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Why Biodiesel is Environmentally Better than Traditional, Fossil-based Diesel: an LCA Approach

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Abstract **– In Latvia, rapeseed methyl ester (RME) is generally considered to have a significant economic potential in the field of biofuels. As investments grow, it is important to evaluate the environmental impacts of this production and to highlight the main sources of these impacts.**

Nowadays, the share of biofuels in the transport sector in Latvia is attested to have a value of 0.3% (around 75% biodiesel and 25% bioethanol). Biofuel production in Latvia doubled in the last two years: the current total biodiesel production is approximately 64 ktonne/year (year 2009).

The aim of this paper is to understand and model the environmental performance of the biodiesel produced from rapeseeds under the local Latvian conditions. Firstly, energy crops were evaluated by assessing their levels of biodiesel productivity. Secondly, the current Latvian climatic conditions and cultivation parameters were taken into account. To conclude, a comparison with the impacts of fossil based diesel was conducted.

Keywords **– Biodiesel, Life Cycle Assessment, renewable energy sources**

I. INTRODUCTION

The EU Renewable Energy Directives' sustainability criteria (EU/2009/28) state that biofuels must offer at least 35% carbon savings compared with fossil fuels. To all Member States, the European Commission has indicated that the use of transport biofuels must reach the level of 5.75% in 2010. In Latvia, rapeseed methyl ester (RME) is generally supposed to be one of the most valuable possibilities to attain this goal.

As investments grow, it is important to evaluate the environmental impacts of this production and to highlight the main sources of these impacts.

Nowadays, the share of biofuels in the transport sector in Latvia is attested to have a value of 0.3% (around 75% biodiesel and 25% bioethanol). Biofuel production in Latvia doubled in the last two years: the total biodiesel production is approximately 64 ktonne/year (year 2009).

The aim of this paper is to understand and model the environmental performance of biodiesel produced by rapeseeds under the local conditions. Firstly, the energy crops have been studied by assessing their levels of biodiesel productivity. Secondly, the current Latvian climatic conditions and cultivation parameters have been taken into account. To conclude, a comparison with the impacts of the related fossil based diesel has been conducted.

The system boundaries include rapeseed cultivation, oil extraction and processing, biodiesel production and final use. The system has been expanded to take into account the valorization of by-products in substitution of natural gas production (from fermentation of straw in the cultivation process), animal feed (rapeseed meal) or chemicals (glycerin). Simapro 7.1 databases and the impacts 2002+ method have been used for the Life Cycle Impact Assessment (LCA). The functional unit was off-road transport over a distance of 100 km by a compact pickup truck.

This study shows that the environmental benefits from biodiesel have better results, compared to conventional diesel. The valorization of by-products leads to considerable environmental improvements. Concerning global warming environmental impacts, the valorazion of the by-product is fundamental in order to have a level lower than that one of conventional diesel.

The results lead to the conclusion that it is feasible to successfully increase the environmental and sustainable efficiency of the Latvian biodiesel production model. The use of the LCA methodology is a fundamental tool in the foreseeable future to enhance Latvian biodiesel production.

II. LATVIAN BIOFUEL PRODUCTION TREND

The Latvian energy supply is characterized by a strong dependence on energy imports and the highest share of renewable energy in the entire European Union. The latter consists of approximately one third of the total energy consumption. Imported energy sources account for roughly two thirds of the Latvia's total energy consumption. Except for peat, which can be found in approximately 10% of its soil, Latvia has no fossil resources for energy production worth mentioning. Natural gas, oil products and coal are mainly imported from Russia.

However, renewable energy sources are substantial. Forests cover approximately 55% of the Latvia's territory, making biomass the largest domestic resource currently used in heat generation. Hydropower is already the biggest contributor to electricity generation, and still has the unused potential. Wind power gained importance in recent years and has a good potential, as wind is abundant. This is particularly the case along the coast, where, in addition, the transmission network is particularly developed.

Latvia can meet about 70% of its electricity demand domestically, mainly with CHP-plants, wind turbines and hydroelectric facilities. The latter two are subject to natural variations in water and wind availability. Therefore, large shares of imported electricity are needed. Many of these imports had come from the Lithuanian nuclear power plant Ignalina, which was shut down in 2009. This situation creates further challenges for the Latvian electricity supply sector and represents a real opportunity for the exploitation of renewable energy sources within the country.

