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The energy balance of soybean biodiesel in Brazil: a case study

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Abstract: Like any other manufactured product, the production of biofuels involves the consumption of several inputs along its production chain. Energy balance results are often contradictory mainly due to differences in the methodologies used for their calculation. Despite the lack of a national database, this paper is a first estimate of the energy balance of biodiesel from soybean in Brazil. Data collected from five plantations located in the state of São Paulo, with a total production of 2000 metric tonnes, along with information about the industrial production process, were taken into account for calculating the energy balance of soybean biodiesel. A renewability factor of 4.3 was found considering an input allocation factor of 18% up to the stage of soybean oil production. This result was compared to information available in the literature. © 2011 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: soybean biodiesel; life cycle approach; energy balance; biofuel chain; allocation

Introduction

The reduction of the consumption of petroleum oil resources has been an important goal for many countries around the world in the last few decades. The increase and volatility of oil prices, and the fact that supply is deeply influenced by few producer countries, affect the security of this energy supply and have been among the main driving-forces for developing alternative energy sources.[1–2]

More recently, the mitigation of greenhouse gas (GHG) emissions has been a very important reason for fostering the consumption of renewable energy sources. The Fourth Assessment Report of IPCC reinforces that global warming is mostly due to the increase of GHG emissions caused by anthropogenic actions. The increase in carbon dioxide concentration is due primarily to fossil fuel use and land-use change.[3] Energy consumption in the transport sector has the highest annual growth rate and the use of biofuels has been pointed out as one of the best alternatives for mitigating GHG emissions.[4]

However, the production of biofuels itself consumes fossil energy. Therefore, the actual benefits of biofuels can only be evaluated based on a total life cycle assessment (LCA). In this sense, the energy balance between the energy produced and the energy consumed is a key issue when evaluating the

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potential contribution of a particular biofuel in reducing GHG emissions.

The energy balance of biofuels varies from one producer region to another due, for example, to different yields, agricultural practices, industrial technologies, distances, and transport used. The main objective of this paper is to present a first estimate of the energy balance of the biodiesel produced from soy, which accounts for about 80% of the current production of biodiesel in Brazil. The assessment includes a sensitivity analysis of the energy balance.

Literature review

Basic concepts

Concerning energy balances, revision of the literature is not an easy task. There are different methodological approaches for calculating energy balances of biofuels which make direct comparisons of results extremely difficult. Table 1 presents different concepts and the equations used by some authors for evaluating the energy balances of biofuels.

In Kaltschmitt *et al.*,[5] the overall life cycle of a renewable energy source was compared to the corresponding life cycle of a finite energy source. The comparison was carried out considering that the same energy service is provided by both energy carriers (i.e. the energy end use is the same in both cases). This approach is interesting because it provides a clear understanding of the net energy which could be extracted from land area, compared to the expenditure of diesel. However, this functional unit cannot be easily compared to other published studies.

Equation 2 includes the solar energy absorbed by the biomass in the photosynthesis process among the energy inputs. The result can be interpreted as the efficiency in converting primary energy into biofuels. This energy efficiency is important for fossil fuels, but this does not provide a useful concept for biofuels.

Equations 3 and 5 provide a powerful concept to evaluate the viability of producing biofuel because it measures the ratio between the renewable energy produced and the fossil expenditure to obtain the biofuel. For this reason it is called the *renewability factor* and has a variant when the energy content of byproduct is taken into account.

Equation 4 measures the ratio between the energy produced by biofuel and coproducts and the expenditure of all primary energy sources, including the renewable, but excluding the solar energy stored in biomass. This energy balance violates the laws of thermodynamics when it excludes solar energy and therefore cannot be used.

Equation 6 could be more useful if the difference were related to energy produced by biofuel instead of to its volume.

Table 1. Concepts and equations used for calculating energy balances of biofuels.

Equation	Energy balance	Comments and literature of reference
(1)	$= \frac{\Sigma PE\ (biofuel - diesel)}{area \times year}$	Kaltschmitt *et al.*[5]
(2)	$LCEE = \frac{HV\ of\ fuel\ product}{\Sigma PE\ of\ all\ inputs\ including\ SE}$	LCEE is called *Life cycle energy efficiency* used by Sheehan *et al.*[6]
(3)	$FER = \frac{HV\ of\ fuel\ product}{\Sigma FE\ of\ all\ inputs}$	FER is called *fossil energy ratio* used by Sheehan *et al.*[6]
(4)	$= \frac{HV\ of\ biofuel + energy\ content\ of\ co\ products}{\Sigma PE\ of\ all\ inputs\ except\ SE}$	Gazzoni *et al.*[7]
(5)	$= \frac{HV\ of\ biofuel + energy\ content\ of\ co\ products}{\Sigma FE\ of\ all\ inputs}$	Lam *et al.*,[8] Vries *et al.*,[9] Macedo *et al.*,[10] Consult. Inc., and others,[11] Hill *et al.*[12]
(6)	$NEB = \frac{(HV\ of\ biofuel + energy\ content\ of\ coproducts) - (\Sigma PE\ of\ all\ inputs)}{Volume\ of\ biofuel}$	NEB is called *net energy balance* used by Hill *et al.*[12]

PE – primary energy, FE – fossil energy, SE – solar energy, HV – heating value.

