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LIFE CYCLE ENERGY REQUIREMENTS OF BIODIESEL PRODUCED FROM RAPESEED OIL IN SERBIA

ENERGETSKE POTREBE ŽIVOTNOG CIKLUSA BIODIZELA PROIZVEDENOG OD ULJA ULJANE REPICE U SRBIJI

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ABSTRACT

The main goal of this paper is to perform a life cycle energy analysis and to evaluate the overall energy efficiency of biodiesel produced from rapeseed oil in Serbia. A comprehensive inventory of material and energy was developed in order to quantify the relevant fossil energy inputs throughout the production chain of biodiesel. The inventory results were calculated by using three different allocation methods so as to demonstrate the effect of allocation on the overall energy efficiency of biodiesel. The sensitivity analysis shows that the choice of the allocation procedure has a major influence on the results. Depending on the allocation method, the fossil energy ratio of biodiesel is between 1.9 and 4.0, which means that biodiesel yields 1.9 to 4 units of fuel product energy per every unit of fossil energy consumed in the life cycle.

Key words: *life cycle assessment, biodiesel, energy efficiency, Serbia.*

REZIME

Cilj rada je utvrđivanje energetske efikasnosti proizvodnog lanca biodizela proizvedenog od ulja uljane repice u Srbiji. Energetska efikasnost proizvodnog lanca se utvrđuje iz odnosa energije sadržane u biodizel gorivu i ukupnih inputa energije iz fosilnih izvora u životnom ciklusu biodizela. Sagledani su relevantni materijalni i energetski tokovi tokom celokupnog proizvodnog lanca biodizela koji obuhvata proizvodnju zrna uljane repice, sušenje zrna, ceđenje i rafinaciju ulja i transesterifikaciju ulja u biodizel. Kvantifikovane su kako neposredne (energija u gorivima fosilnog porekla), tako i posredne energetske potrebe (energija upotrebljena za proizvodnju đubriva, pesticida i ostalih hemikalija) proizvodnog lanca biodizela u fosilnoj energiji. Rezultati istraživanja pokazuju da se na svaki MJ upotrebljene fosilne energije u proizvodnom lancu biodizela dobija između 1,9 i 4,0 MJ energije u biodizel gorivu. Velika varijacija u dobijenim rezultatima je posledica primene različitih metoda alokacija energetskih inputa proizvodnog lanca na biodizel i sporedne proizvode (slama uljane repice, uljana sačma i glicerol).

Ključne reči: *analiza životnog ciklusa, biodizel, energetska efikasnost, Srbija.*

INTRODUCTION

Biodiesel is considered to be more environmentally friendly (*Janković et al. 2007*) and domestically available (*Tešić et al., 2009*) alternative to fossil diesel. Increased use of biodiesel for transport is emerging as an important policy strategy to substitute fossil diesel fuel. However, the extent to which biodiesel can supplant fossil diesel depends on the energy efficiency with which biodiesel can be produced. All processing technologies, including biodiesel production, involve directly and/or indirectly the use of fossil fuels. Therefore, the actual benefits of biodiesel as an alternative fuel depend on the fossil energy requirements of the production chain, which indicate the magnitude of fossil fuel input relative to subsequent fossil fuel savings. In order to assess whether biodiesel has a positive energy balance – i.e. whether more energy is contained in biodiesel than used for its production – a life cycle approach must be employed (*Malca and Freire, 2006*).

Life Cycle Assessment (LCA) is a methodology to assess the environmental performance of a product, process or activity from “cradle-to-grave” by identifying, quantifying and evaluating all resources consumed, and all emissions and waste released into the environment. The LCA is based on the results of life cycle inventory analysis (LCI) which includes information on all of the environmental inputs and outputs associated with a product or service i.e. material and energy requirements, as well as emissions and wastes.

The allocation problem arises in LCA when a production process results in two or more co-products: how the energy and material flows (associated with this process) are portioned between these co-products? This has been one of the most controversial issues in the development of the LCA methodology, as it may significantly influence or even determine the results of the assessment (*Bernesson et al., 2004*). Processes associated with the production chain of biodiesel have diverse main products and by-products. Thus, suitable allocation procedures need to be established and applied to partition the primary energy inputs between biodiesel and other co-products. According to the ISO 14044, whenever several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted.

