.46	$C_{17}H_{33}COOH$
Linoleic Acid	52.0	280.45	$CH_3(CH_2)_4CH=CHCH_2CH=CH(CH_2)_7COOH$
Linolenic Acid	6.0	278.43	$CH_3(CH_2CH=CH)_3(CH_2)_7COOH$
Total	100.0	278.15	
Glycerol	-	92.09	$HOCH_2(HCOH)H_2COH$

<sup>a</sup> National Biodiesel Board, [http://www.biodiesel.org/pdf\\_files/fuelfactsheets/Weight&Formula.PDF](http://www.biodiesel.org/pdf_files/fuelfactsheets/Weight&Formula.PDF)

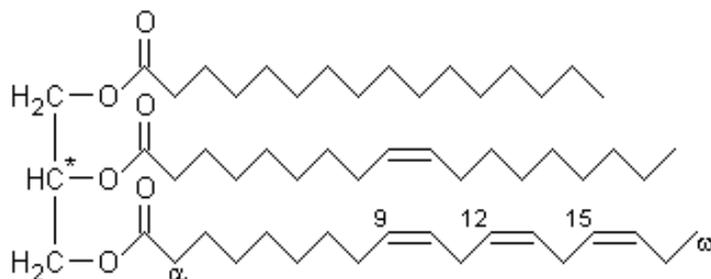


Figure 4: Typical molecule of soybean oil. Left part: glycerol, right part from top to bottom: palmitic acid, oleic acid, alpha-linolenic acid. The overall chemical formula of this molecule is  $C_{55}H_{98}O_6$ . Source: Wikipedia.

The soybean meal is about 57% of the soybean mass. It consists of proteins (40%), phosphatides<sup>5</sup>

<sup>5</sup>Any of various phosphorous-containing lipids that are composed mainly of fatty acids, a phosphate group, and a simple organic molecule.

(2%), the remainder is urease<sup>6</sup>, raffinose<sup>7</sup>, stachyose<sup>8</sup>, saponins<sup>9</sup>, phytosterins<sup>10</sup>, and isoflavone<sup>11</sup> (Domalski et al., 1987).

Note the relatively high water content in soybeans. Some of this water is evaporated during soybean crushing. The dirt and hulls are often discarded.

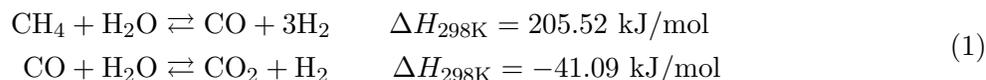
### 3 Production of Methanol from Natural Gas

Stoichiometrically, 3 moles of methanol are needed to transesterify 1 mole of soybean oil triglycerides. Given the ratio of their molecular masses (32:900), this stoichiometric ratio translates into the methanol requirement equal to 10% by mass of the refined, degummed soybean oil. In practice the methanol-to-triglyceride ratio is two times higher to increase yield of biodiesel esters, and the excess methanol is recovered through very costly distillation, e.g., (Sheehan et al., 1998).

Almost all methanol today is made from natural gas, and the dominating process (Synetix) relies on syngas to synthesize methanol.

#### 3.1 Steam Reforming of Methane

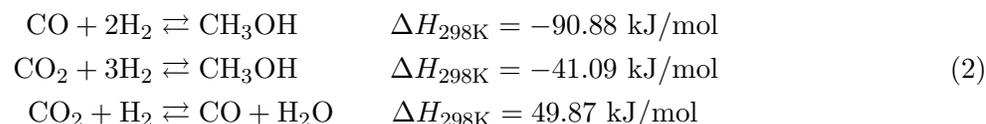
In methane steam reforming, methane is reacted in a highly endothermic reaction with steam over a nickel catalyst at high temperature (800–1000<sup>0</sup>C) and moderate pressure (20–30 atm) to form CO and H<sub>2</sub>. A part of this CO reacts further with steam to yield more H<sub>2</sub> and CO<sub>2</sub> in the water-shift reaction:



At high temperatures the water-shift reaction is suppressed, but methane decomposition with carbon precipitation (“coking”) is enhanced. The syngas must be purified to remove mostly sulfur.