DOI: 10.2478/v10145-011-0033-z
2011
Volume 7

For 2010, the EU-Directive 2001/77/EC sets a target of 49.3% of gross electricity consumption to consist of renewable sources, and a 5.75% biofuel-use is obligatory, according to the Directive 2003/30/EC, in the same period.

The target for renewable energy, as a share of final consumption, is 40% by 2020 according to the EU-Directive 2009/28/EC on the promotion of the use of energy from renewable sources. The same directive demands a minimum of 10% of renewable energy in transport.

National commitments include biofuel targets of 10% by 2016 and 15% by 2020, 8% of electricity produced in biomass-run CHP-plants, as well as the above mentioned 49.3% target for 2010 segmented into different generation technologies.

In relation to the use of biofuel in the transportation sector, the situation is represented by the following Table 1 where one can see that only 0.2% is represented in the transport sector, despite the 5.75% required by the EU Directive [1].

III. LYFE CYCLE DEFINITION

Biofuel sustainability has been widely debated. Nevertheless, political decisions are being made, economic investment is on the course and environmental and social impacts are taking place [2, 3].

Evaluating the sustainability of human activities, involves a comparison between the environmental status resulting from the activity and the natural or desired status [3]. A favorable comparison, in the case of biofuel production, would ideally agree with the following aspects:

1. the fuel should supply an amount of energy superior to that required to produce it;
2. the long-term feedstock supply should be guaranteed, in order to assure long term biofuel;
3. supply to the market, which depends on the sustainability of the underlying activities;
4. the emission of unwanted substances to the environment should be less than those that would result from the use of a fossil fuel to obtain the same amount of energy;
5. land use should not compromise food production, nor the respect for the ecosystem balance.

Due to their comparable physical properties, biodiesel and fossil-based diesel can be used for conventional diesel engines [4-6]. Thus, the primary concern of this study is the question as to whether or not the production of biodiesel is comparable to the production of fossil diesel from an environmental point of view, taking into account all stages of the life cycle of these two products.

Biodiesel production from rapeseed in Latvia has been investigated in three scenarios for this LCA study. These include a model based on the existing Latvian biodiesel production, not including the avoided products coming from the use of the co-products and/or waste from production, a second model which considered the avoided products and the comparable LCA model for diesel production and final use in Latvia.

The potential environmental benefits and/or damages and ascertaining the environmental optimum of biodiesel production in the Latvian condition will be identified. This study was based on the ISO 14044 [7].

IV. GOAL AND SCOPE DEFINITION, FUNCTIONAL UNIT

The development of the biofuels industry in Europe has lead to numerous environmental studies [8-12].

Therefore, the aim of this study is to perform a full comparative Life Cycle Assessment of the production and use of biodiesel, providing a comparison with the corresponding fossil fuel for Latvian conditions, in order to investigate its environmental benefit.

The last step will be the identification of the main sources of the environmental impacts, and the proposition of improvements of the environmental performances.

In the following, the main aims to be reached during the analysis are outlined:

1. Demonstrate that biodiesel has a positive energy balance and it is a renewable source (study of the energy ratio among the renewable energy output produced and the amount of non-renewable energy spent for the production);
2. Savings of green house gas (GHG) emissions;
3. Use of LCA to evaluate the life cycle environmental burdens of a biodiesel (BD) system use (B100) from rapeseed oil;
4. Identify the hot spots of the system and make recommendations.

The functional unit to which all emissions and consumptions in this assessment have been reported is a pick-up truck (Toyota Hilux) covering 100 off-road (not paved road) kilometres. Even if biofuels are generally used as additives, results will be presented for cars working with pure biofuels (B100) as mixing with fossil fuels could have an influence on the conclusions of the comparison, and the aim is to determine which biofuel offers the highest environmental benefit. The Impact 2002+ [13] has been used in this study.

The relevant environmental mid-point impact categories studied are: non-carcinogens effects, respiratory effects, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy.

