Comparison of LCA and external-cost analysis for biodiesel and diesel

L. De Nocker, C. Spirinckx and R. Torfs
VITO, Flemish Institute for Technological Research
Boeretang 200, B-2400 Mol
tel. 32-14-33.58.87 fax. 32-14-32.11.85
email denockel@vito.be URL http:/www.vito.be

Paper presented at the
"2nd International conference LCA in Agriculture, Agro-industry and Forestry"
Brussels, 3-4 December 1998

Abstract
This paper compares the environmental impacts over the entire life cycle from biodiesel from rapeseed and conventional diesel. The emissions over the full life cycle are weighted using both a traditional LCA (life cycle assessment) approach and an external costs analysis. The emission data refer to the demonstration project at VITO on the use of rapeseed methyl ester (RME) or biodiesel as automotive fuel. The comparison illustrates that both methods to assess and evaluate impacts differ a lot but that results are complementary. The LCA analysis shows that the benefits in terms of greenhouse gas emissions are being compensated by higher other environmental impacts, especially for eutrophication. The external costs analysis, based on the ExternE approach, estimates the damages to public health, materials, agriculture and global warming but cannot monetise the ecological impacts. This analysis shows that external costs of biodiesel and fossil diesel are in the same range, and are dominated by the impacts of the use phase.

1. INTRODUCTION

The objective of the paper is to compare *biodiesel from rapeseed and conventional diesel* using two methodologies for the evaluation of environmental impacts over the entire life cycle. The scope, methodology and results of the LCA methodology are compared with the ExternE impact pathway analysis for the calculation of external costs.

Quite a lot of comparative studies of biodiesel and fossil diesel fuel have been made in the past [1-4]. Although these projects often differ with respect to their goal, scope and methodological approach, there is, nevertheless, an ongoing interest in the environmental assessment of biofuels. This paper mainly focuses on the comparison of two methodological approaches for evaluation of the environmental impacts of biodiesel and fossil diesel fuel.

2. BACKGROUND INFORMATION

2.1. Context and goal

Biodiesel is a general term for renewable diesel fuel substitute that is produced by chemically reacting an alcohol with natural oil. Actually rapeseed methyl ester (RME) or biodiesel made from rapeseedoil was explored in the LCA and externality analysis. The emission and technical data for biodiesel are based on a demonstration project at VITO (e.g. on the road emission measurements). Since RME and diesel have comparable physical properties, both fuels can be used for conventional diesel engines.
Additionally, to assess the overall environmental impact and damage cost for both fuels, *from the cradle to the grave*, an LCA and externality analysis have been performed. The primary concern of the LCA 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. The different environmental impacts are weighted based on traditional LCA techniques.
Externality analysis calculates the environmental damage costs caused by the two fuel life cycles. In the context of federal and European research projects, VITO uses *the ExternE methodology* to assess the environmental damage costs from different fuel cycles. This paper uses interim results of this project to compare diesel and biodiesel.

2.2. Functional unit

Both environmental analyses require an objective basis for comparison, the so-called functional unit, which reflects the function of the two fuels. According to VITO-measurements [5], it takes 6.3 kg of biodiesel in relation to 5.7 kg of fossil diesel fuel to drive 100 km with an identical car and the same conditions. So both for the LCA and externality analysis *1 kg of biodiesel is compared with 0.9 kg of fossil diesel fue*l. This functional unit is consistent with the vehicle/km used in external cost analysis for the comparison of different fuels and technologies.

2.3. Scope

Belgium was considered to be the geographical reference area for the biodiesel life cycle. When specific data for the Belgian situation were not available, West European data were included. With regard to the scenario for fossil diesel fuel, West European conditions were taken into account.
Both assessments start at the extraction of primary raw materials and conclude with the combustion of the fuels in the car engine (Figure 1). The most important aspects that fell outside the system boundaries are the production of capital goods (production of the car, machinery, etc.), risks and human labour. Furthermore final transportation to the fuel station is not considered because the average distance and the means of transportation are the same for both fuels. The only minor difference is the quantity of fuel that has to be moved. All other intermediary transportation steps are included.