#### 3.2 Methanol Production

In the dominant ICI (now Synetix) process, the syngas mixture of H<sub>2</sub>, CO, and CO<sub>2</sub> is reacted over a copper-zinc-based catalyst at high pressure (50–100 atm) and moderate temperature (200–300<sup>0</sup>C):



The modern methanol plants have selectivities to methanol of 99%, with energy efficiencies that reach 70% (Olah et al., 2006). According to SZARGUT (1988), Table 5.1, the cumulative consumption of free energy in methanol production is 73.02 MJ/kg of methanol. The cumulative free energy

<sup>6</sup>An enzyme that catalyzes the hydrolysis of urea into carbon dioxide and ammonia.

<sup>7</sup>A trisaccharide also occurring in Australian manna (from *Eucalyptus spp.*, *Myrtaceae*) and in cottonseed meal.

<sup>8</sup>Carbohydrates consisting of between two (disaccharides) and ten monosaccharides connected by either an alpha- or beta-glycosidic link. They are found throughout nature in both the free and bound form.

<sup>9</sup>Saponins are glycosides of steroids, steroid alkaloids (steroids with a nitrogen function) or triterpenes found in plants, especially in the plant skins where they form a waxy protective coating. They dissolve in water to form a soapy froth. Saponins are believed to be useful in the human diet for controlling cholesterol, but some are poisonous if swallowed and can cause urticaria (skin rash) in many people.

<sup>10</sup>Vegetable cholesterol-like compounds.

<sup>11</sup>A type of plant estrogen, 3-phenyl-4H-chromen-4-one 4H-1-Benzopyran-4-one, 3-phenyl- CHEBI:18220.

consumption in the production of sodium methoxide ( $\text{NaOCH}_3$ ) catalyst of the transesterification reaction is 97.6 MJ/kg.

Because this is a simplified First Law analysis, instead of using the free energy consumption numbers above, I use 0.6 as a good estimate (LeBlanc et al., 1994) of the LHV-based thermal efficiency of a modern plant designed to produce 2500 tpd of methanol from methane-derived syngas. I also charge the feed methane with a 5% penalty for its production, compression, and piping. This amounts to the unit energy consumption in methanol production of  $20/0.6 \times 1.05 = 35$  MJ/kg of methanol.

Consequently, the fractional consumption of fossil energy as methanol needed transesterify soybean oil is at least

$$\frac{3 \times 35 \text{ MJ kg}^{-1} \times 32 \text{ kg kmol}^{-1} \text{ methanol}}{39.6 \text{ MJ kg}^{-1} \times 900 \text{ kg kmol}^{-1} \text{ soybean oil}} \approx 0.1 \quad (3)$$

or 10% of the high heating value of biodiesel, regardless of all other fossil energy inputs listed in Table 5. If extraction of the environmental resources needed to produce methanol is accounted for, this ratio will jump to 20%. Therefore, the recent claim (Hill et al., 2006) that biodiesel yields 93% more energy than the fossil energy invested in its production is incorrect.

## 4 Retracing NREL Life Cycle Analysis of Biodiesel Cycle

In this Section I follow the life cycle analysis performed by NREL (Sheehan et al., 1998) for the soybean-biodiesel cycle, and I highlight some of its flaws.

### 4.1 Methodology

My methodology is as follows:

1. I rely on the NREL Report (Sheehan et al., 1998) for all primary energy inputs into biodiesel fuel production from industrially grown soybean.
2. To be consistent with my other work (Patzek, 2004; Patzek, 2006c), I use the high heating values (HHV) instead of the low heating values (LHV) used by NREL, but this is a minor difference.
3. I do *not* follow, however, the mass allocation rule chosen by NREL, see Footnote 23, p. 45, by which 82% of the overall fossil energy inputs are allocated to soybean meal, water, and hulls, while only 18% to biodiesel, see Table 1. This type of allocation is not quite physical and obscures the reasons for growing soybean for biodiesel fuel. This soybean is grown to obtain oil and all else is a byproduct, which may get an energy credit, but is not the reason for the entire cycle.
4. Instead, I ask the following question: If biodiesel fuel were the sole reason for the soybean farming, crushing, conversion and separation, would this cycle produce more energy than it uses to produce the fuel? The answer is no, based on the Life Cycle Inventories (LCI) provided by NREL (Sheehan et al., 1998), see **Table 5**.
5. I assume a nominal 3% loss of soybeans between the field harvest and the crusher. Further, soybean oil losses in the crusher are 7.5% to produce crude degummed soybean oil. These losses are due to gum hydration and oil losses to soybean meal and water. The degummed

crude oil is subsequently refined with alkali and the losses are 4% of the oil. The transesterification reaction with methanol has 1-2% losses of the input triglycerides, and more losses, 2.5%, occur in the settling tanks, see **Table 3** for the summary.