The main goal of this paper is to present a life cycle energy analysis of biodiesel in Serbia, describing the energy inputs/outputs throughout the life cycle of biodiesel and allowing the calculation of overall energy efficiency. Different allocation methods are explored in order to understand their effect on the calculation of overall energy efficiency and renewability of biodiesel.

MATERIAL AND METHOD

Overall energy efficiency

Although various definitions have been used to measure energy efficiency of biofuels *(Malca and Freire, 2006)*, fossil energy ratio (FER) is used in this study as suggested by S*heehan et al. (1998*). FER is defined as:

$$FER = \frac{Biodiesel\ fuel\ energy\ output}{Biodiesel\ share\ of\ fossil\ energy\ input} \qquad (1)$$

According to *Sheehan et al. (1998)* if the FER is less than 1 the fuel is non-renewable, as more non-renewable energy is required to make the fuel than the energy available in the final fuel product. Biofuel with FER greater than 1 can be considered as at least partially renewable. In theory, a total renewable fuel would have no requirements of fossil energy and, thus, its FER would be infinite.

Life cycle inventory of biodiesel

System boundaries

The production chain of biodiesel is divided into four subsystems: rapeseed production, grain drying, solvent extraction with oil refining, and transesterification of refined oil into biodiesel. An inventory of material and energy is developed which quantifies the relevant fossil energy inputs used in each subsystem. The inventory analysis was performed according to the principles of the attributional LCA. The energy and materials used for the manufacturing and maintenance of buildings, agricultural machines and process machines for seed drying, oil extraction and transesterification were not included in the inventory. The main product flow normalised in terms of the production of one metric tone (mt) of biodiesel is presented in Fig. 1. Each stage of the production chain is discussed in more detail bellow.

Rapeseed production. The method of cultivation and harvesting of oilseed rape modelled in this study as far as possible reflects the usual practice in Vojvodina (*Kiš, 2011*). The annual yield of rapeseed is 2,305 kg per hectare based on average yields of rapeseed in Vojvodina in a five year period (2005-2009). A sowing rate of 5 kg per hectare is assumed. Nitrogenous fertilizer is applied at a rate of 140 kg N/ha, corresponding to 400 kg/ha ammonium nitrate (35% N). Furthermore, the crop was fertilized with 40 kg P_2O_5/ha and 80 kg K_2O/ha, corresponding to 83 kg triple superphosphate fertilizer and 133 kg potassium chloride fertilizer, respectively. Fusilade forte and BOSS 300 SL herbicides are applied at a rate of 1 kg/ha and 0.25 kg/ha of Megatrin 2.5 EC is used as insecticide.

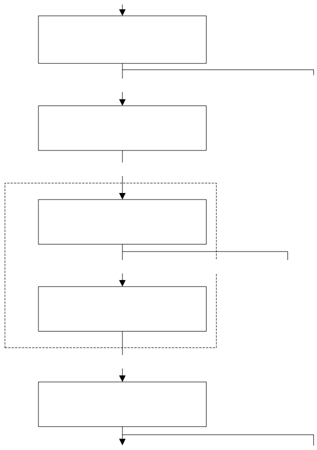

Fig. 1. Main material flows related to the production of 1,000 kg biodiesel in Serbia (Kiš, 2011)

The total diesel fuel consumption in the agricultural machines is 90 l per hectare. The volume of lubricating oil consumed is assumed to be 0.1 l/l of the diesel fuel used. Furthermore, it was assumed that the production chains of fossil diesel and lubricating oil have the same fossil energy requirements. After harvesting raw rapeseed grain is transported via diesel truck to the dryer which is located 37.5 km away. Data on fuel consumption of a diesel truck was taken from *Spielmann et al. (2007)*.

Seed drying. In Vojvodina, oilseed is harvested with a typical moisture content of 13.5%, which must be reduced to at least 9% as a requirement for the oil extraction facilities, and to ensure stability in storage. It is assumed that the drying process takes place at a vertical gravity dryer Strahl 5000 FR (Officine Minute, Italy) powered by light fuel oil with low heating value (LHV) of 41.8 MJ/kg and three electric fans of overall installed capacity of 54 kW. The heat requirement of the process is 260 MJ/mt of dried grain and electricity is consumed at a rate of 2.7 kWh/mt of dried grain *(Pavkov, 2010; pers. comm.)*. The dried grain is transported via diesel truck to the oil mill plant which is located 37.5 km away.