3. COMPARISON BASED ON STANDARD LCA

To assess the overall environmental burdens related to the life cycle of biodiesel and fossil diesel fuel a life cycle assessment (LCA) has been made. The analysis is based upon the LCA methodology described by *ISO in its 14 040 standard* [6]. ISO distinguishes 4 main steps: (1) goal definition and scoping, (2) inventory analysis, (3) impact assessment, and (4) interpretation. This paper especially pays attention to the third step, the result of the impact assessment, and more specifically to the valuation of the results for biodiesel compared to fossil diesel fuel. The most important findings of the goal and scope definition are communicated very briefly in paragraph 2 of this paper. For a detailed interpretation of all methodological steps for the two fuels, reference is made to the final VITO-report [1].

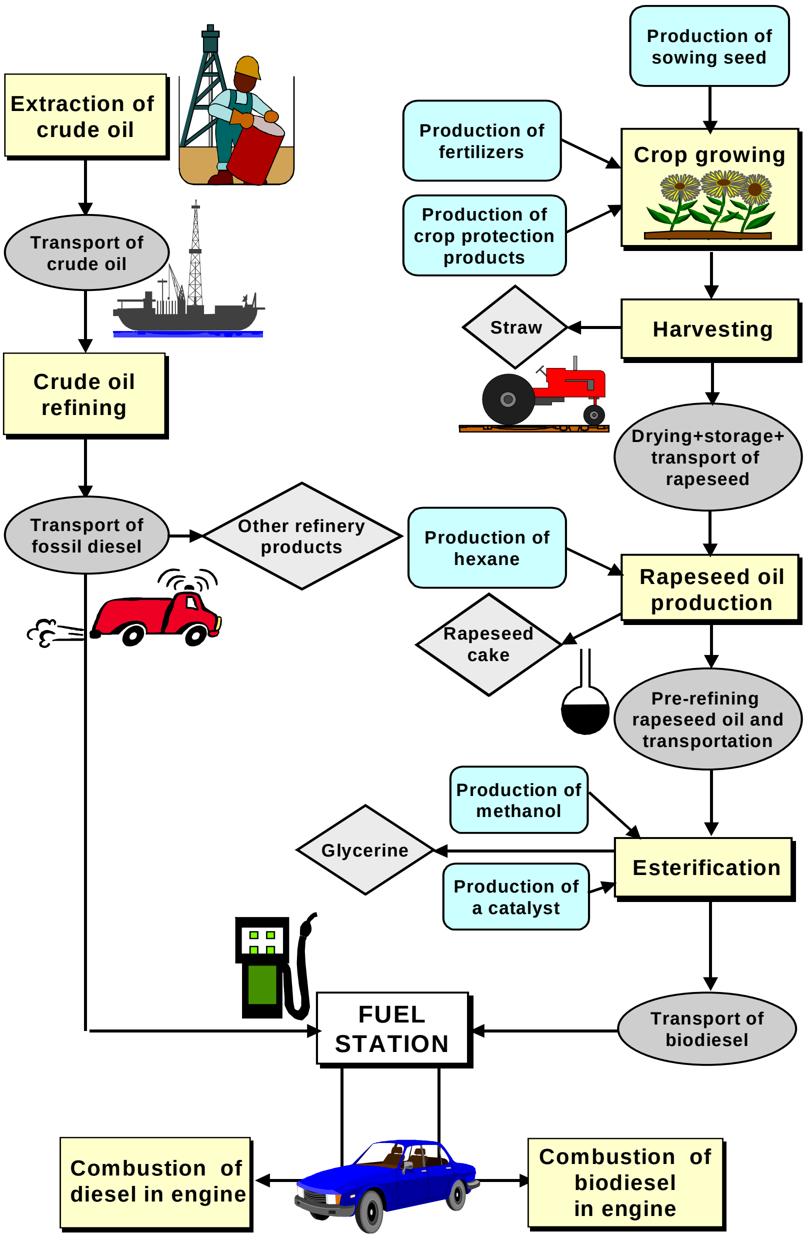


Figure 1. Life cycle tree for biodiesel and fossil diesel fuel

3.1. The environmental profile of biodiesel

Usually the inventory process generates a long list of data, which may be difficult to interpret, especially when comparing products. Therefore the impact assessment relates the large number of *inventory values* to a smaller number of *environmental themes* so that the outcome of the assessment is more