6. Therefore, the overall mass loss in the soybean-biodiesel cycle is:

$$0.97 \times 0.925 \times 0.96 \times 0.98 \times 0.975 = 0.82 \frac{\text{kg of finished biodiesel fuel}}{\text{kg of oil in harvested soybeans}} \quad (4)$$

This coefficient is used in Table 5.

7. The cumulative energy consumption in methanol production of 29 MJ/kg of methanol, calculated by NREL<sup>12</sup>, is too small. Consequently the energy outlay for soybean oil conversion increases to  $5.57241 - 2.9015 + 3.5 = 6.17$  MJ/kg biodiesel.

Table 3: Efficiencies of major steps in biodiesel production. Source: (Sheehan et al., 1998)

Step	Efficiency	Comment
Agriculture	0.97	Nominal bean losses of 3%
Crushing	0.93	Degumming losses of 7.5%
Conversion	0.96	4% Oil refining losses
Conversion	0.98	Transesterification reaction yield
Conversion	0.98	2.5% settling/separation losses
Conversion	0.92	Overall efficiency

## 4.2 Results

The overall fossil energy expenditure in the soybean-biodiesel cycle, summarized in Table 5, is 52.2 MJ/kg of the finished biodiesel fuel, *not* counting the HHV of the meal output, and *not* counting the HHV of the input soybean oil. The properties of biodiesel fuel and methanol are listed in **Table 4**.

The overall efficiency of the soybean-biodiesel cycle is therefore  $40/52.2 = 0.76$ , not *really* counting<sup>13</sup> the extremely high soil losses in soybean fields caused by water and wind erosion. Soybean plants have very shallow roots, see **Figure 5**, and are a row crop. Therefore, erosion losses from the weakly-held and otherwise barren soil can be huge, see **Figure 6**.

Ethanol can be used in place of methanol as a feedstock but is not used commercially as it is more expensive. The biodiesel esters produced from ethanol are ethyl esters rather than methyl esters, and have 5% higher molecular weights and 7% higher viscosities than their methyl analogues. Generally, the dissimilarities between processing with methanol and ethanol are relatively minor, the major difference being in the alcohol recovery step where ethanol forms an azeotrope with free water. Overall, the quality of ethyl esters is lower than methyl esters as the reaction rate is slower with ethanol resulting in a somewhat lower level of conversion and higher levels of mono- and diglycerides and also glycerol in the final product.

<sup>12</sup>In Table 105: LCI Results for Soybean Oil Conversion (for 1 kg of biodiesel), page 116, (Sheehan et al., 1998).

<sup>13</sup>The soil erosion losses of NPK are accounted for in (Sheehan et al., 1998), but the impact of soil erosion on

Table 4: Average high and low heating values of some fossil fuels from (Castorph et al., 1999; Bossel, 2003; Spiers, 1961). Other sources are listed in the footnotes.

Fuel	Density kg/sm <sup>3</sup>	HHV <sup>a</sup> MJ/kg	LHV <sup>a</sup> MJ/kg	HHV <sup>a</sup> MJ/kg	LHV <sup>a</sup> MJ/kg	Source <sup>i</sup>
Gasoline	720-800	46.7 <sup>b</sup>	42.5 <sup>b</sup>	46.8	43.6	Table 339
Diesel fuel	840	45.9	43.0	45.3	42.3	Table 350
Biodiesel <sup>i</sup>	880	40.0	37.5			
Methane	0.66 <sup>d</sup>	55.5 <sup>c</sup>	50.1 <sup>c</sup>	55.1(gas)		Table 347
NG <sup>f</sup>	0.84	48.7	43.9			
Methanol	786 <sup>h</sup>	22.7 <sup>j</sup>	20.0	22.7	19.9	Table 353
Ethanol	787 <sup>h</sup>	29.7 <sup>g</sup>	26.7 <sup>g</sup>	29.6	26.8	Table 353

<sup>a</sup>HHV = High Heating Value; LHV = Low Heating Value

<sup>b</sup>Average of gas station fuels, I choose the mean density of 740 kg/m<sup>3</sup>. The leftmost gasoline, diesel fuel, LPG, and NG data are from (Castorph et al., 1999)

