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CO_2 Mitigation through Biofuels in the Transport Sector

Status and Perspectives

Main Report

Forschungsvereinigung
Verbrennungskraftmaschinen
FVV

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ufop

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Main Report

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More information on this project can be found on
www.ifeu.de/co2mitigation.htm

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FVV – Research Association for Combustion Engines

The ongoing optimisation of the efficiency ratios and emissions of combustion engines – e.g. prime movers and thermal turboengines – necessitates intensive and constant research and development input with regard to all the part aspects of these highly developed and complex machines. An important basis for all R&D activities within one company and in a competitive environment is application-oriented fundamental know-how. The efficient organisation of fundamental research projects on a cost-sharing basis is the core competence of industrial joint research and development in the FVV.

The FVV was founded in 1956 as a non-profit technical and scientific society to establish a permanent and comprehensive network of innovation, communications, and competence from industry and science. Since then, a system that is unique in the world has been built up under its umbrella. One large group of member companies are all well-known car manufacturers in Germany. Others manufacture gas turbines and aero gas turbines, axial-flow and radial-flow compressors, or supply systems and components in the automotive, stationary, and industrial engines industries as well as in the turbo-engine construction industry. From all these companies, experts define and discuss research projects of common interest according to the bottom-up-principle.

(detailed information under www.fvv-net.de)

UFOP – Union for Promoting Oilseeds and Protein Plants

The German Farmer's Association and the German Plant Breeder's Association established the UFOP in 1990. All companies, associations and institutions participating in the production, processing, and marketing of indigenous oil and protein-bearing plants are gathered under the UFOP banner, for example the State Farmer's Associations, the German Cooperative Association, and the Association of the Chambers of Agriculture Plant Breeding Companies.

The promoting of Biodiesel is one of the successful fields of activities. These activities comprise the public relation work to inform the people about the superiority of Biodiesel as an alternative fuel for diesel engines and also the support of investigations to develop Biodiesel as a fuel which has to meet the increasing technical demands as a supposition to stay and develop the market.

(detailed information under www.ufop.de)

Content

Executive Summary

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Executive Summary

Many studies have been conducted world-wide to examine the environmental impact of biofuels for transportation and estimate their cost and quantity potential. These studies have at times shown considerable differences in the findings and conclusions. In order to obtain an overview which identifies the strengths and weaknesses of the available studies and to determine further research needs, the Research Association for Combustion Engines FVV commissioned the IFEU Institute Heidelberg to conduct the present study. FVV and the Union for the Promotion of Oil and Protein Plants UFOP supported this research actively. This study analyses and compares all international, publicly accessible publications about all biofuels for transportation currently used (e.g. biodiesel and bioethanol as well as those potential future biofuels like BTL). More than 800 studies are taken into account. From these, 63 studies satisfy the criteria for detailed analyses, leading to the valuation of 109 energy and CO_2 balances of various biofuels, which are compared either to conventional fuels or other biofuels. In most cases the complete life-cycles of the fuels, from production to consumption, are considered.

The findings of energy and greenhouse gas balances of biofuels, as well as their further environmental impacts and costs estimations vary greatly. This is mainly a result of the different assumptions made regarding the cultivation, the conversion or valuation of the co-products.

Ecological Impacts. Biofuels for transportation show both ecological advantages and disadvantages compared to fossil fuels. The advantages of biofuels include their contribution in conserving fossil resources, and the reduction of greenhouse effect since biofuels are more favourable in energy balance and greenhouse gas balance as compared to fossil fuels. A comparison among various biofuels demonstrates that ETBE shows advantages in energy balance and greenhouse gas balances over other biofuels regarding area related consideration. Bioethanol scores better or worse in dependency on raw material than biodiesel. When same system boundaries are assumed, biodiesel shows advantages compared to vegetable oil. The advantages of a few biofuels are not found in all geographical areas. For example, the bioethanol production from sugar cane is only limited to the tropical climatic conditions. Biofuels from waste materials (e.g. BTL) can be evaluated only if alternative usages of the waste are taken into consideration. This has been ignored in the studies hitherto available. Disadvantages of biofuels from energy crops are the higher level of eutrophication, acidification and ozone depletion associated with their use, due to the nitrogen compounds from agricultural production. No statement of clear tendency can be made for acidification and eutrophication regarding biofuels from waste materials.

A decision based on ecological considerations should take the individual advantages and disadvantages of the biofuels into account. When the conservation of fossil resources and the reduction of greenhouse effect are assigned as the highest priority, biofuels will be considered as favourable. The disadvantages are less dramatic and do not tip the balance of a general overall positive evaluation. The ecological differences between biofuels and fossil fuels will also not change drastically in the future. The advantages of the currently used biofuels will probably increase as compared to conventional fuels.

Costs. The production costs of biofuels for transportation are generally higher than those of conventional fuels. Accounting on the national level, not discussed here, could reverse this assessment. The comparison of the direct costs is determined by many economic and social external factors. The production costs of fossil fuels are dependent upon the world oil price and its fluctuations. The production costs of biofuels vary according to the national agricultural subsidisation and different state-specific personal costs and transportation costs. The range of estimates from these factors is so wide and the uncertainly is so large that no serious or reliable ranking among the biofuels can be made based on the available literature. The discussions regarding future costs also tend to be speculative.

Even in the present biofuels can be produced cheaper than fossil fuels under certain conditions. The production of biodiesel from recycled cooking oil serves as an example.

Quantity Potential. The potential of biofuels production is limited. While the annual produced biomass in the world could theoretically provide our total fuel demand, there are restrictions from other competing land use (food production, natural conservation, sustainable agriculture) and usages (biomass for material uses, source of bioenergy for power and heat production). In this way, competing land use alone reduces the usable potential in Germany to just a few percent of the fuel market. A reliable quantification for the EU or the world is still not available. Such limitations do not apply to the usage of biomass from waste material.

The availability and the efficiency of new production technologies is a determining factor of the quantity potential. These include the technology for BTL, ethanol from lignocellulose or for bio-hydrogen. However, with our present knowledge, it is impossible to predict when and which technologies will become available.

Further research need. Overall, there is a considerable need for further research on biofuels for transportation. There is still a paucity of publications about the energy and greenhouse gas balances of many biofuels such as biodiesel from palm oil and jatropha. With respect to DME, Methanol, and BTL, studies cover only one conversion path. The knowledge gap is even larger in the area of life cycle assessments. For instance, there is a lack of studies on many conversion routes such as in the area of BTL. Detail examinations are missing in many important individual studies, such as those on bioethanol or the motor emissions of biofuels in the most modern motor concepts.

Similar to the need to examine the direct costs of the various aspects in more detail, further studies about the potentials estimations in consideration of specific land use and competing usage for reference areas such as EU or the world should be conducted.

By way of summation and simplification, biofuels for transportation offer ecological advantages in resource conservation and climate protection as compared to fossil fuels. These advantages outweigh the disadvantages in contributing to acidification, eutrophication, and ozone depletion. Biofuels are in general more expensive to produce – national accounting or social effects are not considered here. Due to competing land use and biomass usage, biofuels from agricultural biomass can probably only substitute a small portion of fossil fuels. The production of innovative biofuels like BTL calls for new technologies.

1 Background and Objectives

While the natural greenhouse effect is caused by water vapour in the atmosphere, carbon dioxide, methane, CFCs, ozone, and laughing gas are mainly responsible for the anthropogenic greenhouse effect. The reduction of anthropogenic greenhouse gas emissions is one of the most important policy goals regarding climate change and global warming. The transportation sector contributed 21.9 % of the total CO_2 emissions in Germany in 2000, from which 90 % originate from road traffic (UBA 2002). In Europe at large, the transportation sector accounts for more or less the same proportion of total greenhouse gas emissions (21 % in 2001, EEA 2003). An increased usage of biofuels can contribute to reduce CO_2 emissions in road traffic. This is also an objective of the EU Directive “on the promotion of the use of biofuels or other renewable fuels for transport” implemented on 17 May 2003. According to this directive, the market share of biofuels should reach 2 % in 2005 and 5.75 % by the end of 2010 in all EU member countries (EU 2003). In the Green Paper of the European Commission (2001) “Towards a European strategy for the security of energy supply”, an objective was set to substitute 20 % of the conventional fuels with alternative fuels by 2020. An increased usage of biofuels does not only reduce CO_2 emissions and conserve fossil resources. The production of biofuels also provides income prospects for the agricultural sector and a diversification of energy sources for the European transportation sector. Such a diversification would make Europe become more independent from oil import.

Many Life Cycle Assessments (LCAs) have concluded that biofuels are more or less CO_2 neutral. The findings, however, vary at times considerably. In order to produce a critical evaluation of the existing LCA publications on biofuels, FVV commissioned IFEU to conduct the present study.[1] This study collates, analyses and compares international publications that provide scientifically reliable and comprehensive statements about biofuels. It considers all biofuels that are currently in use such as vegetable oil and biodiesel from rapeseed, bioethanol from sugar-cane and corn, etc. as well as biofuels that are currently not mass produced such as BTL and hydrogen. The examination of the energy and greenhouse gas balances is most important, while acidification, eutrophication, photosmog, and ozone depletion are only considered in qualitative manner.

Since biofuels can only be feasible in the market when they are competitive and available to an adequate extent, this study also analyses the costs and potentials estimations of biofuels in addition to an ecological assessment. The costs and potentials estimations are considered in the context of ecological implication. Furthermore, this study identifies further research needs with respect to the above topics.

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[1] The study was financed by the Research Association for Combustion Engines (FVV), the Union for the Promotion of Oil and Protein Plants, and the German Association for Research on Automobile-Technique.

2 Procedure

To begin, international publications on energy and greenhouse gas balances as well as their subsequent environmental impacts, costs and potentials were collated according to a selection procedure (see Chapter 2.1).

The entire energy demand and greenhouse gas emissions of the biofuels for their production up to the tank (Well-to-Tank Analysis) were quoted. The life cycle of fossil fuels was assessed consistently (see Chapter 2.2).

The fuel demand and greenhouse gas emissions of vehicle usage (Tank-to-Wheel) and the general fuel properties were set to consistent values. These procedures serve to improve the comparability of the studies considered (see Chapter 2.3).

The findings of the selected studies on the energy demand and greenhouse gas emissions of the production of biofuels were compared to each other and inspected critically. For this, general system definitions and the data basis used are drawn upon. All biofuels were arranged in a spectrum with reference to their energy demand, greenhouse gas emissions as well as the production costs (ordered according to their respective resource base; e.g. bioethanol from corn). The criteria for establishing the spectrum are described in Chapter 2.4.

The findings of the non-renewable primary energy demand (energy balance) and the greenhouse gas emissions can be presented in different ways, e.g. according to the fuel's energy unit (MJ), mileage (km) or area coverage (ha). Alternatively one can also refer to an overall balance, which compares a biofuel with a fossil fuel counterpart (biogenous – fossil) or a partial comparison of the fuel production. Different question formulations call for different references. The selected references are compiled in Chapter 2.5.

Following the presentations of the findings on the energy and greenhouse gas balance, the further environmental impacts as well as the costs and potentials estimations, the document will close with a conclusion of the findings.

2.1 Literature Collection

The initial list of publications was a result of a search in IFEU's internal database, internet search engines, online library catalogues, and of information received from colleagues in other institutes as well as from FVV members. The publications were then examined and when necessary revised by experts world-wide.

The publications were then examined according to the following parameters: energy balance, emissions of greenhouse gases (CO_2, CH_4, and N_2O), other airborne emissions (NO_X, SO_X, NMHC, CO, particulate matter, etc.), as well as estimations of potentials and costs. Nevertheless the following criteria were used to exclude publications from the study:

- No primary data were presented in the publication. The findings are based on a detailed study that itself is considered in this investigation.
- More recent publications by the same authors are available.
- The publication considers exclusively data from other authors, rather than primary data.

- The publication is no longer up-to-date.
- Other reasons (the specific reasons for the omissions of publications, that are not explained with the above mentioned reasons, are listed in Appendix A 5)

Guided by the criteria mentioned above, about 80 publications were excluded. These are listed in Appendix A 5. Besides, about 400 publications were excluded because their topics are only of remote relevance to the present study. These publications are however not documented here. Table 1 lists the publications that are analysed in this study. In the table an “x” is marked to the parameters energy balance, greenhouse gases (CO_2, CH_4, and N_2O), further emissions (NO_X, SO_X, NMHC, CO, etc.), potentials estimation and costs estimation when the particular publication contains these findings. For the sake of clarity, further emissions are not broken down individually. Rather, the table lists merely how many parameters are considered in the particular study for that category. An “(x)” shows that the publications contain these parameters. The findings about these parameters are however not considered. This can, for example, be related to the fact that the publication is not about primary data, but about data from other authors, or that the findings are revised in more up-to-date publications. As it is common that more than one fuel chain is examined in a single publication, the number of considered fuel chains is also presented in Table 1. A total of 109 biofuel chains are compared. A detail breakdown of the different biofuels examined in specific studies is found in Appendix A 1.

Table 1 Publications on energy and greenhouse gas balances, further emissions, potentials and costs analysed in this study

Author	Year	Reference	Numb. fuels	Energy balance	GHG			Further emiss.	Poten-tials	Costs
					CO_2	CH_4	N_2O			
Ademe	2002	France	8	x	x	x	x			
Atrax	2002	Sweden	1		x	x	x	5		x
Börjesson	2004	Sweden	1	x	x	x	x	9		x
CONCAWE	2002	EU	3	(x)	(x)	(x)	(x)		x	
CSIRO	2001	Australia	6		x	x	x	2		
DfT	2003	World-wide	7							x
DLR et al.	2003	Europe	8							x
Dreier	2000	World-wide		(x)	(x)				x	
Dreier	1998	Germany	5	x	(x)			4	(x)	x
Elsayed	2003	UK	6	x	x	x	x			
Enerstrat	2003	Australia	1	x	x	x	x			
EST	2002	UK	3						x	
ETSU	1996	UK	3	x	x	x	x	5		
EUCAR	2003	EU	8	(x)	x	x	x			x
FAT	2000	Switzerland	1	x	x	x	x	10		
FfE	1999	Germany	6	x	x			4		
Fromentin	2000	Switzerland	1	x	x	x	x	7		x
GM	2002	EU	10	x	x	x	x			
GM	2001	North America	2	x	x	x	x			
Graboski	2002	USA	1	x						
IEA	2003	North A./EU	5	(x)	(x)	(x)	(x)			x
IEA	1999	World-wide	3	(x)	(x)			(4)	x	
IFEU	2004	Germany							x	

Table 1 continued

IFEU	2003	Germany	1	x	x	x	x	13		
IFEU	2002a	Germany	6	x	x	x	x	13		
IFEU	2002b	Germany	1	x	x	x	x	13		
IFEU	2002c	Germany	2	x	x	x	x	13		
IFEU	2001	Germany	1	x	x	x	x	13		
IFEU et al.	2000	Europe	14	x	x	x	x	11		(x)
IFO	2002	Germany	1							x
Jungmeier	2003	Austria	9		(x)	(x)	(x)			x
JRC	2004	Europe	5						x	
JRC	2003	Europe	6						x	
JRC	2002a	Europe	1	(x)	(x)				x	x
JRC	2002b	Europe	1	(x)	(x)				x	x
Larson	1999	USA	1	x						
LBST	2002	Germany	5	(x)	(x)					x
LBST	2003	EU	6						x	
Levelton	2002	Canada	4	x	x	x	x	5		
Levelton	2000	Canada	1	x	x	x	x	5		
Levelton	1999	Canada	1	x	x	x	x	5		
Levington	2000	UK	1	x	x		x	1		
Macedo	1997	Brazil	1	x	x	x	x			
Marano	2001	USA	1		x	x	x			
Moreira	2002	Brazil	1						x	
NREL	1998	USA	1	x	x	x	x	7		
NREL	2002	USA	1	x	x	x	x	2		x
NREL	1999	Canada	1	x	x	x	x	5	x	
Pehnt	2002a	Germany	1	x	x	x	x	9		
Pehnt	2002b	Germany	1	x	x	x	x	9		
Pimentel	2003	USA	1	x						x
Pimentel	2001	USA	1	(x)					x	
Raschka	2002	n.d.	1							x
(S&T)^2	2003	Canada	1	x	(x)	(x)	(x)			
Schmitz	2003	Germany	4	(x)	(x)	(x)	(x)			x
Tan	2002a	Philippines	1	x	x	x	x			
Thrän	2004	Germany	5						x	
Thuijl	2003	Europe	9							x
TU Münch.	2003	Germany	3	x	(x)	(x)	(x)	(4)		x
USDA	2002	USA	1	x						
VITO	1999	Belgium	1	x	x	x	x	4		
Wang	1999	USA	1	x	x	x	x			
Woods	2003	UK	7							x

x results are regarded

(x) results are not regarded

2.2 Energy Demand and Greenhouse Gas Emissions of Fuel Production

This study examines the consumption of non-renewable primary energy (fossil + nuclear primary energy in MJ LHV) and the greenhouse gases carbon dioxide, laughing gas and methane. The Global Warming Potentials (GWP) based on a 100 years will be evaluated. It describes the climatic effectiveness of greenhouse gases for a time horizon of 100 years; for CO_2 it is 1, for CH_4 23, and for N_2O 296 (IPCC 2001).