surveyable. The result is a figure in which these environmental themes are presented, describing the *environmental profile* of the product for the selected functional unit. Figure 2 presents the environmental profile for biodiesel. In other words, it gives an overview of the relative contribution of the different life cycle stages of biodiesel to the different impact categories considered.

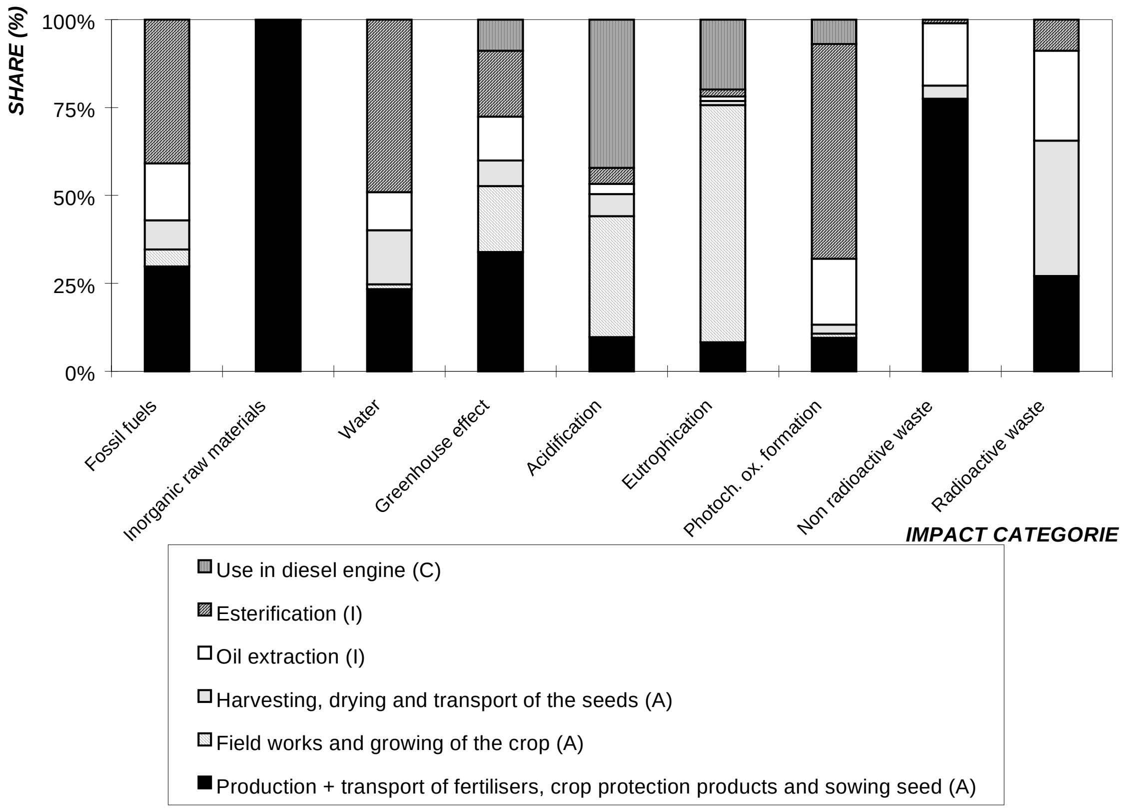


Figure 2. Environmental profile of biodiesel

Firstly it can clearly be seen in figure 2 that the agricultural processes of the biodiesel chain (indicated with the letter "A" in the figure) contribute significantly to all impact categories. More specifically, the production and the use of fertilisers has an important contribution to the consumption of fossil fuels, the use of inorganic raw materials, the greenhouse effect and the production of waste. Subsequently regarding the industrial part of the biodiesel chain (indicated with the letter "I" in the legend of figure 2) especially the esterification process proves to be a significant contributor to some of the impact categories considered. The combustion of the biodiesel in a car engine (indicated with a letter "C" in the legend of figure 2) is the primary contributor to the energy-related impact categories.

