ENERGY EFFICIENCY AND END-USE TECHNOLOGIES OF BIODIESEL PRODUCTION

Introduction

Biodiesel Life Cycle Assessment (LCA) Studies provide an opportunity to quantify the total greenhouse gas emissions and savings for different biodiesel pathways. Also they quantify energy demands and overall energy efficiencies for processes and/or final products.

Life Cycle Assessment studies so far presented the results in a comparative way: biodiesel/ bioethanol pathways versus the regular diesel which finally enables all readers to correctly estimate the biofuels potential to greening the transport sector worldwide.

Understanding the overall energy requirements of biodiesel is key to describe biodiesel made from vegetable or animal, new or used oil, as a "renewable energy" source. In general, the more fossil energy required producing a fuel, less we can say that this fuel is "renewable". Thus, the renewable nature of a fuel can vary across the spectrum from "completely renewable" (i.e., no fossil energy input) to non-renewable (i.e., fossil energy inputs as much or more than the energy output of the fuel).

This paper focuses on the review of the life cycle energy assessment and the energy efficiency assessment of biodiesel. The approach embraced is to compare for every indicator (e.g. fossil fuel ratio) biodiesel with the petroleum diesel specified by the European Standard EN 590. The most relevant indicators reviewed for biodiesel and diesel EN 590 are: life cycle energy demand and inventory, fossil fuel inventory, fossil fuel ratio, energy efficiency of the production and the distribution of both fuels.

Next, a sensitivity analysis has been conducted in order to understand the changes in indicators' values in different alternative scenarios.
Lastly, the technical aspects of end-use technologies are explained.

Defining Energy Efficiency

Energy efficiency estimates inform about the energy (primary or fossil) requirements in the process of obtaining the final fuel (by converting the energy encapsulated in the feedstock or the raw material into the transportation fuel).

There are two types of energy efficiency. The first one represents the overall "life cycle energy efficiency", while the second is referred as the "fossil energy ratio". Each reveals a dissimilar aspect of the life cycle energy balance for the fuels under investigation.

The calculation of the life cycle energy efficiency is simply the ratio of fuel product energy to total primary energy:

Life Cycle Energy Efficiency = Fuel Product Energy/Total Primary Energy[1]

It is a measure of the amount of energy that goes into a fuel cycle, which actually ends up in the fuel product. This efficiency accounts for losses of feedstock energy and additional process energy needed to make the fuel.

The fossil energy ratio tells us something about the degree to which a given fuel is or is not renewable. It is defined simply as the ratio of the final fuel product energy to the amount of fossil energy required to make the fuel:

[1] "Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus", US Department of Agriculture and US Department of Energy, Final Report, May 1998, p. 11

Fossil Energy Ratio = Fuel Energy/Fossil Energy Inputs[2]

If the fossil energy ratio is equal to 1, then the fuel is non-renewable. A fossil energy ratio of "one" means that no loss of energy occurs in the process of converting the fossil energy to a useable fuel. For fossil energy ratios greater than 1, the bigger the ratio, the more "renewable" becomes the fuel. As a fuel approaches being "completely" renewable, its fossil energy ratio approaches "infinity." In other words, a completely renewable fuel has no fossil energy inputs.

From a policy perspective, these considerations are valuable. Policymakers want to understand the extent to which a fuel increases the "renewability" of our energy supply. Another implication of the fossil energy ratio is the question of climate change. Higher fossil energy ratios (that means that the fuels are more from renewable sources) imply lower net CO2 emissions. This is a secondary aspect of the ratio, as we are explicitly estimating total CO2 emissions from each fuel's life cycle. Nevertheless, the fossil energy ratio serves also as a verification tool for the calculations of the CO2 life cycle emissions (since the two indicators should be correlated).

Petroleum Diesel Life Cycle Energy Demand

In order to point out the biodiesel versus petroleum diesel energy efficiency and fossil fuel ratio, we analyzed in this paper several LCA studies done by research institutes, consultancies, regional or national administration across the EU.

For this section we took as basis the CIEMAT study performed for the Spanish Environment Ministry. Its LCA model shows that 1.2007 MJ of primary energy is used to make 1 MJ of petroleum diesel fuel. This corresponds to a life cycle energy efficiency of 83.28%. Ninety-three percent of the primary energy demand is for extracting crude oil from the ground. About 88% of the energy shown for crude oil extraction is associated with the energy value of the crude oil itself. The crude oil refinery step for making diesel fuel dominates the remaining 7% of the primary energy use.