The energy demand and the greenhouse gas emissions of biofuels, from their production to the tank (Well-to-Tank Analysis), are quoted from the publications and organized to the following topics:

- Agriculture. The energy demands and greenhouse gases to be set free from cultivation are summed up. They result predominantly from nitrogen-containing fertilizers and the demand for diesel in agricultural land management. In the case of biofuels from organic residues there is no agricultural prechain.
- Transportation of agricultural products
- Conversion to biofuels
- Credits from co-products. Conventionally produced products are substituted by the co-products arisen from biofuels production. Biofuel credits comprise the non-renewable primary energy need for the manufacturing of the conventional products and the greenhouse gases to be set free in such production. In case of an allocation, no credits will be set out. The expenses in the remaining areas are instead lower accordingly.
- Distribution of biofuels

The energy demand and greenhouse gas emissions of the production of fossil fuels were made consistent. This warrants that only the biogenous life cycles are analysed in a comparison of the analysed studies, and that the comparison is not influenced by the different assumptions and procedure concerning the fossil life cycles. The prechain of fossil fuels were obtained from the IFEU database.

2.3 Fuel Demands and Greenhouse Gas Emissions of Vehicle Usage and General Fuel Properties

In order to make the examined studies comparable, the Tank-to-Wheel fuel demands and greenhouse gas emissions of vehicle usage as well as general fuel properties were made consistent. The following predefinitions were set:

- **Vehicles used for the fuel comparison.** An automobile with a combustion engine was used for all the fuels studied. An automobile with electric engine and fuel cell was used in addition for hydrogen and methanol.
- **Time reference.** The year 2010 was used as time reference, because present and future car technologies were considered.

- **Data basis.** The EUCAR study (2003) serves as the data basis. It is assumed that these data are commonly agreed by the European Council for Automotive R & D (EUCAR), the European Oil Industry Association (CONCAWE), and the Joint Research Centre of the European Commission (JRC). The “Alternative Fuels Contact Group”, which published a status report for market development as well as the technical and economic status of alternative fuels, also bases their report on these data (AFCG 2003).

Table 2 Fuel demands and greenhouse gas emissions according to vehicle usage and general fuel properties in 2010. (EUCAR (2003) and own calculations)

	Fuel properties		**Fuel consumption**			**GHG emissions**			
	LHV	**Density**				**CO_2****	**N_2O**	**CH_4**	**Total**
	MJ/kg	**kg/L***	**MJ/100km**	**L/100km***	**L/100km* gasoline equiv.**	**g CO_2 equivalent/km**			
Vehicle with ICE (clean, not blended fuels)									
Gasoline	43.2	0.745	188.95 (1)	5.87 (1)	5.87	138.65 (1)	0.4 (1)	0.5 (1)	139.55 (1)
CNG	45.1		192.85 (2)		5.99	108.45 (2)	1.7 (2)	0.5 (2)	110.65 (2)
Biogas	47.0 (4)		192.85 (3)		5.99	108.45 (3)	1.7 (3)	0.5 (3)	110.65 (3)
Hydrogen	120.1		167.50		5.20	0.0	0.0	0.5	0.5
Vehicle with ICE (blend to gasoline) (5)									
Ethanol (E5)	26.8	0.794	190.0		5.90	139.3	0.4	0.5	140.2
Methanol (M5)	19.9	0.793	190.0 (6)		5.90	139.3 (6)	0.4 (6)	0.5 (6)	140.2 (6)
ETBE (ETBE5)	36.05 (7)	0.742 (7)	190.0 (8)		5.90	139.3 (8)	0.4 (8)	0.5 (8)	140.2 (8)
MTBE (MTBE5)	35.19 (7)	0.740 (7)	190.0 (10)		5.90	139.3 (9)	0.4 (9)	0.5 (9)	140.2 (9)
Vehicle with diesel engine and DPF (10)									
Diesel fuel	43.1	0.832	179.5	5.00	5.58	131.4	0.2	1.6	133.2
Biodiesel	36.8	0.890	179.7	5.49	5.58	137.0	0.2	1.6	138.8
Vegetable oil	36.0 (11)	0.922 (12)	179.7 (12)	5.41 (12)	5.58	137.0 (12)	0.2 (12)	1.6 (12)	138.8 (12)
DME	28.4	0.670	172.4	9.06	5.36	116.1	0.2	1.6	117.9
BTL	44.0	0.780	179.7	5.24	5.58	127.3	0.2	1.6	129.0
Vehicle with electric motor/fuel cell									
Hydrogen	120.1		94.0		2.92	0.0	0.0	0.0	0.0
Methanol	19.9	0.793	148.0		4.60	108.5	0.4	0.5	109.4

(1) Average value from direct injection and conventional ICEs
(2) Average value from “CNG bi-fuel” and “CNG dedicated”
(3) Assumed that the Biogas consumption based on the heating value corresponds to that of CNG
(4) Source: Sundqvist (2003)
(5) Values are referred to the blend of gasoline and the specified biogenous portion
(6) Assumed that the consumption of M5 based on the heating value corresponds to that of E5
(7) Source: IFEU 2002
(8) Assumed that the consumption of ETBE5 based on the heating value corresponds to that of E5
(9) Assumed that the consumption of MTBE5 based on the heating value corresponds to that of M5
(10) For DME a vehicle without a DPF was considered
(11) Source: IFEU 2003
(12) Assumed that the consumption of vegetable oil based on the LHV corresponds to that of biodiesel

* L stands for litre (volume of a cube of 10 cm edge)
** biogenous CO_2 emissions were evaluated with zero in the balances

- Regarding fuel demand and greenhouse gas emissions of gasoline automobile usage, values for direct injection and conventional gasoline motors in the EUCAR study were used. In this study, no differentiation was made between these two types of vehicles, as the two values differ only about 1 %. It was assumed that both of these car technologies will be in use in 2010 and the mean between the two values was used here.
- Similarly, the mean between the values for “CNG bi-fuel” and “CNG dedicated” was used. It is also assumed that in 2010, there will be automobiles driven with gasoline or natural gas as well as vehicles that are fuelled only with natural gas.
- No values for density were given to the gaseous fuels (CNG, biogas and hydrogen) as these vary greatly depending on pressure. Consequently, volume-related fuel demand of these fuels was also not given.
- Biogas was not a topic of investigation of the EUCAR study. The applied values were derived as follows: the lower heating value of 47.0 MJ/kg was obtained from the study by Sundqvist (2003) and the data about fuel demand and greenhouse gas emissions were derived from the EUCAR study. For the sake of simplification, the heat value related fuel demand of biogas corresponds to that of natural gas. In this way, the greenhouse gas emissions from biogas vehicle usage correspond with that of natural gas. The biogenous CO_2 emissions from biogas were evaluated to zero in the balance.
- Regarding additive ethanol, methanol, ETBE, and MTBE in gasoline, it was assumed that the fuel demands and greenhouse gas emissions of vehicle usage correspond to those of gasoline-ethanol-blend. Additives were not accounted for in case of volume-related fuel demands, since additive are only consumed together with gasoline, and hence, in our opinion, specification on the consumption of an additive would not be convincing.
- It was assumed that in 2010 diesel particulate filters (DPF) will be installed on most diesel engines. The options without DPF are therefore not considered. One exception is made in the DME usage. In this case, the values for a diesel engine without DPF are used because the option “DME in a diesel motor with DPF” is not available in the EUCAR study.
- The CO_2 emissions caused by biofuels usage are evaluated to zero in greenhouse gas balance, since the amount of CO_2 released from combustion is the same as the amount drawn by the energy delivering plants during the cultivation process. The fossil component of methyl-ester (e.g. 109 kg Methanol / t RME) was also assumed to be zero in the CO_2 balance, since this fossil input will be balanced through the glycerine feedback in the biogenous circulation.
- The automobile-induced CO_2 emissions from the fossil components of tertiary butyl ether (e.g. 55 % isobutene for ETBE) are entered in the CO_2 balance.
- In addition to CO_2, the CO_2 equivalent emissions are the summation of the given N_2O and CH_4 emissions. Table 2 sets out the CH_4 and N_2O emissions as CO_2 equivalent using the IPCC factors 23 for CH_4 and 296 for N_2O (IPCC 2001).

Figure 1 shows the fuel demand in L/100 km gasoline equivalent used for the fossil and biofuels that are shown in Table 2. It demonstrates, above all, the small fuel demand of an automobile with an electric motor/fuel cell, with a smaller demand of hydrogen compared to methanol. The fuel demand of a diesel engine is generally lower than that of a gasoline engine. The demand of hydrogen in a gasoline engine is one exception.

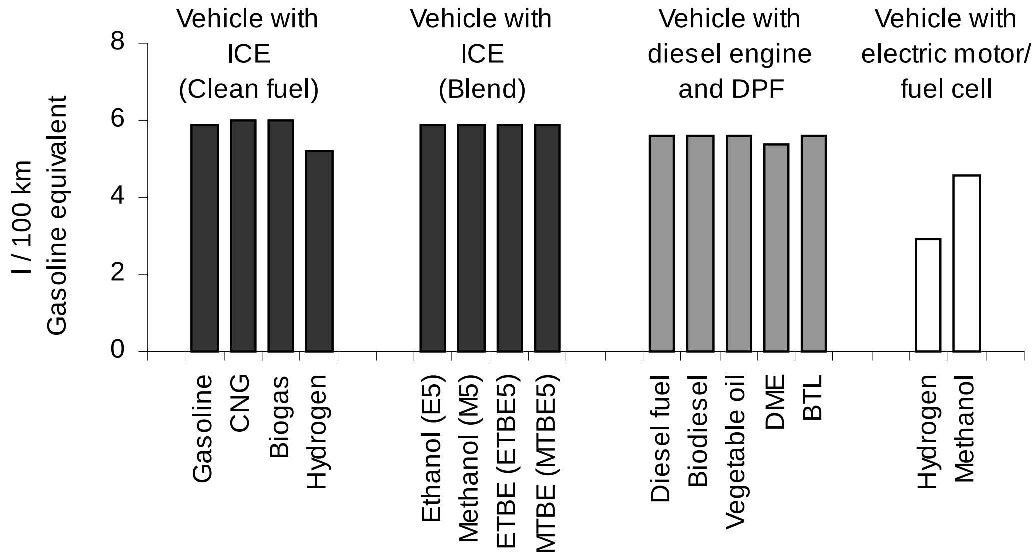

Figure 1 Fuel demand of fossil fuels and biofuels in litres per 100 km gasoline equivalent

2.4 Derivation of Spectrums

The findings of the selected studies on the energy demands, greenhouse gas emissions, and costs of production of biofuels vary considerably. Individual findings of the studies regarding energy and greenhouse gas balances are shown in Appendix A 2. Appendix A 4 illustrates the costs.

The objective of this study is, among others, to delineate individual biofuels – categorized according to resource basis (e.g. bioethanol from corn) – based on energy and greenhouse gas balances and costs as stated in the existing literature. This would allow the complete variability found in the results of individual studies to be depicted in a spectrum. In our opinion, this procedure cannot achieve the objective since the findings or partial findings of some studies are not considered as representative. As a result spectrums with adjustments, new calculations or, where necessary, new estimations of the unrepresentative findings or partial findings will be presented. The determined spectrums show our estimations on the areas in which the findings about the energy and greenhouse gas balances and costs of the individual biofuels (categorized according to resource basis) are found. The following examples show the reasons why the findings of some studies are not representative and how the spectrums were determined.

- In some studies, the assumptions were made from data basis that no longer reflects the state-of-the-art technology. The demands for the production today are lower than that determined by the studies. Examples of these include the studies by Pimentel (2003) and CSIRO (2001). The assumption used by Pimentel (2003) of the primary energy demand for the production of nitrogen fertilizers was about one third higher than that resulted from state-of-the-art technology. In the study by CSIRO (2001), the conversion data used for bioethanol from molasses stemmed from earlier studies updated by Enerstrat (2003). These facts were generally asserted, since only up-to-date studies were reviewed. When obsolete assumptions from conversion technology were used, this was considered in the determination of the spectrum. This is performed on the basis of parameters cited in other studies (see Appendix A2).

- Co-products were not accounted for in some studies, for example in the FfE study (1999).

  According to our concept, all co-products from the production of biofuels should be considered. In the determined spectrums, different possibilities in the use and accounting of co-products were included. Energetic usage delivers thereby mostly the smallest advantage for the co-products, while the advantages vary for the material usage dependent on the substituted conventional products. In the derivation of the spectrums, credits and allocation processes were taken into consideration. Credit processes are considered as more targeted.
- In some studies, not all the greenhouse gas emissions (CO_2, N_2O, and CH_4) considered in this study were analysed. Similarly, not all areas (fertilizer production and emissions from the field) of N_2O emissions from agriculture were accounted. For instance, the N_2O and CH_4 emissions were not determined in ETSU (1996) and Tan (2002) and Macedo (1997) did not consider the N_2O emissions that stemmed from nitrogen fertilizer production. In these cases, the missing items in the findings are supplemented with the establishment of the spectrum.
- Human labour was calculated into the energy balances in some studies, which does not correspond to the accounting practice in the rule of life cycle analyses – without any particular question (e.g. Pimentel 2003). In these cases, the findings are adjusted with the corresponding energy demands during the derivation of the spectrum.

2.5 References for Fuel Comparison

The energy content of the fuel (MJ), the mileage (km) or the area coverage (ha), for example, can be applied to the findings of the non-renewable primary energy demands (in Megajoules or Gigajoules) and the greenhouse gas emissions (in grams, kilograms, or metric tons). One can refer to either a portion of a fuel or the total balance that compares biofuels with conventional fuels.

The references used in this report are listed in the following.

Biofuels from Cultivated Biomass

The findings of the energy and greenhouse gas balances of biofuels from cultivated biomass will be illustrated with the following references in Chapter 4.1.

- **Hectare reference.** As available area for the production of biomass raw material is indisputably the biggest bottleneck for the production of biofuels, the findings of the total balance refers to one hectare and an average harvest year.

- Energy balance	The sum of saved non-renewable primary energy in GJ/ha and year.
- Greenhouse gas balance	The sum of saved CO_2 equivalent in t/ha and year.

Biofuels from Cultivated Biomass and Organic Residues

The findings of the energy and greenhouse gas balances of biofuels from cultivated biomass and organic residues will be illustrated with the following references in Chapter 4.1.

- **Kilometre reference.** The findings illustration of the biofuels from organic residues refers to the per km data. Also here, the total balance is considered. This applies equally to biofuels from cultivated biomass or from potentially other raw material sources. The fuel demands and greenhouse gas emissions resulting from vehicle usage laid down here are illustrated in Table 2.

