Institute for Resource Efficient
and Sustainable Systems
„Process Evaluation"

Life Cycle Assessment – study of Biodiesel from Tallow and Used Vegetable Oil

Anneliese Niederl
Michael Narodoslawsky

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Executive Summary

The study at hand provides a comprehensive life cycle assessment for biodiesel from tallow and used vegetable oil compared to fossil diesel.

As the ISO norms allows different interpretation of impacts a number of scenarios for the life cycle of tallow have been investigated within a sensitivity analysis in order to support the systematic discussion about the overall impact on the environment of Biodiesel production.

Two different impact assessment methods, namely the Sustainable Process Index (SPI), a member of the ecological footprint family, and the problem oriented approach (CML – Centrum Milieukunde Leiden) have been applied and show concordant results. The higher aggregated indicator SPI has been used to compare different scenarios and allocation models. The results from this assessment have been helpful in identifying optimisation potentials from the point of view of lower environmental impacts.

Regardless of the setting of system boundaries biodiesel from tallow and used vegetable oil performs better than fossil diesel and other sorts of biodiesel. The ecological footprint (SPI) of different sorts of biodiesel rises from -1,2 m²a/MJ combustion energy for biodiesel from used vegetable oil (the negative value signifies the large positive impact of the replacement of fossil glycerol by the by-product of this production) to a value between -1,2 and 2,8 m²a/MJ (depending on the scenario) for tallow methyl ester up to 10,3 m²a/MJ for RME (rapeseed methyl ester) compared to 26,1 m²a/MJ for fossil diesel.

Content

List of Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CML	Centrum Milieukunde Leiden
EP	Eutrophication Potential
GWP	Global Warming Potential
ISO	International Standardization Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NGO	Non Governmental Organizations
POCP	Photochemical Ozone Creation Potential
RME	Rapeseed Methyl Ester
SPI	Sustainable Process Index
TME	Tallow Methyl Ester

1 Goal and Scope definition of the Life Cycle Assessment (LCA) of Biodiesel from Used Vegetable Oil (UVO) and Tallow (TME – tallow methyl ester)

1.1 *Goal of the study*

In the last few years biodiesel has become a hot topic, which is impressively demonstrated by the large number of LCA's published to deal with this issue (Ceuterick & Spirinckx 2000; Groves 2002; Kaltschmitt, Reinhardt, & Stelzer 1997; Gärtner & Reinhardt 2003; Reinhardt 1997; Scharmer 2001; Sheehan et al. 1998; Jungmeier, Hausberger, & Canella 2003).

The goal of the study at hand is a comparative life cycle assessment of biodiesel made from used vegetable oil and tallow compared to fossil diesel.

Within the European technology implementation project a 45,000 tonnes per annum multi-feedstock biodiesel plant near Motherwell, Scotland using tallow and used cooking oil as raw materials has been built. The LCA study carried out according to the ISO-norms (EN ISO 140xx 1997; Guinée 2001) is accompanying this project and aims at supporting the stakeholder discussion and decision making during planning phase of new technology installation.

The results of this study must be seen as the base for an informed dialogue with important stakeholders. These stakeholders are on the one hand Non Governmental Organizations (NGO), which are active in the field of environmental protection and sustainable development and on the other hand companies in the field of treating by-products such as tallow and used vegetable oil and producing biodiesel.

Within the scope of a sensitivity analysis the influence of different parameters (e.g. setting of system boundaries, inclusion of substitution processes etc.) on the outcome of the LCA have been investigated. This information on the one hand points out the quality of the results – and accordingly their significance. On the other hand it helps identifying possible optimization results. In this case the LCA process serves as valuable engineer's tool.

1.2 *Scope of the study*

The scope definition includes a description of functions, functional units and reference flows, of the system boundaries, the data categories and the data quality requirements.

1.2.1 Function, Functional Unit and Reference Flow

The function of the product "biodiesel from used vegetable oil", "biodiesel from tallow" and "fossil diesel" is to serve as fuel for combustion in (unspecified) motor vehicles. The functional unit used to quantify this function is the combustion energy of biodiesel and fossil diesel, respectively. The reference flow is 1 MJ of combustion energy.

1.2.2 System boundaries

The scope of this LCA study considers the provision of the product biodiesel from tallow (TME – tallow methyl ester) and biodiesel from used vegetable oil (UVO) from raw material extraction to the usage of the finished product (fuel combustion). The production of energy, raw materials and auxiliary materials is included as is the waste disposal and the treatment of liquid and gaseous emissions during all steps of the life cycle. The production and operation of the infrastructure needed in the provision of the function is excluded from the LCA as it has turned out to be of minor influence (see figure 1-1).

Starting point for the development of the different inventory scenarios is the transesterification process. The scenarios only differ in the generation of the raw material, since the provision with process chemicals and process energy as well as the end use (fuel delivery and fuel combustion) is assumed to be identical.

- Scenario I: This scenario addresses the production of biodiesel from used vegetable oil (UVO). The first step in the life cycle of the production of biodiesel from UVO is the collection of waste cooking oil, causing transport. Then this collected raw material is processed in a transesterification step to yield biodiesel. A further transport unit (fuel delivery) is included before the biodiesel is burned in an engine. Scenario I also accounts for the life cycle of biodiesel from tallow, with the assumption that tallow that comes out of the rendering plant is a waste material. This means, that comparable to the life cycle of UVO a transport unit (here from the rendering plant to the biodiesel plant) stands at the beginning of the life cycle of biodiesel from tallow (TME I).

- Scenario II: In contrast to the previous setting, the system boundaries for biodiesel from tallow are set outside the gate of the slaughtering house. Rendering products leaving the slaughtering process are considered as waste-stream comparable to UVO in scenario I. These render products are further processed in the rendering plant to yield meat-and-bone-meal and tallow. Tallow is then transported to the biodiesel-plant and transesterified.