Removing the feedstock energy of the crude itself from the total primary energy allows us to analyze the relative contributions of the process energy used in each life cycle. Process energy demand represents 20% of the energy. Using the total primary energy reported in the CIEMAT Study[3],

Life Cycle Energy Efficiency = 1 MJ of Fuel Product Energy/1.2007 MJ of Primary Energy Input
= 0.8328

Life Cycle Inventory of Biodiesel and Petroleum Diesel ultimately available in the petroleum diesel fuel product. About 90% of the total process energy is in refining (60%) and extraction (29%). The next largest contribution to total process energy is for transporting foreign crude oil to domestic petroleum refiners.

Biodiesel Life Cycle Energy Demand

Compared on the basis of primary energy inputs, biodiesel and petroleum diesel are essentially equivalent. Biodiesel has a life cycle energy efficiency of 80.55%, compared to 83.28% for petroleum diesel. The slightly lower efficiency reflects a slightly higher demand for process energy across the life of cycle for biodiesel.

One MJ of biodiesel requires an input of 1.2414 MJ of primary energy, resulting in a life cycle energy efficiency of 80.55%. Biodiesel is comparable to petroleum diesel in the conversion of primary energy to fuel product energy (80.55% versus 83.28%). The largest contribution to primary energy (87%) is

2 Idem, p.11
3 Ibid., p.12

the vegetable oil[4] conversion step because this is where we have chosen to include the feedstock energy associated with the soybean oil itself.

Fossil Energy Ratio = 1 MJ Fuel Energy/1.1995 MJ of Fossil Energy Input = 0.8337.

Life Cycle Energy Inventory of Biodiesel and Petroleum Diesel

As with the petroleum life cycle, the stages of the life cycle of biodiesel that are most energy intensive are the feedstock production one (i.e. if we include the soybean oil energy with the farming operation, then soybean agriculture would have been the dominant consumer of primary energy). This is analogous to placing the crude oil feedstock energy in the extraction stage for petroleum diesel fuel. The next two largest primary energy demands for soybean are crushing and soybean oil conversion. They account for most of the remaining 13% of the total demand.

When we analyse the process energy separately from primary energy, we see that energy demands in the biodiesel life cycle are not dominated by soybean oil conversion. The soybean crushing and soy oil conversion to biodiesel demand the most process energy (34.25% and 34.55%, respectively, of the total demand). Agriculture accounts for most of the remaining process energy consumed in life cycle for biodiesel (almost 25% of total demand). Each transportation step is only 2%-3% of the process energy used in the life cycle.

Energy contained in the soybean oil itself represents, in effect, the one place in the biodiesel life cycle where input of solar energy is accounted for. Total radiant energy available to soybean crops is essentially viewed as “free” in the life cycle calculations. It becomes an element accountable in the life cycle only after it has been incorporated in the soybean oil itself. This is analogous to counting the feedstock energy of crude petroleum as the point in its life cycle where solar energy input occurs. Petroleum is essentially stored solar energy. The difference between petroleum and soybean oil as sinks for solar energy is their time scale. While soybean oil traps solar energy on a rapid (“real time”) basis, petroleum storage represents a process that occurs on a geologic time scale. This difference in the dynamic nature of solar energy utilization is the key to the definitions of renewable and non-renewable energy.

For Diesel 590 the production stage that is the most energy consuming is the extraction one, followed by refining and distribution of that fuel to the filling stations.

For the biodiesel production from new vegetable oils, the most energy intensive stage in the production is the cultivation. The trans-etherification stage (where the oil and the methanol are mixed for obtaining biodiesel) actually saves energy from a system expansion perspective. From all the pathways in this category, soy oil is consuming both the most primary energy (44,64 MJ/kg) and most fossil energy (25,63 MJ/kg), while sunflower oil requires the smallest amount both for the total primary (23,58 MJ/kg) and for fossil energy (14,34 MJ/kg). Also rapeseed oil[5] is well performing, requiring only 26,86 MJ/kg primary energy and 15,58 MJ/kg fossil energy.

