The Biodiesel Energy Balance

By Dev S. Shrestha and Jon Van Gerpen

The energy balance of biodiesel and ethanol is a subject that seems to create endless confusion. Analysis is usually reduced to a single number, or ratio, and the energy balance debate typically hinges on whether that ratio is lesser than or greater than one. This article will shed some light on the energy balance ratio and its relationship to the "renewability" of biodiesel.

Why is the energy balance ratio so important in the first place? A major reason is the concern over how renewable a specific biofuel is. Since biofuels are derived from biological materials, the fuel can be replaced in a relatively short period of time. In the case of biodiesel, oil can be obtained from a new crop of oilseeds and or animal fats are available year-round. A renew-

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able fuel serves at least two purposes; it reduces a country's dependence on imported oil and conserves limited natural petroleum supplies for alternative energy uses.

The energy balance debate revolves around whether a biofuel that requires some fossil fuel energy to produce can be defined as a renewable fuel. True, it is derived from a plant grown in a field, but doing so may use a considerable amount of nonrenewable petroleum-based fuel for things like field cultivation, fuel processing and transportation. The renewable qualities of biodiesel can range from completely renewable, if no fossil energy input is required, to nonrenewable, if the fossil energy input required for production is as much or more than the energy content of the biofuel. It's beneficial to know the renewable qualities of a biofuel for two reasons. First, it determines to what degree the fuel is renewable. Second, it allows for the comparison of the renewable nature of the different processes used to produce the fuel.

The extent to which a fuel is renewable is frequently expressed by an energy ratio. Instead of accounting for only the nonrenewable energy input, ratios are calculated to compare the total energy that went into producing a gallon of biofuel with the energy content in that gallon of fuel. For biodiesel, the energy ratio doesn't differ much from the renewable ratio. The total energy input is close to the nonrenewable energy input.

Note that not all of the energy used in farming and soybean crushing goes to produce biodiesel because soybean meal and glycerin are also produced. Therefore, biodiesel should be held accountable for only a fraction of the total energy input when assessing its energy balance.

Figure 1 depicts the energy inputs and outputs for biodiesel. Note that not all of the energy used in farming and soybean crushing goes to produce biodiesel because soybean meal and glycerin are also produced. Therefore, biodiesel should be held accountable for only a fraction of the total energy input when assessing its energy balance.

The fraction of the input energy associated with the meal is designated f1. The biodiesel fraction is f2 and the glycerin fraction is f3. The fractions represent the overall split of input energy going into a coproduct. How the fractions are assigned may vary.

The input energy which is assigned to the meal as shown in Figure 1 is E•f1. Biodiesel is responsible for E•f2 and glycerin is E•f3. The sum of the energy splits is equal to the energy input. One of the most straightforward ways to determine the energy split is to partition the input energy in proportion to the mass fraction of each individual end product. Even though this method is simple and consistent, it does not account for the economic value of the output stream. Therefore, another way of assigning fractions is based on the economic value of each end product.

Em, Eb, and Eg are the energy equivalents of the meal, biodiesel and glycerin, respectively. Another method used for coproduct energy allocation is based on the replacement energy of each coproduct. The method estimates an energy credit for each coproduct based on the energy required to produce a substitute coproduct. The replacement method is often difficult to apply because many coproducts don't have exact substitutes.

To calculate the energy ratio, the calorific value of biodiesel is compared to the energy fraction for which the fuel is reponsible. E•f1 is not equal to Em. In fact, Em is expected to exceed E•f1 because of the solar energy collected during photosynthesis.