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Due to the different methodologies used in assessing energy balances of biofuels, the single comparison of results is not easy. The conversion of one basis of comparison to another requires knowledge of details and is even more difficult.

Life cycle studies of biodiesel production from soybean

In this section a review of results of energy balances is presented. As this paper has the aim of analyzing the energy balance of biodiesel produced from soybean in Brazil, only results that correspond to this crop and to this product are mentioned.

A comprehensive and detailed LCA of soybean biodiesel and mineral diesel was carried out for the US Department of Energy´s Office of Fuels Development and for the US Department of Agriculture Office of Energy by the National Renewable Energy Laboratory.[6] The stages that correspond to crude oil extraction, refining, and fuel transport were considered within the calculation procedures for petroleum diesel. The life cycle inventory showed that 1.20 MJ of primary energy is required for producing 1 MJ of petroleum diesel fuel, which corresponds to a life cycle energy efficiency of 83% (Eqn 2). According to the authors, 93% of the primary energy demand is for extracting the crude oil. Soybean cropping and its crushing, oil transesterification and all transport steps were the stages considered within the assessment of soybean diesel. It is shown that 1 MJ of biodiesel required an input of 1.24 MJ as primary energy, resulting in a life cycle energy efficiency of 80% (Eqn 2). Thus, a conclusion is that the efficiency conversion of primary energy sources to biodiesel is comparable to the production of the conventional fuel (80% for biodiesel versus 83% for the mineral diesel). Another result by the same authors is that the production of 1 MJ of biodiesel from soybean requires the input of 0.31 MJ as fossil energy sources that corresponds to a fossil energy ratio of 3.22 (Eqn 3).

Pimentel and Patzek found a negative energy return for ethanol obtained from corn, switchgrass and wood, and also for biodiesel produced from soybean and sunflower.[13] Their approach accounts for the total energy inputs (based on Eqn 3) associated with the agricultural phase, such as human labor, gasoline, fertilizers, lime, seeds, irrigation, pesticides, electricity, and so on. The energy requirements of the industrial processes associated with raw materials, water, and energy were also included. The embodied energy, or the energy required for the construction of agricultural machinery and equipment, such as steel, stainless steel and cement was also accounted for. In this study, the authors found that ethanol produced from corn, switchgrass, and wood biomass requires up to 29, 50, and 57% more energy than the energy content of the fuel, respectively. Also biodiesel from soybean and sunflower was found to have a negative energy balance as, according to the authors, the energy required in their production chain is 27 and 118% larger than that their respective energy contents.

Gazzoni *et al.*[7] developed an energy balance for biodiesel produced from soybean and sunflower based on the same methodology used by Pimentel and Patzek.[13] The authors used data from different studies regarding the agricultural and industrial phases and their energy balance results are positive for both biofuels. The O/I (output/input) energy ratio based on Eqn 2 (but excluding the solar energy), was calculated as 1.57 and 1.61, respectively, for biodiesel from soybean and sunflower. The exclusion of solar energy in this calculation results in conceptual error, because energy balances obtained applying Eqn 2 must be less than 1, otherwise the laws of thermodynamics are violated. When the energy content of the byproducts is also taken into account (Eqn 4), the energy balance of both biofuels becomes even more favorable (4.74 for soybean and 2.69 for sunflower).

In a study focusing on evaluating the displacement of oil derivatives by corn ethanol and soybean diesel, Escalera *et al.* evaluated that the output/input ratio of soybean diesel is 1.78 (Eqn 3).[14]

Finally, Consultants Inc., and others did an assessment of existing LCA models and used them for evaluating the environmental footprint of biodiesel and competing fuels (e.g. diesel) in Canada.[11] Energy balances were calculated using Canadian data and different software. For instance, using the GHGenius tool, the authors found that the output/input energy ratio for biodiesel from soybean is 1.95 when just biodiesel is considered as product (Eqn 3) and 3.82 when byproducts are also taken into account (Eqn 5).

Methodology used

In this paper, the mass balance was carried out in accordance with the general principles set out in International Standard ISO 14040 – Environment management – Life cycle assessment – Principles and Framework (2006).[15] Details of the overall methodology are presented below.

Functional unit

The functional unit in this paper is 1000 kg of biodiesel from soybean. From this, the results can be easily compared with those by other authors and also easily expressed on an energy basis.

Product system and boundaries

The energy balance of a biofuel covered the following stages: agriculture, soybean drying, soybean crushing, oil extraction by solvent, oil conversion to biodiesel, and fuel distribution to the point of use. At each stage, the energy contribution of all inputs (also considering their life cycle) was accounted for. Figure 1 shows the boundaries set for calculating the energy balance. The inputs considered for the agricultural stage were fertilizers (nitrogen, phosphorous, and potash), pesticides, seeds, and diesel oil. Soybean drying was done by using electrical energy and firewood. Soybean crushing, oil extraction and biodiesel production were produced inside integrated facilities using hexane, methanol, water, electricity, heavy fuel oil and water (pumping, treatment, and distribution processes were taken into account). The fuel distribution includes the distance of biodiesel plants up to the distributors and the filling stations. All transport operations are clearly identified in Fig. 1.