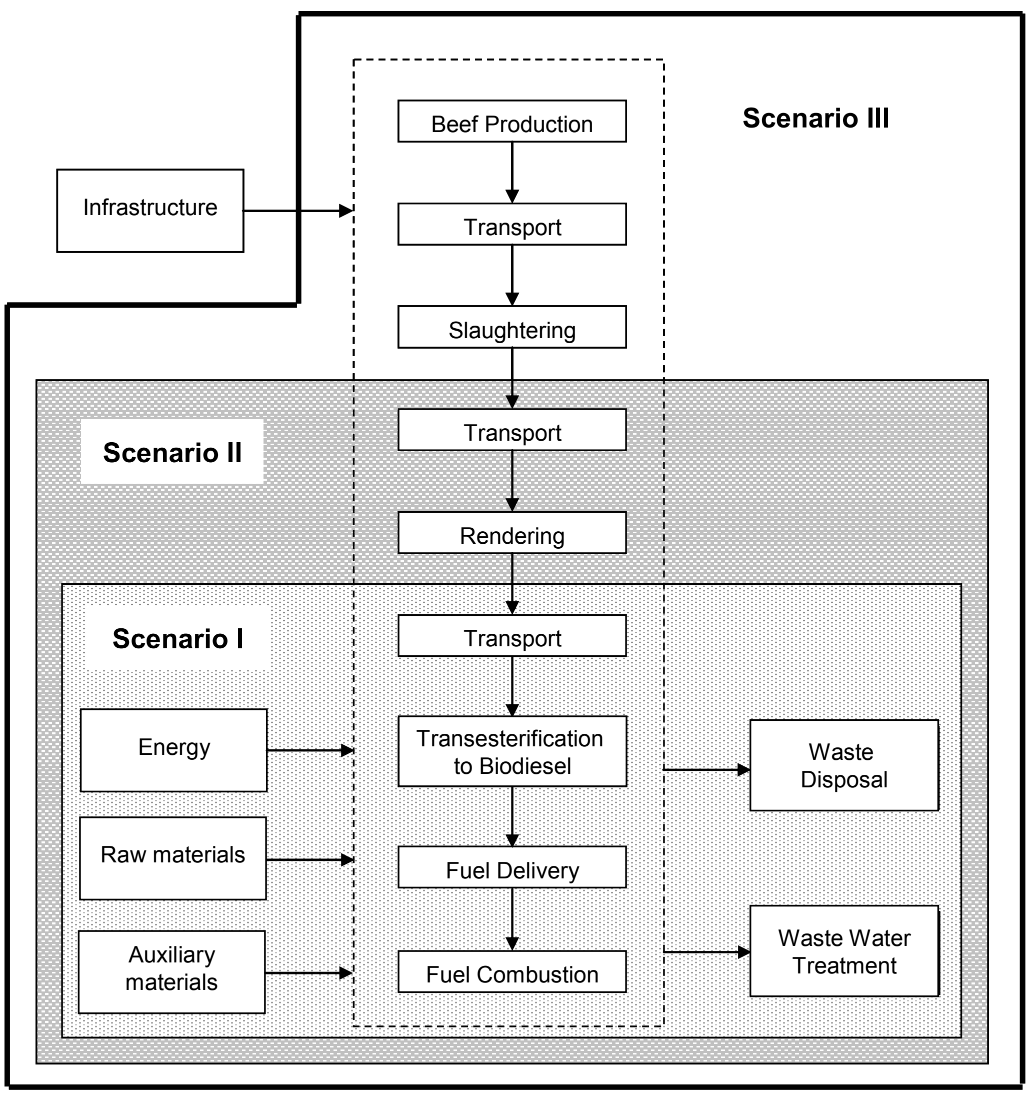


Figure 1-1: Different System boundaries in the Life Cycle of Biodiesel from Tallow and Used Vegetable Oil

- Scenario III: The slaughtering process is above all carried out to produce meat. Without the returns from meat sale the slaughtering process and the upstream processes related to meat production would not be profitable. Without meat sales there would be no upstream processes and no slaughtering. Still, in order to investigate the influence of the agrarian chain for biodiesel from tallow Scenario III includes the slaughtering process and the production of cattle, fodder and fertilizers together with all its connected processes in the agrarian sector.

1.2.3 Data categories

Data has been collected in economic and environmental flows. Economic flows are flows that connect processes. Examples of economic flows are energy, transport services, raw materials, process chemicals and waste that go to a treatment facility. In contrast to economic flows, environmental flows do not flow between two processes, but from the environment to a process (resources) or from a process to the environment (emissions) (Heijungs 2003)

1.2.4 Data quality requirements

The most of the data that have been considered are from well-established published data sources.

- Data on energy and transport systems have been taken from ESU-ETHZ (Suter & Frischknecht 1996). ESU-ETHZ represents the average Swiss and European state of the production at the beginning of the nineties. European data have been used to model energy provision and transport for biodiesel production. As Great Britain is not included in the European energy net (UCPTE), European averages do not necessarily give a correct picture of the British situation. However, it has been assumed that the average British production technologies correspond to the average European technologies. A specific UK energy mix has been calculated. Partly, the energy systems have been considered in a highly aggregated way.
- Data on process chemicals come from BUWAL (Bundesamt für Umwelt 1996) and from “Umweltbundesamt” (1999). KOH is modelled on the basis of own calculations. In general the data quality of process chemicals is lower than for energy systems. Process chemicals’ modelling is highly aggregated. The

published data represents recent technology that is (geographically) well standardised.

- Data on the transesterification process have been provided by BDI (Biodiesel technology supplier, Graz Austria).
- Data on combustion emission are taken from the combustion of Rapeseed Methyl Ester (RME) from the study of Reinhardt (Reinhardt 1997).
- Data on the treatment of glycerol and the production of synthetically glycerol are taken from (Borken, Patyk, & Reinhardt 1999). This source presents German data and these data are highly aggregated.
- Data on the production of synthetically K-fertiliser are taken from (Jungbluth 2000). This source presents mainly Swiss data for the mid-nineties.
- Data on the provision and combustion of fossil diesel have also been taken from ESU-ETHZ (Suter & Frischknecht 1996). These data are highly aggregated.
- Data on the agrarian value chains have been taken from (Jungbluth 2000). This source presents mainly Swiss data for the mid-nineties. According to differences in agricultural practices between Switzerland and the UK significant differences in the LCA results are not unlikely. An adaptation of the data was not within the scope of the investigation. The data source is reliable and the inappropriate geographical coverage of the data does not discredit the general conclusions of the sensitivity analysis within the LCA (system boundary expansion to scenario III). The agro-chain has been modelled without further aggregation.
- Data on the rendering process have been provided by Argent Energy, Scotland.

2 Inventory Analysis of the LCA

2.1 *Unit processes*

Appendix 1 (page 21) shows the unit processes included in the biodiesel from used vegetable oil and tallow model. For the processes enumerated inputs and outputs of economic and environmental flows have been balanced. Processes have been given the name of its primary products. Multi output processes have more than one economic output. Outputs of one process are at the same time inputs to one or a number of other processes. This is how the value chains are formed. Environmental flows are then attributed to each of the production processes. Appendix 2 (page 21) shows the environmental flows considered.

2.2 *Data collection*

For information about the collected data see Chapter 1.2.4. Table 2-1 shows the average transport distances for the investigated life cycle model. For transport it was assumed that HGVs (16 t) have an efficiency of 40%.

Table 2-1 : Average transport distances

Transport type	distance
Fuel delivery of biodiesel from tallow and used vegetable oil	50 km
Collection of waste cooking oil	100 km
Transport of tallow from rendering plant to biodiesel plant	100 km
Render products to rendering plant	112 km
Life stock to slaughterhouse	120 km

2.3 *Calculation procedures*

For the calculation of the Sustainable Process Index (SPI) an in-house developed programme (SPIonXls) has been used (Krotscheck, Narodoslawsky, & Schichl 1995).