<sup>c</sup>From BOSSEL, Table A, (Bossel, 2003)

<sup>d</sup>(Lide, 1994), 6-25

<sup>e</sup>A mixture of propane and butane, C<sub>3</sub>H<sub>8</sub> and C<sub>4</sub>H<sub>10</sub>

<sup>f</sup>An average of natural gas compositions from Groningen, Orenb., Ekofisk, and Leman Bank

<sup>g</sup>[http://bioenergy.ornl.gov/papers/misc/energy\\_conv.html](http://bioenergy.ornl.gov/papers/misc/energy_conv.html)

<sup>h</sup>(Lide, 1994), 15-46

<sup>i</sup>Source: *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*, U.S. Environmental Protection Agency, EPA420-P-02-001, October 2002

<sup>j</sup>(Lide, 1994), 5-76

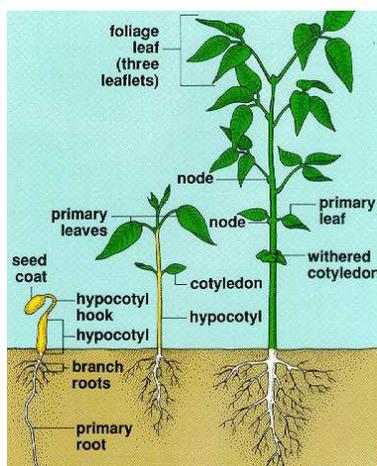


Figure 5: Soybean plant development.

### 4.3 Comparison with the Hill et al. (2006) Analysis

As shown in Table 5, the energy costs of soybean agriculture are higher in the PNAS study (Hill et al., 2006), because the costs of machinery and on-farm labor are also accounted for. On the other

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sustained productivity is not. With 10-50 tonnes/ha-yr of soil erosion, soybean farming is completely unsustainable in the long run in the U.S. Midwest, and in the Brazilian Amazon Forest.

Table 5: Primary energy expenditures in biodiesel production

Production Stage	Primary Energy	Units	Data <sup>a</sup> Source	Data <sup>b</sup> Multiplier	PNAS Study
Agriculture	21.254	MJ/kg biodiesel	Table 62, p. 116	1/(0.184 × 0.82)	29.834 <sup>d</sup>
Transport to crusher	1.059	MJ/kg biodiesel	Table 63, p. 118	1/(0.184 × 0.835)	1.064 <sup>e</sup>
Crushing	22.661	MJ/kg biodiesel	Table 83, p. 137	1/(0.184 × 0.835)	0.819 <sup>f</sup>
Oil Transport	0.366	MJ/kg biodiesel	Table 83, p. 137	1/(0.925 × 0.92)	0.266 <sup>g</sup>
Conversion	6.708	MJ/kg biodiesel	Table 105 <sup>c</sup> , p. 166	1/0.92	1.193 <sup>h</sup>
Distribution	0.176	MJ/kg biodiesel	Table 106, p. 169	1/0.92	1.227 <sup>i</sup>
<b>Total</b>	<b>52.223</b>	MJ/kg biodiesel			<b>34.403</b>

<sup>a</sup> All tables in (Sheehan et al., 1998)

<sup>b</sup> These multipliers were used to translate from the mass-fraction allocation of primary energy outlays in biodiesel production used in (Sheehan et al., 1998). For the individual multipliers, see **Table 3** and Eq. (4)

<sup>c</sup> After the update of methanol production costs from 2.9 to 3.5 MJ/kg biodiesel, see Section 4.1

<sup>d</sup> (17.99 + 1.414 + 0.06 + 6.79)/0.88 MJ/kg biodiesel, Tables 2, 3, 4 and 5, Supporting Materials, (Hill et al., 2006)

<sup>e</sup> 0.8 × 1.07/0.88 MJ/kg biodiesel, Table 5, Supporting Materials, (Hill et al., 2006)

<sup>f</sup> (0.260 × 2.44 + 0.024 × 3.6)/0.88 MJ/kg biodiesel, Table 5, Supporting Materials, (Hill et al., 2006)

<sup>h</sup> 0.2 × 1.07/0.88 MJ/kg biodiesel, Table 5, Supporting Materials, (Hill et al., 2006)