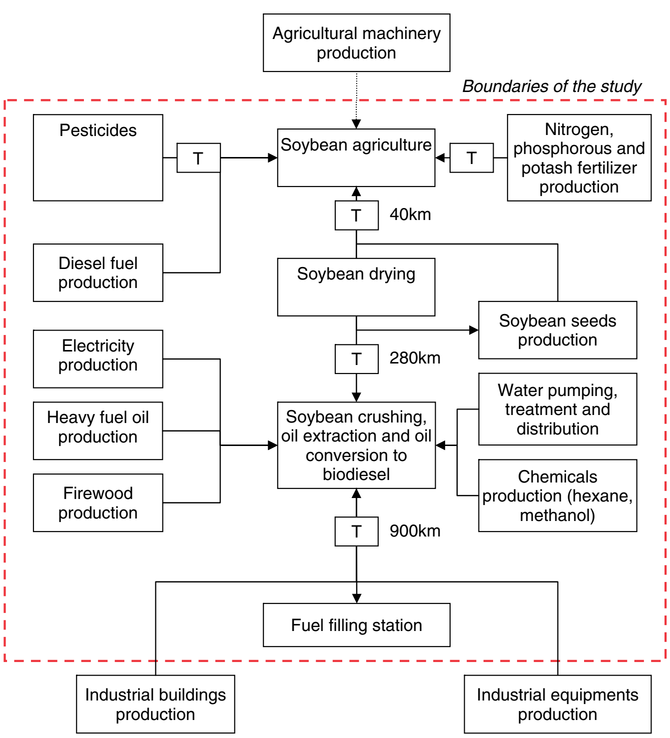

Figure 1. Boundaries of the biofuel system considered for energy balance. The dotted line illustrates the boundaries of this study.

Here, the sodium methylate catalyst and soap generated during the transesterification process were not considered. These components represent individually less than 2.5% of total ester mass produced and have a low impact on the energy balance.

In addition, the embodied energy associated with agricultural machinery, industrial equipment and buildings was not considered. This approach is not a simplification of the procedure but is based on a well-established position of the authors: if the embodied energy associated with agricultural machinery and industrial equipment is accounted for, then other indirect energy consumption such as the energy required for transporting employees, the embodied energy in highways, etc., should be taken into account as well. In general, such indirect energy inputs have a low impact on the final results and their inclusion makes data-gathering more time-consuming, calculations more complex, and the interpretation of results more difficult. It is important to avoid the inclusion of aspects not directly related to the renewability capacity of the specific biofuel.

Data collection

Data collection was obtained through questionnaires completed by the participating companies and through personal interviews conducted at farm level and on the industrial facilities. This study is based on data from five soybean farms and one biodiesel processing plant, all located in the state of São Paulo, south-east Brazil. Due to the restricted sampling of this study and the fact that the major soybean producing region is the center-west, the results presented here need to be understood only as a first estimate of the Brazilian profile.

In this study, biodiesel production based on alkaline transesterification in methanol medium, and in the presence of sodium methylate catalyst, was considered. The specific data of a single biodiesel producer were combined with data provided by other sources, such as the Brazilian Association of Vegetable Oil Industries,[16] the Brazilian Energy Balance[17] and Brazilian Institute of Geography and Statistics[18] regarding detailed data of soybean cropping.

Typical transport distances were informed by two biodiesel producers, which represent 25% of total production in the country. As the production of soybean is massive in Brazil, the logistic has been optimized and in general the trucks used for grain transportation carry different goods on the return trip. This is why here the average distance of a one-way trip of 280 km was considered.

The average distribution distance between the biodiesel facilities and the fuel filling stations of 900 km represents the average distance in the main soybean producer region, the state of Mato Grosso.

Energy contribution

The low heating value (LHV) of different fuels and the energy requirements throughout the life cycle of products were used to estimate the energy contribution of each input or output of the production chain. Due to the lack of an accurate national database, it was necessary to get part of the required information from the literature. Details about the main inputs are presented below.

Electricity

Electricity production in Brazil in 2008 amounted to 445 TWh and the bulk was generated by hydroelectric power plants – 80% – while 5% was produced from renewable biomass.[16] The rest was produced by conventional thermal power plants (e.g. natural gas, coal) and nuclear power plants. In this paper, the energy demand of 1.584 GJ of primary energy per GJ of consumed electricity was considered.[19] This figure is a conservative estimate, as significant investments have been made in recent years to reduce losses in transmission and distribution. Conservatively, a factor of 83% was applied to estimate the renewable content for electricity generation in Brazil, being the lowest of the last five years.