2.4 *Allocation*

Inputs, outputs and the related environmental impacts can be allocated to products according to physical properties of the product flows (mass or energy flows). If this is not possible or not justifiable the usual way is to allocate according to the economic value of the products (prices). In our study both, mass and price allocation have been applied.

Table 2-2 : Multi output processes in the production of biodiesel

Process	Outputs
Slaughtering process	Meat after slaughtering Render products Hides Offal Rest
Rendering process	Fat after rendering Meat and bone meal
Transesterification	Biodiesel from transesterification Glycerol K2SO4
KOH-production	KOH Chlorine gas Hydrogen

Table 2-2 shows the multi output processes of the biodiesel from tallow model. Four processes have more than one economic output. For the life cycle of biodiesel from used vegetable oil only the two letter processes (transesterification and KOH-production) are relevant.

- Slaughtering process

The slaughtering process produces meat (36,2 %), render products (22,5 %), hides (8,3 %), offal (3,2 %) and rest (29,8 %). Mass allocation ("render products are hold responsible for the environmental impact of the value chain to the same extent as meat") might seem unjust vis-à-vis the co-products of the slaughtering process. Therefore price-allocation has been applied. The following prices have been assumed for the products: meat: 3,6 €/kg, hides: 1,2 €/kg, offal: 1,3 €/kg, render products: 0,08 €/kg.

The share of the agrarian upstream processes allocated to biodiesel production is reduced considerably to 1,2 % when price allocation is applied compared to 32 % with mass allocation. The lion's share of the upstream environmental burden is allocated to the main product meat (see table 2-3).

Table 2-3: Comparison between different Allocation Models for the Slaughtering Process

	Mass Allocation	**Price**	**Price Allocation**
	[%]	[€/kg]	[%]
Meat	51.5	3.6	89.0
Hides	12.0	1.2	6.9
Render Products	**32.0**	0.08	**1.2**
Offals	4.5	1.3	2.8

- Rendering process

The rendering process produces fat (24 %), meat and bone meal (21 %) and water (55 %) from 100 % render products at the input side. Upstream processes have to be allocated to the 2 products. At present in Europe, meat and bone meal (MBM) is not used to produce goods of economic value. With this in mind, one could argue that all upstream environmental impact should be allocated to the only output of market value, the fat. But the rendering process is not only carried out to gain fat. MBM is a desired

– if not economically then at least from the point of view of human health –co-product. This makes an allocation justifiable. As a market price is not available, mass allocation has been carried out.

- KOH-production

Potassium hydroxide is a by-product of chlorine production in the chlor-alkali process. Its low relative market value (Chlorine 37,5 €/kg; H_2 123,8 €/kg; KOH 0,65 €/kg) makes economic allocation seem sensible. The process would run without the KOH by-product but nor for KOH production exclusively.

- Transesterification

Glycerol is a marketable co-product of the biodiesel transesterification process. Therefore, mass allocation can be justified. Due to similar prices for biodiesel and glycerol, economic allocation would only yield a slightly changed picture.

2.5 *Substitution processes*

Allocation can be avoided by system boundary expansion, where co-products are balanced through substitution processes (Weidema 2001). This means that the main-product biodiesel gets credit for the co-products glycerol and K_2SO_4, because these by-products can substitute equivalent products and therefore energy consumption and emissions, respectively. (see Figure 2-1).

The equivalent product to biodiesel-glycerol is synthetic glycerol that is petrochemically produced. Although the main market share of glycerol comes from natural sources, natural glycerol is an unsuitable equivalent to glycerol from the transesterification process, because it is - in the same extent as biodiesel-glycerol – a by-product of for example the production of organic tensides.

K_2SO_4 from the transesterification process is used as fertilizer. Therefore, the production of K-fertilizer was chosen as substitution process.

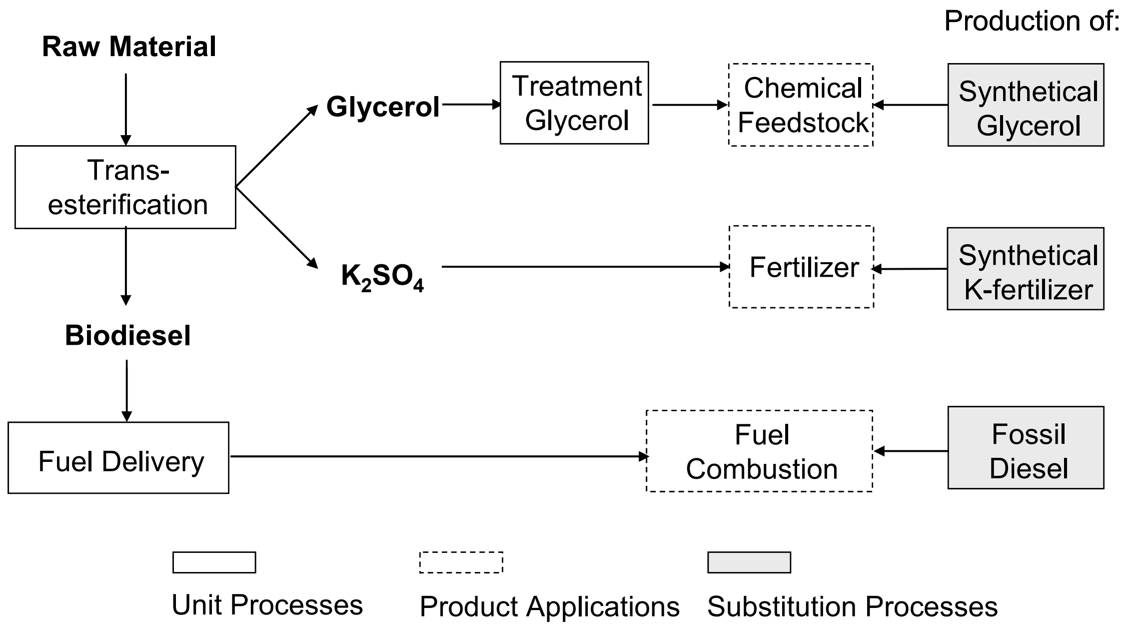


Figure 2-1: Substitution processes.

3 Life Cycle Impact Assessment (LCIA)

For the impact assessment of the study at hand the method of the Sustainable Process Index (SPI) has been applied.

The Sustainable Process Index (SPI) developed by (Narodoslawsky & Krotscheck 1995) is based on the assumption that a sustainable economy builds only on solar exergy. Surface area is needed for the conversion of exergy into products and services. Surface area is a limited resource in sustainable economy because the Earth has a finite surface. Area is the underlying dimension of the SPI, the more area a process needs to fulfil a service the more it 'costs' from sustainable point of view.

