Biodiesel Energy Balance

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In a recent paper by David Pimentel and Tad Patzek [1], the issue of the energy balance for biodiesel production was brought back to the public's attention through press releases and numerous articles in the popular press. The issue had been relatively quiet since the release of the extraordinarily detailed study conducted by the USDA and USDOE, sometimes known as the NREL study [2]. The NREL study had claimed that the energy in a gallon of biodiesel was 3.2 times greater than the fossil-based energy required to produce it. Pimentel and Patzek claim that their analysis shows that biodiesel production actually requires 27% more fossil energy than is present in the biodiesel. This wide disparity in results is surprising and suggests that the differences are based on more than subtle differences in assumptions about crop yields or fertilizer application rates.

The Pimentel and Patzek analysis is summarized in the diagram shown below on the basis of 1000 kg of biodiesel produced.

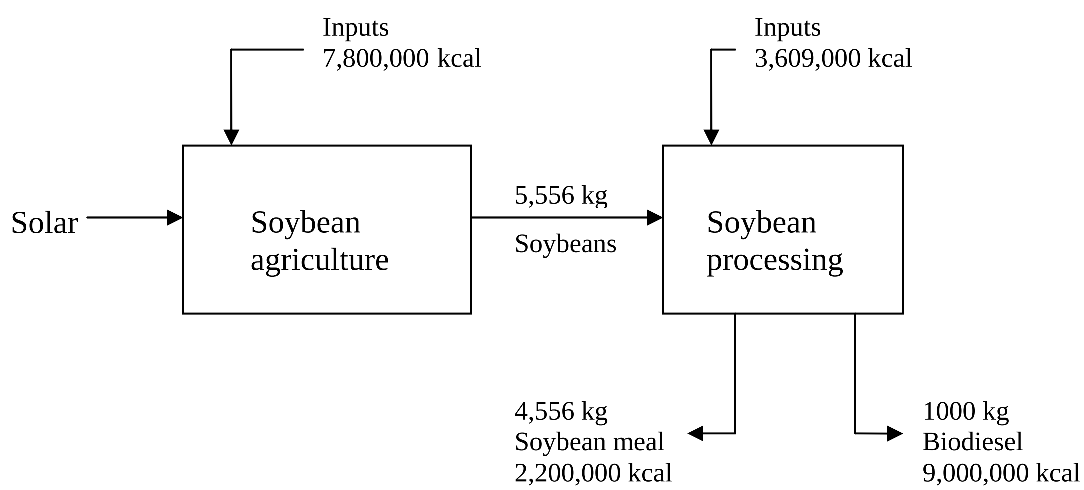

Figure 1. Pimentel and Patzek biodiesel energy balance (for 1000 kg of biodiesel)

As shown in the diagram, Pimentel and Patzek calculate that 7,800,000 kcal of energy is required to grow 5,556 kg of soybeans. As is usual practice in these energy balance studies, solar energy inputs are not included in this total so processes may actually appear to be creating energy rather than simply converting it from one form to another. Another 3,609,000 kcal are required to convert these soybeans to biodiesel. The total of these two energy inputs can be divided by the 9,000,000 kcal of energy in the 1000 kg of biodiesel

$$\frac{7{,}800{,}000 + 3{,}609{,}000}{9{,}000{,}000} = 1.27$$

This calculation makes it appear that the energy inputs are 27% higher than the energy content of the biodiesel. This is the number that is reported in the abstract of Pimentel and Patzek's paper. In the text of the paper, they acknowledge that the process also yields soybean meal and they state that some credit should be provided for this output. Their estimate for this is 2,200,000 kcal. The authors apply this energy as a credit against the energy inputs as shown below.

$$\frac{7{,}800{,}000 + 3{,}609{,}000 - 2{,}200{,}000}{9{,}000{,}000} = 1.02$$

When the energy for the soybean meal is included in this fashion, the calculation indicates that input energy is 2% higher than the energy in the biodiesel. In Pimentel and Patzek's paper, the number given is 8% but this is based on an addition error in their Table 7 that is corrected in some parts of the paper but not in the calculation that gave 8%.

Although the 27% energy deficit is the most frequently cited number in the popular press when describing Pimentel and Patzek's paper, the authors acknowledge that the 2% figure is more appropriate by stating "*However, a credit should be taken for the soy meal that is produced and this has an energy value of 2.2 million kcal*." It isn't clear why the authors chose to only include the 27% figure in their abstract. The people who read only the abstract would be misled about the actual calculation.

Regardless of which figure is used, the difference between the NREL study and the Pimentel and Patzek study is still large. There has been some focus on the assumption for lime application, which is the largest energy term in the soybean agriculture calculation, and which appears to be incorrect. Questions have also been raised about the low energy attributed to the soybean meal. These issues will be addressed later in this discussion. However, even if these numbers are corrected, there is a fundamental difference in the way the analysis has been conducted. The primary difference appears to be in the way the input energy is allocated to the various output streams.

In the NREL study, the input energy for soybean production and oil extraction was calculated and then this energy was allocated between the two output streams. Since soybeans consist of about 18% oil and 82% meal (by weight), the energy input to produce the soybeans and extract the oil was split so that 18% was assigned to the oil and 82% to the meal. The authors of the NREL study acknowledged that other ways of allocating the energy could be used but that a mass-based assumption is a frequent choice for this type of analysis. Other choices might be to split the energy based on the relative monetary value of the product streams or based on the ratio of their energy contents. In Pimentel and Patzek's study, by subtracting the energy value of the meal directly from the input energy, they are assuming that the meal is produced with no energy loss (or gain). If losses are present, then they will all be assigned to the biodiesel. As will be seen later, this approach can lead to absurd results.