V. LIFE CYCLE INVENTORY AND SYSTEM BOUNDARIES

Data gathering on rapeseed cultivation and biodiesel production has been based on international conditions, and local Latvian sources (see Tables 1 and 2).

Other types of data have been collected from the ecoinvent 2.1 database (included in the Simapro 7.2 software [14] and from GEMIS [15].

Different scenarios were evaluated in order to assess methods for decreasing potential negative environmental impacts. For the simplification of the simulation, the following four stages have been considered per energy crop:

1. soil preparation and cultivation (including nursery of the seeds);
2. rapeseed oil production (including refinery);
3. biodiesel production (including refinery),
4. final end use (see Fig. 1).

As evident in the model, it has been assumed that the straw is used for the production of biogas, the seed cake for production of animal feeds, and waste products (e.g. sodium phosphates) as fertilizers. The model foresees the co-production of glycerine in the process. The use of these wastes and co-products is fundamental to increase the environmental benefits of the whole

DOI: 10.2478/v10145-011-0033-z 2011
Volume 7

process, as they displace the production of other products (natural gas, grass siling artificial fertilizer, fossil glycerine).

TABLE 1

INFLOWS AND OUTFLOW IN THE MODEL

FLOWS	Cultivation	RS oil production	BD production	Source
Land [ha]	-0.97			[16]
Seeds [kg]	-3.39			[16]
N fertilizer [kg]	-49.44			[16]
P fertilizer [kg]	-12.80			[16]
K fertilizer [kg]	-60.35			[16]
S fertilizer [kg]	-84.34			[16]
Pesticides [kg]	-1.95			[16]
Leaf fertile.[kg]	-7.46			[16]
Straw [t]	5.82			[17]
Rapeseeds [t]	3.10	-3.10		[16]
Rapeseed cake [t]		2.01		[18]
H_3PO_4 (deg.) [t]		0.00		[18]
NaOH (deg.) [t]		-0.02		[18]
Citric acid (deg.) [t]		-0.0003		[18]
Rapeseeds oil [t]		1.05	-1.05	[18]
Methanol [t]			-0.11	[18]
KOH (trans.) [t]			-0.01	[18]
H_2SO_4 (trans.) [t]			-0.01	[18]
NaOH (glyc.) [t]			-0.02	[18]
H_3PO_4 (refin.) [t]			-0.0011	[18]
Gliceryn [t]			0.11	[18]
Biodiesel (RME) [t]			1,00	

The production (or nursery) of the seeds needed to produce the future rapeseed culture is the preliminary step, the data entered into the model is directly extracted from the ecoinvent 2.1 database.

TABLE 2

ENERGY AND NON RENEWABLE FUELS REQUIREMENTS

ENERGY and NON RENEWABLE FUELS	Cultivation	RS oil production	BD production	Source
Electricity [kWh/biodiesel tonne]			203.35*	[18]
Thermal energy [MJ/ biodiesel tonne]			2737*	[18]
Diesel [tonne/biodiesel tonne]			0.07*	[18, 19]
Machinery [tractor/ha]	0.0009			[19]
Boiler efficiency [15 MW boiler house]		90%	90%	[20-22]
Biodiesel (RME) [t]			1,00	

The culture of rapeseed is the first real step in the production of biofuel. The production of the fertilizers (N, P, K) and the pesticides, soil/water/ground emissions, the consumptions and emissions of the tractors (fertilizing, tillage, sowing, harvesting, transport) and the valorization of by-products, like rapeseed straw, substituting fertilizers (also in terms of N, P, K) or producing biogas have been taken into account.

The next step is the conversion of the feedstock to biofuel. After drying the rapeseed grains, oil is extracted in two steps, involving a mechanical extraction followed by an extraction with an organic solvent. Two products are generated: oil, and rapeseed meal (or seed-cake), rich in proteins and easily integrated in the rations of animal feed. The extracted oil is then refined, and finally reacts with fossil methanol to produce rapeseed methyl ester and glycerine, which is purified and used in the chemical industry.

