Available online at www.sciencedirect.com
SCIENCE DIRECT®

Renewable Energy 29 (2004) 861–871

RENEWABLE ENERGY

www.elsevier.com/locate/renene

Reduction of energy consumption in biodiesel fuel life cycle

P. Janulis *

Laboratory of Agrotechnological Research, Institute of Environment, Lithuanian University of Agriculture, LT-4324 Akademija, Kaunas r., Lithuania

Received 7 May 2003; accepted 9 October 2003

Abstract

Essential requirements for biofuel are that (a) it should be produced from renewable raw material, and (b) it should have a lower negative environmental impact than that of fossil fuels. Apart from direct assessment of the engine emissions, environmental impact is also determined by performing life cycle analysis. Life cycle energy balance depends on specific climatic conditions and the agro- and processing technologies used. Rapeseed oil methyl ester life cycle energy ratios in Lithuanian conditions have been calculated as a function of rapeseed productivity, oil pressing and transesterification technologies used.

Opportunities to improve biodiesel fuel life cycle energy efficiency, by implementing new technologies in agriculture as well as in industrial processing, were reviewed. The effectiveness of new technologies was evaluated on the basis of energy balance comparison.

Keywords: Rapeseed; Rapeseed oil; Biodiesel fuel; Life cycle; Energy balances

---

1. Introduction

Understanding the importance of the environment and possible production- and consumption-related negative environmental impacts has forced science to look for ways to evaluate this impact. For this purpose, life cycle assessment methodology has been created and presented in the standards of the International Standard Organisation ISO 14040–14049 [1–4]. Life cycle analysis is used to evaluate environmental impact and potential factors related to product life cycle energy balance, including raw materials, production, consumption, and waste utilization.

---

* Tel./fax: +370-377-52292.
E-mail address: agrotech@nora.lzua.lt (P. Janulis).

0960-1481/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2003.10.004

Fuel life cycle analysis starts with raw material extraction stage and ends with fuel consumption in vehicle engine. Life cycle analysis demonstrates the additional quantity of energy required to turn the energy present in the raw materials into useable energy of the fuel. Direct (petroleum products, electricity) and indirect (used for production of materials and equipment) energy consumption is evaluated in fuel life cycle [5].

Biodiesel fuel life cycle analysis calculates the following indicators: R_1—the ratio of biodiesel fuel energy (calorific value) to the total energy used for fuel production, R_2—the ratio of energy accumulated in all products (including by-products) obtained in the biofuel production process to the total energy consumed for the fuel production, and ecobalance R_3—the ratio of fuel energy (calorific value) to the total energy related solely to the biofuel production.

Fuel is considered to be non-renewable, if the amount of fossil fuel energy used in production is significantly higher than that accumulated in the product, i.e. when R_1 is less than 1. All energy ratios depend on climatic conditions and on the agro- and processing technologies used. Thus, R_1 values calculated for commonly used biodiesel fuel—rapeseed oil methyl ester (RME)—in various countries are different, though they exceed 1 [6–10]. In the European Union ALTENER (DGXVII) documents, the following values are given: for fossil diesel fuel $R_1 = 0.88$, for rapeseed oil $R_1 = 3.2$–3.5, for RME $R_1 = 1.9$, $R_3 = 2.7$ [11].

French Environmental Protection and Energy Management Agency (ADEME) present a thorough energy balance calculation methodology and the following values of RME energy ratios: $R_1 = 1.9$, $R_2 = 5.4$ (with straw), 2.6 (without straw), $R_3 = 3.7$ (with straw), 2.7 (without straw) [12]. For fossil diesel fuel, $R_1 = 0.885$ is presented for comparison. Usage of rapeseed cake substantially improves energy conversion ratios, while the effect of glycerol on these indices is less. Rapeseed straw has the largest impact on energy ratios.

Soybean oil methyl ester (SME) life cycle analysis performed by the US National Laboratory of Renewable Energy using a different methodology indicates that to receive 1 MJ of biodiesel fuel energy, 1.2414 MJ of primary energy and 0.3110 MJ of fossil fuel energy are used. The ratio of energy accumulated in SME to fossil fuel energy used for SME production is 3.215 [13].