Diesel

Diesel is consumed by machinery in operations such as soil preparation, sowing, pesticide application, and harvesting. In addition, diesel is consumed for transporting grains from farms to the industrial units where they are crushed and the oil is extracted and converted to esters. The LHV of diesel was assumed as 42.29 MJ/kg[17] and the energy requirement to produce it was set at 50.7 MJ/kg based on the results of a diesel LCA conducted in the USA.[6] The share of electricity in this inventory was estimated as 11%, mainly due to the extraction of crude oil and pumping operations. Based on this figure and on the estimated 83% average renewable content of the Brazilian electric sector, 9% was set as the average renewable content of mineral diesel.

Fuel oil

Fuel oil is burned to raise steam for power crushing, and steam is consumed in operations such as oil extraction and transesterification. Steam can be raised from burning wood residues and tallow, for instance, but in this paper it was considered that only fuel oil is used for this purpose. It was assumed that the LHV of fuel oil is 40.15 MJ/kg[17] and that its primary energy is 47.8 MJ/kg, based on the LCA of diesel oil carried out in the USA.[6] As in the case of diesel oil, the same figure of 9% was used as the renewable content of fuel oil.

Firewood

Firewood is also used in Brazil for steam-raising in vegetable oil industries. It was assumed that industrial plants only consume eucalyptus from forestry and that its LHV is 12.98 MJ/kg.[17] The use of fertilizers, pesticides, and other farm chemicals on eucalyptus cropping was neglected, as on a mass basis they represent less than 0.001% of the total biomass produced. Major energy inputs correspond to diesel oil consumption in harvesting operations, truck loading, and road transportation. Considering typical conditions of eucalyptus production in south-eastern Brazil and an average transport distance of 120 km, the energy required in harvesting and transport activities was estimated as 103 MJ/m^3 as shown by Oliveira and Seixas,[20] or 0.26 MJ/kg for an average density of 390 kg/m^3 of fuel wood.[17] So, the firewood energy input is 13.24 MJ/kg, with a renewable content of 98%.

Fertilizers

Fertilizers are generally formulated as a combination of three inorganic salts that provide the nutrients for plants: Nitrogen (N), Phosphorus (P), and Potash (K). The so-called

NPK formula is usually defined in order to meet the specific needs of a crop in a certain type of soil. In the case of the soybean production assessed in this paper, the average NPK ratio is 3.6–20.8–17.6. Based on data of fertilizer production in the USA[6] the energy content of NPK with such a formulation was set as 5.88 MJ/kg of fertilizers.

Pesticides

Pesticides are used in soybean fields to protect the plant against the velvetbean caterpillar *Anticarsia gemmatalis Hübner* and the stink bug *Piezodorus guildinii*, in addition to control weeds. The energy content was estimated as 475 MJ/kg of pesticides, based in consumption of energy to produce and distribute glyphosate, one of the main components of pesticides applied for soybean plants, based on data of Helsel.[21]

Methanol

Methanol is the most common alcohol used in the transesterification process that yields the soybean methyl esters. Its energy content was set as 39.29 MJ/kg based on an assessment conducted in the USA.[6]

Hexane

Hexane is the organic solvent used to extract oil from soybean grains. Its energy content was set as 44.5 MJ/kg, also based on an assessment conducted in the USA.[6]

Due to the lack of appropriate information regarding the Brazilian case, a simplified approach was used to estimate the renewable content of fertilizers, defensives, hexane, and methanol; this procedure was also used as an assessment of ethanol production in Brazil by Macedo *et al.*[10] In 2006, the energy consumption of the Brazilian chemical industry was 308 TJ and 73.5% was the share of fossil energy sources[17] and, thus, the renewability content of all chemicals mentioned above was set as 26.5%.

Seeds

In this paper the energy input due to seeds was estimated as 150% of the total energy required for producing dried soybean; the same factor was used by Sheehan *et al.*[6] in a study regarding biodiesel production from soybean in the USA. Seeds require more energy than harvested grains not only as a result of the fact that they must meet much more stringent quality requirements, but also because their production involves additional stages such as packaging, storage, and transportation. Based on the data collected from farms and the solar energy stored in grains, the energy required to produce dried soybean was calculated as 16.8 MJ/kg; thus, the energy requirement for seed production was set at 25.3 MJ/kg. The same renewable content factors (or fossil factors) previously described (e.g. for electricity, fertilizers, fuel wood) were applied, resulting in a fossil content of 9% associated with the production of seeds.

Treated water

Treated water is used in processes such as oil extraction and biodiesel washing. In this paper, energy consumption figures of water treated by a utility company that operates in the state of São Paulo (SABESP – state of São Paulo Water and Sewage Utility Company) were considered, resulting in 2.647 MJ/t of water.[22] This corresponds to the energy consumption in operations such as water pumping and treatment as well as, water distribution and sewage collection and treatment.