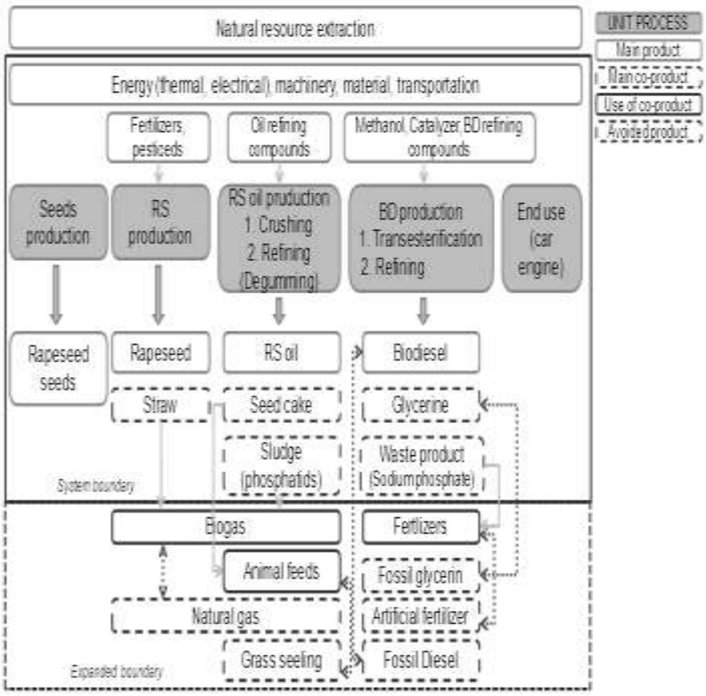

Fig. 1. LCA model and boundary: scheme implemented in the Simapro software also considering the expanded boundaries. The main inflows and outflows in the model in terms of material/product, as well as the avoided products, are reported.

The exhaust emissions and fuel consumptions of the vehicle used for this study have been calculated on the basis of fossil fuel vehicles. The energetic contents of the biofuels are different from those of the corresponding fossil fuels and consumption, expressed in kg/km, is also different. In the study, amounts of 16.5 kg/km in regard to the car fuelled by biodiesel and 18.0 kg/km for a car totally fuelled by diesel have been taken into account.

As it belongs to the natural cycle of carbon, carbon based emission (CO_2 and CO) emitted by the combustion of the biofuels does not contribute to global warming and is subsequently not taken into account in the model. Using biodiesel leads to an increase of the emissions of nitrogen oxides, a decrease of the emissions particulates (PM) and hydrocarbon [23].

In our study, in reference to a diesel engine of an off-road pick-up truck type [24], the following coefficients have been used:

DOI: 10.2478/v10145-011-0033-z *2011*
Volume 7

1. NO_X = 0.312 g/km – increase of 10% respect diesel engine;
2. PM = 0.039g/km – decrease of 45%.

The complete Life Cycle Inventory has been established using Simapro 7.2 databases. By-products have been taken into account with energetic or mass allocation. Environmental credits (avoided impacts of the production of equivalent products) for the substitution to other products, like animal feed or chemical products, have been calculated. As no data were available for some of the by-products, an assumption has been made to calculate equivalencies with some products described in the Simapro databases.