The SPI is the fraction of the area per inhabitant related to the delivery of a certain product or service unit. The SPI is calculated with equation 1 from partial areas.

$$SPI = \frac{a_{tot}}{a_{in}} \qquad \text{[cap/unit]} \qquad (1)$$

a_{in} is the area per inhabitant in the region being relevant to the process. a_{tot} is the specific (sustainable) service area and is calculated with equation 2.

$$a_{tot} = \frac{A_{tot}}{S_{tot}} \qquad [m^2 \cdot a/unit] \qquad (2)$$

S_{tot} is the number of unit-services (e.g. product units) supplied by the process in question for a reference period of normally one year. And the total area A_{tot} is calculated with equation 3.

$$A_{tot} = A_R + A_E + A_I + A_S + A_P \qquad [m^2] \qquad (3)$$

The areas on the right hand side are called “partial areas” and refer to impacts of different productive aspects. A_R, the area required for the production of raw materials, is the sum of the renewable raw material area (A_{RR}) and the non-renewable raw material area (A_{RN}). A_E is the area necessary to provide process energy. A_I, the area to provide the installation for the process, is the sum of the direct use of land area (A_{ID}) and the indirect use of land area (A_{II}). A_S is the area required for the staff and A_P is the area for sustainable dissipation of products and by-products. The reference period for these partial areas is normally one year. There is an in-house developed spreadsheet programme for the calculation of the SPI called SPIonXls.

The results of the partial areas show which type of expenditure influences the results to the largest extent, which can help in process optimisation (Narodoslawsky & Krotscheck 1995;Krotscheck & Narodoslawsky 1996;Krotscheck 1997).

Within the framework of the EU-project BIODIEPRO (Project number: NNE5/2001/832) a comparison of impact assessment methods between the Sustainable Process Index (SPI) and the problem oriented approach (CML- Centrum Milieukunde Leiden (Heijungs 2003)) has been carried out. CML is the most commonly used impact assessment method in LCA providing information about different impact categories.

The aggregated indicator SPI has been chosen for this life cycle study as these two assessment methods show concordant results (for details see chapter 4 and (Niederl & Narodoslawsky 2004)) and the common currency area allows better comparison between different scenarios, allocation methods and the system boundary expansion including substitution processes.

4 Results of the LCA

4.1 *Comparison of different scenarios and allocation models of biodiesel from tallow and used vegetable oil*

Starting point for the Life Cycle Impact Assessment (LCIA) is the transesterification process. Its inputs are classified as energy, process chemicals and raw material (fat after rendering or collected waste cooking oil). Together with the environmental impacts of these inputs, the impacts of the combustion of biodiesel and the transport (collection of raw material and fuel delivery) are assessed. The sub-chains of process chemicals, energy and raw materials are further broken down in order to give deeper insight into the generation of the impacts. The tree structure of the assessment is given in Figure 4-1.

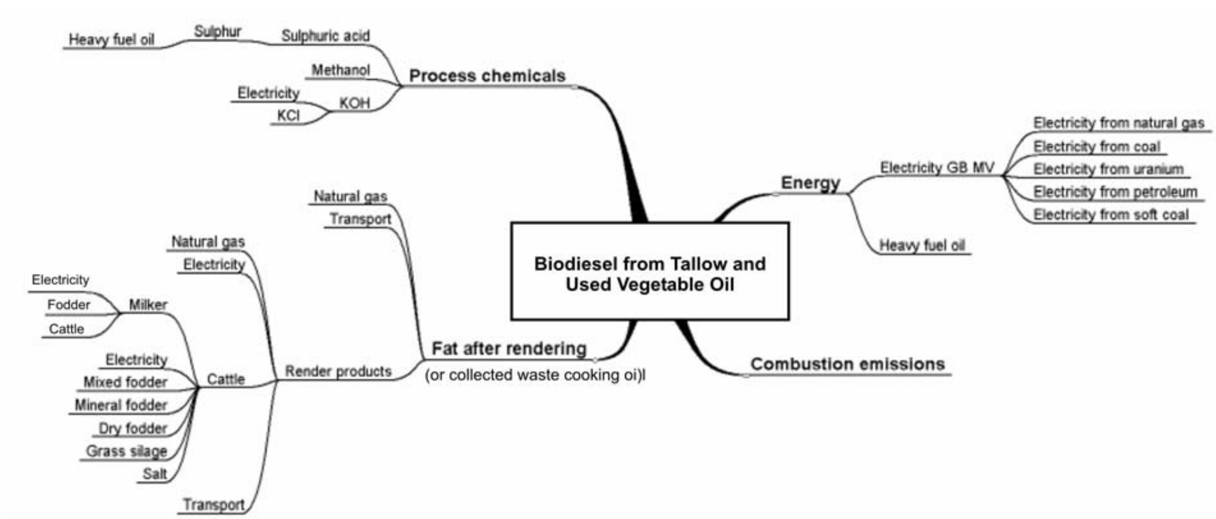


Figure 4-1: Tree structure of the Life Cycle Impact Assessment

Consistent with the goal and scope definition four different life cycles have been compared: fossil diesel, biodiesel from used vegetable oil, biodiesel from tallow scenario II + III. As the overall absolute impacts as well as the relative contributions of the LC phases of biodiesel from tallow are highly sensitive to the allocation in the slaughtering process, mass allocation has been compared to allocation according to market prices within a sensitivity analysis.