Soybean grain

Soybean grain can be considered as a way to stock solar energy. Its lower heating value – LHV was set as 19.4 MJ/kg estimating that its low heating value is 6% lower than the higher heating value of 20.7 MJ/kg.[23]

Soybean oil

Soybean oil can also be considered as a way to stock solar energy. Its lower heating value (LHV) was set as 34.04 MJ/kg based on the average value informed one Brazilian industry.

Soybean meal

Soybean meal is a byproduct of seed crushing for oil extraction processes. Its LHV was set as 15.4 MJ/kg for a dry grain based on an assessment conducted by Patzek.[24]

Soybean hulls

Soybean hulls are removed from the beans because of their lower protein and higher fiber contents compared to soy meal. The LHV of soybean hulls is estimated as 15.1 MJ/kg estimating that its low heating value is 6% lower than the higher heating value of 15.7 MJ/kg.[23]

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Glycerin

Glycerin is a byproduct of the oil transesterification process. The raw glycerin obtained contains soap, inorganic salts, and other organic residues, and it was experimentally evaluated that its LHV is 25.3 MJ/kg by Trigo *et al.*[25] However, in this paper the LHV of pure glycerin (16.2 MJ/kg) was used, since the raw glycerin can be purified.

Soybean methyl esters

Soybean methyl esters are the main components of the product fuel, commonly known as 'soybean biodiesel'. Its energy content was taken as the average LHV of the biodiesel (based on three studies, according to Sheehan *et al.*[6] 37.0 MJ/kg (15 887 Btu/lb)).

Fuel consumption

Fuel consumption of diesel oil by trucks was assumed as 26.6 liters/100 km and 35.1 liters/100 km, respectively, for medium and heavy-duty trucks. These data were drawn from a comprehensive survey on fuel consumption by trucks, in Canada, conducted in 2005 and covering more than 18.6 million vehicles.[26]

Allocation methods

According to ISO 14044,[27] wherever possible, allocation should be avoided in LCAs; the recommended alternative approaches are the division of the unit process in two or more independent sub-processes or the expansion of the product system to include the additional functions related to the coproducts. However, when the target is setting the energy balance, neither one of these two routes seems to be adequate. According to this standard, alternatively inputs and outputs shall be allocated in a way that reflects the underlying physical relationships between them. In case physical ratios cannot be defined, inputs should be allocated among products and functions in order to reflect other important issues, such as the economic value of the products.

Aiming at exploring the impact of allocation methods into the final results, in this paper two different methods were used, as this is presented in the following sub-sections.

Energy balance without any allocation

This is the simplest procedure and it is commonly used in biofuel studies. In case of biodiesel, for example, the energy contribution of meal, hulls, and glycerin is accounted for improving the results of the main product.

Energy balance with mass allocation

Biodiesel production is not an independent process and, consequently, it is convenient to deal with the production chain as a whole. In some cases, the main driving force is not the production of biodiesel and, from an economic point of view, vegetable oils and biodiesel could be seen as byproducts. The coproducts of biodiesel production from soy – meal, glycerin, and hulls – are not fuels and an allocation method based on the energy contents of the products seems inadequate. Meal, for example, is an important component of animal feed due to its high protein content.[28]

The market value of soybean is due to the importance of its two main products – meal and oil, which are commodities; on the other hand, glycerin is a byproduct of the transesterification process. In this case, a common practice in LCAs is the allocation between meal and oil proportionally to the mass of each main product. In this case, soy oil represents 18% of total production – mass basis – in the crushing and oil-extraction phase.

In this case, only 18% of the input contents are allocated to soybean oil and the remaining 82% are allocated to the meal.

No mass allocation was accounted for due to glycerin. The overproduction of glycerin as a consequence of the ever-increasing production of biodiesel, impacts on its price and causes disposal problems.[29] Over the next few years, this situation could change since investments have been made with a focus aiming at the development of new applications for glycerin as a raw material.

In this work, the energy balance was calculated using the mass allocation method applied only for products that already have an established market. This allocation can be summarized in Eqn 7:

$$E = 0.18E_1 + 1E_2 + 1E_3 \quad (7)$$

where:

E = energy consumed for biodiesel production

E_1 = energy consumed at agricultural, drying, soybean transport, crushing and oil extraction stages

E_2 = energy consumed at transesterification stage

E_3 = energy consumed in biodiesel distribution

Results and discussion

Inventory of material flows

In this paper, the weighted average agricultural inventory was combined with data concerned to the industrial stage into a traditional life cycle assessment. The final results of the inventory of material flows, with the contribution different stages are presented in Table 2.

An average fertilizer consumption was observed of 72.4 kg per ton of humid soybean or 488 kg per ton of biodiesel. Fertilizers are made up of inorganic salts that are essential for plant growth. In agricultural terms, the weighted average fertilizer consumption was of 234 kg/hectare for an average NPK ratio of 3.6–20.8–17.6 that is the equivalent of 98 kg of active ingredients per hectare. This value is twice the consumption of 48 kg of active ingredient per hectare stated by Pradhan *et al.*[30] The Brazilian consumption could be due to the higher natural losses in tropical conditions that take place such as volatilization, oxidative and/or thermal degradation and leaching during rainy periods.