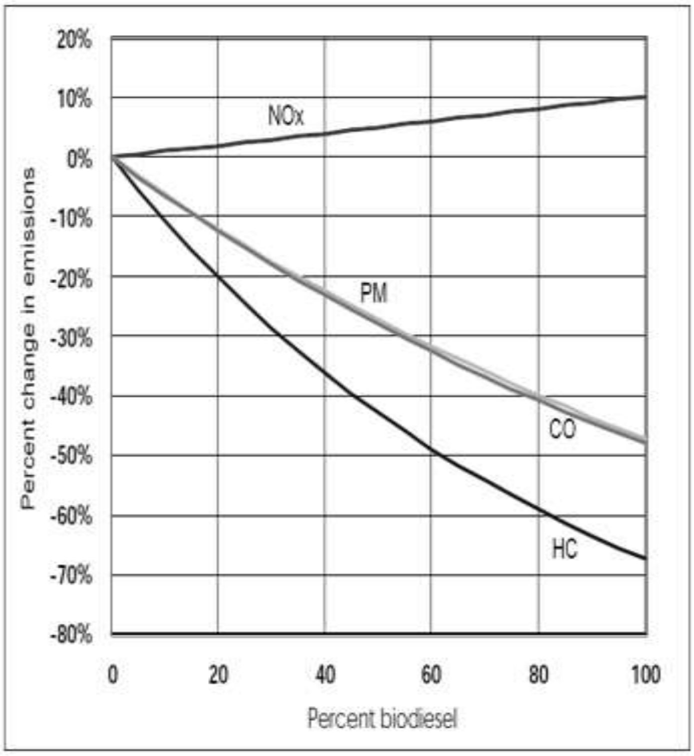

Fig. 2. Percent change in emission of a biodiesel engine with respect to a fossil-based diesel engine [23].

The glycerin at the end of the production process was assumed to substitute for the chemical glycerin produced by hydrolysis of epichlorohydrin (from Ecoinvent 2.1 database).

The system boundaries include biodiesel production (rapeseed cultivation and processing for biofuel, extraction and refining for fossil fuels), but also the final use of the fuel and the valorization of its different by-products. In Tables 1, 2 and 3, the best principle data concerning the LCI are shown.

It is considered in the model that the plant is unable to produce the rapeseed oil needed for the required diesel production. Consequently a model has been calculated that 2/3 of the oil is obtained from an imported oil mix, not from the plant's production.

C-derived emissions were left out of the biodiesel system, assuming the neutrality of the carbon cycle. The system foresees the use of two boiler house systems (around 15 MW total capacity) which are supplied by fossil diesel. The emissions related to the use of fossil diesel for the needs of thermal energy required from the plant processes have been directly taken from the database of the ecoinvent 2.1. The total amount of the thermal energy in the whole production processes was equal to 2737 MJ/tonne biodiesel.

The main assumptions, also taken into account for the model, were:

1. 25-year biodiesel plant technical lifetime;
2. Use of straw for biogas production;
3. Use of average EU electricity mix (EU25);
4. Transportation distances estimation based on the data in the Table 3.

The production of biogas from 1 straw has been studied with the relation of: 0.38 m^3 biogas =1 kg straw [25].

The amount of artificial fertilizers displaced has been calculated at: 1 kg of slurry = 0.15kg NKP fertilizers [24].

TABLE 3
TRANSPORTATION ASSUMPTION

Material	Unit process	From	Distance [km]	Way of transport
Seeds	Cultivation	UK (50%), FR (50%)	1270, 1750	40 t truck
Fertilizers	Cultivation	GER	1400	40 t truck
Pesticides	Cultivation	GER	1400	40 t truck
Tractor	Cultivation	SWE	400	Medium size cargo, 89000 t
Rapeseed	RS oil production	LV (35%), LT (35%), BY (15%), KZ (15%)	150, 300, 600, 1000	40 t truck
Oil mix	BD production	RU (60%), BY (40%)	500, 600	40 t truck
Methanol	BD production	RU	500	40 t truck

The relative amount of the displaced natural gas has been calculated with respect to the ratios of the values of the two low heating values (LHV), using the following data:

1. Biogas LHV = 23.3 MJ/m^3 [15],
2. Natural gas LHV = 35.1 MJ/m^3 [15].

This corresponds to an overall avoided amount of natural gas equal to 1514 m^3.

VI. LCA RESULTS

The life cycle's environmental impact assessment was carried out by IMPACT2002+ [13] which is included in the SimaPro database.

Six mid-point categories were analyzed, with four end-point categories. The characterization and weighted results are presented in terms of mPt, where one point is the impact on one person per year. The biodiesel results concern the implementation, and not the avoided products in the model. Subsequently, a final comparison with the fossil diesel LCA is performed.

DOI: 10.2478/v10145-011-0033-z *2011*
Volume 7

In Figure 3, it is possible to understand the main impact category that presents the strongest environmental load.
The biodiesel LCA model takes into account the avoided products. A negative value represents an environmental benefit. If this is compared with the model without avoided products, it becomes evident how strong the effect of reusing waste and/or co-products is (approximately a fivefold increase). One can also see how, for the model considering fossil based diesel, almost 80% of the total impact is related to the non-renewable energy source
used.