3.2. Biodiesel more environmentally friendly than fossil diesel fuel?

The main question to be answered by the LCA is whether biodiesel is environmentally friendlier than fossil diesel. So in figure 3 the environmental profiles of the two automotive fuels are compared for the different impact categories taken into account in the study. The fuel with the highest contribution to a particular environmental effect is indicated with a 100% bar. The contribution of the alternative fuel is expressed in percentage of the fuel with the highest contribution to a particular environmental effect.

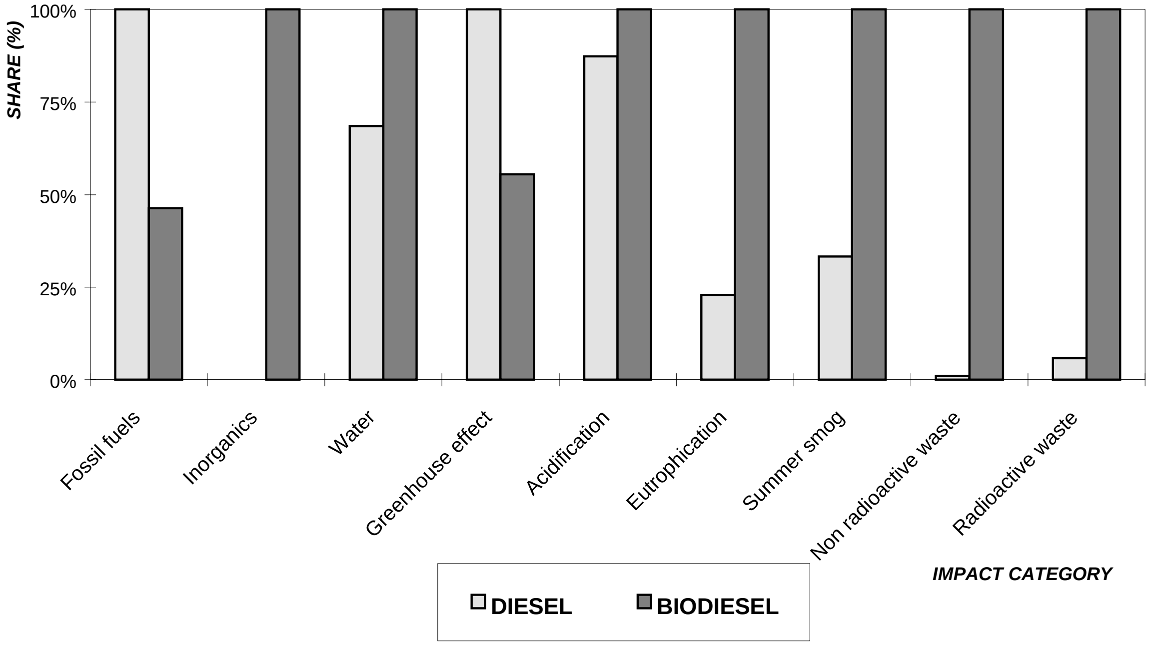


Figure 3. Comparison of the two environmental profiles

When comparing *the two ecobalances*, it is clear that the biodiesel life cycle only has a better effect score for the use of *fossil fuels* and for *global warming*. The better environmental score for the greenhouse effect is caused by the fact that rapeseed assimilates CO_2 during its growth. Indeed, the CO_2 balance has been closed in the life cycle inventory part of biodiesel; only the CO_2 emissions with a 'fossil' origin have been taken into account. Considering the use of fossil fuels, it goes without saying that the biodiesel scenario consumes less fossil fuel in comparison with the fossil diesel scenario during its life cycle.