Energy balances depend on agro- and processing technologies used for biodiesel fuel production. The objective of this study was to evaluate possibilities of implementation of new low energy input and environmentally friendly technologies in all stages of biodiesel fuel production.

2. Methods

Biodiesel fuel life cycle was analyzed according to ISO 14040–14049 requirements. All energy flows from production to disposal during the biodiesel fuel life cycle were calculated.

Energy consumption in agriculture was calculated by evaluating direct (petroleum products and electricity) and indirect energy impact (energy accumulated in fertilizers, chemicals, tractors and agricultural machinery). Consumption of the energy accumulated in agricultural machinery was calculated according to the energy consumption for machinery production (MJ/h) and machinery productivity norms (ha/h) as presented in Mechanized Agroservice Works Pricelist (crop care, harvesting work) prepared by the Labor Economics Center at the Agriculture and Forestry Ministry, Lithuania. Fuel consumption in agriculture was calculated according to the above mentioned document. Energy accumulated in fertilizers and plant protection materials was calculated according to norms recommended in Lithuania and energy equivalents of the chemicals used.

Energy consumption for rapeseed growing and oil pressing (E_{agr}) was calculated by the following equation:

$$E_{\mathrm{agr}} = E_{\mathrm{f}} + E_{\mathrm{m}} + \frac{E_{\mathrm{t}} + E_{\mathrm{am}}}{W_{\mathrm{c}}}, \tag{1}$$

where E_{f}, the fuel energy (MJ/ha); E_{m}, the energy accumulated in fertilizers, seed, plant protection materials (MJ/ha); E_{t}, the energy accumulated in tractors and harvesters (MJ/ha); E_{am}, the energy accumulated in other agromachinery (MJ/ha); W_{c}, the capacity of the aggregate (ha/h).

Energy consumption for rapeseed oil extraction and transesterification (for 1 t of biodiesel fuel production, E_{p}) was calculated by the following equation:

$$E_{\mathrm{p}} = E_{\mathrm{fe}} + \frac{E_{\mathrm{e}}}{W_{\mathrm{c}}} + E_{\mathrm{ch}}, \tag{2}$$

where E_{fe}, the fuel energy and electricity (MJ/t); E_{e}, the energy accumulated in equipment (MJ/h); E_{ch}, the energy accumulated in chemical materials (MJ/t); W_{c}, the capacity of equipment (t/h).

Total energy consumption for 1 t biodiesel fuel production (E) was calculated by the following equation:

$$E = \frac{E_{\mathrm{agr}}}{P \cdot O} + E_{\mathrm{p}}, \tag{3}$$

where P, the rapeseed productivity (t/ha); O, the output of biodiesel fuel ($\mathrm{t}/\mathrm{t}_{\mathrm{seed}}$); E_{agr}, the energy consumption for rapeseed growing (MJ/ha); E_{p}, the energy consumption for oil extraction and transesterification (MJ/t). Energy ratios R_1, R_2, and R_3 were calculated from the data obtained.

3. Results and discussion

3.1. Energy consumption in agriculture

Energy accumulated in biodiesel fuel and by-products is a relatively fixed value; thus, the largest influence on the energy balance is made by the energy demands for biodiesel fuel production. Total energy consumption in the RME life cycle can be divided into three main sections: energy used in agriculture, energy consumed for oil extraction, and energy used for oil transesterification.

Energy consumption for 1 ha of rapeseed growing in Lithuania conditions is presented in Table 1. The largest energy demands are related to fertilizers and plant

Table 1
Energy consumption in agriculture

Classification	Using mineral fertilizers and drying of seed		Using biofertilizers and seed preservation technology	
	Consumption of energy (MJ/ha)	%	Consumption of energy (MJ/ha)	%
Primary energy accumulated in agricultural machinery and equipment	2034.6	10.9	2034.6	22.7
Energy from fossil fuel and lubricant used in agricultural machinery	2556.8	13.8	2556.8	28.5
Primary energy accumulated in equipment for rapeseed preparation (cleaning, drying or preservation of seeds)	235.4	1.3	201.2	2.2
Energy from fossil fuel and electricity used for seed cleaning, drying or preservation	1777.0	9.6	1134.3	12.6
Primary energy accumulated in rapeseed	37.1	0.2	37.1	0.4
Primary energy accumulated in fertilizer	10,930.5	58.7	1993.5	22.2
Primary energy accumulated in chemicals for plant protection	1020.0	5.5	1020.0	11.4
Total	18,591.4	100	8977.5	100

protection materials. Energy accumulated in fertilizers makes up more than 58% of the total energy consumption in agriculture. Input of energy from fuel, lubricants, and electricity is almost 2.5 times lower than those of fertilizers. A substantial quantity of energy is required for rapeseed drying.