When biodiesel is produced from used oils, the energy (total primary and fossil) consumption is incontestably the most reduced compared to diesel or biodiesel from new vegetable oils. Moreover it is considered that the collection of used oils is energy neutral due anyway existing stringent laws asking for special collecting and disposal of all used oils as waste.[6]

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[4] “Analysis de Cyclo de Vida de Combustibles Alternativos para el Transporte. Phase II. Analisis de Cyclo de vida comparativo del Biodiesel y del Diesel”, Centro de Investigaciones Energeticas, Medioambientales y Tecnológicas, CIEMAT, Ministerio del Medio Ambiente, 2006; This Study analyzed here the soybean vegetable oil; all figures are from this pathway

[5] Crude rapeseed oil produced in the EU

[6] “Analysis de Cyclo de Vida de Combustibles Alternativos para el Transporte. Phase II. Analisis de Cyclo de vida comparativo del Biodiesel y del Diesel”, Centro de Investigaciones Energeticas, Medioambientales y Tecnológicas, CIEMAT, Ministerio del Medio Ambiente, 2006, p.90

Fossil fuel inventory and fossil energy ratio of biodiesel and petroleum diesel

Biodiesel has a positive fossil energy ratio because most of its feedstock requirements (on average 90 %) are renewable (i.e. the oil is of vegetal nature). On the basis of fossil energy inputs, biodiesel enhances the effective use of this finite energy resource.

Fossil energy demand for the conversion step is almost twice that of its process energy demand, making this stage of the life cycle the largest contributor to fossil energy demand, after the cultivation step.

Another assumption in the literature is to have natural gas derived methanol for the conversion step. This reveals an opportunity for further improvement of the fossil energy ratio by substituting natural gas-derived methanol with renewable sources of methanol, ethanol or other alcohols.

The basic hypothesis for calculation of the fossil fuel inventory is that the biodiesel is produced from different origins and the fossil fuel is accounted for in all stages apart from the distribution one.

The results of the CIEMAT 2006 study show that there is a **4 to 1 ratio** of final fuel to fossil fuel for the **biodiesel from crude vegetable oils** and a **44,4 to 1 ratio for the biodiesel from used oils.** The fossil energy ratio for diesel EN-590 is of 1 meaning that for 1 MJ of final energy it takes 1 MJ of fossil energy.

Other studies carried by research institutes or universities show similar results for the fossil energy ratio calculated on the same basis (MJ final fuel/MJ fossil energy):

- ADEME, 2002: Rapeseed: 3,03 and Sunflower: 3,16
- IFEU, 2000: Rapeseed: 5,46 and Sunflower: 5,83[7]
- Wiewls, 2004: Rapeseed: 5,24
- Rollefson et al, 2002: Rapeseed:2,06
- Ecobilan 2002: Rapeseed: 2,99 and Sunflower: 3,16
- USDA, 1998: Biodiesel uses 0.3110 MJ of fossil energy to produce one MJ of fuel product; this equates to a fossil energy ratio of 3.215. In other words, the biodiesel life cycle produces more then three times as much energy in its final fuel product as it uses in fossil energy

Energy Efficiency of the production and distribution of diesel EN-590 and biodiesel from crude and used vegetable oils

The final energy (primary and/or fossil) is greater than the total input energy used to produce the final fuel. The exceptions are the Diesel EN-590 and the B5 (diesel EN-590 blended with 5% Biodiesel) from both crude and used vegetable oil.

The table below summarizes the energy efficiencies of the pathways[8]:

	Life cycle energy efficiency (MJ final energy/MJ total primary energy)	**Fossil energy ratio** (MJ final energy/MJ fossil energy)
Diesel EN - 590	0,965	0,968
B5 Crude Veg oils	0,984	1,002
B10 Vrude Veg Oils	1,004	1,038
B100 Crude Veg Oils	**1,746**	**3,856**
B5 Used Veg Oils	0,997	1,014
B10 Used Veg Oils	1,032	1,065
B100 Used Veg Oils	3,149	21,861

[7] The IFEU measurements take into account glycerine on a calorific power basis, showing better fossil ratio results than the other studies presented

[8] Opus cit., p.92

Logically, the more biodiesel is blended, the higher are both the energy efficiency and the fossil fuel ratio.

Sensitivity analysis

The purpose of conducting a sensitivity analysis is to clarify the relevance of the variables used in the main analysis. The way to perform the sensitivity analysis is to elaborate alternative scenarios and to test alternative hypothesis. Accordingly the results will confirm or infirm the variables and the main results.

This paper takes the example of the CIEMAT 2006 Study's Sensitivity Analysis for a set of reasons: the recent date of the conducting of the study, the wide geographical area analysed, the overall relevance- the study was conducted for the Spanish Ministry of Environment, the Spanish Ministry for Education and Research.