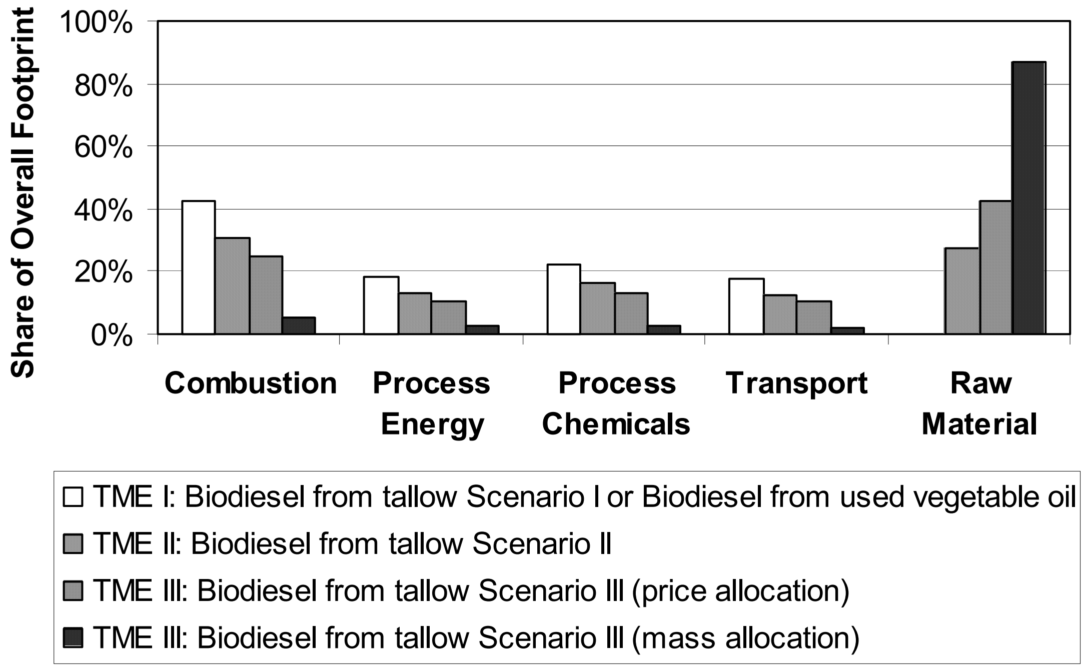


Figure 4-2: Relative contribution of life cycle phases: Comparison of different scenarios and allocation models

The distribution of the overall ecological footprint on the five subgroups of biodiesel production and usage depends very much on the setting of system boundaries and the underlying allocation model. Figure 4-2 shows the distribution on the usage (combustion), transport, the energy and chemicals necessary for the production of biodiesel and the upstream agrarian chain comprising the breeding of cattle as well as the rendering and slaughtering processes. When allocating the render products that come out of the slaughter house in scenario III by mass compared to meat, hides or other by-products, the agrarian chain has the most important environmental impact for TME.

Price allocation leads to a reduction in the overall footprint per MJ energy resulting from combustion of TME of 37.79 m^2a/MJ TME I to 8.28 m^2a/MJ TME I. The absolute footprints (see table 4-1) of the inputs for the transesterification-process energy (0.86 m^2a/MJ biodiesel) and process chemicals (1,06 m^2a/MJ biodiesel) as well as for combustion (2,03 m^2a/MJ biodiesel) and transport (0,84 m^2a/MJ biodiesel) are constant and the same for biodiesel from tallow and used vegetable oil. But the footprint of the raw material tallow changes from 32,61 m^2a/MJ TME to 3,5 m^2a/MJ TME with the allocation model.

Combustion-emissions in the course of biodiesel-usage have a footprint of 2,03 m^2a/MJ biodiesel due to NOx - emission. Apart from the raw material production this footprint yields the highest contribution to the overall footprint (43 % for Biodiesel from UVO and up to 31 % for biodiesel from tallow - scenario III).

In the transesterification process methanol as transesterification agent and potassium hydroxide and sulphuric acid as catalysts are used as process chemicals with a share of 22% of the overall footprint for biodiesel from UVO. Especially methanol has a significant part in the overall footprint (21 %). It is important to point out that almost the whole footprint of methanol has to be attributed to the utilization of fossil carbon. With the input of methanol in the biodiesel production the carbon of biodiesel comes not only from renewable carbon-sources but also contains carbon of fossil origin.

As far as potassium hydroxide and sulphuric acid within the scope of environmental impact of biodiesel usage and production are concerned, they only play a minor role due to their application as catalysts (insignificant consumption).

For the production of biodiesel in the transesterification-process the use of light fuel oil as energy-source leads to a high environmental impact accounting for 13 % of the overall footprint. As a second energy source electricity is used and accounts for 5 % of the overall footprint.

Fuels for the production of electricity represent a share of the electricity's footprint of 19,14 % from natural gas, 38,37 % from mineral coal, 40,91 % from nuclear power, 0,99 % from oil and 0,58 % from brown coal (according to the UK energy mix: 37,3% natural gas, 33,9% mineral coal, 23,2% nuclear power, 3,9% hydro power, 1,6% oil, 0,2% brown coal). 90 % of the single substance footprints for fossil fuels are due to fossil carbon. The rest is caused by NOx-emissions and in case of oil by SOx-emissions. Almost 100 % of the electricity's footprint coming from nuclear power plants arise from radioactive substances.

The total energy-consumption during the transesterification process has a footprint of 0,86 m^2a/MJ biodiesel, thus meaning 18 % of the overall footprint of Scenario I.

Table 4-1: Results from Life Cycle Impact Assessment with the SPI

		allocation		System boundary expansion	
		footprint [m²a/MJ]	share of overall footprint [%]	footprint [m²a/MJ]	share of overall footprint [%]
Combustion emissions		**2,03**	**42,47**	**2,03**	**39,42**
	NOx (g)	1,81	37,87	1,81	35,15
	Benzol (l)	0,22	4,60	0,22	4,27
Fuel Delivery (50 km)		**0,30**	**6,28**	**0,30**	**5,83**
Transport to Transesterification (100 km)		**0,54**	**11,30**	**0,62**	**12,04**
Energy		**0,86**	**17,99**	**0,99**	**19,22**
	Electricity	0,24	5,02	0,28	5,44
	Light fuel oil	0,62	12,97	0,72	13,98
Process Chemicals		**1,06**	**22,18**	**1,21**	**23,50**
	MeOH	1,02	21,34	1,17	22,72
	KOH	0,01	0,21	0,01	0,19
	NaOH	0,02	0,42	0,03	0,58
	H_2SO_4	0,01	0,21	0,01	0,19
Biodiesel from UVO (Scenario I)		**4,78**	**100**	**5,15**	**100**
Rendering		**1,82**	**27,58**	**2,09**	**28,87**
	Natural Gas	0,34	5,15	0,39	5,39
	Transport	1,48	22,42	1,70	23,48
Biodiesel from Tallow (Scenario II)		**6,60**	**100**	**7,24**	**100**
Agrarian Chain		**1,68**	**20,29**	**1,94**	**21,13**
Biodiesel from Tallow (Scenario III; price allocation)		**8,28**	**100**	**9,18**	**100**
Agrarian Chain		**30,79**	**82,35**	**1,94**	**21,13**
Biodiesel from Tallow (Scenario III; mass allocation)		**37,39**	**100**	**9,18**	**100**
Glycerol preparation				0,06	m²a/MJ
Synthetic glycerol production				-6,36	m²a/MJ
K-fertilizer production				-0,09	m²a/MJ
Biodiesel from UVO with substitution processes				**-1,24**	**m²a/MJ**

Biodiesel from Tallow (Scenario II) with substitution processes	**0,85 m²a/MJ**
Biodiesel from Tallow (Scenario I; price allocation) with substitution processes	**2,79 m²a/MJ**

As far as transportation is concerned (assumptions see table 2-1) the transport of the raw material (tallow from rendering plants or collection of UVO) result in an 11 % and the fuel delivery to a 6 % contribution to the overall footprint. Transport of render products and livestock, respectively, is included in the agrarian chain. Within the system boundaries of this life cycle, that is to say infrastructure is excluded, the environmental impact of diesel-usage accounts for the total footprint of transport.