- Energy balance	The sum of saved non-renewable primary energy in MJ / km.
- Greenhouse gas balance	The sum of saved CO_2 equivalent in g / km.

Chapter 4.3 illustrates the production and avoidance costs of biofuels with the following considerations:

- **Production costs.** The costs for the production of biofuels are calculated as € / GJ fuel content and € / 100 km.
- **Avoidance costs.** In addition to the presentation of the production costs in Chapter 4.3, the avoidance costs – cost per avoided primary energy source demand or avoided greenhouse gas emissions – is also illustrated.

- Energy balance	Costs (Production costs of biofuels minus the production costs for the fossil fuels) for the sum of saved non-renewable primary energy in € / GJ.
- Greenhouse gas balance	Costs (Production costs of biofuels minus the production costs for the fossil fuels) for the sum of saved CO_2 equivalent in € / t.

In addition to the references mentioned above, there is one more series of additional references. These are sensible either for detailed investigation and vivid illustrations. The following references are documented in Appendix A 2.3.

- **WTT.** In the so-called Well-to-Tank Analysis, exclusively the energy demand and the greenhouse gas emissions of the production of a fuel path (end point: fuel in the tank of a vehicle) are considered . This means it is not a complete accounting balance! MJ fuel content is ordinary here as reference. The results for all fuels considered are found in Appendix A 2.4.1.

- Energy balance	The sum of non-renewable primary energy for fuel production in MJ / MJ fuel content.
- Greenhouse gas balance	The sum of greenhouse gas emissions resulting from fuel production in g CO_2 equivalent / MJ fuel content.

- **WTW.** The so-called Well-to-Wheel Analysis is a combination of the Well-to-Tank and Tank-to-Wheel Analyses. The Tank-to-Wheel Analysis calculates the energy demand and greenhouse gas emissions from vehicle usage in MJ / km or g CO_2 equiv. / km (see Chapter 2.2). The results of the Well-to-Wheel Analysis are shown in Appendix A 2.4.2.

- Energy balance	The sum of non-renewable primary energy for fuel production and vehicle usage in MJ / km.
- Greenhouse gas balance	The sum of greenhouse gas emissions resulting from fuel production and vehicle usage in g CO_2 equivalents / km.

- **Fuel content.** The results of the total balance of biofuels from organic residues and cultivated biomass per MJ fuel content is illustrated in Appendix A 2.4.3.

- Energy balance	The sum of saved non-renewable primary energy in MJ / MJ fuel content.
- Greenhouse gas balance	The sum of saved CO_2 equivalents in g / MJ fuel content.

- **Efficiency.** The greenhouse gas balance in relation to the energy balance is shown in Appendix A 2.4.5. The results of the greenhouse gas emissions are shown as efficiency criterion. The same reference is used for biofuels from cultivated biomass and biofuels from organic residues.

- Energy balance	The sum of saved CO_2 equivalent in kg divided by the sum of saved non-renewable primary energy in MJ.

3 Fuels Considered

All fuels made from cultivated biomass or organic residues that are more or less linked to the carbon cycle are considered in this study. The role of biofuels in the global carbon cycle will be considered in Chapter 3.1. Chapter 3.2 will describe briefly the individual biofuels.

3.1 Biofuels in the Context of Global Carbon Cycle

Biofuels are produced from biomass. Exactly the same amount of CO_2 absorbed from the atmosphere by the plants through photosynthesis is set free through combustion. This accounts for an almost closed CO_2 cycle (cf. Fig. 2). Besides combustion, CO_2 emissions also take place through the production of the biofuels. For example, CO_2 is produced, for example, in the production of nitrogen-containing fertilizers or from the diesel used in agriculture machines. On the other hand, in the production of biofuels co-products are generated, which substitute conventionally manufactured products and the necessary non-renewable primary energy used in their production.

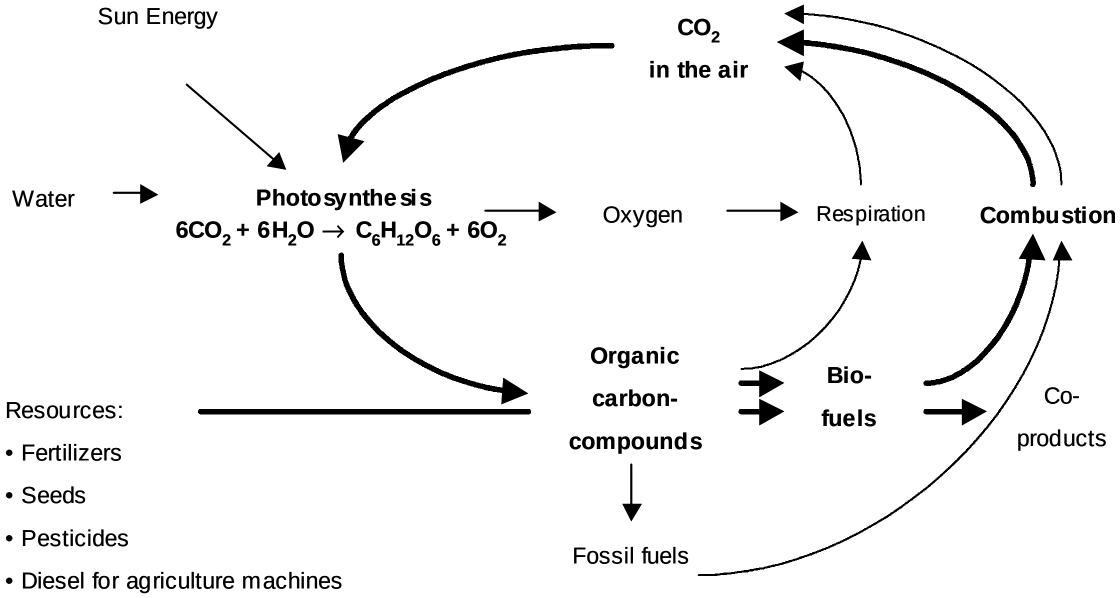

Figure 2 CO_2 neutrality of biofuels in the context of global carbon cycle

Plants use CO_2, water and sunlight to produce carbohydrates and oxygen through photosynthesis. They then convert the carbohydrates produced from the photosynthesis to other organic materials, e.g. proteins. The energy needed for this process stems from the breaking down of the carbohydrates. Through this process of respiration, the oxygen produced from photosynthesis is used to create CO_2. Respiration functions in the opposite of photosynthesis. Since more mass is created in the process of photosynthesis than consumed through respiration, the plants maintain a larger energy amount. Peat, coal, crude oil, and natural gas are created by organic carbon removed from the cycle and deposited (cf. Fig. 2). This fossil carbon stock, which has been built up for a long time, is now being burnt. CO_2 is released through the combustion and reaches the atmosphere. This has intensified since industrialization and has caused the so-called greenhouse effect. Between 1989 and 1998, 6.3 Gt C (Gigatonnes of carbon, 6 300 million metric tons C) were released annually through the combustion of fossil fuels. In addition, as much as 1.6 Gt C emissions were recorded annually from land-use changes especially from slashing and burning in the tropics. These emissions are countered by an annual increment of 3.3 Gt C of the atmosphere and an annual ocean uptake of 2.3 Gt C. In the balance, there remains a 2.3 Gt C for the sinking processes each year (Tab. 3). This is achieved primarily through forest growth in the northern hemisphere, plants' increasing CO_2 fertilization (through higher CO_2 concentration), and anthropogenic nitrogen input (Kohlmaier & Rohner 1998).

Table 3 World-wide CO_2 sources and sinks in Gigatonnes (thousand million metric tons) carbon per year 1989 – 1998 (IPCC 2000)

	C in Gt per year
World-wide CO_2 sources	**7.9 ± 1.4**
Emissions from fossil fuel combustion	6.3 ± 0.6
Emissions from land-use change, especially slashing and burning in the tropics	1.6 ± 0.8
World-wide CO_2 sinks	**7.9 ± 2.3**
Storage in the atmosphere	3.3 ± 0.2
Ocean uptake	2.3 ± 0.8
Residual terrestrial uptake (e.g. sustainable forests, CO_2 fertilization effect, anthropogenic nitrogen input)	2.3 ± 1.3

Carbon sequestration in forests and soils is considered as a possibility to compensate the rising CO_2 emissions since the last decades. According to the calculations by IPCC (IPCC 1996, in Kohlmaier & Rohner 1998), on average, a potential of about 1.3 Gt C carbon sequestration per year (cf. Tab. 4) can be achieved by conservative measures in forests and reforestation/afforestation between 1995 to 2050. That is about one sixth of the world-wide CO_2 sources (cf. Tab. 3). The carbon storage through reforestation/afforestation exists, however, as long as the potential reservoirs are not filled. There is also the carbon stock, which is stored in wood and buildings for more than five decades, in civilising applications, like furniture manufacturing for 10 to 20 years, and in paper and packaging materials for only 1 to 2 years (Kohlmaier & Rohner 1998).

In the agricultural sector, the storage capacity of soils for carbon offers a much bigger reservoir than the temporary CO_2 bond of crops. The sinking ability of the soils for CO_2 is determined by location factors and usage. The input of organic fertilizers and conservative soil management leads to an influx of organic matter (Rogasik et al. 2000). A considerable carbon sink arises in the soil after deeper tillage. This results first in a thinning out of the organic matter and then new creation of humus, and finally to an alignment to the original balanced C-content (Nieder et al. 1993).

However, as the carbon storage through reforestation/afforestation exists only when the potential reservoirs are not yet filled, and as the carbon storage in soils is also limited, these are at best only short term possibilities to compensate CO_2 emissions.

Table 4 World-wide potential of carbon sequestration in forests between 1995 and 2050 in Gigatonnes (thousand million metric tons) carbon per year (Source: IPCC 1996, in Kohlmaier & Rohner 1998)

	C in Gt 1995 – 2050	C in Gt per year
High latitudes		
Reforestation	2.4	0.0
Middle latitudes		
Reforestation	11.8	0.2
Plantations	0.7	0.0
Low latitudes		
Reforestation	16.4	0.3
Plantations	6.3	0.1
Regeneration	11.5 – 28.7	0.2 – 0.5
Slowed deforestation	10.8 – 20.8	0.2 – 0.4
Total	**59.9 – 87.1**	**1.1 – 1.6**

3.2 Choice and Brief Description of Fuels Considered

As shown in Chapter 3.1, among others, biofuels are mostly CO_2 neutral. In the following, the biofuels considered in this study will be described. The fuels are sub-divided into categories, namely those which are currently in use and those which are not yet mass produced (Fig. 3).

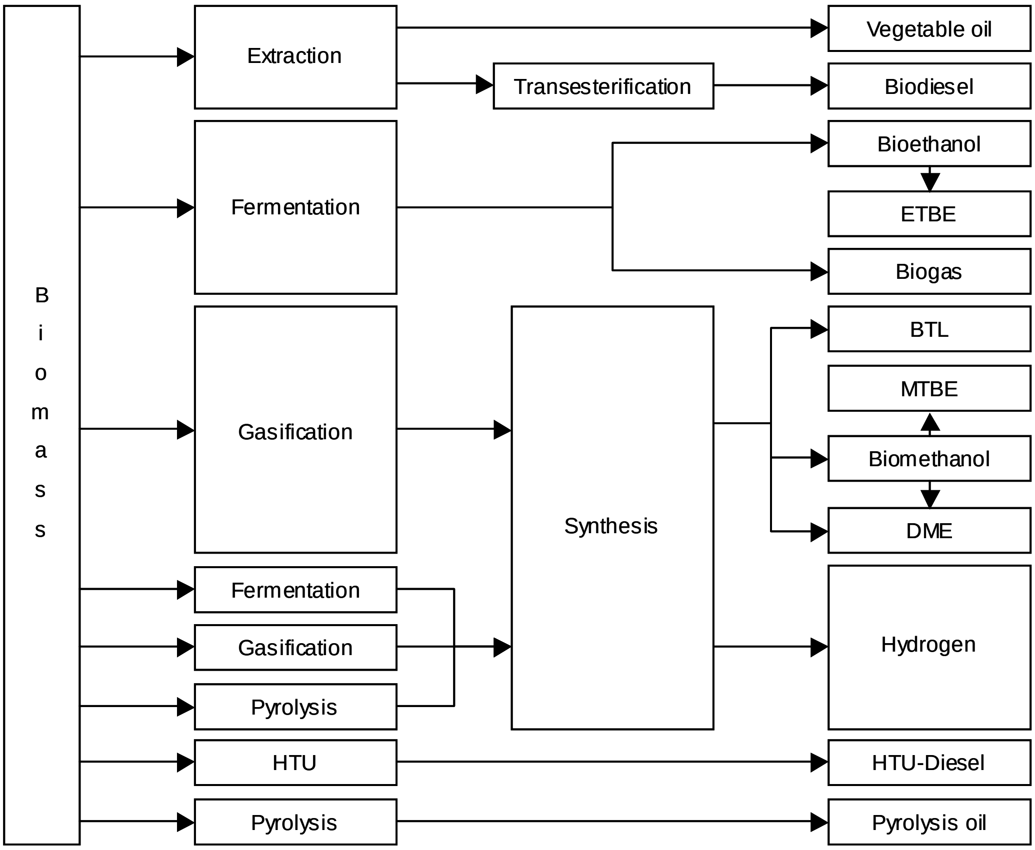

Figure 3 Biofuel paths

Biofuels Currently in Use

- **Bioethanol (EtOH)**

Bioethanol is the most widely used renewable fuels world-wide. The largest proportion is, however, produced in Brazil and the USA. Ethanol from sugar-cane is used mainly in Brazil, while ethanol from corn is mainly produced in the USA. In Europe, on the other hand, ethanol is mainly produced from wheat and sugar-beets. Ethanol production from lignocellulose, potatoes, millet, and municipal wastes are comparatively unimportant in the moment.

- **ETBE (Ethyl Tertiary Butyl Ether)**

The raw materials used in specific countries mentioned above apply also for the ETBE production. ETBE is blended in up to 15 % of gasoline in France.

- **Biodiesel**

In Europe, biodiesel is produced prevailingly from rapeseed and to a much lesser extent from sunflowers. In North America, biodiesel is mainly produced from soybeans and to lesser extent from canola. In South Asia, biodiesel is produced from palm oil and to lesser extent also from coconut oil. In Great Britain, biodiesel is produced from recycled vegetable oil and in Austria and Germany, also from animal grease or used cooking grease or cooking oil.

The transesterification of biodiesel involves generally methanol of fossil origin. It can, however, also be done with biomethanol or with bioethanol to create vegetable oil ethyl esters. There have nonetheless been no studies on this subject.

- **Vegetable oil**

Only a marginal amount of pure vegetable oil is used as fuel nowadays. In Germany, mainly locally pressed rapeseed oil is used, while in the USA principally soybean oil is used. The relative unimportance of pure vegetable oil as compared to biodiesel is reflected in the clearly smaller number of research about it.

Biofuels Not Currently Mass Produced

- **Biomethanol (MeOH), MTBE (Methyl Tertiary Butyl Ether), DME (Dimethyl Ether), BTL (Biomass-to-Liquid)**

These fuels can be produced from synthesis gas a result of biomass gasification. Materials used for the gasification are mainly materials with lignocellulose content such as straw and wood, while other biomass raw materials can also be used.

- **Pyrolysis Oil Diesel**

Pyrolysis oil is produced by pyrolysis (thermal conversion of biomass in the absence of oxygen). It can be used for the production of a diesel substitute. Materials with lignocellulose content are also likely to be preferred for this process in the future. There are no studies on the energy and greenhouse gas balances of pyrolysis oil diesel.

- **HTU Diesel (Hydro Thermal Upgrading)**

Bio-crude oil is produced from soaked and rotted biomass in the production of HTU diesel. This can be used to substitute diesel. Biomass raw materials with high water content, e.g.

sugar-beet pulps, serve as suitable materials for this process. There are also no studies on the energy and greenhouse gas balances of HTU diesel.