3.3. Valuation of the results

Because the different impact categories do not have the same denominator, figure 3 does not allow adding up the absolute values of the different environmental themes. So in order to convert each ecoprofile into one environmental score and moreover to improve the interpretation of figure 3, the two environmental profiles are *normalised* (reduced to the same denominator) and weighted (added up). For this study the environmental profile of the two automotive fuels is *normalised to the total impact of all Belgium economic activities* in the year 1997. Specific data on the use of inorganic raw materials and the production of waste were not available at that moment. Therefore these environmental effects were not balanced during normalisation. Weighting is based upon a Dutch report on *Eco-indicators* [7]. In fact weighting factors represent the relative seriousness of the impact category considered. However they can differ largely from country to country, or even within one country due to difference in local conditions or political views. For the rest the Dutch report did not publish any factors for the use of fossil fuels and the consumption of water. So the final valuation only could be carried out for the greenhouse effect, acidification, eutrophication and summer smog.

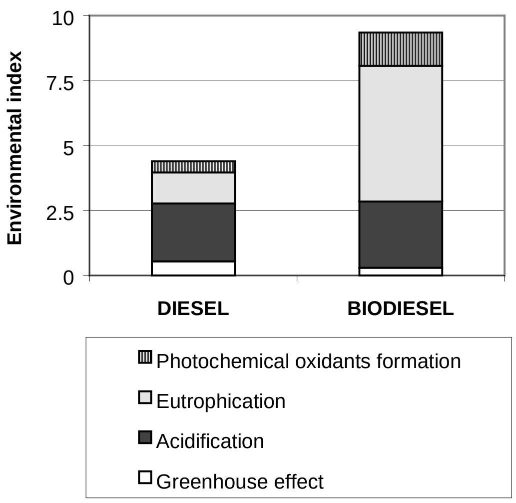


Figure 4. Result of LCA-valuation

In figure 4 the environmental score for biodiesel and fossil diesel fuel is expressed for 10^{10} times their functional unit (1 kg biodiesel vs. 0.9 kg fossil diesel fuel). As a result of the valuation, it can be clearly seen in figure 4 that *the environmental index of biodiesel is a factor 2 higher than the one for fossil diesel*. Thus, we could conclude that fossil diesel fuel is environmentally better than biodiesel taken into account all assumptions made during the LCA-assessment. However, not all impact categories were weighted during valuation and moreover weighting factors, to a large extent, have a rather subjective nature.

Even though figure 4 does not give straightforward conclusions, it clearly shows that substitution of fossil diesel fuel with an equivalent amount of biodiesel in Belgium will enlarge the eutrophication problem and that more photochemical oxidants will be formed in Belgium.

4. COMPARISON BASED ON EXTERNAL COST ANALYSIS (EXTERNE-97)

4.1. Application of the ExternE methodology in an LCA context

A more sophisticated method to weigh the different types of impact categories is to make a detailed assessment of the environmental damages caused by the emissions of the biodiesel and diesel fuel chain. To this purpose, VITO uses the *ExternE (Externalities of Energy)* accounting framework, developed under the Joule research project of the EC since 1992 [8,9,10]. These days it is widely recognised as the most complete and up to date methodology for the quantification of external costs (damages) from energy and transport, as it integrates a large amount of European and US scientific data and knowledge. It applies the *impact pathway approach* for a detailed and systematic assessment of the long way from an emission or burden to an impact and damage (figure 5). To this purpose, site and technology dependent emissions are quantified; dispersion of these emissions is modelled using local and regional dispersion models. By means of *dose-response functions*, the impacts on public health, agriculture, buildings and ecosystems are being quantified. For global warming, specific models are being used to quantify the physical impacts. In a last step, these impacts are valued based on market prices or results from *'willingness to pay'* studies. To date, an accounting framework is available for the quantification of site and technology specific damages from the most important energy related emissions, including particles, SO_2, NO_x, CO, VOC, benzene, and greenhouse gasses. We report interim results, based on the ExternE 1997 methodology. As our scientific understanding of the impacts changes, this methodology is being updated in ongoing projects.