<sup>g</sup> (0.395 × 2.44 + 0.024 × 3.6)/0.88 MJ/kg biodiesel, Table 5, Supporting Materials, (Hill et al., 2006)

<sup>i</sup> 1.08/0.88 MJ/kg biodiesel, Table 5, Supporting Materials, (Hill et al., 2006)



Figure 6: The Root River drains two SE Minnesota counties (Fillmore and Houston) and discharges its deep-brown waters to the Mississippi River. Top soil runoff from corn/soybean crop rotation fields after a 2" rain. This aerial photograph was taken mid-July, 2005, by the University of Minnesota. Source: Private communication, Mr. JEFF WEBSTER, who lives in that neighborhood, Nov. 9, 2005.

hand, the energy costs of soybean crushing and oil conversion are unrealistically low. According to Hill et al.'s data, the fossil fuel ratio in biodiesel production is  $40/34.4 = 1.16$ . The authors then propose a coproduct energy allocation scheme that increases this ratio to  $1/0.07 = 14.29$ . In other words the PNAS paper claims than only  $0.07 \times 40 = 2.8$  MJ/kg biodiesel of fossil energy is used to

produce biodiesel. The corrected NREL analysis and the uncorrected PNAS analysis are compared in **Figure 7**.

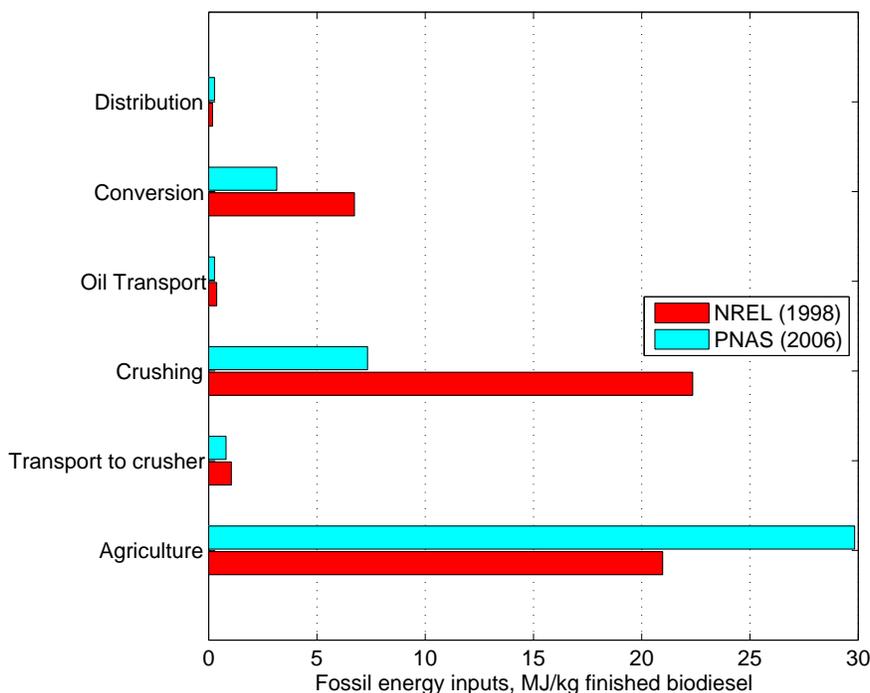


Figure 7: Fossil energy inputs to soybean diesel production. The NREL numbers were rescaled using the multipliers listed in column 5 of Table 5.

## 5 First Law Analysis of the Soybean-Biodiesel Cycle

The principles of this analysis were laid out in detail (Patzek, 2006c; Patzek, 2006d), and the system to be analyzed is shown in **Figure 8**.

### 5.0.1 Overall Energy Efficiency of Soybean Farming (Subsystem 1 + Environment)

If one assumes for simplicity that the high heating value of soya beans is equal to the solar energy sequestered as soya beans, then the overall energetic efficiency of industrial soybean farming can be defined as:

$$\eta_{\text{soybean}} = \frac{1}{1 + \sum \text{Farming Energy Inputs} + \sum \text{Restoration Work Inputs}} \quad (5)$$

$$\eta_{\text{soybean}} = \frac{\text{Output Soybean Energy}}{\text{Sequestered Solar Energy} \left( 1 + \sum \text{Fossil/Environmental Energy Subsidy Fractions} \right)}$$

where the dimensionless Farming Energy Inputs, Restoration Work Inputs, and their sum, Energy Subsidy Fractions, have the units of MJ/MJ in sequestered solar energy. The second term in Eq. (5)<sub>2</sub> describes external energy inputs to industrial soybean agriculture. In perfect, solar-driven agriculture  $\eta_{\text{soybean}} \equiv 1$ .