Total energy consumption in agriculture could be reduced by using biofertilizers produced from biological waste, most of which is currently not utilized. For the production of biofertilizers, it is possible to use sewage sludge, manure, slaughterhouse waste (meat bone mass). The proposed energy-efficient biofertilizer production process consists of the following main stages, which comply with the EU regulations, related to utilization of biological waste: waste crushing, meat bone mass treatment with mineral acids (chemical thermal sterilization of the meat bone mass), anaerobic digestion in the bioreactor (thermal sterilization), and drying of the obtained digestate above 70 °C to a humidity of not more than 12%. Potassium salts are added for nutrient correction in the fertilizer. The amount of biogas produced in the bioreactor is fully sufficient for drying of the biofertilizers obtained and for electricity production in the co-generator, i.e. the biofertilizer production process does not use additional electricity or fossil fuel energy. Calculation of the energy accumulated in the equipment and chemicals additionally used in the biofertilizer production process indicated the decrease of fertilizer energy consumption (for growing 1 ha of rapeseed) in the biodiesel fuel life cycle from 10,930.5 to 1993.5 MJ/ha.

An alternative method to reduce energy consumption in agriculture would be to implement seed preservation technologies, which could substitute the usual seed drying. Chemical preservation reduces energy consumption by 1.5 times when compared to drying in silo hothouses, while total energy consumption related to agriculture including the usage of biofertilizers and seed preservation is reduced by two times (Table 1). Although the presented methods have been researched, they are not applied widely. They provide further energy cost cutting opportunities.

3.2. Energy consumption for rapeseed processing into the biodiesel fuel

Various rapeseed oil extraction and transesterification technologies are currently used in the production of biodiesel fuel.

The main currently used oil production methods involve pressing and extraction by organic solvents. Compared to cold pressing (at temperatures not higher than 60 °C), hot pressing at temperatures of 110–120 °C yields a larger quantity of oil. However, 6–7% of oil is left in the cake even when slow presses are used. Cold pressing method requires less energy for processing of 1 t of seeds and there are less phospholipids in the oil, which is desirable in the production of the biodiesel fuel. However, 12–14% of oil is left in the cake. Using the extraction method, only 0.1–0.8% of oil is left in the cake [14]. However, the quantity of phospholipids in the hexane-extracted oil is twice as high compared to that in the pressed oil [15–18]. For this reason, additional energy consuming operation of oil degumming is required before transesterification.

To decrease energy consumption and environmental pollution, and to receive higher quality oil and cake, the fermentation hydrolysis principle-based biotechnological oil production method should be used for oil extraction in the biodiesel fuel production. During the hydrolysis process, fermentation preparations and their compositions destroy cell walls of the oil plant seeds and release the oil present in them. The destroyed albumens go to the water phase, while the oil is separated using classical separation methods [18].

Energy consumption for oil extraction in biodiesel fuel production applying the classic cold press technology was 2328.0 MJ (for 1 t RME production). Using biotechnological method for oil extraction, which has been tested on the experimental equipment, 2089.1 MJ of energy was used for extraction of oil required for 1 t of RME production.

Total energy consumption in the production of the biodiesel fuel could be reduced by exclusively using renewable energy sources for the production of ester. Usually, rapeseed oil is transesterified by synthetic methanol. The methanol energy ratio R_1 is 0.76. It is expedient to use bioethanol for transesterification of rapeseed oil. Having appropriately selected raw materials and technology, and rational spirits grain processing, the ratio R_1 for ethanol is 1.34.

In the production of rapeseed oil ethyl ester (REE), a higher yield of biodiesel fuel from 1 t of oil is obtained. If 1 t of RME is produced from 1.1 t of oil by applying low productivity (1000 t of RME per year) equipment and cold pressing technology, for production of 1 t of REE using the same equipment, 1 t of oil is used. Thus, energy consumption in both agriculture and oil production stages is reduced.