Table 1. Life cycle energy and material inputs in the production chain of 1,000 kg of biodiesel

Stage in the production chain	Life cycle inputs (before allocation on by-products)	Unit	Quantity
Rapeseed cultivation and harvesting	Ammonium nitrate fertilizer	kg N	155.1
	Triple superphosphate fertilizer	kg P_2O_5	44.3
	Potassium chloride fertilizer	kg K_2O	88.6
	Pesticides	kg	1.4
	Sowing seeds	kg	5.5
	Diesel fuel used in agricultural machinery	kg	84.8
	Lubrication oil in agricultural machinery	kg	8.5
	Diesel fuel used for the transport of rapeseed grain	kg	5.4
Drying of the rapeseed grain	Light fuel oil for process heating	kg	15.1
	Electricity	MJ	23.6
	Diesel fuel used for the transport of dried grain	kg	5.2
Pressing and solvent extraction	Light fuel oil used for steam generation	kg	43.7
	Electricity	MJ	426.1
	Hexane	kg	1.2
Crude oil refining	Electricity	MJ	104.0
	Light fuel oil used for steam generation	kg	6.2
	Phosphoric acid (85% in H_2O)	kg	0.8
	Sodium hydroxide (50% in H_2O)	kg	2.1
	Sulphuric acid (100%)	kg	1.9
	Bentonite (clay)	kg	9.0
	Diesel fuel used for the transport of refined oil	kg	0.03
Transesterification of refined oil into biodiesel	Electricity	MJ	43.2
	Natural gas used for steam generation	m^3	33.4
	Sodium methoxide (100%)	kg	5.0
	Sodium hydroxide (50% in H_2O)	kg	1.5
	Hydrochloric acid (36% in H_2O)	kg	10.0
	Methanol	kg	96.0
	Diesel used for the transport of biodiesel	kg	1.4

Solvent extraction and oil refining. After the drying process, typical oilseeds contain 40-44% oil and 54-58% high protein meal *(Schmidt, 2007)*. The oil is extracted from the dried rapeseed by solvent extraction. The material and energy requirements of the process are presented by *Schmidt (2007)*. The only material used in the solvent extraction is hexane at a rate of 1.19 kg per mt of crude rapeseed oil. The heating requirement of the plant is provided by steam produced from light fuel burned in industrial boiler, using 43 kg (LHV=41.8 MJ/kg) light fuel oil per mt of crude rapeseed oil produced. Electricity is required at 419 MJ per mt of crude oil produced.

In the refining step the phospholipids from the crude rapeseed oil are removed by the addition of phosphoric acid. The remaining free fatty acids are converted to soap by the addition of sodium hydroxide, and removed using a centrifuge. Other impurities are removed via filtration using acid treated natural clay. Data on material and energy requirement of the refining process are available from *Schmidt (2007*). Light fuel oil is required at 6.1 kg/mt crude oil to provide the refining plants' heating and electricity is required at 104 MJ/mt of refined oil. Environmental impacts associated with the production of demineralised water used for steam generation were not taken into account. The refined oil is transported with diesel truck to the nearby transesterification plant located 1 km away.

Transesterification. The transesterification of refined rapeseed oil into biodiesel takes place at a state of art biodiesel production facility with annual production capacity of 100,000 mt of biodiesel. The transesterification process is performed with methanol in the presence of sodium methoxide as an alkali catalyst. The material and energy consumption during the transesterification process is described in *Kiss et al., (2010)*. After the transesterification process biodiesel is transported to the final consumer located 25 km away.

Table 1 gives an overview of processes included in the LCI of biodiesel with specification of material and energy inputs for each of the subsystems.