With the overall biodiesel production process efficiency of 0.82, and the soybean oil content of 18.4% by mass, 6.63 kg of soya beans are required to produce 1 kg of biodiesel. According to Tables

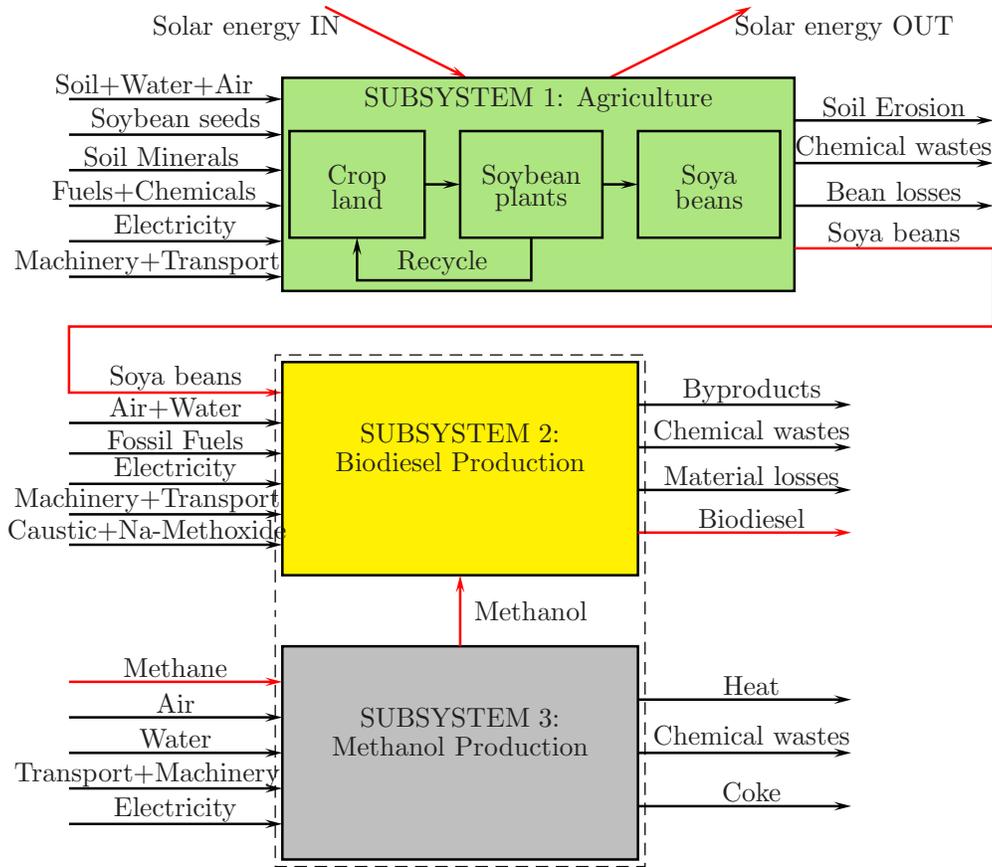


Figure 8: The soybean  $\rightarrow$  biodiesel system consists of three subsystems. In these subsystems, the energy costs of labor have been omitted. Subsystems 2-3 can be lumped together inside the dashed boundary. It is assumed that soybean plants are decomposed and recycled to improve soil structure. The  $\text{CO}_2$  produced in Subsystems 1-3, becomes an input to Subsystem 1, thus creating an incomplete carbon cycle. The evaporated and contaminated water outputs also become inputs after purification, creating a partial water cycle, see (Patzek, 2004), Part III. Subsystem 3 feeds methanol produced from methane. The soybean meal byproduct output of Subsystem 2, is *not* recycled back into Subsystem 1.