Comparative indices of total energy demands for 1 t of RME and REE production using the same equipment and rapeseed growing agrotechnologies (rapeseed productivity of 3 t/ha, and oil yield using cold pressing method of 0.33 t of oil from 1 t of seed) are presented in Table 2.

Total energy consumption for the production of 1 t of REE is lower than that in the case of RME production using the same equipment and rapeseed growing agrotechnologies (rapeseed productivity of 3 t/ha, and oil yield using cold pressing method of 0.33 t of oil from 1 t of seed) (Table 2). Energy consumed in the agricultural stage makes up the biggest part of the total energy demand. This consumption can be reduced by using more efficient agrotechnologies—improving rapeseed productivity, substituting seed drying with preservation, and substituting mineral fertilizers with biofertilizers.

3.3. Energy accumulated in biodiesel fuel life cycle

In RME or REE life cycle analysis, it is important to evaluate energy accumulated in all products obtained in the biodiesel fuel production process. In the agricultural stage, not only rapeseed, but also some 6 t of straw per hectare are produced, which make a significant impact on the energy balance. Though the

Table 2
Total energy consumption for production of 1 t RME and 1 t REE

Classification	Energy consumption of RME (MJ/t)	Energy consumption of REE (MJ/t)
Agriculture		
Agromachinery and equipment	2775.1	2639.6
Fuel and oils	5209.5	4955.1
Electricity	84.3	80.2
Seeds and chemicals	14,654.8	13957.0
Total	22,723.7	21,613.9
Oil pressing		
Electricity	792.0	751.4
Equipment	1536.0	1536.0
Total	2328.0	2287.4
Transesterification		
Electricity	540.0	540.0
Equipment	1205.2	1205.2
Chemicals	4610.0	4780.0
Total	6355.2	6525.2
Grand total	31,406.9	30,426.5

calorific value of straw is three times lower than that of biodiesel fuel, it can be used as a biofuel.

In rapeseed oil pressing and transesterification processes, an average of 1.5 t of cake and 0.1 t of glycerol is obtained per 1 t of ester. Values of the energy accumulated in the products obtained in the process of production of 1 t of ester are presented in Table 3. REE yields more energy than RME. The largest amount of energy is accumulated in the straw. Straw accumulates twice as much energy as the esters, while the cake accumulates a little less energy than the fuel.

3.4. *Life cycle energy balances*

As used in energy balance calculations, total energy consumption includes not just the energy received from the traditional fossil fuels like petroleum, natural gas, coal, etc. However, electric energy produced in nuclear and hydropower plants can be omitted from these calculations. According to statistics, Lithuanian energy balance includes 80–85% of nuclear energy and 2.5% of hydroenergy. For this reason, nuclear energy and hydroenergy were eliminated from the calculation of the total electric energy consumption in fertilizer production, rapeseed drying, oil pressing and transesterification [12].

Energy ratios R_2 and R_3 were calculated in two cases—by taking into account the energy accumulated in all products obtained, (a) including straw, and (b) excluding straw.

In Table 4 are presented values of REE and RME energy ratios, depending on rapeseed productivity by applying common agrotechnologies (variant I) and implementing seed preservation and using biofertilizers (variant II).

Average rapeseed productivity in Lithuania reaches 1.8 t/ha, because currently mostly the lower yielding spring rapeseed is grown. It can be concluded that at the present levels of productivity and without the implementation of energy-saving technologies in agriculture and industrial processing, the quantity of energy obtained from RME is almost equal to that used in the production of RME. REE has a slightly higher energy conversion level; however, its R_1 is also substantially lower than the average RME value ($R_1 = 1.9$) calculated for the European Union.