Allocation method

Rapeseed production, oil extraction and transesterification result in the production of three important by-products: rapeseed straw, rapeseed meal and crude glycerine, respectively. Since this energy life cycle focuses exclusively on biodiesel, the energy associated with the other three by-products must be estimated and excluded from the inventory. Several allocation methods can be used to estimate the share of by-products in the total energy requirement of the system. In the mass-based allocation method input energy is allocated to various co-products proportionally to their share in the total mass of all co-products. For example, the total mass of co-products in the agricultural phase is 5,874 kg (Fig. 1). Rapeseed straw makes 57% of the total mass output of the agricultural phase, therefore 57% of the overall energy inputs in the agricultural phase are allocated to straw and 43% to rapeseed grain (Table 2). Another allocation method is the economic method, where allocation factors are determined by the relative share of co-products in the total revenue of the process. And finally, in the energy-based allocation method the total energy input is shared amongst co-products proportionally to their share in the total energy content of co-products. In this study the energy allocated to biodiesel is calculated using (2):

$$\text{Energy allocated to biodiesel} = E_1 \cdot f_1 \cdot f_2 \cdot f_3 + E_2 \cdot f_2 \cdot f_3 + E_3 \cdot f_3 \quad (2)$$

where E_1 is the fossil energy input for rapeseed cultivation and harvesting; f_1 is the fraction of E_1 allocated to raw rapeseed grain; E_2 is the fossil energy input for grain drying, solvent extraction and oil refining; f_2 is the fraction of E_2 allocated to refined rapeseed oil; E_3 is the fossil energy input during the transesterification process; f_3 is the fraction of E_3 allocated to biodiesel.

Assumptions (*Kiš, 2011*): (a) Energy content of co-products was calculated by multiplying the mass of the co-product (Fig. 1) and its low heating value. The low heating values of co-products are as follows: rapeseed grain 23.79 MJ/kg; rapeseed straw 15.56 MJ/kg; refined oil 36 MJ/kg; rapeseed meal 14.8 MJ/kg; biodiesel 37.2 MJ/kg; glycerol 16 MJ/kg, (b) see Fig. 1, (c) Revenue was calculated using the mass of the co-product (Fig. 1) and the following market prices: raw rapeseed grain 265 EUR/mt; rapeseed straw 28 EUR/mt; refined oil 730 EUR/mt; rapeseed meal 170 EUR/mt; biodiesel 900 EUR/mt; glycerol 80 EUR/mt.

Table 2. Allocation factors depending on the allocation method

Allocation factors	Allocation principle			No allocation
	Energy content [(a)]	Mass-based [(b)]	Economic [(c)]	
f_1	54%	43%	88%	100%
f_2	64%	42%	76%	100%
f_3	95%	89%	99%	100%

Life cycle energy equivalents of inputs

All materials listed in the inventory (Table 1) were converted to their equivalent life cycle energy content using the Cumulative Energy Demand method as described by *Frischknecht and Jungbluth (2004*).

Table 3. Life cycle energy equivalents of various inputs

Input	Embedded energy (HHV)	Upstream processes (HHV)	Life cycle energy equivalent	*References*
Fuel inputs				
Diesel fuel	45.8 MJ/kg	7.9 MJ/kg	53.7 MJ/kg	*Jungbluth, 2007*
Lubricating oil	45.8 MJ/kg	7.9 MJ/kg	53.7 MJ/kg	*same as for diesel fuel*
Light fuel oil	43.8 MJ/kg	10.3 MJ/kg	54.1 MJ/kg	*Jungbluth, 2007*
Natural gas	38.3 MJ/m^3	6.4 MJ/m^3	44.7 MJ/m^3	*Faist et al., 2007*
Electricity	1 MJ/MJ	2.85 MJ/MJ	3.85 MJ/MJ	*Frischknecht et al. 2007*
Material inputs				
Nitrogen fertilizer (as N)	–	57.4 MJ/kg	57.4 MJ/kg	*Nemecek et al. 2007*
Phosphorus fertilizer (P_2O_5)	–	26.8 MJ/kg	26.8 MJ/kg	*Nemecek et al., 2007*
Potassium fertilizer (K_2O)	–	8.6 MJ/kg	8.6 MJ/kg	*Nemecek et al. 2007*
Pesticide	–	190 MJ/kg	190 MJ/kg	*Nemecek et al. 2007*
Seeds	–	5.4 MJ/kg	5.4 MJ/kg	*Nemecek et al. 2007*
Hexane	–	60 MJ/kg	60 MJ/kg	*Jungbluth et al., 2007*
Phosphoric acid (85%)	–	17.8 MJ/kg	17.8 MJ/kg	*Althaus et al. 2007*
Sodium hydroxide (50%)	–	13.7 MJ/kg	13.7 MJ/kg	*Althaus et al., 2007*
Sulphuric acid (100%)	–	1.9 MJ/kg	1.9 MJ/kg	*Althaus et al., 2007*
Bentonite (clay)	–	0.4 MJ/kg	0.4 MJ/kg	*Kellenberger et al., 2007*
Hydrochloric acid (36%)	–	2 MJ/kg	2 MJ/kg	*Jungbluth et al., 2007*
Sodium methoxide (100%)	–	76.4 MJ/kg	76.4 MJ/kg	*Sutter, 2007*
Methanol	–	36.9 MJ/kg	36.9 MJ/kg	*Althaus et al.,2007*