The low nitrogen requirement is possible due to Brazilian soybeans being able to obtain between 70 and 85% of the nitrogen required through biological fixation (Alves *et al.* 2003).[31]

The average pesticide consumption found was 0.6 kg of active ingredient per ton of soybean harvested (1.9 kg per hectare) or 4 kg per biodiesel ton. This figure is 35% higher than the pesticide use of 1.4 kg per hectare showed

Table 2. Final inventory of material flows for soybean methyl ester (or biodiesel).

Parameter	Quantity (kg/t of biodiesel)									
	Agriculture and drying(a)		Soybean transport, Crushing, oil extraction		Oil conversion to biodiesel(d)		Distribution(f)		Total	
	I	O	I	O	I	O	I	O	I	O
Diesel for agriculture equipment (kg)	56.8	–	–	–	–	–	–	–	56.8	–
Fertilizers (kg)	488	–	–	–	–	–	–	–	488	–
Pesticides (38% active ingredient) (kg)	11	–	–	–	–	–	–	–	11	–
Seeds (kg)	155	–	–	–	–	–	–	–	155	–
Soybeans grains (kg)		5658	5658	–	–	–	–	–	–	–
Soybean oil (kg)	–	–	–	1075(b)	1075	–	–	–	–	–
Hexane (kg)	–	–	4(d)	–	–	–	–	–	4	–
Water (kg)	–	–	2460(d)	–	491	–	–	–	2951	–
Soybean meal (kg)	–	–	–	4,362(b)	–	–	–	–	–	4362
Soybean hulls (kg)	–	–	–	194(c)	–	–	–	–	–	194
Methanol (kg)	–	–		–	141	–	–	–	141	–
Glycerin (80% of glycerol) (kg)	–	–	–	–	–	113	–	–	–	113
Biodiesel (kg)	–	–	–	–	–	1000	1000	1000	–	1000
Electric power (MJ)	240	–	1419(d)	–	162	–	–	–	1821	–
Fuel oil (kg)	–	–	288(d)	–	2	–	–	–	290	–
Firewood (kg)	44	–	–	–	430	–	–	–	474	
Diesel for transport (kg)	12.4	–	21.2(e)	–	–	–	12.1	–	45.7	–

I = input, O = output, (*) = wet weight, as received.
(a) = weighted average values of farms evaluated; (b) = average value from Brazilian Association of Vegetable Oil Industries between 2003 and 2008; (c) = estimated from a mass balance; (d) = annual average value of 1 industrial plant and (e) = calculated for an average weighted distance from farms to industrial plants of 280 km for 25% of total biodiesel produced in the country and (f) = calculated for an average weighted distance of 900 km from biodiesel producers and filling stations representing 17% of total biodiesel distributed. For conversion purposes, the following factors can be used: $LHV_{biodiesel}$ = 36.95 MJ/kg[6], Specific $gravity_{biodiesel}$ = 880 kg/m^3[28], Specific $gravity_{diesel}$ = 840kg/m^3.[28]

by the Pradhan study,[30] probably due to the same climatic conditions.

The national average yield from crushing and oil extraction processes was considered according to ABIOVE – the Brazilian Association of Vegetable Oil Industries – taking into account production between 2003 and 2008.

Gathering data from the industry sector is usually difficult for confidential reasons. The oil conversion to biodiesel production data was collected from one industrial plant.

Energy balances for soybean biodiesel production

The energy balances were calculated based on the final inventory depicted in Table 2. The adopted procedure i.e. energy contributions and the renewability factors, and the allocation procedures have been described previously. A resumed inventory of energy flows is shown in Table 3.

The total fossil energy required for this productive chain is 26 058 MJ/t of biodiesel and 8645 MJ/t of biodiesel when mass allocation is considered. The agricultural stage is responsible for 81.5%, followed by oil conversion to biodiesel with 16.4%, and distribution with 2.1%. These percentages are modified to 44.2%, 49.3%, and 6.4%, respectively, when allocation per mass is considered.

The results of the energy balance are shown in Table 4. It can be seen that the life cycle energy efficiency in converting solar energy stored in soybean oil into useful renewable energy (71%) is not very high when considering only the energy contribution of biodiesel. When the energy content of all products and byproducts is accounted for (i.e. besides the biodiesel, the soybean meal, hulls and glycerin) this efficiency rose to 99%.

In terms of the renewability factor, the process is always positive. When the energy content of all products and byproducts is accounted for the energy balance is favorable: for each unit of fossil energy as input, 4.18 units of energy are produced.

When using allocation based on mass, with 18% of the inputs consumed up to the oil production stage accounting for energy balance, the result is that for each unit of fossil energy used as input, 4.27 units of renewable energy are produced as soybean biodiesel.

Mass allocation is a simple method, which makes any comparison easy. In addition, following this approach, it is possible to have a final energy balance just for the biofuel, excluding non-fuel byproducts, such as soy meal.

Another important parameter from this energy balance is the total energy that could be extracted from the land: 17.7 MJ of energy is produced per hectare cultivated.