Fat, the raw material for the transesterification process, causes a footprint of 1,82 m^2a/MJ TME II or 3,5 m^2a/MJ TME III that account for 28 % or 42 % of the overall footprint depending on the scenario.

The rendering-process has a footprint of 1,82 m^2a/MJ TME II. The main environmental impact comes from the transport of render products from the slaughter house to the rendering plant. The rest of the footprint in the rendering-process is caused by the energy-supply with gas. In Scenario II (Render products that come out of the slaughterhouse are regarded as waste) the provision of the raw material accounts for 28% of the overall footprint.

Looking at scenario III the agrarian chain consists of the slaughtering process and cattle-breeding. Here the cattle-breeding plays an outstanding role in the production of biodiesel from tallow, where the main part of the cattle-breeding footprint can be attributed to fodder-production and emission of ammonia. As already mentioned for this stage the largest discrepancy between the two different allocation models can be seen: 82% (30,8 m^2a/MJ TME) for mass-allocation in contrast to 20% (1,68 m^2a/MJ TME) for price-allocation.

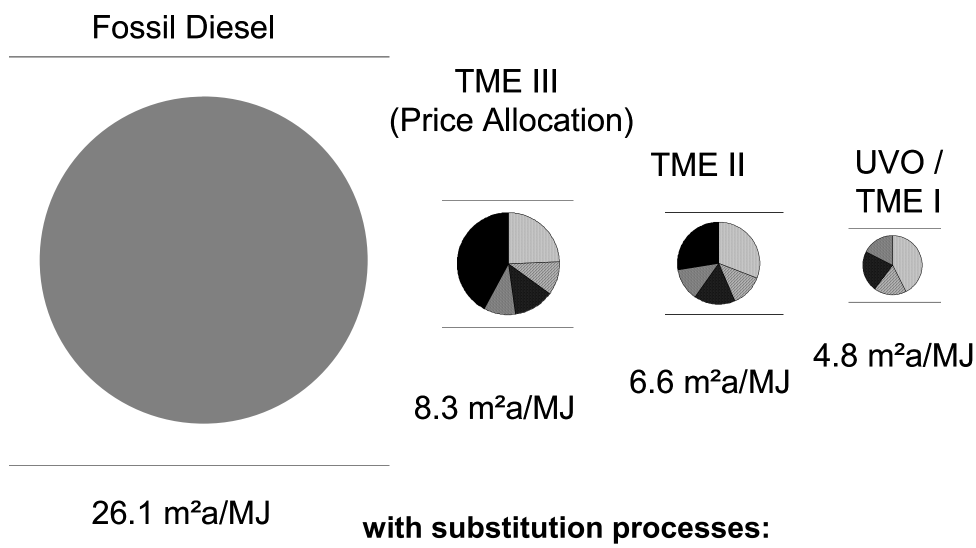
In the case of system boundary expansion no allocation step in the transesterification process is applied. In order to be able to compare glycerol from the biodiesel process with synthetic glycerol it needs to be purified in a distillation step. This preparation accounts for 0,06 m²a/MJ and is added to the footprint of biodiesel. Whereas the footprint of the substitution processes is subtracted from the overall footprint. The equivalent process of synthetic glycerol production plays an outstanding role in the life cycle of biodiesel with a footprint of 6,36 m²a/MJ. Together with the substitution process potassium-fertilizer production (0,09 m²a/MJ) the overall footprint for biodiesel from used vegetable oil has a negative value of -1,24 m²a/MJ combustion energy. In the same extent the footprint for biodiesel from tallow is lowered to 0,85 for scenario II and to 2,79 m²a/MJ for scenario III.

4.2 *Comparison of biodiesel and fossil diesel*

The footprint of fossil diesel was calculated to be 26,1 m²a/MJ combustion energy. 49% of the footprint are due to the usage of fossil carbon, 41% due to NO_x-emission and 2% to SO_x-emission during combustion.

Concluding it is to say that all considered sorts of biodiesel are more environmentally friendly than fossil diesel (see figure 4-3). Biodiesel from UVO shows the lowest value (4,78 and -1,24 m²a/MJ depending on the handling of by-products during the transesterification step). The same values would hold true for TME if the raw material tallow would be regarded as waste. Taking also into consideration the rendering step (scenario II) the footprint of biodiesel from tallow shows an increase of approximately 30% to 6,60 and 0,85 m²a/MJ, respectively.

Although the cattle breeding, slaughtering and rendering will not be influenced by the production of biodiesel, scenario III was investigated in order to have an insight in what part the agrarian chain plays for the overall life cycle of biodiesel from tallow. It turned out that compared to the raw material used cooking oil biodiesel from tallow shows an increase of 70% due to the agrarian chain.



with substitution processes:

26.1 m²a/MJ 2.8 m²a/MJ 0.9 m²a/MJ -1.2 m²a/MJ

Figure 4-3: The Sustainable Process Index of different scenarios for Biodiesel compared to fossil Diesel

4.3 *Comparison between different impact Assessment methods*

The comparison of the two different impact assessment methods was made on the basis of Scenario I, the production of biodiesel from waste cooking oil without the consideration of substitution processes. Since SPI and CML results cannot be directly compared the main focus of investigation is to discuss if both methods point to the same environmental problems arising over the life cycle and identifying the process steps contributing most prominently to the ecological impact.

Table 4-2. Comparison between different impact assessment methods of biodiesel from used vegetable oil

	Combustion	**Process Energy**	**Process Chemicals**	**Transport**	**Total**	**Fossil Diesel**
	[%]	[%]	[%]	[%]	absolute values	
SPI	42.5	18.0	22.0	17.8	4.78	26.1
GWP	29.1	20.7	40.5	9.7	1.8E-2	9.0E-2
AP	85.8	4.2	7.8	2.21	2.1E-4	2.3E-4
EP	94.8	2.4	1.4	1.4	3.3E-5	2.2E-5
ADP	0.7	67.1	2.0	30.2	3.7E-5	5.4E-4
POCP	88.5	2.5	5.8	3.2	1.2E-5	1.9E-5
SPI (Sustainable Process Index) in m^2a						

GWP (Global Warming Potential) in kg CO_2 eq yr^{-1} MJ^{-1}
AP (Acidification Potential) in kg SO_2 eq yr^{-1} MJ^{-1}
EP (Eutriphication Potential) in kg PO_4 eq yr^{-1} MJ^{-1}
ADP (Abiotic Depletion Potential) in kg antimony eq yr^{-1} MJ^{-1}
POCP (Photooxidant Creation Potential) in kg ethylene eq yr^{-1} MJ^{-1}

Starting point for the analysis of the different stages of the biodiesel life cycle is again the transesterification process with its inputs process energy and process chemicals. The other two stages of the life cycle are classified as transport, considering both collection of the raw material and fuel delivery, and the combustion of biodiesel (see table 4-2).