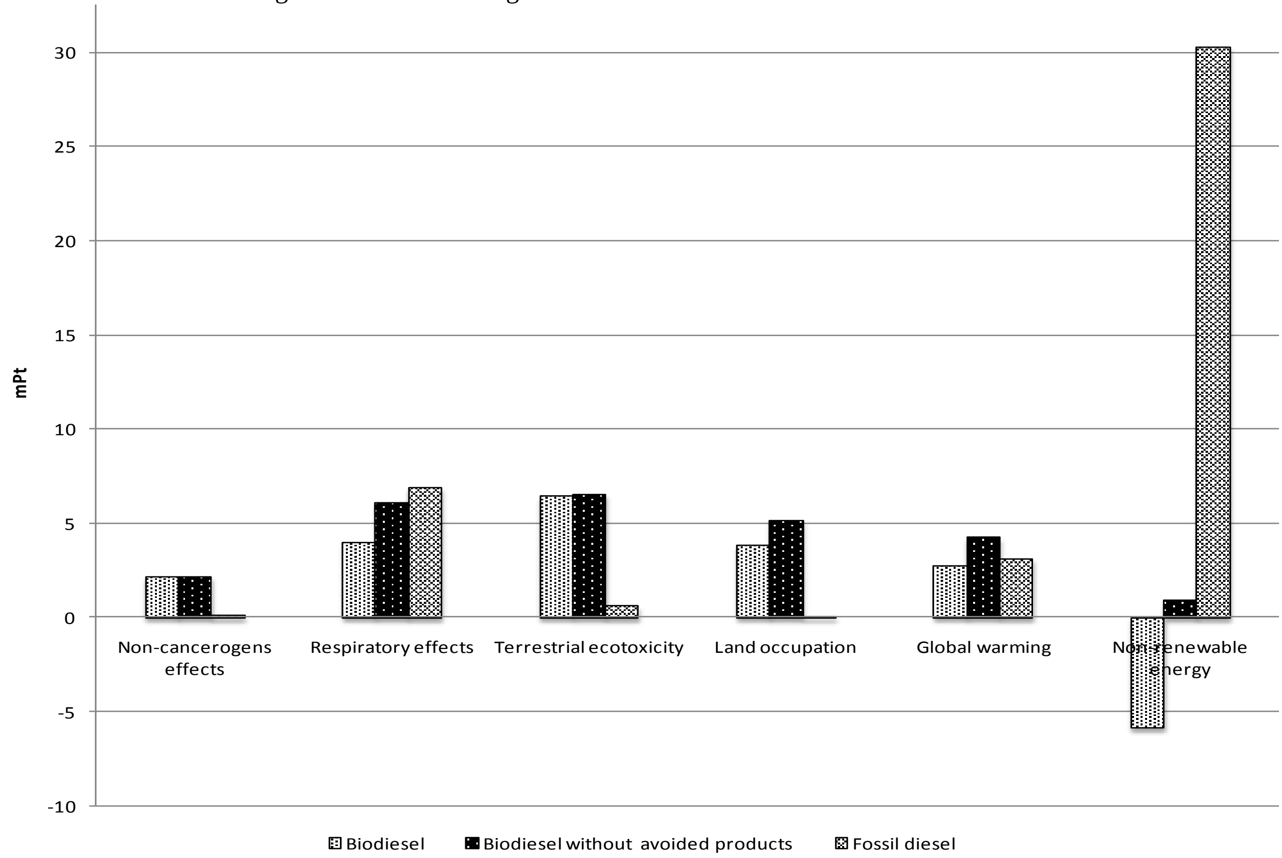

Fig. 3. Midpoint impact categories [mPt/functional unit].

Mainly due to the use of fertilizers, pesticides and arable land the LCAs for the biodiesel present higher impacts in relation to the land use and ecotoxicity impact category. By giving attention to the global warming impact category, the fundamental degree in which the avoided products are relevant in the overall reduction of the CO_2 equivalent in biodiesel production becomes evident. Our model demonstrates a 15% reduction of this value.

In Figure 4, the same results, but in terms of the end-point categories, are presented. These are human health, ecotoxicity quality, climate change and use of resources.