Sensitivity analysis

As mentioned before, the results of an energy balance depend on and are influenced by several parameters and it follows that a sensitivity analysis is essential in such kinds of assessments. As the authors considered that the energy balance result that

Table 3. Resumed inventory of energy flows.

Parameter	Agriculture and drying		Soybean transport, Crushing, oil extraction		Oil conversion to biodiesel		Distribution		Total	
	PE	FE	PE	FE	PE	FE	PE	FE	PE	FE
Inputs flows (MJ/t of biodiesel)										
No mass allocation	13 192	7191	127 294	14 044	11 524	4266	612	556	152 621	26 058
18% of mass allocation according to equation 7	2375	1294	22 913	2528	11 524	4266	612	556	37 423	8645
Outputs flows (MJ/t of biodiesel)										
Soybean biodiesel					36 950				36 950	
Soybean meal					67 178				67 178	
Soybean hulls					2923				2923	
Glycerin (80% of glycerol) (kg)					1831				1831	

PE = primary energy; FE = fossil energy.

Table 4. Energy balance of biodiesel production.

Parameter	Equation	Energy balance	
		No mass allocation	Mass allocation
LCEE (biodiesel contribution)	2	0.24	0.99
Energy balance (biodiesel and byproducts contribution)	4*	0.71	–
RF (biodiesel and byproducts contribution)	5	4.18	–
RF (biodiesel contribution)	3	1.42	4.27

RF = Renewability factor; LCEE = Life cycle energy efficiency; 4* = equation 4 including solar energy.

corresponds to the application of Eqn 3, using an allocation method based on mass flow which is the most appropriate for comparisons, sensitivity analysis was just developed for this case. The analysis was carried out varying the main parameters ±50% in terms of the mean values used in the calculation procedure. Results are presented in Table 5.

It is interesting to note that individual variations of inputs do not have a large impact on the renewability factor that has a 15% variation in the worst case. The consumption of fuel oil (15%) and the soybean yield (13%) are the parameters with the largest impact on the renewability factor.

The consumption of fuel oil for raising steam that is used in industrial processes has a considerable impact on the final result of the energy balance, despite the fact that it has been reduced in recent years. It is important to notice that fuel oil can be displaced by renewable energy carriers, such as fuel wood and tallow residues, but this has not been a priority in Brazil.

The impact of soybean yields on the energy balance is also significant. In the sensitivity analysis, yields varied from 1614 (–50%) to 4842 (+50%) kg/ha. Considering the harvest season 2006/2007, the lowest yield in Brazil (2180 kg/ha)[32] was recorded in the state of Piauí, north-east Brazil, that would result in a renewability factor of 4.0. On the other hand, the highest yield in recent years (4020 kg/ha, in 2003) was recorded on the Marabá farm, located in the state of Mato Grosso, central Brazil.[33] This high productivity would result in a renewability factor of 4.4. The average yield in the harvest season 2007/2008 in Brazil was 2816 kg/ha, and in this case the renewability factor would be 4.2.

Considering the set of cases shown in Table 4, the renewability factor varies from 3.7 to 4.9.

Lime is used in different quantities to correct soil acidity, but this practice does not occur on the plantations where data were collected. Only as a matter of comparison, in case

Table 5. Sensitivity analysis of energy balance.

Parameter	Weighted average value	Renewability factor (Eq. 3) with mass allocation		
		Average value variation (%)		
		–50	0	+50
Fertilizers (kg/t soybeans)	72.4	4.36	4.27	4.17
Pesticides and herbicides (kg/t soybeans)	1.6	4.33	4.27	4.20
Yield (kg soybean/hectare)	3228.0	3.73	4.27	4.48
Electricity consumption in oil extraction (MJ/t soybeans)	250.0	4.28	4.27	4.25
Fuel oil consumption in oil extraction (MJ/t soybeans)	51.0	4.91	4.27	3.77
Electricity consumption in the transesterification process (MJ/t biodiesel)	163.0	4.28	4.27	4.26
Weighted average distance between soybeans farms and biodiesel processing plants (km)	280.0	4.31	4.27	4.22
Weighted average distance between biodiesel processing plants and fuel filling stations (km)	900.0	4.41	4.27	4.13
Diesel consumption of heavy truck transport (liters/100 km)	35.1	4.46	4.27	4.09

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lime were applied exactly as reported by Hill[12] (313 MJ/hectare) the renewability factor would be 4.0.

Comparison with other energy balances

Comparison with other results is an extremely difficult task due to the large differences in equations used to calculate energy balances, factors employed, boundaries of studies, and allocation procedures. With the aim of evaluating the results found in Brazil, two studies were selected in function of their robustness, data availability, and clarity of method employed.

In Sheehan *et al.*´s study[6] the authors performed an assessment for biodiesel production from soy in the USA and considered a mass allocation method, with 18% being the proportion factor for soybean oil (up to the extraction) and 87% for soybean methyl ester (in the transesterification stage). This latter factor is slightly lower than the one considered in this paper and this could be due to a higher efficiency of the transesterification process.