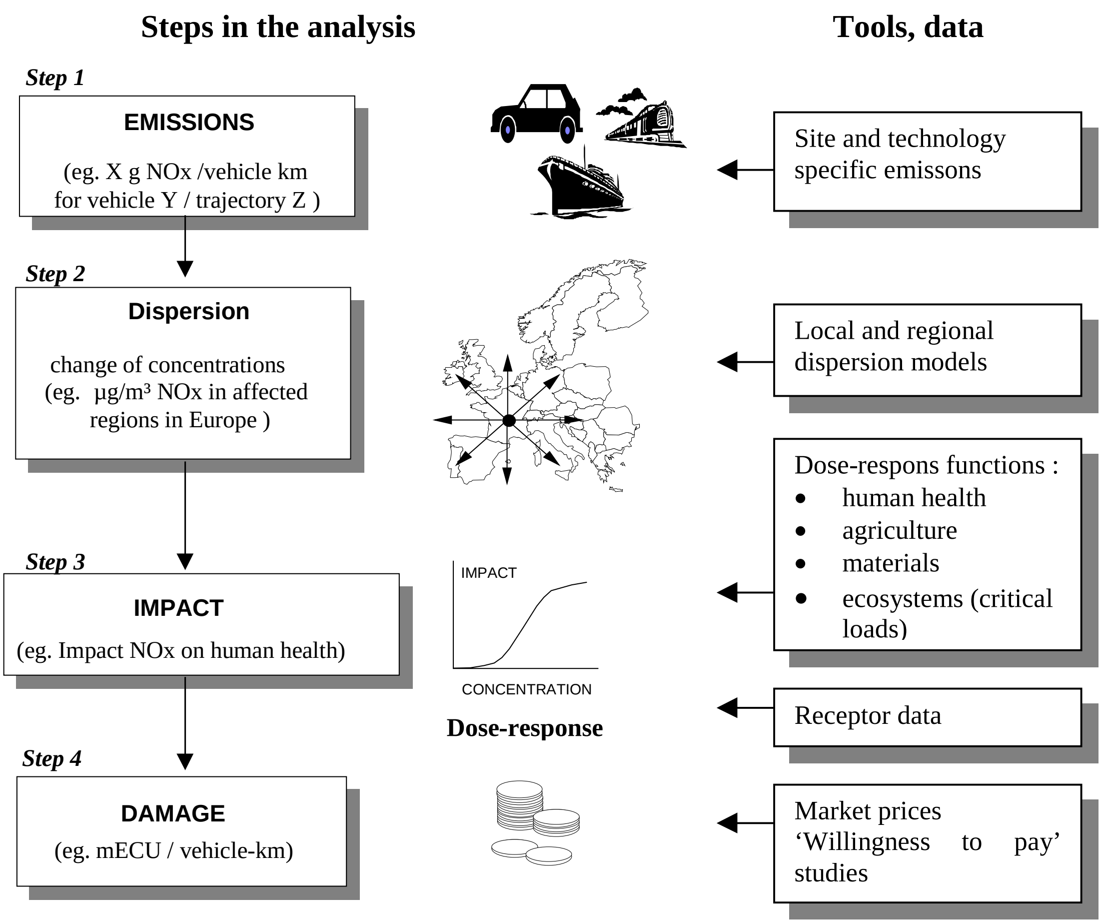


Figure 5. The ExternE methodology: impact pathway damage function approach

Table 1 lists the external costs per unit of pollutant. It shows that public health impacts are the dominant impact for the air borne pollutants. This impact depends on the population density of the receptor areas. As the external cost per pollutant are site and technology specific, it may be difficult to use them in LCA analysis as the total emissions of the fuel cycle are the sum of a large number of different emissions from a wide variety of sources and locations. For the comparison of diesel and biodiesel, the estimation of a representative external cost per kg emission is less problematic because a single, well located source dominates total emissions, in this case *the use of the diesel in an engine*. Therefore, we used averages representative for a Belgian situation. Further fine-tuning of the analysis is possible, taking into account e.g. the differences between emissions in and outside Europe. Such a sensitivity analysis has been performed for fossil diesel but results are not reported here. It shows that in general only 1 third of the upstream emissions is located in Belgium, and about half of the emissions are located outside Europe. As the Belgian location is rather an upper bound for the impacts, figure 6 indicates that such refinement will hardly change the overall results.