For this sensitivity analysis, a series of variables were chosen. These are:

1. *rapeseed origin*[9]
2. *the energy consumption in the crushing stage*[10]
3. *crude vegetable oils composition*:
   a) 40 % soybean oil, 25% rapeseed oil, 25% palm oil, 10% sunflower oil
   b) 40 % rapeeed oil, 60 % sunflower oil
   c) 65 % sunflower oil, 25% rapeseed oil, 7,5% palm oil, 2,5 % soybean oil
   d) 100 % soybean oil
   e) 100 % rapeseed oil
   f) 100 % sunflower oil
   g) 100 % palm oil
4. *Co-products allocation method*
5. *Saturation of the glycerine market*

Results of the sensitivity analysis

Without going through the stages of hypothesis testing, a simple description of results is presented below:

1. *rapeseed origin* : in the alternative scenario with rapeseed of Spanish origin 95%, the energy consumption is higher, the fossil energy ratio is less good and the energy efficiency is lower

2. *the energy consumption at the crushing stage* : an optimized energy consumption at the crushing stage will improve but sensitively both the energy efficiency and the fossil energy ratio.

3. *crude vegetable oils composition*: a new re-ordering according to the energy efficiency and the fossil energy ratio performances are the following ones:
   a) 65 % sunflower oil, 25% rapeseed oil, 7,5% palm oil, 2,5 % soybean oil
   b) 40 % rapeseed oil, 60 % sunflower oil
   c) 40 % soybean oil, 25% rapeseed oil, 25% palm oil, 10% sunflower oil

   d) 100 % sunflower oil
   e) 100 % rapeseed oil
   f) 100 % soybean oil
   g) 100 % palm oil

4. *Co-products allocation method*: the basic method is allocation by energy content while the alternative method used for the sensitivity analysis is the economic value of the co-products. Different methods of counting for the by-products have been used in order to evaluate the impact of the method on the results of the LCA. However in all cases, the base method was

[9] EU origin (5% Spanish, 95% Rest of the EU)
[10] The CIEMAT study considered that all crushing processes except for palm oil require the same amount of energy input

the energy content, while the alternative one was the economic value. As it was expected, when using the economic value method of allocation for the by-products, the energy used in the process increased considerably, but especially in the one-oil biodiesel fuels (not the oil mixes). Accordingly the energy efficiency and the fossil energy ratios are worsening.

5. *Saturation of the glycerine market*: if the glycerine market is not saturated then the avoided costs of the production of synthetic glycerine should be accounted for in the LCA of biodiesel production and distribution. The alternative scenario for this variable is that the biodiesel co-product is not avoiding the synthetic glycerine production therefore no benefits are accounted for in the biodiesel LCA. As a result, the energy consumption for both pure biodiesel B100 and the blends is considerably increased. Accordingly, by increasing the energy consumption, the energy efficiency and the fossil energy ratio are worsening.

End-Use Technologies

Some considerations are deemed necessary on the end- uses technologies of the fuels modelled in the large majority of studies. This paper will restrict itself to some basic assumptions of the end-uses to consider, such as:

· Use of biodiesel and low-sulphur diesel fuel in modern urban diesel buses
· Fleet use only (a consequence of the previous assumption)
· Engine-specific comparisons

For the relevance of any end-use technologies analysis, it is important to limit the end-uses of the fuels to a single application. Bus applications examples have been chosen for the purpose of this paper due to the wide availability of literature[11]. Moreover, introducing this limitation to buses applications, allows the use of the best-characterized empirical database on biodiesel available. Urban buses applications are depicted as "fleets" and are characterized by the central fuelling system.

The other important aspect of end-use technologies is the engine-specific comparisons between the two fuel alternatives (biodiesel and petroleum diesel). By analyzing any database (e.g. the biodiesel database used by the USDA Study[12]), a simple conclusion can be extrapolated: emissions will vary considerably according to the type of fuel used, to the engine, etc.

Against this background, as a technical aspect of conducting end-use technologies analysis, it is highly necessary to chose a particular type of engine and to compare the use of different types of fuels on that engine, or to chose a particular fuel blend and to compare its use in different engines.

Conclusion

This paper analysed in a comparative approach the energy efficiency and the fossil fuel ratio of biodiesel and of diesel EN 590. It was shown, by way of surveying the relevant literature, that the energy efficiency of biodiesel is almost the same one as the energy efficiency of the diesel EN 590. However the crucial difference between the two fuels is done by the fossil fuel ratio, the studies cited showing a fossil fuel ratio very positive for biodiesel (in a range of 2.06 – 5.46 MJ of final primary energy/MJ fossil energy). Consequently, in a heated international debate and quest of sustainability of production and consumption, these results show that biodiesel is once again demonstrating its indubitable renewable nature and benefits.

[11]"Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus", US Department of Agriculture and US Department of Energy, Final Report, May 1998
[12] idem