Pradhan *et al.*[30] update the previous study by Sheehan *et al*. from 1998 to 2009. As previously mentioned, the authors understand that the best procedure is the mass allocation method, but applied only to coproducts which have a significant market value. For comparison of results, the original Pradhan inputs were used to estimate an energy balance based on the same mass allocation principle used in this present study. Table 6 shows a comparison of the main parameters of these studies.

The energy consumption at the agricultural stage in Brazil is just 75% of the figure presented by Pradhan *et al.*[30] for the USA. The difference can be partially explained by the different yields considered in both studies (2805 kg/ha in the USA versus 3228 kg/ha in this study, that is the average yield in the plantations assessed), but differences at the mechanization level is a hypothesis still to be checked.

The figures of fossil energy consumption at the industrial stage (i.e. crushing, oil extraction, and transesterification) are also smaller (91%) in the Brazilian case regarding those reported by Pradhan *et al.*[30] It can be supposed that this is partially due to the lower share of fossil fuels used in power generation in Brazil.

As the biodiesel industry is relatively new in Brazil, factories are integrated with crushing, oil-extraction, and conversion operations carried out at the same facility in order to minimize the costs of biofuel production and be as near as possible to the plantations. The logistic of this chain was carefully planned to minimize the biofuel production cost.

However, the advantages of agricultural production in Brazil are reduced by the higher energy consumption along the transportation stage that is 65% higher than in the USA, where barges and trains are used for long distances and trucks for medium and short distances. As in Brazil, the bulk of transportation is carried out by trucks, there is significant room for improvement.

Table 6. Comparison with other studies.

Stage	MJ consumed/MJ of biofuel produced				
	Sheehan *et al*.[6(*)]		Pradhan *et al*.[30(**)]	This study[(**)]	
	PE	FE	FE	PE	FE
Agriculture	0.0660	0.0656	0.0425	0.0399	0.0319
Soybean drying	–	–	–	0.0059	0.0015
Soybean transport	0.0034	0.0034	0.0068	0.0018	0.0017
Crushing and oil extraction	0.0875	0.0868	0.0368	0.0843	0.0684
Transesterification	1.0801	0.1508	0.1657	1.3883	0.1155
Biodiesel distribution	0.0044	0.0044	0.0091	0.0166	0.0151
Total	1.2414	0.3110	0.2608	1.5368	0.2340
Renewability factor		**3.22**	**3.83**		**4.27**
Soybean yield (kg/hectare)	**2,556**		**2,805**	**3,228**	

PE = primary energy; FE = fossil energy.
(*) = comparison considers 18% of mass allocation of all inputs up to oil extraction and 87% in transesterification stage; (**) = comparison considers 18% of mass allocation of all inputs up to oil extraction.

The renewability factor presented in this paper for Brazil (4.3) is higher than that for the USA, but it is important to note that this result does not have the same representativeness of the references used for comparison. As previously mentioned, this paper reports a first attempt on evaluating the energy balance of biodiesel of soy in Brazil.

Due to the tradition and importance of ethanol production in Brazil, a comparison with its energy balances seems to be suitable. According to Macedo *et al.*,[10] the fossil energy ratio of typical ethanol production in Brazil is 9.3, which means that the production of biofuels from sugarcane is about two times more efficient than the production of biodiesel from soybean. This result can be explained by the difference between the yields of sugarcane and oil seeds (e.g. the average productivity of sugarcane in Brazil was considered as 87.1 t/ha), and also by the fact that ethanol production from sugarcane in Brazil has been impacted by a learning process that has taken about 35 years.

Conclusions

Energy balances have been performed in different ways and this report clearly shows that their results are dependent on the hypothesis and on the allocation methods used. In this sense, the final results of energy balances can only be analyzed considering all assumptions made.

A renewability factor of 4.3 was obtained for soybean production in this Brazilian case study. This number is a result of the following approach:

- The study is characterized as a cradle-to-grave approach and includes the following stages: agricultural and intermediate processes up to the fuel filling station, including all transport steps.
- The renewability factor was calculated using Eqn 3, which evaluates the efficiency of converting fossil energy into renewable energy.
- Mass allocation method of 18% for the production of soybean oil was applied considering only products that have market value.
- Human labor and the embodied energy of agricultural machinery, industrial equipment and buildings were excluded.

Sensitivity analysis showed that individual variations from –50 to +50% of the main parameters have a low impact on the renewability factors, ranging from 3.7 to 4.9.

Finally, it is important to note that the results obtained are highly dependent on the external life cycle studies and energy factors employed. As a consequence, national databases, not available for this study, are fundamental. Although this study is characterized as a 'case study' due to the small representativeness of the data collected, the results of the sensitivity analysis indicate that the energy balance figures should be close to the values here presented.

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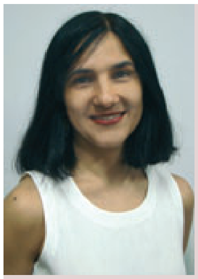

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