For *global warming*, site specificity is not an issue. To assess the impacts, specific models have been used which resulted in a best range estimate of 18 to 46 ECU/ton of CO_2-eq (CO_2-equivalent), with a more conservative range of 4 to 140 ECU/ton of CO_2-eq. For *ecological impacts*, the exceedance of critical loads is quantified but cannot be monetised. Therefore, the results per litre of (bio)diesel are subtotals, not totals.

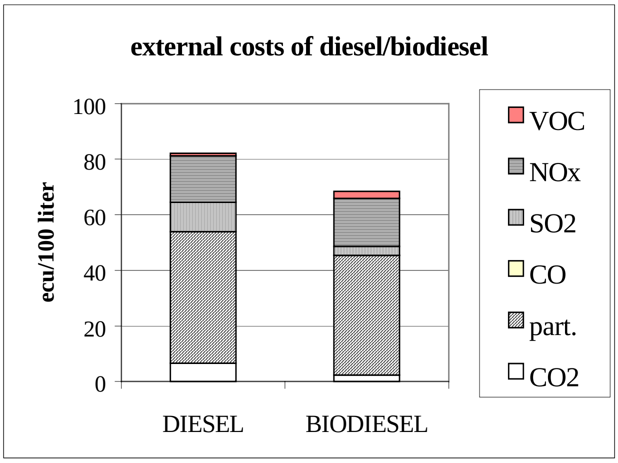
Table 1: Environmental damage costs per unit of pollutant. (ECU/kg pollutant)

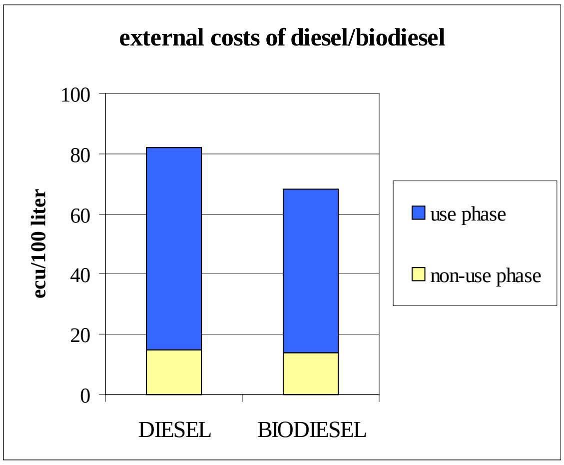
Pollutant	range for best estimates	Share of different impact categories		
		public health	agriculture	materials
GHG[1] emissions	0.018 - 0.046 . [2]	n.s.	n.s.	n.s.
CO	0.001 - 0.004	100 %	-	-
particles [3]	200 – 1500 [3]	100 %	-	n.a.y.
SO_2	12 – 18	92 %	0.5 %	7 %
NO_x	8 – 15	100 %	-	-
VOC	0.1	77 %	23 %	-

[1]GHG= greenhouse gas emissions
[2] ECU /kg CO_2–eq
[3] ECU/kg PM 2.5
n.s.: not specified; n.a.y. = not available yet.

4.2. Externalities are high for both diesel and biodiesel

For both fossil and biodiesel, *damages from particles on public health* are the most important external cost category (figure 6). This reflects the growing concern over recent years about the impact from particles, sulphates and nitrates on health, especially with respect to chronic mortality. Its valuation takes the number of year lost into account. The emissions of particles come for 90 % from the use phase and because the impacts depend very much on population densities near to the roads, table 1 shows a wide range for this pollutant. One has to take care for the comparisons of the fuels because potential differences in the nature and size of the particles from diesel and biodiesel are not fully reflected in these interim results and further research is needed. Impacts from SO_2 and NO_x are especially public health impacts from sulphates and are less location or technology specific. The evaluation of the contribution of VOC to photochemical oxidation (ozone) is based on a European single average value, which hides a large but unknown variation. The marginal contribution of NO_x emissions in Belgium to ozone formation is considered to be zero, based on results for Belgium from ozone models.
Comparing these results for Belgium with literature on air-borne emissions for the whole life cycle for biodiesel and diesel confirms our conclusions [2], [10].