1 and 5, the fraction of direct fossil fuel inputs to agriculture is then  $21.25/(6.63 \times 18.1) = 0.18$ . If the indirect costs of obtaining these inputs, as well as energy embodied in machinery and hybrid seeds are included, this ratio usually doubles, and I add a very *small* 0.2 for the environment restoration work, for details see (Patzek, 2004; Patzek, 2006d). With these assumptions the overall efficiency of soybean agriculture,

$$\eta_{\text{soybean}} = \frac{1}{1 + 0.18 + 0.18 + 0.2} = 0.64 \frac{\text{MJ soybean}}{\text{MJ sequestered solar energy}} \quad (6)$$

is essentially the same as that of corn agriculture. The fossil energy inputs are significantly smaller for soybean, but so are the yields.

### 5.0.2 Overall Energy Efficiency of Soybean Crushing and Conversion, and Methanol Production)

By drawing the dashed line around Subsystems 2 and 3 in Figure 8, we can write the following steady-state, approximate energy balance for both of them:

$$\begin{aligned}
 & 1. \text{ Energy of Soya Beans} + \\
 & 2. \text{ Energy of Fossil/Synthetic Chemical Inputs to Soybean Crushing} + \\
 & 3. \text{ Energy of Fossil/Synthetic Chemical Inputs to Soybean Conversion} + \\
 & 4. \text{ Energy of Fossil/Synthetic Chemical Inputs to Methanol Production} + \\
 & \quad 5. \text{ Energy of Water In} + \\
 & \quad 6. \text{ Energy of O}_2 \text{ from Air, etc.} = \\
 & \quad 7. \text{ Energy of Finished Biodiesel} + \\
 & 8. \text{ Energy of **Dry** Soybean Meal} + \\
 & \quad 9. \text{ Energy of Glycerine} + \\
 & 10. \text{ Energy of Solid, Liquid, and Gaseous Effluents from Soybean Processing}
 \end{aligned} \tag{7}$$

Equation (7) can be further simplified, just as in (Patzek, 2006c):

$$\begin{aligned}
 & 1. \text{ Energy of Soya Beans} + \\
 & 2. \sum \text{Fossil Energy Inputs} = \\
 & 3. \text{ Energy of Finished Biodiesel} + \\
 & 4. \text{ Energy of **Dry** Soybean Meal} + \\
 & \quad 5. \text{ Energy Losses}
 \end{aligned} \tag{8}$$

By using the scaled NREL numbers in Table 5, the mass losses in Table 3, and the heating values listed in Table 1, we get the following energy balance:

$$\begin{aligned}
 & 1. 6.43 \text{ kg of soybeans} \times 18.1 \text{ MJ/kg soybeans} \\
 & \quad 2. 22.661 + 0.366 + 6.708 + 0.176 \text{ MJ/kg} = \\
 & \quad 3. 40 \text{ MJ/kg} + \\
 & 4. 6.43 \text{ kg of soybeans} \times 0.82 \times 16.5 \text{ MJ/kg soybeans} + \\
 & \quad 5. 19.3 \text{ MJ/kg}
 \end{aligned} \tag{9}$$

or

$$\underbrace{116.3 \text{ MJ/kg biodiesel}}_{\text{Soybean}} + \underbrace{30 \text{ MJ/kg}}_{\text{Fossil Energy}} = \underbrace{40 \text{ MJ/kg}}_{\text{Biodiesel}} + \underbrace{87 \text{ MJ/kg}}_{\text{Meal}} + \underbrace{19.3 \text{ MJ/kg}}_{\text{Other+Losses}} \tag{10}$$

The overall efficiency of biodiesel production is

$$\begin{aligned}
 \eta_{\text{biodiesel}} &= \frac{\text{Output Biodiesel Energy}}{\sum \text{Refinery Energy Inputs}} \\
 \eta_{\text{biodiesel}} &= \frac{\text{Output Biodiesel Energy}}{\text{Input Soybean Energy} \cdot 1 + \sum \text{Fossil/Env. Energy Input Fractions}}
 \end{aligned} \tag{11}$$

where the dimensionless Energy Input Fractions have the units of MJ/MJ in soybean.

Therefore

$$\eta_{\text{biodiesel}} = \frac{40}{116.3} \frac{1}{1 + 30/116.3} = 0.27 \frac{\text{MJ biodiesel}}{\text{MJ soybeans}} \quad (12)$$

and the overall thermodynamic efficiency of the soybean farming - biodiesel refining process is

$$\eta_1 = \eta_{\text{soybean}} \times \eta_{\text{biodiesel}} = 0.64 \times 0.27 = 0.18 \quad (13)$$

We conclude that roughly 1 in 5 parts of the solar energy (sequestered as soybean) and the input fossil energy become biodiesel.