The results confirm what has already been highlighted in the mid-point category analysis:

1. For climate change and human health impact categories, the role of the use of waste and co-products is fundamental in order to have an environmental load lower than the one foreseen in the fossil-based LCA model.
2. The impact on the ecosystem quality for the fossil diesel is almost negligible, in reference to those of the biodiesel models. This is related to the effects of the use of fertilizers, pesticides and the impact on the arable land.

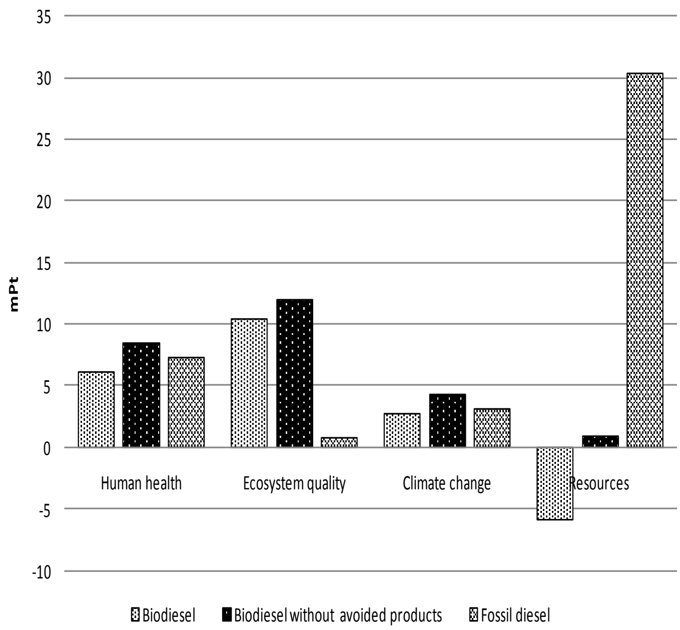

Fig. 4. Endpoint impact categories [mPt/functional unit].

Figure 4 clearly shows the reduction in terms of total environmental impact. The driving force for this reduction is the use of biodiesel.

Without including any use of the waste or co-products, the decrease is around 38%. By including the avoided products and their benefits, the total decrease reaches 67%.

To initialize a benchmarking analysis, the energy balance should be performed, along with the implementation of the LCA. The following Table (4) presents the indicator Ei.

TABLE 4
ENERGY INDICATOR

LCA	E_i
Biodiesel	- 0.18
Biodiesel (without allocation)	0.14
Other sources	- 1.34 < Ei < 0,64

Where:
$Ei = MJ_{in} / MJ_{out}$ = energy indicator;
MJ_{in} = global non-renewable sources spent within the model [MJ];
MJ_{out} = biodiesel energy (specific heating value – 37.7 MJ/kg).

In our analysis, the values are in line with those found in literature.

This is defined as the ratio of the total energy used for fuel production (in terms of non-renewable sources) and biodiesel fuel energy (in terms of calorific value).

This process will make it possible to evaluate the theoretical strength and level of the renewable processes. This is the result of the lower ratio leading to a process where the renewable peculiarities have a greater efficiency.

VII. CONCLUSIONS

The results lead to the conclusion that it is feasible to successfully increase the environmental and sustainable efficiency of the analyzed Latvian biodiesel production model. Specifically, the work concludes that for the Latvian conditions:

1. Biodiesel is a renewable energy source using the energy indicator E_i presented as the benchmark (lower then 1);
2. It has been shown that using biodiesel reduces the consumption of non-renewable energy;
3. Biodiesel effects on the environment are roughly 38% less than for fossil diesel. By taking into consideration the avoided product, the percentage increases to 67%;
4. For climate change and human health impact categories, the role of the use of waste and co-products is fundamental in order to have an environmental load lower than foreseen in the fossil based LCA model;
5. The impact on ecosystem quality of fossil diesel is almost negligible, if referenced to the biodiesel models. This is related to the use of fertilizers and pesticides and their impact on the arable land;
6. The global warming impact category demonstrates how fundamental the role of the avoided products to the overall reduction of the CO_2 equivalent in the biodiesel production is. From our model, this reduction is approximately 15%.