The LCI data of materials are available from the Ecoinvent v 2.0 database integrated into the SimaPro 7.3 LCA software. The life cycle energy of a material is defined as the total fossil energy embedded and incurred during the upstream processes of that material. The embedded energy fraction of life cycle energy for materials used for fuel, such as diesel, gasoline, and natural gas, was taken to be the same as the high heating value (HHV) of that material. The fossil energy requirements of the upstream processes were calculated as the sum of fossil energy required to mine, extract, manufacture, and transport the product based on the HHV of the energy sources.

Fossil energy requirements of electricity used throughout the life cycle are based on the Serbian weighted average. About 68% of the electricity generated in Serbia comes from fossil sources (prevailingly from lignite) while the remaining part is produced using hydroelectric power. The life cycle energy equivalents of material and energy inputs listed in the LCI are presented in Ta ble 3.

RESULTS AND DISCUSSION

The life cycle fossil energy requirement to produce 1,000 kg of biodiesel from rapeseed oil in Serbia is 28,281 MJ (Table 4). The agricultural stage uses the most energy, accounting for about 58% of the total fossil energy required in the production chain of biodiesel. The transesterification accounts for about 20%, followed by oil extraction and refining, which requires almost 17% of the total energy. The drying process requires less than 5% of the total fossil energy inputs in the production chain of biodiesel.

Table 4. Life cycle fossil energy requirement and the fossil energy ratio of biodiesel

Subsystems and indicators	Total fossil energy inputs (MJ)	Biodiesel fraction of energy inputs (MJ)			
		Energy-based	Mass-based	Economic allocation	No allocation
Rapeseed production	16,490	5,414	2,651	10,918	16,490
Grain drying	1,296	788	484	975	1,296
Oil mill	4,766	2,898	1,781	3,586	4,766
Transesterification	5,730	5,443	5,099	5,672	5,730
Total fossil energy inputs	28,281	14,542	10,016	21,151	28,281
Biodiesel energy output	40,400	40,400	40,400	40,400	40,400
Fossil energy ratio (FER)	1.43	2.78	4.03	1.91	1.43
FER^{-1}	0.70	0.36	0.25	0.52	0.70
FER^{-1} (f_l=100%)	0.70	0.47	0.33	0.56	0.70

The results presented in Table 4 show a large variation of the fossil energy ratio of biodiesel with a high sensitivity to the method used to allocate the impacts between co-products. The FER may vary between 1.91 and 4.03 depending on the allocation method applied. There is no impeccable allocation method for LCA of biofuels *(Gnansounou et al. 2009)*. Allocation on a mass basis relates products and co-products using a physical property that is available and easy to interpret. But some researcher claim that it cannot be a good measure of energy functions (*Malca and Freire, 2006*). Energy allocation is often used in European biofuel studies and it is also the methodology recommended by the European Parliament and the Council *(Directive 2009/28/EC)*. However, an objection can be made against this approach in the case where the co-products are not meant for energy purposes. The rationale for economic allocation is that environmental burdens of a multifunctional process could be allocated according to the share on sales value, because demand is the main driving force of the production system. Price variation subsides, and market interferences could however imply difficulties in its implementation.

Another important question is whether energy should be allocated to the rapeseed straw. Smith *et al.* (2007) argue that rapeseed straw is not a co-product since it is generally left in the field without further application; therefore, energy should not be allocated to straw. Other researchers, however, tend to include the positive impacts of straw on biodiesels` energy balance *(Mortimer et al. 2003)*. If no energy would be allocated to straw (i.e. f_l=100%) the FER of biodiesel would decrease by ca. 25% when mass or energy-based allocation is applied (Table 4). The exclusion of straw as a valuable co-product would have just a minor impact on FER when economic allocation is applied due to the relatively low market price of rapeseed straw.