- **Biogas**

Biogas is produced from the anaerobic fermentation of organic materials (liquid manure, straw, grass, waste, etc.). The biogas has to be dissected into its components methane, carbon dioxide and nitrogen, before it can be used as fuel. The methane resulted in the process can be used in the same way as natural gas.

- **Hydrogen**

There are different possibilities for the production of hydrogen from biomass.

- **Gasification.** The most commonly used process in pilot and demonstration studies is the biomass gasification that can take place at lower temperature than coal gasification and produce a hydrogen-rich synthesis gas. Different gasification types and processes are available for hydrogen production. Allothermal steam gasification, to which heat is externally supplied, shows the highest hydrogen concentration.
- **Fermentation (biogas).** Fermentation can yield methane-containing biogas from suitable raw materials. This biogas can be reformed like natural gas and processed to pure hydrogen.
- **Fermentation of hydrogen-containing intermediate products.** Hydrogen-containing intermediate products, e.g. ethanol, can be produced through fermentation. This can also be reformed to hydrogen.
- **Pyrolysis.** Biomass pyrolysis can contribute directly to hydrogen production or in combination with other thermo-chemical processes. For example, pyrolysis oil or pyrolysis gas can be combined with, among others, the burning of pyrolysis coke be reformed to hydrogen.
- **Hydrogen generated from algae.** Special green algae that contain the enzyme hydrogenase are capable to produce hydrogen. Hydrogen production takes place when sulphur is removed from water. The algae are no longer able to grow in the absence of sulphur. Instead, the energy generated from photosynthesis is used, with the help of the enzyme hydrogenase, to split the water into hydrogen and oxygen. That means, the algae are no longer able to use the energy from photosynthesis and therefore energy will be released in form of hydrogen.

Table 5 lists all the biofuels with publications to energy and greenhouse gas balances analysed in this study.

Table 5 Biofuels considered in this study and their fossil fuel counterparts

Biofuels	Fossil fuel counterparts
Bioethanol	
— Bioethanol from sugar-cane	— Gasoline
— Bioethanol from corn	— Gasoline
— Bioethanol from wheat	— Gasoline
— Bioethanol from sugar-beets	— Gasoline
— Bioethanol from lignocellulose	— Gasoline
— Bioethanol from potatoes	— Gasoline
— Bioethanol from molasses	— Gasoline
ETBE	
— ETBE from wheat	— Fossil MTBE
— ETBE from sugar-beets	— Fossil MTBE
— ETBE from lignocellulose	— Fossil MTBE
— ETBE from potatoes	— Fossil MTBE
Biodiesel	
— Biodiesel from rapeseed	— Fossil diesel fuel
— Biodiesel from sunflowers	— Fossil diesel fuel
— Biodiesel from soybeans	— Fossil diesel fuel
— Biodiesel from canola	— Fossil diesel fuel
— Biodiesel from coconut oil	— Fossil diesel fuel
— Biodiesel from recycled vegetable oil	— Fossil diesel fuel
— Biodiesel from animal grease	— Fossil diesel fuel
— Biodiesel from used cooking grease	— Fossil diesel fuel
Vegetable oil	
— Vegetable oil from rapeseed	— Fossil diesel fuel
— Vegetable oil from sunflowers	— Fossil diesel fuel
Biomethanol	
— Biomethanol from lignocellulose	— Gasoline * / Methanol from natural gas
MTBE	
— MTBE from lignocellulose	— Fossil MTBE
DME	
— DME from lignocellulose	— Fossil diesel fuel
BTL	
— BTL from lignocellulose	— Fossil diesel fuel
Biogas	
— Biogas from organic residues	— Gasoline * / Natural gas
— Biogas from cultivated biomass	— Gasoline * / Natural gas
Hydrogen	
— Hydrogen from lignocellulose	— Gasoline * / Hydrogen from natural gas
— Hydrogen from organic residues	— Gasoline * / Hydrogen from natural gas

***** fuel counterparts used in figure 4 and 5
(further fuel counterparts and drive propulsion technologies were considered in the appendix A 2.4.6)

4 Findings

In this chapter, findings of the analyses and comparison of the biofuels considered will be presented and discussed. The findings will be organized into the following sections “Energy and Greenhouse Gas Balances”, “Further Environmental Impacts”, “Costs”, “Potential” and “Future Development”. The respective detailed description and detailed presentations as well as interim findings are documented in the Appendix.

4.1 Energy and Greenhouse Gas Balances of Biofuels

The described procedure in Chapter 2 describes accordingly the analyses, comparisons and interpretations. The individual detailed findings are presented in details in Appendix A 2. The findings are summarized in the following.

Finding 1 The existing LCAs do not cover all biofuels

For many biofuels, studies on their energy and greenhouse gas balances are available. These biofuels can be organized into a wide spectrum, in which different options (different yields, usage of co-products, assumptions of data basis) of the biofuel production are considered. For some biofuels there are however only a few or no studies.

- Concerning the biofuels currently in use, biodiesel from palm oil has not been investigated.
- Concerning the biofuels that are not mass produced today, no studies are found for biodiesel from jatropha, pyrolysis oil, and HTU diesel.
- Regarding conversion path, studies only exist for DME, methanol, and BTL (production from lignocellulose). There is no available research on all other possibilities, from cultivated biomass to the use of organic residues.
- For some biofuels from cultivated biomass, supplementary analyses had to be added in order to secure the spectrum. These include biodiesel from coconut oil and bioethanol as well as ETBE from sugar-cane and potatoes.

Finding 2 Not all LCAs can be considered as representative: derivation of spectrums is thus necessary

The findings of a list of LCAs could not be considered as representative. It was therefore necessary to derive own spectrums, which differ from the minimum and maximum values of the analysed studies. LCAs are considered as non-representative due to the following reasons (for details, see Ch. 2.4):

- Co-products are not considered
- The greenhouse gas N_2O (emissions during fertilizer production, fertilizer application, from the agricultural reference system) is not or only partially considered
- Consideration of human labour
- The data basis no longer reflects the state-of-the-art technology (conversion technology, amount of fertilizer used, etc.)
- Failure to consider agricultural reference system or alternative usages

Finding 3 The findings vary depending on assumptions concerned, which accounts for a wide spectrum

The spectrum (see Fig. 4 and 5 for biofuels in comparison with fossil fuel counterparts) resulted from the difference in data basis, yields, process technology, and the assessment of co-products. This will be elaborated with examples in the following:

Data basis

In the agricultural sector, individual studies on different resources were used. For example, the use of nitrogen fertilizer in the analysed studies on bioethanol from wheat vary between 53 (Elsayed 2003) and 195 kg N/ha (Levington 2000). Nitrogen fertilizers are often the largest factor in agriculture as regards use of non-renewable primary energy, CO_2 and N_2O emissions. However, not only does the used amount vary greatly, the primary energy demand for the production of nitrogen fertilizers also varies much. In the studies on bioethanol from corn, it varies between 70 MJ/kg N (Pimentel 2003) and 42 MJ/kg N (GM 2001).

Yields

In the studies on ethanol, the sugar-beet yields vary between 56 tonnes/ha (IFEU et al. 2000, Germany as reference) and 86 t/ha (IFEU et al. 2000, the Netherlands as reference) and the wheat yields vary between 2.7 t/ha (S&T 2003) and 9.0 t/ha (Ademe 2002). These yields are representative for their reference location respectively.

Process technology

The different process technology affects for example the BTL production. Here, the non-renewable primary energy demand and consequently also the greenhouse gas emissions are, above all, dependent on how well the endothermal synthesis gas production and the exothermal Fischer-Tropsch synthesis can be attuned.

Assessment of co-products

The primary energy demands and greenhouse gas emissions are 100 % assigned to the final products in a few studies, so that the co-products are not accounted for (FfE 1999). In the IFEU study (2002) on bioethanol from sugar-beets, the allocations vary between 15 and 95 % as applied to bioethanol. The study on bioethanol from wheat shows that the advantages of bioethanol are comparatively small when the credit procedure is used. The advantages of bioethanol are four times higher when the allocations procedure is being applied.

Finding 4 The findings are dependent on the type of the fossil fuel counterparts

As shown in Figure 5, the energy and greenhouse gas balances of liquid hydrogen from lignocellulose are favourable as compared to gasoline as counter case, when the auxiliary energy for the liquefaction stems from a fossil-based power mix. On the contrary, the results of liquid hydrogen from lignocellulose as compared to liquid hydrogen from natural gas are favourable to the biofuel in any case. This can be explained by the substantially higher demand for the production of liquid hydrogen from natural gas as compared to gasoline. The detailed findings of individual biofuels as compared to different fossil energy counterparts as well as to different motor technologies (ICE vs. FC) are found in Appendix A 2.4.6.

Finding 5 Qualitative findings of biofuels from cultivated biomass are consistent: they are advantageous in energy and greenhouse gas balances

The energy and greenhouse gas balances of the considered biofuels from cultivated biomass are favourable for all biofuels compared to their fossil fuel counterparts. This is valid for all cases in our opinion although a few studies concluded the opposite (cf. e.g. Pimentel 2003). Furthermore, the following detailed results can be concluded:

- Primary energy saved and the avoided greenhouse gas emissions correlate very closely when bioethanol, ETBE, biodiesel, and vegetable oil from different raw materials are *compared within one of the four groups*. The statement made to primary energy can thus generally be applied also to the reduced greenhouse gas emissions.
  - The comparison *between* ETBE and biodiesel shows advantages for ETBE concerning reduction in primary energy use, as long as fossil MTBE is substituted by ETBE. Depending on the raw materials and procedure considered, the reduction in greenhouse gas emissions can work in the opposite direction.
- In spite of the extra procedural steps, ETBE shows advantages compared to bioethanol among all examined biomass raw materials, as long as ETBE substitutes MTBE. This can be explained by the fact that ETBE substitutes MTBE, which is produced with relatively high energy demand, while bioethanol substitutes gasoline, which is produced with lower energy demand.
  - From the fact that ETBE has more advantages than bioethanol, and bioethanol from sugar-cane is the most favourable among all forms of ethanol, it can be concluded that ETBE from sugar-cane is most favourable.
  - The production of ETBE from sugar-beets is the second best option, while it has the most advantages when more than average level of sugar-beet yields is applied.
- Whether bioethanol is better than biodiesel depends on the raw materials used for the two fuels in such a comparison of the bioethanol and biodiesel options.
- Biodiesel from rapeseed is more favourable than pure rapeseed oil as the co-product glycerine produced in transesterification can be used to substitute technically produced glycerine.

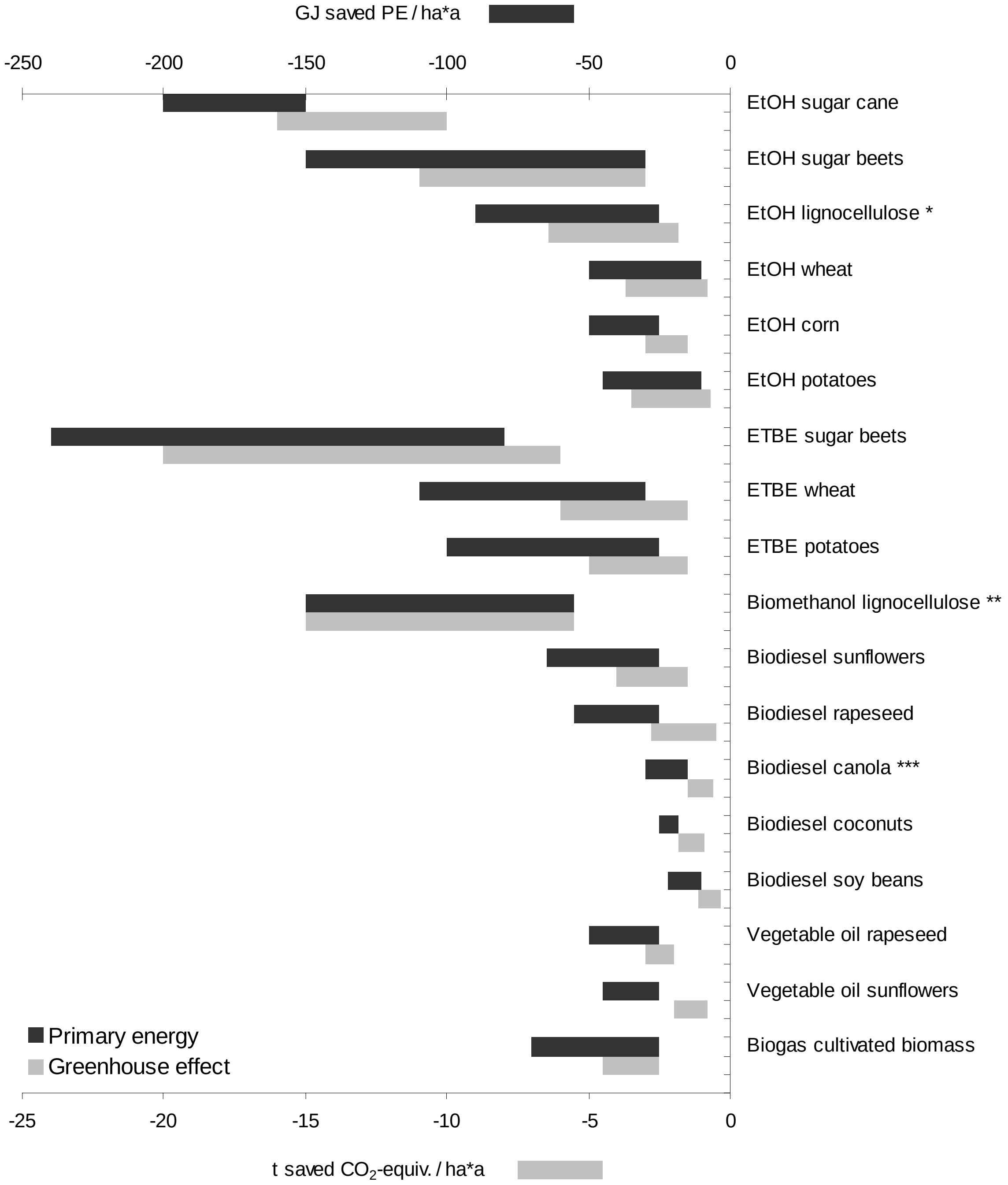

Figure 4 Results of the energy and greenhouse gas balances of the analysed biofuels from cultivate biomass as compared to the fossil fuel counterparts (cf. Table 5) in GJ saved primary energy/(ha∗a) and in metric tons saved CO_2 equivalent/(ha∗a). The negative values imply advantages for the biofuels, as in this case primary energy or CO_2 equiv. emissions are saved in the total balance. The zero mark means that the CO_2 emissions are balanced, when the total life cycle (biofuel minus fossil fuel) is considered.

* The spectrums for ethanol from lignocellulose are not unrestrictedly comparable with the others, since lignocellulose from cultivated biomass and that from organic residues are put together here.

** only from cultivated biomass

*** Canadian brand name of summer rapeseed

Finding 6 To answer different questions usually different references must be used, which results in sometimes the same and sometimes different answers

Different question formulations require different references. For the limited land area available for biofuels from cultivated biomass, the area reference is very important (see Fig. 4). On the other hand, when the mileage of biofuel-driven vehicles is compared to those driven with fossil fuels, the kilometre reference should be used (see Fig. 5). While only biofuels from cultivated biomass are listed in Figure 4, the kilometre reference was used to compare the efficiency of all fuels (from cultivated biomass and organic residues). The comparison shows that many findings align with each other qualitatively. For example, “Finding 5” concerns also the kilometre reference. In a few cases, in comparing with biofuels from organic residues, different or additional findings are reported:

- Contrary to the area reference, ethanol (from all studied biomass raw materials) is favourable in km reference compared to ETBE. The area-related advantages of ETBE as compared to ethanol can be explained with the comparatively high energy-related hectare yield of ETBE.