Even if a rapeseed productivity of 3.5 t/ha is achieved, with the application of the commonly used agro- and processing technologies, the value of R_1 exceeds the EU value when REE is produced and only when rapeseed productivity exceeds 3.5 t/ha, which is not realistic in Lithuania at the moment. Upon the implementation

Table 3
Energy content in products in 1 t of ester production

Product	Energy content of RME (MJ/t)	Energy content of REE (MJ/t)
Ester	37,699.8	41,514.0
Glycerol	1659.8	1581.0
Straw	88,220.0	83,700.0
Cake	36,428.5	34,562.5

Table 4
Dependence of RME and REE energy balances on rapeseed productivity

Productivity (t/ha)	RME						REE					
	R_1		R_2		R_3		R_1		R_2		R_3	
	I	II	I	II	I	II	I	II	I	II	I	II
2.0	1.04	1.66	3.80[a]	6.08[a]	3.68[a]	5.87[a]	1.20	1.96	3.90[a]	6.39[a]	4.13[a]	6.75[a]
			1.76[b]	2.82[b]	2.24[b]	3.57[b]			1.88[b]	3.08[b]	2.40[b]	3.92[b]
2.5	1.19	1.90	4.55[a]	7.28[a]	3.98[a]	6.35[a]	1.42	2.32	4.65[a]	7.63[a]	4.43[a]	7.24[a]
			2.10[b]	3.36[b]	2.47[b]	3.94[b]			2.23[b]	3.65[b]	2.74[b]	4.48[b]
3.0	1.43	2.28	5.23[a]	8.37[a]	4.21[a]	6.71[a]	1.62	2.66	5.29[a]	8.68[a]	4.66[a]	7.65[a]
			2.41[b]	3.86[b]	2.73[b]	4.35[b]			2.55[b]	4.18[b]	3.02[b]	4.96[b]
3.5	1.59	2.54	5.81[a]	9.29[a]	4.38[a]	6.99[a]	1.81	2.97	5.92[a]	9.71[a]	4.84[a]	7.92[a]
			2.68[b]	4.29[b]	2.95[b]	4.71[b]			2.84[b]	4.65[b]	3.27[b]	5.37[b]

[a] With straw.

[b] Without straw.

of the proposed innovations (usage of biofertilizers, seed preservation, biotechnological production of oil) and producing RME, R_1 value would reach 1.9 at a rapeseed productivity of 2.5 t/ha, while in the case of REE production, rapeseed productivity could be slightly lower than 2.0 t/ha.

Ratio R_2 has a linear relationship to rapeseed productivity and efficiency of the production process used. If biodiesel fuel is produced by the classic method and all products obtained during the RME production process are used for energy purposes (R_2), the energy efficiency is increased by more than 3.6 times, compared to the case, when only the energy accumulated in the biofuel is considered. However, in the production of REE, this coefficient is lower and reaches about 3.25. This can be explained by the fact that portion of the straw energy in the total quantity of energy is the largest, and the quantity of straw produced in growing rapeseed for the production of RME is only slightly larger than that produced in REE production.

Ecological energy balance R_3 indicates the ratio of the energy obtained from biodiesel fuel to the energy allotted solely to biodiesel fuel. When RME is produced, R_3 exceeds 3.6 when rapeseed productivity is 2 t/ha and increases to 4.38 when productivity is 3.5 t/ha (with straw). When straw is excluded, the energy accumulated in RME is 2.24–2.95 times higher than the energy used exclusively for fuel production. All respective values of REE energy ratios are higher than those of RME, i.e. ecologic efficiency of REE is higher. The implementation of new, environmentally friendly agro- and processing technologies increases ecological efficiency of biofuel by 1.6 times.

All biodiesel fuel energy ratios also depend on the efficiency of technologies used for oil processing into biodiesel fuel. Table 5 presents RME and REE life cycle energy balances when fuel is produced by the cold pressing and low productivity oil transesterification equipment (variant I) and when fuel is produced by high productivity hot pressing and transesterification production technology (variant II) when rapeseed productivity is 3 t/ha.

Table 5
RME and REE energy balances using different production technologies (rapeseed productivity 3 t/ha)

R_1				R_2				R_3			
I		II		I		II		I		II	
a	b	a	b	a	b	a	b	a	b	a	b
RME											
1.43	2.28	1.72	2.82	5.23* 2.41**	8.37* 3.86**	5.53* 2.63**	8.89* 4.32**	4.21* 2.73**	6.71* 4.35**	5.36* 3.19**	8.64* 5.18**
REE											
1.62	2.66	1.94	3.22	5.29* 2.55**	8.68* 4.18**	5.64* 2.80**	9.35* 4.68**	4.66* 3.02**	7.65* 4.96**	5.61* 3.33**	9.30* 5.56**

a, Classical method of biodiesel fuel production; b, new energy-saving technologies.