The relative contributions of different processes to the fossil energy demand in the biodiesels` production chain are illustrated in Fig. 2. The production chain of fertilisers contribute the most to the energy requirements of the agricultural stage, followed by the energy requirements of the diesel fuel used in agricultural machinery. Around 80% of the total energy requirements of fertilisers come from the ammonium-nitrate fertiliser. The consumption of light fuel oil and electricity are responsible for most of the energy requirements in the grain drying and oil mill phases. The production of methanol and other chemicals necessary for transesterification has a dominant role in the energy requirements of this stage.

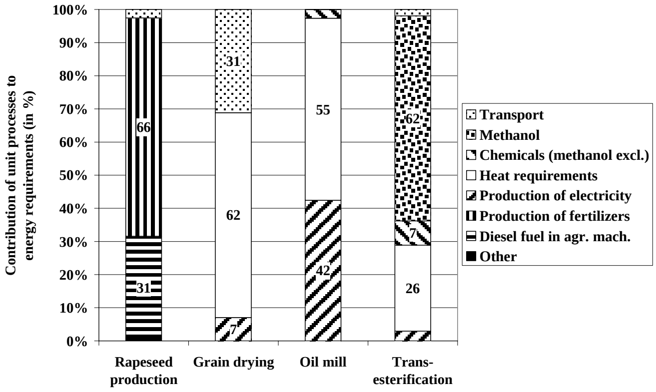

Fig. 2. Contribution of unit processes to the energy requirements of life cycle stages

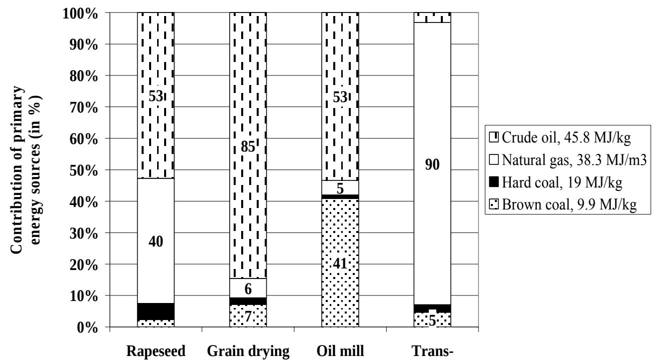

Fig. 3. Share of primary energy sources in the overall energy inputs of the production chain

The relative share of primary energy sources in the overall fossil energy inputs in the production chain of biodiesel is presented in Fig. 3. The life cycle consumption of crude oil is 273 kg per mt of biodiesel before allocation of energy to by-products (i.e. when f_x=100%). Oil consumption reflects the use of light fuel oil as a heat source and the use of diesel fuel in agricultural machines and trucks. The production chain of 1,000 kg biodiesel requires 272 kg of brown coal and 56 kg of hard coal (if f_x=100%). The coal consumption is generally related to electricity generation. The natural gas requirements of biodiesels` production chain are 313 Nm^3 per mt of biodiesel (if f_x=100%). Use of natural gas is mainly associated with the transesterification process and the agricultural stage. In the transesterification process around two thirds of natural gas consumption is related to the production chain of methanol while the remaining part is mainly associated with the generation of the process energy. In the agricultural stage the consumption of natural gas is mainly (ca. 80%) related to the production chain of the ammonium nitrate fertilizer.

CONCLUSION

The fossil energy ratio of biodiesel is highly sensitive to the chosen method used for the allocation of energy inputs between co-products. The fossil energy ratio of biodiesel is between 1.9 and 4.0 which means that biodiesel yields 1.9 to 4 units of fuel product energy for every unit of fossil energy consumed in the life cycle. By contrast, the petroleum diesels` life cycle fossil energy ratio is only 0.85. The dominating production step regarding energy requirement was the agricultural phase, in which the production of fertilisers and diesel fuel used in agricultural machines made major contributions. Any improvement in the production or use efficiency of nitrogen would have a major impact on the biodiesel energy balance. Both converting processes (rapeseed to oil, oil to biodiesel) consume a large volume of energy of fossil origin. Replacing the fossil energy sources in converting processes with energy from renewable sources may improve the energy balance of biodiesel. This may be particularly valid for the replacement of the light fuel oil as a heating source. An opinion worth of discussion is the possibility of using bioethanol instead of fossil methanol (made from natural gas prevailingly) in the transesterification of the rapeseed oil.

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