The results and corresponding references for other questions formulations are listed in Appendix A 2.4, where their total life cycles are compared (references: per MJ fuel content, saved CO_2 equivalent per saved non-renewable primary energy etc.). The results for the WTW and WTT Analyses are also provided there.

Illustrations of the arrow with a question mark ⇨ ?

The arrow with a question mark was used for all biofuels from organic residues in Figure 5. The symbol means that advantages of biofuels can be reduced when alternative usages (e.g. used cooking grease as animal feed) are considered. In the existing analyses, the alternative usages are equated to zero. As the alternative usages cannot be quantified in this study, the arrow with a question mark is used to mark the direction of change occurred in the balances when alternative usages can be considered (see also Finding 7).

Finding 7 A big research need for a few biofuels from organic residues such as BTL

There are only very few studies conducted on the potentials of a few biofuels which can be generated from organic residues (cf. “Finding 1”). In addition, from the LCA perspective, the real or potential alternative usages of organic residues such as used cooking grease or residual wood should in principle be considered. This has been ignored by existing analyses as the alternative usages are evaluated to zero. It is well-noted that a few kinds of used cooking oil can be used as animal feed, or few kinds of residual wood can be used to generate energy. In most cases, to a greater or lesser extent, a big credit arises that reduce the advantages of biofuel. The direction is shown by the **arrows** drawn to the concerned biofuels in Figure 5. As there is neither detailed research nor reliable spectrums that can be used, a **question mark** is added. This makes clear that a biofuel can be, in an extreme case, worse than fossil fuel. An example would be when saw dust is not used for energy generation directly because the lignocellulose content is converted to biofuel with a certain conversion loss.

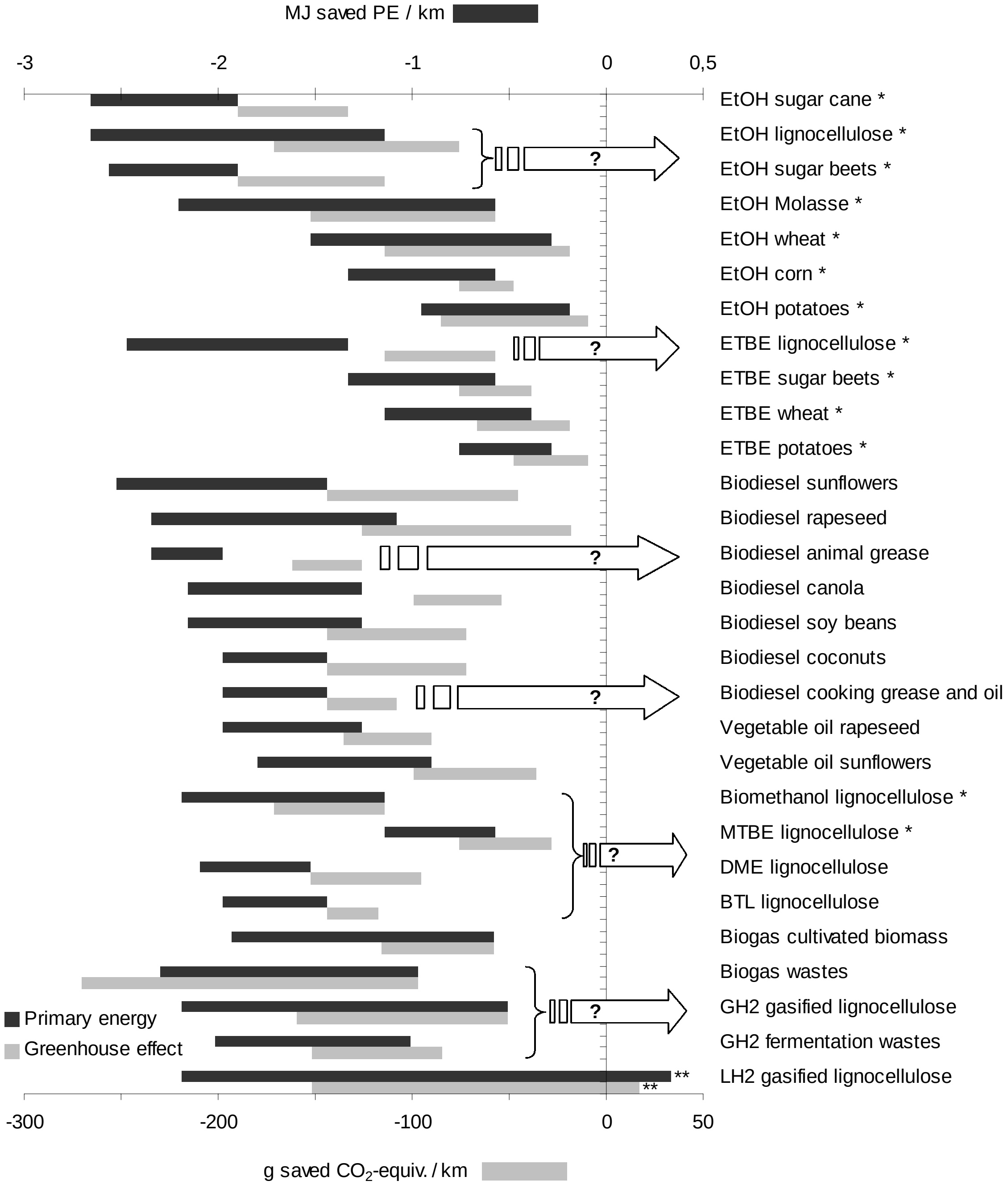

Figure 5 Results of energy and greenhouse gas balances in the comparison between the analysed biofuels and their fossil fuel counterparts (cf. Table 5) in MJ saved primary energy and g saved CO_2 equivalent/km. The negative values imply advantages for biofuels, as in these cases the primary energy or CO_2 equiv. emissions are reduced in the total comparison. The zero mark means that the CO_2 emissions are balanced, when the total life cycle (biofuel minus fossil fuel) is considered.

* Reference: 100 % biofuel (also the fossil proportion of ETBE/MTBE in case of ETBE/MTBE); fuel consumption was arranged to be that of the blend.

** Wide spectrum as the energy used for the production and distribution can be taken from non-renewable primary energy sources or from the product gas produced (see also Finding 4).

4.2 Further Environmental Impacts of Biofuels

In addition to the energy resource consumption and greenhouse gas emissions, there are further environmental impacts that are connected to the production and usage of fuels. Here, environmental impacts that are taken into account in different LCA studies will be considered. These include the impact categories acidification, eutrophication and photosmog, the parameter laughing gas (N_2O) for the impact category ozone depletion and a few toxic substances (see Tab. 6).

Table 6 Environmental impacts considered in this study

Environmental impact	**Aggregation**	**Parameter**
Resource consumption energy	Cumulated primary energy from non-renewable sources	crude oil, natural gas, hard coal, lignite, uranium
Greenhouse effect	CO_2 equivalent	CO_2, CH_4, N_2O, SF_6, CFC, some CHC, …
Acidification	SO_2 equivalent	SO_2, NO_x, NH_3, HCl, HF, H_2S, …
Eutrophication	PO_4 equivalent	NO_x, NH_3, NH_4^+, PO_4^{3-}, NO_3^-
Photosmog	C_2H_4 equivalent or NO_x adjusted C_2H_4 equivalent, respectively	CH_4, NMHC, NO_x, …
Ozone depletion		N_2O
Toxicity		miscellaneous

The comparison and interpretation are made specific to each fuel. A list of which individual literature was used for which fuel is found in the detailed results in Appendix A 3. A summary of the findings is as follows:

Finding 8 The number of LCA studies on further environmental impacts is extremely small

The analysis of all the studies shows that an interpretation of the further environmental impacts of biofuels in a few studies was possible only on the basis of few studies. In many studies, only a few individual parameters were accounted (e.g. SO_2), which does not allow an interpretation of the environmental impacts. When for example only SO_2 is accounted, a discussion on acidification is not possible as in particular NO_x and NH_3 emissions of the biofuels from cultivated biomass are particularly important. In one case, not all the steps in the life cycle were considered for the further environmental impacts. The results are therefore not comparable with other studies. Table 7 offers an overview how many comparable studies for individual fuels are available. Table 8 lists the studies that have accounted thoroughly for the further environmental impacts of the fuels considered.

While the further environmental impacts of commonly used biofuels such as biodiesel and bioethanol are presented in many studies, research on future fuels like BTL and MTBE is missing in these analyses. Also, for some biofuels that are already available in the market, like bioethanol from sugar-cane or biodiesel from used cooking oil, there is a lack of studies about their further environmental impacts.

Table 7 Number of literature sources on further environmental impacts of individual biofuels

Biofuel	**all Biomass types**	**Cultivated biomass**	**Organic residues**
Bioethanol	3 (+ 6 incomplete)	2 (+ 5 incomplete)	2 (+ 2 incomplete)
ETBE	4	3	2
Biodiesel	5 (+ 5 incomplete)	5 (+ 5 incomplete)	(1 incomplete)
Vegetable oil	1 (+ 1 incomplete)	1 (+ 1 incomplete)	0
Biomethanol	2 (+ 3 incomplete)	1 (+ 3 incomplete)	1 (+ 1 incomplete)
MTBE	0	0	0
DME	1 (+ 1 incomplete)	0	1
BTL	0	0	0
Biogas	(2 incomplete)	(1 incomplete)	(2 incomplete)
Hydrogen	(2 incomplete and not comparable)	0	(2 incomplete and not comparable)

Table 8 Literature sources with complete presentation of further environmental impacts

Sources	**considered Biofuels**
FAT 2000	Biodiesel from rapeseed
Fromentin 2000	Bioethanol from cultivated biomass and organic residues
IFEU et al. 2000	ETBE and biodiesel from diverse cultivated biomass types
IFEU 2001	Rapeseed oil
IFEU 2002a	Bioethanol and ETBE from diverse cultivated biomass types
IFEU 2002b	Biodiesel from sunflowers
IFEU 2002c	Biomethanol from organic residues, DME from organic residues
IFEU 2003	Biodiesel from rapeseed
NREL 1999	ETBE from organic residues
NREL 2002	Bioethanol from organic residues
Pehnt 2002	Biomethanol from organic residues
VITO 1997	Biodiesel from rapeseed

Finding 9 The results are highly dependent on the questions and accounting methods

The analysis of different LCA studies shows that the results on energy and greenhouse gas balances depend greatly upon the question formulations and accounting methods. Particularly worth mentioning is:

- **Alternative usage of fuels from remnants or organic residues.** Depending on the question formulation, the system boundaries for the same biofuel can differ notably – especially when organic residues are used as raw materials. In an LCA on biodiesel from used grease, depending on the question formulation, the used grease can be entered as without "ecological baggage" in the balance, or it can be calculated to have alternative usages e.g. energy generation by combustion. For another example, straw produced from wheat cultivation could be considered energy delivering in the process of ethanol production from wheat.

- **Provision of energy demand.** The energy demand for the conversion to ready-to-use biofuel can be satisfied by different sources: from the power network, through industries' own power or heat provision means such as natural gas, light or heavy heating oil, etc., which in general have less important effects in greenhouse gas balances and energy balances, but a larger impact in emissions of NO_x and SO_2. If biogenous energy sources are used supplementary to fossil fuels to satisfy the energy demands, it can also have a big impact. For example: CSIRO (2001) demonstrates that bioethanol from wheat can be produced by a process with fossil fuels or with wheat straw, which can lead to a change of sign in case of photosmog.
- **Location of emissions.** Different from the situation regarding energy balances and greenhouse gas balances, the location of emissions is also very important. For example, the diesel particulate emissions released (heavy oil combustion etc.) from ocean steamers on the high seas are assessed completely differently in toxicity compared to that emitted from vehicles in the inner cities. In some cases, the total balance can lead to a change of sign (see Tab. 9 developed from Reinhardt 1999). This can also be found in the description of account methods like in Borken (1999). This was considered by IFEU (all years), but hitherto no other LCAs for biofuels.

Table 9 RME balance of toxicological relevant and total nitrogen oxides emissions with reference to 1 kg diesel fuel or diesel fuel equivalent

Life cycle segment	**Nitrogen oxides regional** (location category I and II)* g/kg diesel fuel	**Nitrogen oxides total** (location category I, II, and III)* mg/kg diesel fuel
RME supply	0.85	-1.34
RME use	10.19	10.19
Diesel fuel supply	0.65	0.79
Diesel fuel use	10.19	10.19
Balance	**0.20**	**-2.12**

* location category I = emission place city, location category II = emission place country, location category III = emission place ocean

- **Consideration of co-products.** There are different LCA techniques to deal with co-products resulting from biofuel production. Credits should preferably be given to these co-products in order to better describe the reality. In few studies, the total expenditures for the different products are divided. For example the rapeseed meal that results from the seeds through extraction of rapeseed oil can be used as feeding stuff. In this case, another protein feeding stuff like soybean meal will be accounted. There are however also studies which divide the demand based on mass, economic values, or energy content. This produced dramatic differences in the findings.

Finding 10 Results here can only be described qualitatively

As mentioned above, there is only an extremely small number of LCA studies for each biofuel (see Tab. 7). Thus, the topics discussed in “Finding 9” depend heavily on qualitative results. The derivation of spectrums for the considered magnitude corresponding to the procedure of energy and greenhouse gas balances is hence not scientifically reliable.

Finding 11 Different results for biofuels from cultivated biomass and organic residues

There are obvious differences in environmental impacts acidification, eutrophication and the parameter laughing gas in the case of biofuels from cultivated biomass and that from organic residues.

- **Biofuels from cultivated biomass.** Due to the large nitrogen emissions (N_2O, NO_x, NH_3, NO_3^-, NH_4^+) produced in connection with agricultural production of cultivated biomass, biofuels are consistently less favourable in the results for acidification, eutrophication, and laughing gas. This applies even when different accounting methods for acidification (aquatic and terrestrial, via water- or airborne emissions) are used for the comparison between biofuels and fossil fuels.

  An analysis of individual cases, which examines the exact circumstances, is needed when a quantitative confirmation is desired.
- **Biofuels from organic residues.** The results on biofuels from organic residues are, on the contrary, not consistent. The advantages or disadvantages in acidification and eutrophication have to be examined on each individual case in respective studies even for a qualitative confirmation. The parameter N_2O is generally not important for these biofuels, but should be checked for individual cases.

Finding 12 A conclusion about photosmog is not yet possible

The understanding about photosmog is limited. This is because until now photosmog is accounted by means of POCP equivalent to which practically only hydrocarbons are entered. Depending on its concentration relative to that of hydrocarbons, NO_x can also contribute significantly in the production of photosmog under specific meteorological conditions. This is considered by the so-called NO_x adjusted POCP equivalent which has hitherto been applied in very few LCA studies. A change of sign arises in (IFEU 2003) about RME. Insofar we can conclude from our present knowledge that a consistent conclusion about photosmog is only possible in the cases when the hydrocarbons and NO_x have the same sign in the total balance. Particularly in this case, the emission accounting has to be conducted considering the environmental and toxicological impact (see “Location of emissions” in Finding 9). This has not been investigated in LCAs on biofuels except by IFEU (all years).

Both the accounting method and total system accounted can lead to advantages or disadvantages for biofuels. An individual case study is always needed for particular external conditions.

Finding 13 There is a big knowledge gap in toxic parameters and emissions difference by motor usages

Only very few studies consider more than about five parameters (see Tab. 1). The magnitudes of hydrocarbons formaldehyde, benzene, and PAH or particulates as well, which cause ecological and human toxicity, are all very important in the total estimation of ecological impact of biofuels. There is a lack of reliable estimations about the total life cycle on this topic. Present information about different blends, which are discussed or partly available in the market, and their emissions in different motor concepts is also scientifically not reliable. This applies also for NO_x if significant emission differences should appear.