* With straw.

** Without straw.

Application of more efficient oil extraction and transesterification technology (variant II) increases energy efficiency indices. REE production life cycle energy ratio R_1 is higher than an average EU value of 1.9 at the rapeseed productivity of 3.0 t/ha, while for RME this index is only 1.72. R_2 and R_3 values are also substantially increased, and in the case of REE, they are higher than those in the case of RME. Complex application of the aforementioned conservation technologies, use of biofertilizers, and biotechnological oil pressing method increase the ecological balance R_3 in REE production (taking into account the contribution of straw) to 9.3, i.e. it exceeds the value calculated for REE production using low productivity oil transesterification technology by 1.2 times.

4. Conclusions

- Biodiesel fuel life cycle energy ratios have linear dependence on the efficiency of the agricultural and processing technologies applied.
- Average EU value of energy ratio R_1 can be achieved in Lithuania only by producing REE according to the energy-efficient high productivity oil pressing and transesterification method and obtaining rapeseed productivity of at least 3 t/ha.
- Energy conversion degree is substantially improved, when biofertilizers are used in agriculture, the usual seed drying is substituted with chemical conservation, and the energy-efficient biotechnological method of oil extraction is applied.

Acknowledgements

The author is grateful to E. Poitrat (ADEME, France) and K. Walker (Scottish Agricultural College, UK) for methodical and technical help in his work.

References

[1] ISO 14040:1997. Environmental management—life cycle assessment—principles and framework.

[2] ISO 14041:1998. Environmental management—life cycle assessment—goal and scope definition and inventory analysis.

[3] ISO 14042:2000. Environmental management—life cycle assessment—life cycle impact assessment.

[4] ISO 14043:2000. Environmental management—life cycle assessment—life cycle interpretation.

[5] VDI 4600. Kumulierter Energieaufwand. Begriffe, Definition, Berechnungsmethoden.

[6] Cook P, Walker KC, Booth EJ, Entwistle G. The potential for biodiesel production in UK. Farm Manage 1993;8:361–8.

[7] Holman C, Fergusson M, Mitchell C. Road transport and air pollution future prospects. Rees Jefreys Road Fund transport and Society. Discussion paper 25. Oxford, UK, 1991.

[8] Korbitz W. The technical and environmental properties of biodiesel. Proceedings of New Directions for Agriculture Conference. Aberdeen, UK; 1994, p. 1–6.

[9] Boo W. Environmental and energy aspects of liquid biofuels. Deljt, Netherlands: Centrum voor energiebesparing en schone technologie; 1993, p. 2.

[10] Batchelor SE, Booth EJ, Walker KC. A comparison of the energy balance of rape methyl ester and bioethanol. Proceedings of Ninth International Rapeseed Congress. Rapeseed today and tomorrow, vol. 4. Dorchester: Henry Ling Ltd, The Dorset Press; 1995, p. 1363–5.

[11] NTB liquid biofuels network. Available from: http://www.nf-2000.org.html.

[12] ADEME. Base de données Ademe, matériaux d'emballage. Raport final, 1997.

[13] Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H. An overview of biodiesel and petroleum diesel life cycles. National Renewable Energy Laboratory NREL/TP-580-24772, 1988.

[14] Unger EH. Commercial processing of canola and rapeseed crushing and oil extraction. In: Shaidi F, editor. Canola and rapeseed. New York: Culinary and Hospitality Publication Services; 1990 [Chapter 14], p. 335.

[15] Patterson HBW. Basic components and procedures. Bailey's industrial oil and fat products. Theory and practice. Champaign (IL): AOCS Press; 1992, p. 102–62.

[16] Przybylski B, Eskin NAM. Phospholipid composition of canola oils during the early stages of processing as measured by TLC with flame ionization detector. JAOCS 1991;68(4):241–5.

[17] Prior EM, Vadke VS, Sosulski FW. Effect on heat treatment on canola press oils. Non-triglyceride components. JAOCS 1991;68(6):401–6.

[18] Makareviciene V. Rapeseed oil ethyl ester production, use as fuel and impact on environment. Doctoral thesis, Lithuanian University of Agriculture, 2001.