It is illustrative to use Pimentel and Patzek's estimates of energy inputs with the energy allocation approach used by NREL. If the 11,409,000 kcal of energy per 1000 kg calculated by Pimentel and Patzek is split between the oil and meal assuming 18% and 82%, the energy input assigned to the oil will be 2,053,620 kcal. Further, since biodiesel production converts about 82% of the input mass to biodiesel and 18% to crude glycerin (NREL estimate), the 2,053,620 kcal should be reduced to 1,683,968 kcal. When the input energy is allocated in this way, it can be noted that the ratio of the biodiesel fuel energy to the input energy is:

$$\frac{9{,}000{,}000}{1{,}683{,}968} = 5.3$$

The energy of the biodiesel is 5.3 times greater than the input energy. So, using the energy calculations of Pimentel and Patzek with the NREL approach to allocating the input energy, gives an energy gain that is even higher than the 3.2 value from the NREL report.

The difference between the 5.3 and 3.2 values appears to be due primarily to differences in the processing energy for converting soybean oil to biodiesel. It is not clear from their paper whether Pimentel and Patzek recognize the difference between soybean oil and biodiesel. They refer to the final product of their calculation variously as: biodiesel oil, soy oil, soy biodiesel, and biodiesel. While there is not sufficient detail in their paper to be sure, it appears that their calculations only include the energy required to extract and refine the soybean oil. The fact that methanol and catalyst are not included in their list of inputs is further evidence that this part of the biodiesel production process has been neglected.

NREL has estimated 1,404,000 kcal for oil transport and the transesterification process per metric ton of biodiesel production. This energy includes methanol and other chemicals production and the electricity and steam used in the biodiesel production plant. The NREL report assigned 39,000 kcal for biodiesel transport. These terms are ignored in Pimentel and Patzek's report. Assigning 18% of the soybean crushing energy (using Pimentel and Patzek's number), 82% of the energy from oil transport and transesterification (from the NREL report) and 100% of the energy for biodiesel transport (from the NREL report) to the biodiesel life cycle, the fuel energy to input energy ratio would be:

$$\frac{9{,}000{,}000}{(11{,}409{,}000 \times 0.18) + (1{,}404{,}000 \times 0.82) + 39{,}000} = 2.8$$

Therefore, the energy gain is 2.8. This is still a pretty good ratio for gain from biodiesel production.

Lime Application Rates

The paper presented by Pimentel [1] contains a critical error related to lime use. The paper assumes that 4800 kg/ha of lime will be applied to the field as preparation for growing the soybean crop. Lime is added to correct the pH in acidic soils and, in those cases where it is needed, is applied only once every several years [3]. Pimentel and Patzek charged all of the lime to a single year's soybean crop. It also should be noted that one of the results of Kassel and Tidman [3], the reference which Pimental and Patzek cite in their paper, was that yield improvements from lime use are small and it takes yield increases over 2-3 years to pay for a single year's lime application.

Since lime alone accounts for 36% of the agricultural energy input by Pimentel, this error causes a significant error in the overall analysis. If a single application of 4800 kg per hectare of lime is split for 5 years, it would come down to 270 Mcal/ha, using Pimentel's value of energy input for lime. This reduces the soybean agriculture energy input from 7,800,000 kcal to 5,551,000 kcal. This will increase the energy input-output ratio to:

$$\frac{5{,}551{,}000 + 3{,}609{,}000 - 2{,}200{,}000}{9{,}000{,}000} = 0.77$$

So, just correcting Pimentel and Patzek's lime calculation shows that the energy required to product biodiesel is only 77% of the energy in the fuel.

Soybean meal energy content

There appears to be an additional error in the quantity used to estimate the energy of the meal produced from soybean oil extraction. Pimentel and Patzek assign a value of 2,200,000 kcal to the energy of the meal stream but do not provide a reference. The 2,200,000 kcal of energy for 4,556 kg of meal gives a specific energy content of 482.9 kcal/kg. Most biomass has an energy content of about 4,150 kcal/kg. Soybean meal would be expected to have an energy content that is similar to this. When this value is inserted into the input-output ratio, it becomes:

$$\frac{5{,}551{,}000 + 3{,}609{,}000 - 4{,}150\,(4{,}556\ kg)}{9{,}000{,}000} = -1.08$$

The negative number illustrates why Pimentel and Patzek's approach of simply subtracting the energy content of the meal from the inputs leads to an absurd result. In this case, the energy content of the meal is larger than all of the energy inputs so it appears that we are getting the energy in the biodiesel without having to provide any input energy at all! Of course the reason this is possible is due to the solar energy inputs which are not included in the calculation.

We have shown that Pimentel and Patzek's claim that biodiesel consumes more energy than is provided in the fuel is incorrect. Their conclusion is based on several critical errors in their analysis that when corrected lead to the exact opposite conclusion, that biodiesel actually provides much more energy than is consumed in its production.

References

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2. Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, and H. Shapouri, *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*, Final Report, National Renewable Energy Laboratory, NREL/SR-580-24089 UC Category 1503, May, 1998.

3. Kassel, P. and M. Tidman, “Ag lime impact on yield in several tillage systems,” Iowa State University Website: http://www.ipm.iastate.edu/ipm/icm/1999/9-13-1999/aglimeimp.html, accessed on Nov. 15, 2005.