4.3 Costs of Biofuels

In this chapter, the production costs of biofuels and those of conventional fuels are compared. The production costs of biofuels include the costs of raw materials, transport costs of raw materials, conversion costs, and proceeds from co-products as well as the distribution costs. Taxes and profit surcharges of the fuels are not considered, as this will falsify the comparison.

The data are collected from the literature sources as listed in Table 1 after critical examination and adjustment where necessary. The details are documented in Appendix A 4.

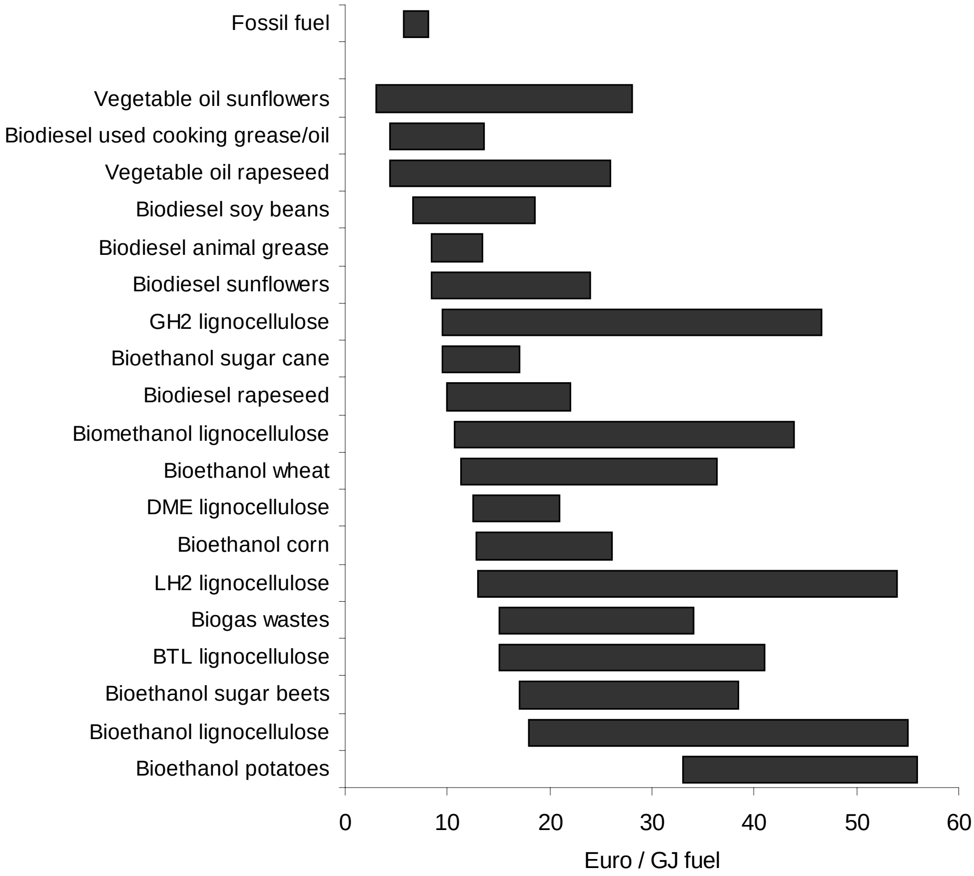

Figure 6 Production costs of biofuels compared to the production costs of fossil fuel in Euro/GJ fuel content

Finding 14 The existing cost estimations do not cover all biofuels

- There are no costs estimations for ETBE.
- There is no division of production costs to individual components (raw material costs, conversions, proceeds from co-products and distribution) for some biofuels (bioethanol from sugar-cane, biodiesel from soybeans). These cost estimations are not comprehensible and cannot be interpreted.

Finding 15 The production costs of fossil fuels are in most cases lower compared to those of biofuels

The comparison of production costs in Euro / GJ fuel content shows that fossil fuels are in most cases cheaper to produce than biofuels (Fig. 6). In a few cases, however, biofuels are produced for the costs of fossil fuels.

- This applies to biodiesel from used cooking grease, when no raw material costs are assumed and that low conversion costs are applied. The conversion costs spread out in a spectrum and can be higher, so that biodiesel from used cooking grease cannot be produced for the price of fossil fuels.
- The production costs from vegetable oil from rapeseed and sunflowers spread out in a widely fluctuating spectrum and can, under favourable conditions, also be as low as the price of fossil fuels. For the spectrum shown in the figure, the raw material costs for the production of vegetable oil are identical with those of biodiesel and the conversion costs for vegetable oil production – due to the missing procedural steps for the transesterification – are lower than those of biodiesel production. Whether the production costs of vegetable oil are smaller than those of biodiesel is dependent in particular on the amount compensated through the sale of glycerine. In case of high proceeds, the production costs for biodiesel are lower than those of vegetable oil, while low proceeds will lead to higher costs than vegetable oil.

These basic connections apply also for other references, for example for Euro per 100 km (see Fig. 7). Due to its low fuel demand, hydrogen is more favourable compared to all other fuels as against the reference Euro per GJ fuel content. This applies to a lesser extent also for the biodiesel options, which are comparatively better than the ethanol options in contrast to the reference per GJ fuel content.

Finding 16 No clear differences between biofuels from cultivated biomass and organic residues

The production of biofuels form organic residues is in some cases cheaper than that from cultivated biomass. A generalization is not possible due to the extremely wide spectrum especially for the production costs for organic residues (free supply, costly collection from forest residual wood, etc.). Comparisons have to be made for each biofuel with their respective basis conditions.

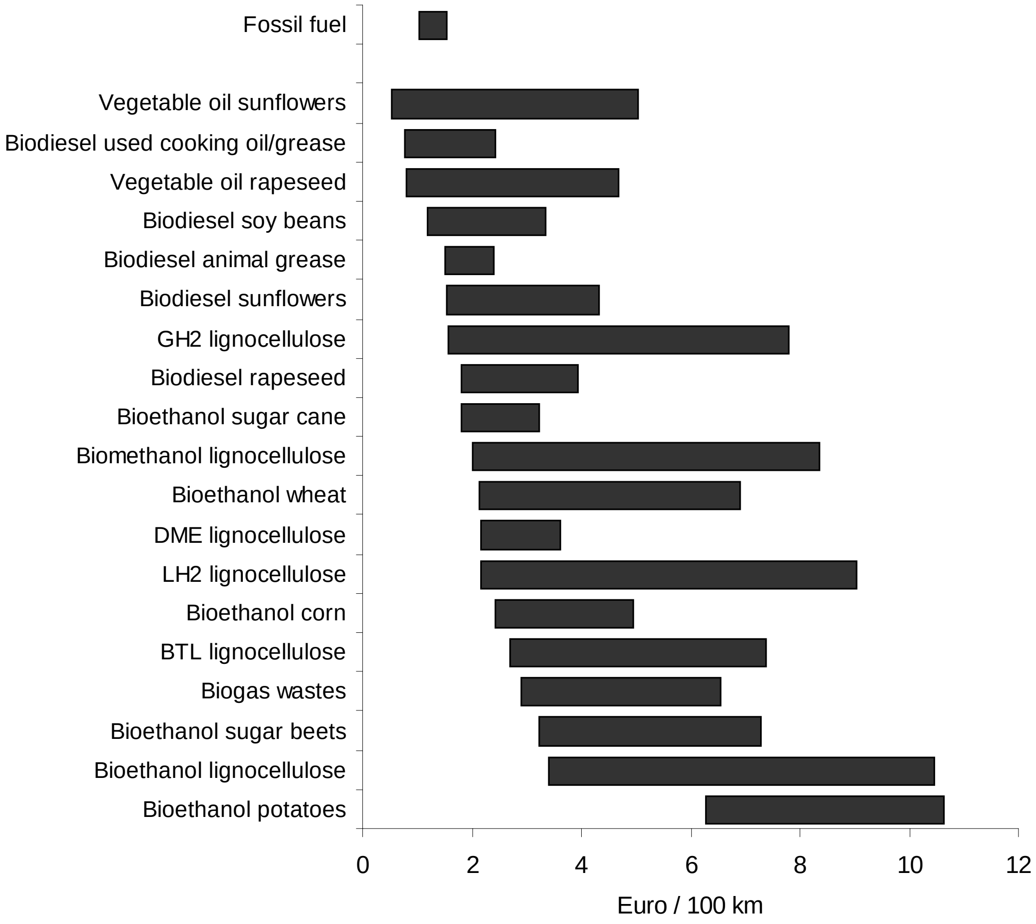

Figure 7 Production costs of biofuels (without vehicle costs) compared to the production costs of fossil fuel in Euro / 100 km.

* Reference: 100 % biofuels; fuel consumption was arranged to be that of the blend (cf. Tab. 2).

Finding 17 The avoidance costs (costs per saved greenhouse gas emissions or saved energy source) show an extreme spectrum

In situations where biofuels are produced more cheaply than fossil fuels (see “Finding 15”) no costs per saved greenhouse gas emissions or saved energy sources are recorded, rather there is a “gain”. There are however avoidance costs for the majority of the biofuels, which spread out in wide spectrum (Fig. 8). The avoidance costs are the highest for biofuels with high production costs and small saved primary energy or greenhouse gas emissions. An example would be bioethanol from potatoes.

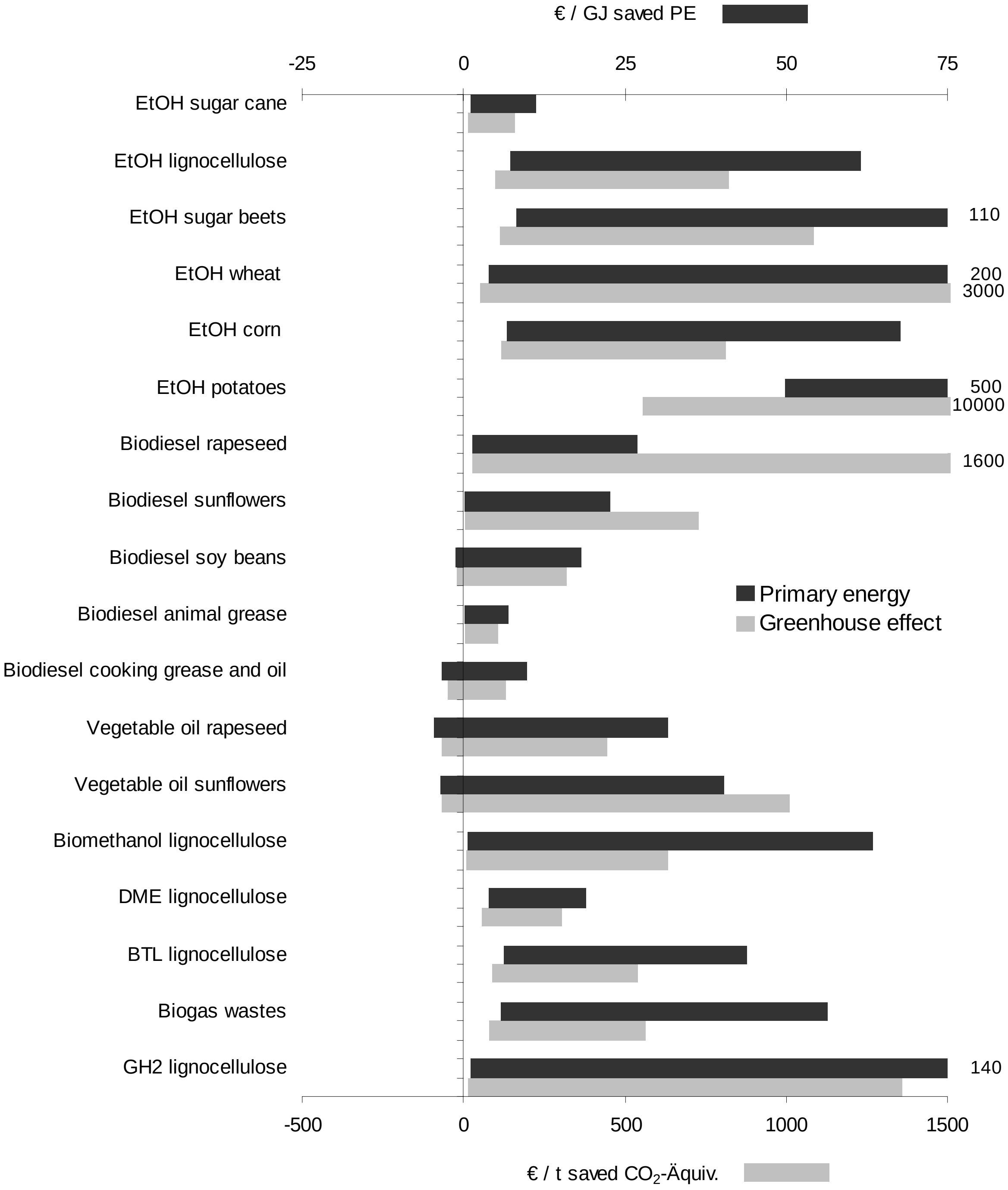

Figure 8 Costs per saved primary energy source consumption or greenhouse gas emissions in Euro/GJ saved non-renewable primary energy or Euro per metric ton saved CO_2 equivalent (€/t).

Finding 18 The results are very variable and only conditionally comparable to each other

The production costs can vary enormously. In fact, there exists a wide spectrum for each biofuel. The comparability is highly limited due to the following reasons:

- The production costs of fossil fuels and the conversion costs are particularly dependent on the price of crude oil, while there are other important factors for biofuels. In the case of fuels from cultivated biomass, the agricultural production costs, which are subsidized in many countries, are foremost important. The costs for rapeseed vary between 8 (IEA 2003) and 35 Euro / GJ fuel content (Woods 2003) and for wheat between 5.6 and 33.5 Euro / GJ fuel content (JRC 2003) in the studies considered. Concerning biofuels from remnants or organic residues, the alternative usages and saved disposal costs can also be important.
- The production costs were put together for different reference locations and thus natural and economic conditions that cannot be compared directly to each other. These include bioethanol from sugar-cane in Brazil, biodiesel from soybeans in the USA, and bioethanol from sugar-beets in Europe.
- The production costs of the currently available fuels based on real costs are used on the one hand, while future, currently not mass produced fuels are also considered on the other hand. The production costs in these studies can only be estimated.

Lastly, it should be noted that the described costs here represent only a snap shot. For different reference locations and the currently available fuels as well as future fuels, the costs depend in particular on the world market price of crude oil, country-specific agricultural subsidies and federal state-specific different personnel and transport costs. This makes a prognosis impossible. A snap shot can however provide a clue in coherence with the spectrum that offers the best possible comparability.

4.4 Potentials of Biofuels

The analysis of the potentials of biofuels is based on the literature for the reference area Germany, EU, and the world listed in Table 1. It shows that there are research studies which quantify the available potentials, while others describe the potentials qualitatively, some analyse scenarios or some about the achievement of objectives like that of the EU objectives according to the EU Directive on the promotion of the use of biofuels implemented on 17 May 2003. In the following, no core arguments will be presented on the scenario or qualitative argumentation developed thus far. Table 10 provides an overview on the studies considered and the respective potentials estimations thus far available.

- **JRC (2004).** The core argument of this study is that, considering the present usage of biofuels, a big effort is still necessary to achieve the goal of raising the proportion to 2 % by 2005 or a proportion to 5.75 % by 2010 (according to the biofuel directive).