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DOI: 10.2478/v10145-011-0033-z
2011
Volume 7

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Jeļena Pubule, Frančesko Romagnoli, Dagnija Blumberga. Kādēļ biodīzeļdegviela ir videi draudzīgāka par tradicionālo fosilo dīzeļdegvielu: dzīves cikla novērtējuma pieeja
Eiropas Parlamenta un Padomes direktīva 2009/28/EK par atjaunojamo energoresursu izmantošanas veicināšanu nosaka, ka siltumnīcefekta gāzu emisiju ietaupījumiem no biodegvielas izmantošanas ir jābūt vismaz 35 %. 2010. gadā Eiropas Savienības dalībvalstīs biodegvielas īpatsvaram transporta sektorā bija jāsasniedz 5,75 % no kopējā degvielas patēriņa.
Rapšu metilesteris (RME) ir visplašāk izmantotais biodegvielas veids Latvijā. Ņemot vērā šī biodegvielas veida īpatsvara straujo pieaugumu, ir jānosaka šī enerģijas veida ietekme uz vidi. Tajā pat laikā šobrīd Latvijā biodegvielas patēriņš ir tikai 0,3 % (no tiem 75% biodīzeļdegviela un 25% bioetanols) no kopējā degvielas patēriņa. Pēdējos divos gados biodegvielas ražošanas apjoms Latvijā ir dubultojies: kopējā biodegvielas ražošanas jauda 2009. gadā bija 64 ktonnas.
Pētījuma mērķis bija noteikt un modelēt Latvijā ražotas biodegvielas ietekmi uz vidi. Dzīves cikla novērtējumam tika izmantota IMPACT 2002+ metode. Biodīzeļdegvielas radītā ietekme tika salīdzināta ar fosilās dīzeļdegvielas ietekmi uz vidi. Pētījuma ietvaros tika noteikts, ka Latvijā ražota biodīzeļdegviela ir videi draudzīgāka par fosilo dīzeļdegvielu un tā atbilst ilgtspējīgas attīstības principiem.
Pētījuma rezultāti parādīja, ka Latvijā ražota biodīzeļdegviela ir atjaunojamais enerģijas avots un izmantojot biodīzeļdegvielu, tiek samazināts neatjaunojamo enerģijas avotu patēriņš. Dīzeļdegviela atstāj ietekmi uz ekosistēmas kvalitāti, tajā pat laikā biodīzeļdegvielas ražošanas blakusproduktu izmantošana ļauj samazināt biodīzeļdegvielas kopējo radīto ietekmi par 25%.

Елена Пубуле, Франческо Ромагноли, Дагния Блумберга. Почему биодизельное топливо является более экологически чистые, чем традиционный дизель: методика оценки жизненного цикла
В соответствии с директивой Европейского парламента и Совет 2009/28/ЕС по поощрению использования возобновляемых источников энергии, необходимо, чтобы выбросы парниковых газов при использовании биотоплива были не менее, чем на 35% меньше эмиссий фоссильных ископаемых. В 2010-м году доля биотоплива в транспортном секторе Членов Европейского союза, что составляло 5,75% от общего объема потребления топлива.
Рапсовое топливо - метиловый эфир (RME) является наиболее широко используемым видом биотоплива в Латвии. В то же время потребление биотоплива в Латвии составляет всего 0,3% (75 % биодизель и 25% этанол) от общего объема потребления топлива. За последние два года производство биотоплива в Латвии удвоилось: общий объем производства биотоплива в 2009-м году составил 64 ктонны.
Цель исследования заключалась в выявлении и моделировании влияния произведённого с Латвии биотоплива на окружающую среду. Для оценки жизненного цикла был использован IMPACT 2002+. Влияние биодизеля во время исследования сравнивалось с влиянием дизельного топлива на окружающую среду. Исследование показало, что производство биодизельного топлива в Латвийских условиях является более экологически чистые, чем использование дизельного топлива и соответствует принципам устойчивого развития.
Результаты исследования показали, что произведённое в латвийских производствах биодизельное топливо является возобновляемым источником энергии, и использование биодизеля приведет к сокращению невозобновляемых источников энергии. Дизельное топливо оказывает влияние на качество экосистемы, в то же время использование побочных продуктов биодизеля снижает общее воздействие на 25%.