If *bone dry* soybean meal<sup>14</sup> is treated as another finished fuel, the efficiency of its production in the biodiesel refining process is

$$\eta_{\text{meal}} = \frac{87}{146.3} = 0.59 \frac{\text{MJ soybean meal}}{\text{MJ soybeans}} \quad (14)$$

and the overall efficiency is

$$\eta_2 = \eta_{\text{soybean}} \times \eta_{\text{meal}} = 0.64 \times 0.59 = 0.38 \quad (15)$$

Thus, roughly 1 in 2.5 parts of the sequestered solar energy and fossil energy inputs become soybean meal.

If both biodiesel and soybean meal are lumped together as finished fossil fuels, the overall efficiency is

$$\eta_3 = \eta_1 + \eta_2 = 0.56 \quad (16)$$

and approximately 1 in 2 parts of the sequestered solar energy and fossil inputs become biodiesel and soybean meal.

## 6 Replacing Diesel Fuel Used in the U.S. with Soybean Biodiesel?

With the high average efficiency of 0.82, the 2005 world crop of soybean, 210 million tonnes, would produce

$$\frac{210 \times 10^6 \times 0.184 \times 0.82}{880 \times 3.785} = 9.5 \text{ billion gallons of biodiesel} \quad (17)$$

Because of its oxygen content, this biodiesel has 91% by volume of the HHV of petroleum diesel fuel, see Figure 4 and Table 4. In 2004, the U.S. used 62 billion gallons of distillate oil, 45 billion gallons of which was diesel fuel.

**Remark 1** Conversion of the world soybean crop to biodiesel in 2005 would satisfy 14% of distillate oil consumption in the U.S. Since, 10% of biodiesel by mass is methanol, one would need at least 21 million tonnes of methanol made from roughly 14.3 million tonnes or 21.7 billion sm<sup>3</sup> (0.76 Tcf of methane, or  $1.13 \times 0.76 = 0.87$  Tcf of natural gas). If free energy consumption in methanol production were accounted for, the methane requirement would double to ~8% of annual consumption of natural gas in U.S. The U.S. soybean crop would satisfy 6% of our consumption in agreement with (Hill et al., 2006), and not counting the fossil energy expenditures in soybean agriculture and processing.  $\square$

<sup>14</sup>The fossil energy required to dry this soybean meal is not included.

## 7 Conclusions

The NREL (Sheehan et al., 1998) assessment of the soybean biodiesel cycle was a solid and thorough analysis of the cycle components. The individual energy inputs were then weighted in such a way that soybean meal, hulls, water, and dirt inherited 82% of the energy inputs and biodiesel only 18%, and this was not quite correct.

With minor corrections, the NREL estimates of the energy inputs can be used in a proper First Law energy balance of the cycle that also accounts for the solar energy sequestered as soya beans and for some of the extensive restoration work of the fields damaged by soybean agriculture.

The overall energy efficiency of biodiesel production is 0.18, i.e., only 1 in 5 parts of the sequestered solar energy and invested fossil energy becomes biodiesel. Soybean meal is produced with an overall energetic efficiency of 0.38, but it is not a fossil fuel. If both biodiesel and soybean meal are treated as finished fossil fuels, the overall energy efficiency of their production is 0.56.

Not surprisingly, the First Law efficiency of the soybean biodiesel fuel (0.18) is similar to that calculated in (Patzek, 2006c; Patzek, 2006a) for corn ethanol (0.25). The energy efficiency of producing the DDGS coproduct is 0.15.

Therefore, production of soybean biodiesel is energetically somewhat less efficient than production of corn ethanol, but production of soybean meal is four times more efficient than production of DDGS from corn. The combined energy efficiency of the output fuel and coproduct for the soybean biodiesel cycle is 40% higher (0.55) than that for the corn ethanol cycle (0.40).

The efficiency of the soybean biodiesel cycle presented in (Hill et al., 2006) is at odds with the NREL analysis and the current analysis. The main difference seems to be in the very significant underestimation of the fossil energy inputs into soybean crushing and conversion.

If both corn ethanol and soybean diesel were produced in massive quantities their byproducts, DDGS and soybean meal, would be too abundant for the feedlot animals to consume them. Therefore, energy credits assigned to these byproducts are questionable.

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