  This study defines the land area demand to achieve the EU objectives (EU-15, EU-25, and EU-27).
    - EU-15: 5 – 12 %
    - EU-25: 5 – 9 %
    - EU-27: 4 – 8.5 %
  - In order to reach a 5.75 % biofuel proportion by 2010, the following proportion of agricultural land would be necessary:
    - EU-15: 16 – 40 %
    - EU-25: 14 – 27 %
    - EU-27: 12 – 23 %

- **IEA (1999).** This study includes estimations which examined the potentials for 10 % of fuel usages to be substituted by alternative fuels world-wide. In do so, a short-term scenario (1 to 5 years) and a long-term scenario (15 to 25 years) are designed to consider the following biofuels: methanol from cellulose, ethanol from sugar-containing plants, ethanol from starchy plants and RME.
  - In order to reach the above mentioned goals, the agricultural used area represents a limited factor. With the reference to the area used, the goal of 10 % usage of biofuels cannot be reached in the short-term scenario. In the long-term scenario, the 10 % goal can be reached on in the case of ethanol from sugar-beets or other plants with high sugar content and methanol from lignocellulose.
  - The production capacity to reach the 10 % gaol is not possible for any biofuel in the short-term scenario. In the long-term scenario, it is possible for methanol from lignocellulose, ethanol from sugar-containing and starchy plants and for RME.
  - Infrastructure is available for the considered biofuels both in the short-term and long-term scenarios.
  - There is no problem in the usage of biofuels considered both in the short-term and long-term scenarios.

- **Pimentel (2001).** The study shows that there is a certain potential in the conversion with biomass to energy, which can contribute to the reduction of energy demand world-wide. However, the related problems regarding the environment, health, and the economy should be thoroughly assessed. The highest priority should be attached to the production of foodstuff in order to feed the rapidly increasing world population. Pimentel concludes negative impacts to the social and economic systems in the production of ethanol from grains. A big ethanol programme would lead to a fuel inflation and high foodstuff prices.

Table 10 Estimations of potentials by different authors with reference in Germany, UK, EU, and the world

<table>
<tr><th>Source</th><th>Reference</th><th>Potential in PJ/a</th><th colspan="3">Comments</th></tr>
<tr><td>Thrän 2004</td><td>Germany</td><td>430 – 834*</td><td colspan="3">from biogenous solid fuels</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">thereof</td></tr>
<tr><td></td><td></td><td></td><td>178 – 207</td><td colspan="2">via spear</td></tr>
<tr><td></td><td></td><td></td><td>563</td><td colspan="2">via residual wood</td></tr>
<tr><td></td><td></td><td>103 – 252*</td><td colspan="3">from cultivated biomass</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">thereof</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">max. 103 via vegetable oil / RME</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">max. 120 via ethanol from wheat</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">max. 252 via ethanol from sugar-beets</td></tr>
<tr><td></td><td></td><td>318 – 464*</td><td colspan="3">from organic residues to biogas generation</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">* technical generation potential, numbers not summable</td></tr>
<tr><td>IFEU 2004</td><td>Germany</td><td>10 – 530</td><td></td><td>technical potential</td><td>sustainable potential</td></tr>
<tr><td></td><td></td><td></td><td>2010</td><td>220</td><td>10</td></tr>
<tr><td></td><td></td><td></td><td>2030</td><td>380</td><td>170</td></tr>
<tr><td></td><td></td><td></td><td>2050</td><td>530</td><td>350</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">only cultivated biomass</td></tr>
<tr><td>Öko-Institut 2004</td><td>Germany</td><td></td><td></td><td>”Biomass” Scenario</td><td>”Environment” Scenario</td></tr>
<tr><td></td><td></td><td></td><td>2010</td><td>143</td><td>102</td></tr>
<tr><td></td><td></td><td></td><td>2020</td><td>149</td><td>87</td></tr>
<tr><td></td><td></td><td></td><td>2030</td><td>153</td><td>103</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">Cultivated biomass and organic residues</td></tr>
<tr><td>DLR 2004</td><td>Germany</td><td></td><td></td><td>Biomass* is used in transport sector preferably</td><td>Biomass** is used in stationary sector preferably</td></tr>
<tr><td></td><td></td><td></td><td>2010</td><td>150</td><td>30</td></tr>
<tr><td></td><td></td><td></td><td>2030</td><td>320</td><td>65</td></tr>
<tr><td></td><td></td><td></td><td>2050</td><td>420</td><td>100</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">* Cultivated biomass</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">** Cultivated biomass and organic residues</td></tr>
<tr><td>EST 2002</td><td>UK</td><td>200 – 1000</td><td>200*</td><td colspan="2">via RME</td></tr>
<tr><td></td><td></td><td></td><td>200 – 500*</td><td colspan="2">via ethanol</td></tr>
<tr><td></td><td></td><td></td><td>800 – 1000*</td><td colspan="2">via methanol or hydrogen from lignocellulose</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">* Numbers are not summable, as the area of 4 mill. ha forecast for energy crops cultivation can be used only once</td></tr>
<tr><td>JRC 2003</td><td>EU-CC-12</td><td></td><td></td><td>2005</td><td>2010</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">biodiesel</td></tr>
<tr><td></td><td></td><td></td><td>Conventional Scenario</td><td>42.8</td><td>71.1</td></tr>
<tr><td></td><td></td><td></td><td>Optimal Scenario</td><td>36.0</td><td>127.3</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">bioethanol</td></tr>
<tr><td></td><td></td><td></td><td>Conventional Scenario</td><td>44.9</td><td>50.9</td></tr>
<tr><td></td><td></td><td></td><td>Optimal Scenario</td><td>85.2</td><td>172.3</td></tr>
</table>

Table 10 continued

LBST 2003	EU	680 – 1630	from residual wood and straw		
			thereof	min	max
			hydrogen	975	1568
			methanol	690	1625
			BTL	1011	1597
			ethanol	681	1076
		410 –1140	from fast growing trees		
			thereof	min	max
			hydrogen	708	1104
			methanol	501	1144
			BTL	734	1124
			ethanol	411	630
		360 –590	biogas from grass		
		360 –590	via biogas		
			thereof	min	max
			biogas	360	592
			hydrogen	249	410
			methanol	272	446
		319	vegetable oil		
CONCAWE 2002	EU-15	260 – 680	7.1 Mt/a = 260 PJ/a* via RME 11.5 Mt/a = 310 PJ/a* via ethanol from wheat 25.3 Mt/a = 680 PJ/a* via ethanol from sugar-beets * Numbers are not summable, as the area of 5.6 mill. ha estimated for energy crops (= set-aside land) can be used only once		
JRC 2002a/b	EU	197 – 770	5.0 Mt/a = 197 PJ/a* via RME 10.7 Mt/a = 284 PJ/a* via ethanol from wheat 28.8 Mt/a = 770 PJ/a* via ethanol from sugar-beets * Numbers are not summable, as the area of 5.6 mill. ha estimated for energy crops (= set-aside land) can be used only once		
JRC 2004	EU	n.d.	qualitative see above		
Moreira 2002	world	47 000	ethanol from sugar-cane in 2020		
Dreier 2000	world	263 000	from cultivated biomass and sustainable forestry 150 000 ethanol 108 000 methanol 5 000 vegetable oil		
		43 000	organic residues, residual wood, harvest residues 20 000 ethanol 15 000 methanol 8 000 biogas		
IEA 1999	world	n.d.	Scenarios see above		
Pimentel 2001	world	n.d.	qualitative see above		

Finding 19 Generally high potentials of biofuels, however reduced when competing land use and biomass usages are considered

The comparison of potentials analyses of biofuels shows that the results vary very widely. A few authors estimate that the potential of biofuels is small (Pimentel 2001, JRC 2004), while other authors consider a high potential for biofuels and can contribute significantly to fuel supply. For example, Dreier (2000) states that the technical potential of biofuels can be increased to three times of current fuel demand world-wide. In addition, the potentials of methanol or hydrogen in Great Britain come up to 50 % of the current fuel demands in Great Britain (1 600 PJ/a; the future fuel demand is calculated depending on transport needs and applied technology with 1 000 – 2 250 PJ/a; EST 2002). In comparison, the current biofuel usage is about 0.8 % in Germany, about 0.5 % in the EU, and about 0.9 % in the USA (IEA 2003).

The potentials specifications offered by different authors are contradictory because of many factors which explain the different properties of each study:

Biofuels considered. The potentials of biofuels is dependent upon which biofuels are being considered. The potentials are lower if only biofuels available today are considered, e.g. in CONCAWE 2002, JRC 2002, JRC 2003, and JRC 2004, compared to studies which also consider future fuels, e.g. BTL and hydrogen (Thrän 2004, EST 2002, LBST 2003, Dreier 2000). This can be explained by the fact that the future fuels are mainly produced from lignocellulose like residual wood, straw, or fast-growing trees, from which an additional raw material for biofuels production comes, and the potentials increase through this addition usage. Furthermore, the potentials of biofuels depend on the type of biomass cultivation. Considering as example biofuels currently available, the potential per unit area of ethanol from sugarbeets is more than double the potential of biodiesel from rapeseed.

Competing land use. The biofuels currently in use are mainly generated from cultivated biomass (rapeseed, soybeans, corn, wheat, sugar-cane, sugar-beets) and to a smaller extent from organic residues (used cooking grease). The potentials of biofuels from cultivated biomass depend foremost on the land available, while those from organic residues do not depend on the amount of land available. Biofuels are in competition with foodstuff production and natural conservation for the land. All authors consider the foodstuff production as a higher priority than the cultivation of energy-producing plants. The amount of land for foodstuff production is foremost dependent on the population growth, which is predicted differently in each reference area. While a population decrease is predicted in Germany, the world is expecting a population growth. Therefore, land available for the cultivation of energy crops tends to increase in Germany while decrease in the world.

In addition to foodstuff production, natural conservation also demands land area, although an extraction of biomass from a portion of this land area is possible under certain circumstances. The area of natural conservation competes directly with foodstuff production for land area. Since foodstuff production has a higher priority than the cultivation of energy crops, foodstuff production reduces the area for energy crops.

A potential estimation reflecting diverse sustainability objectives with the consideration of natural, surface water and soil conservation exists already for Germany (IFEU 2004). A list of other assumptions is also considered here:

- Less specific land area used for transport, households, and industries in the future
- Expansion of organic farming, resulting in a larger land demand because of a lower area-related yield (The Federal Government predicts an increase of organic farming from today's about 4 % to 20 %.)
- The land area needed for the implementation of the goals set by the Federal Natural Conservation Act (§3 and §5 BNatSchG)
- A larger land area need resulting from long-term cultivation on heavily eroded locations

The results show that the potentials differ sometimes considerably from the technical potentials when these objectives are observed (cf. Tab. 10). For other reference locations like the EU and the world, similar differentiated potentials estimations like ours is not known. Recently the WBGU (German Advisory Council on Global Change) completed a kind of road map: the area for natural conservation will remain at 10-20 % level and not more than 3 % to be used for the cultivation of energy crops and for plantations for carbon sink (WBGU 2004).

Competing biomass usages. Competing usages of biomass are also important for the potentials of biofuels. In most studies the technical potential of available biomass is determined to be 100 % for the fuel market. This is an upper theoretical limit. In reality the biomass potentials are dependent on the specific pre-conditions and will get different shares in the power and heat market as well as biobased materials. The results can change considerably when these are taken into consideration. For example, the potential of biofuels in Germany in 2050 is reduced to one quarter when one assumes that the biomass potential is preferably used in the stationary sector rather than in the transport sector (cf. Tab. 10, DLR 2004). There are no detailed potentials estimations of biofuels which consider the competing usages of biomass available for the remaining reference areas (EU and the world).

Political framework. In addition to the availability of new technologies in biofuels production from lignocellulose and the competing land use and biomass usage, the potentials of biofuels depends also heavily on the political framework. It can be demonstrated for example by the introduction of the obligation to set land aside. This market instrument determines that a certain amount of the agricultural area cannot be used for foodstuff production for some time, if at all for the cultivation of certain renewable raw materials like rapeseed for biodiesel. The potentials estimations of a few studies are based on the cultivated biomass exactly on these set-aside land (cf. CONCAWE 2002 and JRC 2002).

Finding 20 Quantification of potentials in the sustainability perspective and competing biomass usages are still missing, especially for the reference location “world-wide”

The previous discussion for Finding 19 applies here.

4.5 Future Development of Biofuels

The future development of biofuels currently in use with regard to their energy and greenhouse gas balances as well as to further environmental impacts are presented in this chapter. For the biofuels that are not yet mass produced today, the spectrums of energy and greenhouse gas balances as presented in Chapter 4.1 demonstrate the future development. The analysis of the future costs development was documented in Chapter 4.3, Finding 18 and down, while the future potentials were described in Chapter 4.4.

The publications listed in Table 11 were studied for the analysis of the future development of biofuels. Here, no new spectrums of the energy and greenhouse gas balances are derived. Rather verbal arguments were provided to discuss the possible future changes in energy and greenhouse gas balances. This draws upon an analysis of determinant sectors (agriculture and conversion) and the data basis determinant for these sectors.

Table 11 Publications on the future development of biofuels examined in this study

Reference year	Author	Year	Reference location	Energy balance	GHG CO_2	GHG CH_4	GHG N_2O	Further emiss.
Bioethanol from corn								
2012	Graboski	2002	USA	x				
2010	Levelton	2000	Canada	x	x	x	x	(5)
2010	Wang	1999	USA	x	(x)	(x)	(x)	
Bioethanol from wheat								
2009	Ademe	2002	France	x	x	x	x	
2010	IEA *	2003	North Amer./EU	(x)	(x)	(x)	(x)	
Bioethanol from sugar-beet								
2009	Ademe	2002	France	x	x	x	x	
2010	IEA *	2003	EU	(x)	(x)	(x)	(x)	
2028	CEC *	2001	USA	(x)				
Bioethanol from lignocellulose								
2010	Levelton	1999	Canada	x	x	x	x	(5)
Bioethanol from organic residues								
2028	CEC *	2001	USA	(x)				
Biodiesel from rapeseed								
2009	Ademe	2002	France	x	x	x	x	
Biodiesel from sunflowers								
2009	Ademe	2002	France	x	x	x	x	
Biodiesel from soybeans								
2010	Levelton *	2002	Canada	(x)	(x)	(x)	(x)	(5)
Biodiesel from canola								
2010	Levelton *	2002	Canada	(x)	(x)	(x)	(x)	(5)
Biodiesel from animal grease								
2010	Levelton *	2002	Canada	(x)	(x)	(x)	(x)	(5)

* contain only partial statements for the future development of biofuels

Finding 21 Future development of energy and greenhouse gas balances can be shown merely to 2010

The objective of this study was to show the future development of energy and greenhouse gas balances of biofuels till 2025. It draws upon the publications available. As the available publications contain statements only to 2010, consequently no statement can be made beyond 2010 in this study. The future development of energy and greenhouse gas balances cannot be estimated reliably beyond the 10/15 years time span. Different scenarios can however be created for the next 50 years, similar to that on the potentials of biofuels in Chapter 4.4.

Finding 22 Lower primary energy demand and lower greenhouse gas emissions for biofuels from cultivated biomass compared to conventional fuels in the future

The advantages of biofuels from cultivated biomass with reference to the primary energy demand and greenhouse gas emissions compared to conventional fuels will increase in the future because of the development in the agricultural sector (increase of biomass yields and smaller primary energy demand for agricultural resources) as well as the development in conversion (higher biofuel yields and smaller primary energy demand for conversion). The higher biofuel yields lead however to the decrease in credits earned from co-products in the future, which will reduce the advantages of biofuels as mentioned before (cf. Levelton 1999).

A detail discussion regarding the development of primary energy demand and greenhouse gas emissions in the agricultural sector and the conversion follows:

Development of the agricultural sector

All authors (Tab. 12) assume an increase in advantages for biofuels as compared to conventional fuels in the agricultural sector.

It can be assume in general that the primary energy demand and consequently greenhouse gas emissions of the agricultural resources will be lower in the future, which results in an increase in advantages for biofuels as compared to conventional fuels. The primary energy demand is determined by the amount of resources on the one hand, and the primary energy demand for the production of the resources on the other hand.

Among all the agricultural resources applied, nitrogen usage affects the energy and greenhouse gas balances the most. The primary energy demand for the production of mineral nitrogen fertilizers could be reduced continually in the last years. The predictions on the future use of nitrogen fertilizers diverge in this respect. While a few authors predict an increase in nitrogen fertilizer usage (Graboski 2002), other authors assume a regress in nitrogen fertilizer usage (Levelton 2000) (Tab. 12).