The main impact to climate change is due to process chemicals. Methanol from fossil resources used at this stage accounts for 40 % of the overall global warming potential caused by biodiesel, whereas the impact of other chemicals, like KOH or H_2SO_4, can be neglected. The same holds true for the outcomes of the SPI. 22% of the total ecological footprint can be contributed to chemicals used during transesterification. The main share that makes up for 21% of the overall footprint is due to the depletion of fossil resources for methanol usage.

The largest factor of the overall footprint (42.5%) comes from the combustion of biodiesel itself causing high emissions of nitrogen oxides. This is reflected in the problem oriented approach with the high contribution of combustion emissions to the acidification, eutrophication and photooxidant creation potential of 85.5 %, 94.8 % and 88.5 %, respectively.

Both, for the provision of process energy and for transport the depletion of abiotic resources is the predominant impact category. Of course the still prevalent use of fossil resources like diesel, charcoal, heavy and light fuel oil in energy provision systems is to be blamed, thus also contributing significantly to greenhouse gas emissions. It is noteworthy, that the SPI also takes into account radioactive substances emitted in the production of nuclear power. For example according to the UK energy mix (37.3 % natural gas, 33.9 % mineral coal, 23.2 % nuclear power, 3.9 % hydro power, 1.6 % oil and 0.2 % brown coal) nuclear power would cause 41 % of the electricity's footprint.

As far as the absolute values of biodiesel compared to fossil diesel are concerned, both assessment methods show similar trends. Under the terms of the problem oriented approach biodiesel performs better in all impact categories except for the eutrophication potential (see table 4-2). The ecological footprint of fossil diesel is approximately the six fold of the biodiesel's footprint.

4.4 *Optimisation Potentials*

Having a closer look on where the environmental pressure of the transesterification process comes from, a detailed impact assessment with the SPI provides a powerful tool for the process engineer. Especially in an early stage of process development he has the possibility to consider and choose the more sustainable process options.

Originally in the project that was accompanied by the LCA of the presented case study heavy fuel oil was planned to be the main energy source for the transesterification process. A screening life cycle pointed out that the environmental impact of the process energy can be reduced by 30% with the usage of light fuel oil instead. In the context of the overall life cycle of biodiesel from UVO this means a reduction of the environmental burden of 5% or 0,25 m^2a/MJ combustion energy.

As already mentioned in the case study fossil based methanol used as transesterifying agent contributes to a high amount (>20%) to the overall footprint of biodiesel. Future sources for this bulk chemical should be sought from renewable resources rather than from fossil origin.

A further optimisation potential was identified as on-site incineration of the distillation residue that is a by-products of the biodiesel process. With this measure 50% of the light fuel oil can be saved. In total this means 30% less process energy and a reduction of the overall footprint of biodiesel (from UVO) of 5,3% to 4,53 m^2a/MJ combustion energy

Looking across the border of the process plant further chances for environmental improvement can be seen in scenario building on the one hand and the choice of raw material on the other hand.

During the LCA it turned out that transport plays an important role (see table 4-1). For different scenarios (Where is the plant located?, How many plants will be built?, Where do I get the raw materials from?, Where will the fuel be sold?) you can easily calculate the SPI and directly compare and choose your options.

When planning to produce biodiesel one has a great variety of possible raw materials. According to the case study used vegetable oil and tallow from the rendering plant are in the same order of magnitude, the latter having slight disadvantages due to the agrarian chain. Based on the life cycle inventory of (Reinhardt 1997; Gärtner & Reinhardt 2003), which is based on the same assumptions as our case study, the footprint for biodiesel from rapeseed methyl ester (RME) was calculated to be 10,3 m²a/MJ (also including substitution processes like synthetic glycerol production). This gives a clear indication that also from an environmental point of view it is much better to use waste or by-products as raw materials for fuel production.

As far as the reduction of NO_x emissions during combustion are concerned this task can not be fulfilled by biodiesel producers but provides a challenge for engine-/ car-manufacturers.

5 Conclusion

The outcomes of a LCA are very much dependent on the setting of system boundaries especially when considering side products from agriculture, as it was clearly shown in this example of biodiesel from tallow and used vegetable oil.

For the environmental assessment of biodiesel from tallow it is crucial to decide whether tallow is a by-product of meat production or whether such very low-value products like render products should be considered as waste.

It can be argued that the agricultural upstream process – with their costs and environmental impact – would not be undertaken alone for the production of by-products such as tallow. Mass allocation of the agricultural upstream processes yields an environmental impact that might be prohibitive to the production of biodiesel from tallow from an ecological point of view.

Price allocation changes the environmental impacts of biodiesel from tallow considerably. In this case, prices reflect the interest of society to have meat and tallow produced and hence the driving force for this production.

A further large influence on the results of LCA can be found in the introduction of substitution process when expanding the system boundaries. In the case of biodiesel from used vegetable oil the ecological footprint is even shifted to a negative value from 4.8 m²a to -1.2 m²a per MJ combustion energy.

Regardless the setting of system boundaries, assuming that tallow shouldn't be made responsible for the environmental impact of the agrarian chain to the same extent as meat, biodiesel from tallow and used vegetable oil have a lower ecological footprint than fossil diesel.

Biodiesel from tallow and waste cooking oil perform also better compared to other sorts of biodiesel that are not based on by-products or waste, but for example on rape seed oil. The ecological footprint for RME was calculated as 10.3 m²a/MJ based on data from Reinhardt (Reinhardt 1997). This LCA also includes substitution processes such as soy meal or glycerol production and therefore needs to be compared with -1.2 m²a/MJ UVO, 0.85 m²a/MJ TME II and 2.79 m²a/MJ TME III.

As far as the impact assessment with the two different methods CML and SPI are concerned the results show concordant trends. The CML method addresses with its impact categories the various environmental problems in detail and is capable of highlighting the trade-offs between them. In contrast to this the Sustainable Process Index is aggregated across different impact categories and allows comparison of these effects based on natural flows and natural qualities.

From the application point of view these two assessment methods both have their distinctive advantages. The CML method clearly focuses on well known environmental problems and valuates the contribution of a given life cycle to these problems. This view is especially important for the analysis of legal compliance of different steps within the life cycle in question as well as for the discussion between different stakeholders, namely environmental organisations, government agencies and business.

The SPI has the advantage to offer a clearer picture on the overall impact of a life cycle, allowing for direct comparison of different alternatives. On top of that the SPI allows to valuate trade-offs for different technological as well as organisational alternatives, thus supporting technology design and life cycle optimisation. As the data necessary for the SPI evaluation are generally known at a very early state of design, costly design failures may be avoided and the general set-up of a certain life cycle may be optimised.