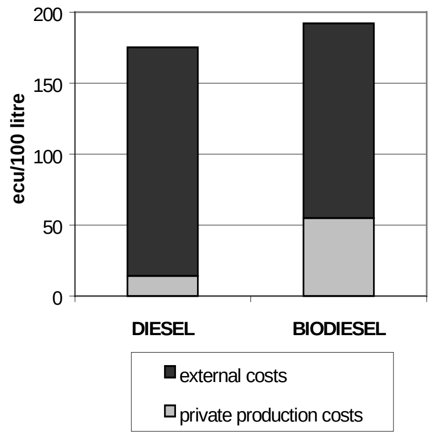


'litre' = 0.95 litre fossil diesel = 1 litre biodiesel (correction for differences in energy content and density)

Figure 6: External costs of diesel and biodiesel, following the ExternE 1997 methodology.

4.3. Conclusions

The main conclusion is that, compared to the private production costs, external costs are high for both diesel and biodiesel. In comparison to fossil diesel, total external costs of biodiesel are 5% tot 20 % lower, depending on different assumptions. One has however to take into account that a number of indicators for which biodiesel performs worse (impacts on water, eutrophication, acidification and photochemical oxidant formation) have not or only partly been quantified and monetised. Figure 7 shows that the total social costs (private production costs + external environmental damage cost) of biodiesel are higher than for fossil diesel. Indeed, the private costs for biodiesel are substantially higher than for diesel, which is not completely compensated by somewhat lower environmental costs.



1 litre biodiesel= 0.95 litre fossil diesel

Figure 7: The social costs.

5. COMPARISON OF THE METHODS AND THEIR RESULTS

The comparative analysis of the biodiesel case shows that starting from the same emission inventory, the LCA and external cost methodology lead to very different results. This is not surprising because they start from *a different paradigm* to assess and evaluate impacts [11]. LCA identifies *potential* impacts, weighted following a 'distance to target' approach, i.e. to which extent current levels of emissions exceed stated policy objectives. The ExternE method on the contrary aims to quantify *real* impacts, and uses individual preferences (expressed as willingness to pay) to weigh each endpoint of the impact categories.

The above analysis shows that it is useful to use both methods to profit from their relative strengths and compensate for the weaknesses in each method. The LCA Eco-indicator approach covers a wide range of ecological impacts and reveals their importance for the biodiesel chain. As the external costs analysis does not monetise ecological impacts, it cannot confirm nor contradict these findings. The external cost analysis points to the importance of emissions of *particles* in the use phase of both fuels, as well as to the public health impacts from NO_x (via nitrates). Although there are several attempts to integrate public health into LCA analysis, the methodology used by VITO in the 1995 report did not take public health into account, and no equivalence factors for particles were available. Second, external cost analysis indicates that *site and technology specificity* needs to be taken into account, as e.g. the damages from particle emissions in the use phase of diesel are much higher compared to emissions in other stages. The integration of site- and technology specificity does not necessarily require a detailed analysis of all emissions at all sites, as certain steps may dominate certain emissions, as was shown in the diesel-biodiesel comparison.

As a conclusion, both approaches confirm that although biodiesel offers advantages in terms of greenhouse gas emissions, it has similar or higher impacts on public health and the environment.

6. ACKNOWLEDGEMENTS

This paper is based on work co-financed by the Belgian Federal Office for Scientific, Technical and Cultural Affairs (OSTC) in the 'Sustainable Mobility' program (see (www.belspo.be/belspo/home/home_uk.htm) and by JOULE program of the European Commission. (see http://externe.jrc.es).

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