How the energy ratio is defined makes a large difference in the final value of the energy ratio. According to the Sheehan et al. (1998), also known as the National Renewable Energy Laboratory (NREL) study, the energy ratio should be defined as:

$$R_{NREL} = \frac{E_b}{E.f_2}$$

Pimentel and Patzek (2005) defined the energy ratio differently. They subtracted the energy contained in the meal (Em) from the total input energy and divided the biodiesel energy content by this amount to get the energy ratio as:

$$R_{Pimentel} = \frac{E_b}{E - E_m}$$

The disadvantage of using the meal energy equivalent instead of E•f1 is that the energy ratio could be problematic. As pointed out above, Em can approach or even exceed E. In that case, the energy ratio approaches infinity or may even be a negative number making the energy ratio meaningless.

In Ahmed (1994), the energy ratio was defined as:

$$R_{Ahmed} = \frac{E_b + E(1 - f_2)}{E}$$

Ahmed's definition of the energy ratio is logical if the coproducts are also used for fuel, as is the case for ethanol production from sugarcane. The total energy output in this model would be the energy content of biodiesel and its coproducts. Since soybean meal is generally not burned for energy production, this definition carries less meaning in evaluating the renewable characteristics of the fuel.

Hill et al. (2006) defined the energy ratio as:

$$R_{Hill} = \frac{E_b + E_m + E_g}{E}$$

This definition of the energy ratio is a hybrid between Pimentel and Ahmed's definition.

Each energy ratio defined above provides a unique numerical value for the energy ratio even for the same input data set. Consider the following numerical example: The total energy input to E to produce all products from an acre is about 1,900 million calories and f2 equals 0.25. Energy in biodiesel produced from acre of land (Eb) is nearly 1,500 million calories. The value of Em is roughly 400 million calories per acre, according to Pimentel's paper. Eg is estimated as 100 million calories per acre. With these assumptions, the following energy ratios were obtained.

- NREL definition: 3.2:1
- Pimentel's definition: 1:1
- Ahmed's definition: 1.5:1
- Hill's definition: 1.1:1

The variation in the results clearly shows that the reported number should be interpreted carefully as they do not mean the same thing. Which definition to use depends on what question is being answered. If the renewable nature of the fuel is being addressed, the NREL definition of energy ratio is more appropriate since it doesn't treat coproducts as a fuel. Further processing of coproducts, which may alter their calorific value, doesn't affect biodiesel renewability.

What happens with this definition if some of the crude glycerin or meal is burned to offset the fossil energy input? Does its renewable nature increase? If part of E could be replaced by meal or

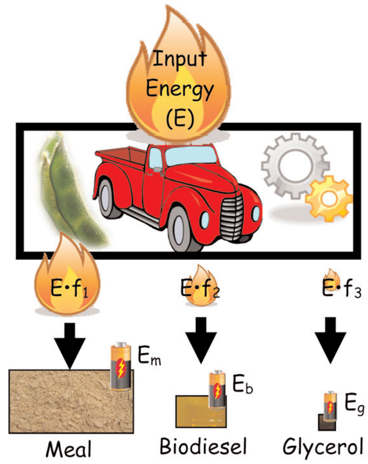

Figure 1. Total input energy E used for farming, transportation and processing is factored to all coproducts. Meal, biodiesel and glycerin have energy equivalent Em, Eb, and Eg respectively.

When comparing two bioenergy sources—one using a byproduct as an energy source and another not—we get very different energy balance ratios. Comparing the energy ratio of those fuels is like comparing apples to oranges.

glycerin, the energy ratio becomes higher. In that sense, biodiesel becomes even more of a renewable fuel. This is one of the reasons sugarcane-based ethanol has a higher energy balance than corn-based ethanol. Sugarcane bagasse is burned to reduce the need for outside fossil fuel energy inputs.

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What would happen if some of the biodiesel share of energy E•f2, which equals 475 million calories in the above example, is replaced by biodiesel itself? If 400 million calories were replaced by biodiesel then,

$$\textit{Energy ratio} = \frac{1500 - 400}{475 - 400} \approx 15$$

If we use more renewable energy in the production process, the renewability ratio could be more than 10. More importantly, the biodiesel industry needs to establish a standard definition of energy balance so the rest of us aren't left to guess at what it refers to. ■

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