An important feature of the SPI is that it focuses the attention of designers and decision makers on the most pressing environmental questions, which usually arise as a combination of different impacts emerging from a specific step in the life cycle. Within the project planning phase the process energy optimisation has already been considered. Further potentials for a reduction of the ecological footprint have been identified e.g. in the usage of methanol from renewable resources or the optimisation of transport distances.

Concluding we may say that not the absolute values of any assessment count, but Life Cycle Assessment should be a participatory process, as it has turned out as a good communication and learning tool. By assessing different scenarios a systematic discussion built on agreed assumptions with stakeholders and decision makers about optimal solutions for sustainable development became possible.

Appendix 1: Unit processes considered in the LCA of biodiesel from used vegetable oil and tallow

Category	Process
Agriculture	Ammoniac
	Ammoniumnitratphosphat-N
	Ammoniumnitratphosphat-P
	Ammoniumnitrat-Urea-N
	Ammoniumphosphat-N
	Ammoniumphosphat-P
	Application of dung
	Application of K-fertiliser
	Application of manure
	Application of Mg-fertiliser
	Application of N-fertiliser
	Application of pesticides
	Application of P-fertiliser
	Beans
	Calciumammoniumnitrat-N
	Cattle
	Chlorine
	Diesel in agricultural machinery
	Dry fodder
	Fodder from pasture
	Grass silage
	Green manure
	Green manure org
	HCl
	K-Fertiliser
	LDPE-Granulate
	Maize
	Maize silage
	Mg-Fertiliser
	Milk powder
	Milker
	Mineral fodder
	Mixed fodder
	NaOH
	Naphta from refinery Europe
	Natural pasture
	N-Fertiliser
	Nitric acid
	Oat
	Pasture
	Pea
	Pesticides
	P-Fertiliser
	Phosphoric acid
	Polyethylenwax
	Potatoes
	Rapeseed
	Raw phosphate
	Rye
	Salt

	Seed "gebeizt"
	Seed "ungebeizt"
	Singlesuperphosphat-P
	Soy
	Spelt
	Summer wheat
	Triplesuperphosphat-P
	Unskimmed milk
	Urea
	Water decarbonated
	Water desalinated
	Winter barley
	Winter wheat
Transport	Break horsepower hour
	Open sea cargo ship container tkm
	Transport HGV 16 t
	Transport HGV 28 t
	Transport HGV 40 t
	Transport inland cargo ship container tkm
	Transport Railway
Energy	Coal
	Combustion energy
	Diesel Europe
	Diesel in construction machinery
	Electricity charcoal
	Electricity coal
	Electricity GB HV
	Electricity GB LV
	Electricity GB MV
	Electricity hydropower
	Electricity natural gas
	Electricity petroleum
	Electricity uranium
	Fuel oil extra light in heating 1MW
	Fuel oil, extra light
	Fuel oil, extra light in heating100kW
	Fuel oil, heavy
	Fuel oil, heavy, Euro in heating 1MW
	Heat from industrial combustion >100 kW
	Industrial carbon combustion 1-10 MW
	Leakage natural gas
	Natural gas
	Natural gas in fan burner <100kW
	Natural gas in industrial combustion >100kW
	Steam production
Chemicals	KCl
	KOH
	Methanol
	Sulfuric acid H_2SO_4
	Sulphur
Food industry and biodiesel production	Biodiesel from transesterification
	Fat after rendering
	Meat after slaughtering
	Refinery gas
	Waste water food industry

Waste processing and disposal	Hazardous waste incineration
	Inert landfill
	Reactor landfill pro kg
	Slag landfill pro kg
	Solid waste landfill pro kg
	Waste incineration 95 pro kg
Multiple	Explosives
	Iron sulfate
	Lime CaO
	Limestone
	Natriumchloride
	Organic chemicals
Substitution processes	Treatment glycerol
	Polyethylenwachs
	Synthetically glycerol
	Synthetically K-Fertilizer

Appendix 2: Environmental flows in the LCA of biodiesel from used vegetable oil and tallow

Category	Name
Resources	calcium (Ca)
	phosphorus (P)
	uranium (U)
	coal hard
	coal soft, lignite
	natural gas
	oil crude
	bauxite
	iron (ore
Emissions to air	ammonia
	aromatics (unspecified)
	arsenic
	Benzene
	benzo[a]pyrene
	Butane
	cadmium (II) ion
	carbendazim
	Carbon dioxide
	Carbon Monoxide
	chlorothalonil
	chromium (III) ion
	cobalt
	copper (II) ion
	Cyanides
	cypermethrin
	Dichloromethane
	Dinitrogen oxide
	dust (PM10)
	Ethane
	Formaldehyde
	HALON-1301
	hexachlorobenzene
	Hydrocarbons, aromatic
	Hydrocarbons, Chloro-Fluor-
	hydrogen chloride
	hydrogen fluoride
	isoproturon
	lead (II) ion
	Manganese (II) ion
	mercury (II) ion
	Methane
	nickel
	nitrogen
	nitrogen dioxide
	nitrogen oxides (as NO2)
	pentachlorobenzene
	pentachlorophenol
	Phosphorus
	pirimicarb

	Polycyclic Aromatic Hydrocarbons (PAH) (unspecified)
	Propane
	Radon-222 (Rn-222)
	sulphur dioxide
	sulphur trioxide
	Tetrachloromethane
	Toluene
	Volatile Organic Compounds (VOC)
	Volatile Organic Compounds non-methane- (non methane VOC)
	zinc (II) ion
Emissions to water	ammonia
	ammonium
	arsenic
	barium
	Biological Oxygen Demand (BOD)
	Boron
	cadmium (II) ion
	Chemical oxigen demand (COD)
	Chlorine
	chromium III
	cobalt
	copper (II) ion
	lead (II) ion
	manganese (II) ion
	mercury (II) ion
	nickel
	Nitrate
	Nitrite
	Nitrogen
	phenol
	phosphate
	Phosphorus
	Polycyclic Aromatic Hydrocarbons Carcinogenic- (carcinogenic-PAH)
	Radium-226 (Ra-226)
	sulfates
	Sulphuric acid
	toluene
	zinc (II) ion
Emissions to agricultural soil	arsenic
	cadmium (II) ion
	chromium (III) ion
	cobalt
	copper (II) ion
	lead (II) ion
	mercury (II) ion
	molybdenum
	nickel
	Phosphorus
	selenium
	zinc (II) ion
Emissions to industrial soil	arsenic
	cadmium (II) ion
	chromium (III) ion
	cobalt

	copper (II) ion
	lead (II) ion
	mercury (II) ion
	nickel
	Phosphorus
	zinc (II) ion
Land use	land use II-III
	land use II-IV
	land use III-IV

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