Both Graboski (2002) and Levelton (2000) predict a regress in phosphorous fertilizer usage.

Diesel usage will regress also according to Graboski (2002). He explains this by the increase in land area where no tillage takes place. Graboski (2002) considers that the biggest reduction of resource use will be the reduction of pesticide usage, which will be cut down to only half from 2000 to 2012. He explains this with the better management in handling pesticides, more effective pesticides needed in smaller amount, as well as the application of genetically modified seeds which do not need insecticides. The impact of the use of pesticides on energy and greenhouse gas balances is however small.

Table 12 Future development of data basis on energy and greenhouse gas balance. Units are metric tons per hectare, kilograms per hectare, and litres per metric ton

Author	Biofuel	Biomass	Reference location	Reference year	Biomass yield in t/ha	N-fertilizer input in kg/ha	Biofuel yield in L/t
Graboski 2002	Ethanol	corn	USA	2000	8.7	150	399
Graboski 2002	Ethanol	corn	USA	2012	9.5	153	422
Levelton 2000	Ethanol	corn	Canada	2000	7.2	140	n.d.
Levelton 2000	Ethanol	corn	Canada	2010	8.3	133	n.d.
Wang 1999	Ethanol	corn	USA	2000	7.8	151	384
Wang 1999	Ethanol	corn	USA	2005	8.2	145	399
Wang 1999	Ethanol	corn	USA	2010	n.b. *	n.b. *	n.b. *
Wang 1999	Ethanol	wood	USA	2005	n.d.	n.d.	288
Wang 1999	Ethanol	wood	USA	2010	n.d.	n.d.	371
Wang 1999	Ethanol	grass	USA	2005	n.d.	n.d.	303
Wang 1999	Ethanol	grass	USA	2010	n.d.	n.d.	390
Levelton 1999	Ethanol	corn	Canada	2000	n.d.	n.d.	470
Levelton 1999	Ethanol	corn	Canada	2010	n.d.	n.d.	475
Levelton 1999	Ethanol	corn straw	Canada	2000	n.d.	n.d.	345
Levelton 1999	Ethanol	corn straw	Canada	2010	n.d.	n.d.	420
Levelton 1999	Ethanol	wheat straw	Canada	2000	n.d.	n.d.	330
Levelton 1999	Ethanol	wheat straw	Canada	2010	n.d.	n.d.	400
Levelton 1999	Ethanol	hay	Canada	2000	n.d.	n.d.	305
Levelton 1999	Ethanol	hay	Canada	2010	n.d.	n.d.	370
Levelton 1999	Ethanol	grass	Canada	2000	n.d.	n.d.	310
Levelton 1999	Ethanol	grass	Canada	2010	n.d.	n.d.	375
Öko-Institut 2004 **	Biodiesel	rapeseed	Germany	2000	3.4	165	437
Öko-Institut 2004 **	Biodiesel	rapeseed	Germany	2010	5.1	247	437
Öko-Institut 2004 **	Biodiesel	rapeseed	Germany	2020	6.1	296	437
Öko-Institut 2004 **	Biodiesel	rapeseed	Germany	2030	7.2	348	437
Öko-Institut 2004 **	Ethanol	wheat	Germany	2000	7.44	165	370
Öko-Institut 2004 **	Ethanol	wheat	Germany	2010	9.30	206	370
Öko-Institut 2004 **	Ethanol	wheat	Germany	2020	11.16	247	370
Öko-Institut 2004 **	Ethanol	wheat	Germany	2030	13.02	288	370
Öko-Institut 2004 **	Ethanol	potato	Germany	2000	39.3	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	potato	Germany	2010	45.2	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	potato	Germany	2020	51.1	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	potato	Germany	2030	56.9	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	sugar-beet	Germany	2000	55.5	145	98
Öko-Institut 2004 **	Ethanol	sugar-beet	Germany	2010	61.0	160	98
Öko-Institut 2004 **	Ethanol	sugar-beet	Germany	2020	66.6	174	98
Öko-Institut 2004 **	Ethanol	sugar-beet	Germany	2030	72.1	189	98
Öko-Institut 2004 **	Ethanol	hay	Germany	2000	8.30	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	hay	Germany	2010	8.80	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	hay	Germany	2020	9.40	n.d.	n.d.
Öko-Institut 2004 **	Ethanol	hay	Germany	2030	9.90	n.d.	n.d.

* This case was not regarded because Wang (1999) assumes that in the year 2010 ethanol is made from lignocellulose and from cellulose, respectively (see below).

** Data basis for the calculation of the biofuel potentials

Development in conversion

Regarding conversion, all authors assume that the biofuel yields will rise due to technological advances (Tab. 12), which give an edge to biofuels in comparison to conventional fuels.
The energy demand and the emissions of CO_2 equivalent as a result of conversion of biofuels depend on the assumption of individual authors, but all conclude an advantage for biofuels compared to the conventional ones.

- Graboski (2002) assumes that about 81 % ethanol from corn is generated from dry milling process in 2012. The energy demand of the dry milling process is lower than the wet milling method, which is mostly applied today. The energy demand for the production of ethanol from corn is therefore in average lower in 2012. Graboski (2002) argues that the facilities that exist today for the dry milling process do not however have the potential to reduce energy demand in the near future.
- According to Wang (1999) the energy demand of dry and wet milling methods will decrease in the future.

Finding 23 Future energy and greenhouse gas balances of biofuels from organic residues compared to fossil fuels is not predictable

In the case of biofuels from organic residues, there can be alternative usages of the organic residues, so that the future energy and greenhouse gas balances of biofuels from organic residues compared to fossil fuels are not predictable.

5 Further Research Needs

It is evident that the existing studies do not or have not yet covered all biofuels thoroughly. In particular, the following research needs were determined:

On energy and greenhouse gas balance

- Of currently in-use biofuels, there is no study on biodiesel from palm oil regarding the energy and greenhouse gas balances.
- Of currently not yet mass produced biofuels, there are no studies on biodiesel from jatropha, pyrolysis oil, and HTU diesel.
- Studies for only one conversion path exist for DME, methanol, and BTL (production from lignocellulose). There are no studies for all the other possibilities from cultivated biomass to the use of organic residues.
- For a few biofuels from cultivated biomass, a better confirmation of the spectrum with supplementary analyses is necessary. These include biodiesel from coconut oil and bioethanol respectively ETBE from sugar-cane and potatoes.
- Only a few biofuels that can potentially be generated from organic residues were the subject of research. In addition, from an LCA perspective, the realistic and potential alternative usages of organic residues, e.g. used cooking grease or residual wood, that are used for biofuels production should be assessed. In the analysed studies, such alternative usages were ignored by setting them to zero. Here, appropriate balances must be performed, as only then can a reliable spectrum be derived, as in extreme cases, they could suggest disadvantages for biofuels as compared to fossil fuels (see Chapter 4.1).

On further ecological impacts

- Since consistent results were only found for biodiesel from rapeseed and sunflowers, various ethanols and ETBE, appropriate analyses for all other biofuels are necessary. There are in some cases different topics of interest:
  - **Biofuels from cultivated biomass.** Compared to their fossil fuel counterparts, biofuels from energy crops are favourable with respect to acidification, eutrophication, and laughing gas. However, the results vary considerably. A relatively exact accounting of quantitative effects can be performed for individual cases, for which the scope of the study to be specified and the state-of-the-art of the LCA have to be considered. The results are particularly helpful when they can be applied to the weak points analyses, i.e., to find out how the negative effects of biofuels can be minimized through process optimization or changes in the cultivation regime.
  - **Biofuels from organic residues.** Concerning biofuels from organic residues compared to their fossil counterparts, there is a need to assess new balances or supplement existing ones concerning the further emissions. Hereby, especially the specific conditions (type of raw material, conversion routes, conditions, and alternative usages) must be considered. This can be, when necessary, done by way of optimisation analyses with the above in mind. This applies without exception to all biofuels from organic residues, ethanol from lignocellulose, biodiesel from used grease, and BTL from diverse organic residues.

- This sort of balances still does not take into account that “further environmental impacts” – other than energy and greenhouse gas balances – depend in particular on the realistic relationship and external factors like energy supply structure, conversion technologies, agricultural ratio, etc. Thus, studies of specific existing and individual case analyses are necessary.
- In addition to further environmental impacts (acidification, eutrophication, ozone depletion, etc.), biofuels should also be assessed from the natural conservation point of view.
- Representative measurements of exhaust for vehicles using biofuels (in all blends possible) based on current motor concepts are necessary to support the LCAs and also to improve the estimation of the impacts of biofuels on air quality. In addition to regulated components, unregulated components, e.g. aromatics, PAH, and aldehydes as well as particulate count, particulate size distribution, and the mutagenic and cytotoxic impacts of biofuels compared to conventional fuels should also be studied. As a result, the physical properties of biofuels should be studied more closely.

On productions costs of biofuels

- The studies reviewed did not contain cost estimations on ETBE.
- Detailed costs estimations are not available for some biofuels (bioethanol from sugarcane, biodiesel from soybeans). For these, the total production costs are not divided into different components (raw materials, conversion costs, proceeds from co-production, and distribution). These costs estimations are not comprehensive and cannot be interpreted.
- It is recommended that a study on the agricultural subsidies and personnel costs in different reference locations should be conducted and distributed, to ensure best possible comparisons.
- Parallel to the energy and greenhouse gas balance, the production costs of biofuels from organic residues, their realistic or potential alternative usages should also be considered.

On potentials of biofuels

- In the available studies on potentials estimations of biofuels, competing land use with reference to natural conservation and competing biomass usages (to generate power and heat from fuels) are only considered in one study and only for the reference location Germany. Such studies are missing for other reference areas (EU, world).

On further environmental impacts of biofuels

- The future development of energy and greenhouse gas balances of biofuels that are currently in use is limited to the year 2010 in available publications. While it is impossible to predict the future, scenarios for different time frames can and should be created.
- Even the analysis of developments until 2010 is only available for a portion of the currently in-use biofuels: there are none on ETBE, vegetable oil, bioethanol from sugar-cane and potatoes and just a few about biodiesel from rapeseed and sunflowers.
- There are thus far no studies on the future development of further environmental impacts.

6 Summary

The analysis of existing international publications on energy and greenhouse gas balances of biofuels as well as their further environmental impacts, costs and potentials estimations has shown that the findings vary greatly. The findings are often only comparable conditionally and in some cases, considerable further research is needed. Nonetheless, findings on selected topics can be derived and are presented in the following. The report describes in which areas and why some findings are only comparable with others conditionally as well as where further research is needed.

Energy and Greenhouse Gas Balance

- **Advantages of biofuels.** The energy and greenhouse gas balances of the biofuels considered are favourable as compared to fossil fuels (disregarding extreme cases).
- **High variability of the results.** An examination of various studies in energy and greenhouse gas balances of biofuels shows a high level of variability in the findings. A direct comparison between the different biofuel options is not always possible. The high level of variability arises from the favourable or unfavourable assumptions taken on the external factors, e.g. those related to the cultivation, the conversion or valuation of the co-products. In order to make direct comparison among different biofuel options, the system boundaries must be determined exactly.
- **Ranking of biofuels.**
  - Regarding the area-related consideration, ETBE shows advantages compared to all other biofuels.
  - Bioethanol scores better or worse in dependency on resource basis than biodiesel and vegetable oil.
  - Biodiesel shows advantages compared to vegetable oil, when same system boundaries are assumed.
  - In order to assess comprehensively biofuels from organic residues (e.g. BTL), alternative usages of the residues must be taken into consideration. This has been ignored in the studies analysed.
- **Geographically specific advantages.** The advantages of a few biofuels are not found in all geographical areas. For example, the bioethanol production from sugar-cane is only limited to the tropical climatic conditions while the cultivation of sugar-beets in the temperate regions is only found on particularly fertile soils.
- **Future development.** In the future the advantages of currently used biofuels from cultivated biomass (as compared to conventional fuels) will be enhanced. This is based on an increase in biomass yields, lower primary energy demand for agricultural resources, higher biofuel yields as well as a lower level of energy consumption as a result of the conversion (cf. Ch. 4.5)
- **Further research need.** The existing body of life cycle analyses does not yet cover all biofuels.

Further environmental impacts

In addition to the fossil resources used and the intensification of the greenhouse effect, the production and usage of fuels also cause further environmental impacts like eutrophication, acidification, and ozone depletion.

- **Biofuels from cultivated biomass.** In the production of biofuels from cultivated biomass, nitrogen emissions produced in the course of agricultural production contribute also to the fact that biofuels from cultivated biomass show disadvantages compared to fossil fuels with reference to acidification, eutrophication, and ozone depletion.
- **Biofuels from organic residues.** A consistent conclusion on environmental impacts for biofuels from organic residues is not possible. Qualitative studies of the advantages and disadvantages with reference to acidification and eutrophication should be analysed based each on specific case conditions. Generally, N_2O as a parameter for the environmental impact ozone depletion is not important for biofuels from organic residues.
- **Results depend on question formulations.** The results depend more heavily on the question formulation and accounting methods than those of the energy and greenhouse gas balance. Airborne emissions play for example a particularly important role in the vicinity of the source. Diesel particulate emissions released (heavy oil combustion etc.) from ocean steamers on the high seas have different toxic effects than those emitted from vehicles in the inner cities (more examples are found in Ch. 4.3., Finding 9).
- **Further research need.** For a few fuels, there is a lack of investigation on the further environmental impacts. And in the available studies, only a few parameters are accounted (e.g. SO_2). This makes an interpretation based on the environmental impacts impossible.

Summary on ecological impact

Advantages and disadvantages. The individual studies considered show that both biofuels and fossil fuels have advantages and disadvantages. The ecological advantages of biofuels lie on their conservation of fossil resources and the reduction of the greenhouse effect. In opposite, biofuels from cultivated biomass contribute to eutrophication, acidification, and ozone depletion. It is therefore not possible to reach a scientifically objective decision for or against biofuels or fossil fuels from an ecological point of view. The final conclusion must therefore be made within a subjective value system. If the conservation of fossil resources and the reduction of greenhouse effect are considered to be of highest priority, the conclusion that biofuels are ecologically more favourable is justified.

Production costs

Lower production costs for fossil fuels. The comparison of production costs shows that fossil fuels can be produced more cheaply than biofuels. Under favourable conditions, biofuels from used cooking grease, vegetable oil from rapeseed, and vegetable oil from sunflowers can be produced with the same cost as fossil fuels. These results do however not have to hold in the future. A prediction can therefore not be derived from these numbers.

- **High variability in the results.** Referring to the production costs also, depending on the assumption of favourable or less favourable conditions for the cultivation, the conversion or the assessment of co-products produce a wide fluctuation spectrum which makes a direct comparison between the different biofuel options not always possible. The production costs of biofuels from cultivated biomass can be distorted by agricultural subsidies. In the context of biofuels from remnants and organic residues, the proceeds of forgone alternative usages are also important as are the avoided disposal costs.

- **Comparability of reference locations.** The natural and economic conditions of different reference locations are not directly comparable to each other. Examples are bioethanol from sugar-cane in Brazil, biodiesel from soybeans in the USA, and bioethanol from sugar-beets in Europe.
- **Assessment for the future fuels.** The production costs of the currently available fuels based on real costs are used on the one hand, while future, currently not mass produced fuels are also considered on the other hand.
- **Further research need.** Cost estimations are not yet available for all biofuels, and often total production costs are not divided into individual parts, so that they are not comprehensible.

Potentials

The technical potentials of biofuels are generally very high when all possibilities of biofuel production and currently not available technologies in the production of biofuels are considered. Whether and when these technologies can be available is not yet predictable with our present knowledge. A leading automobile manufacturer claims that the technology for the production of BTL should be available in the medium-term, and that for the production of hydrogen should be available in the long run.

Contrary to the high biofuel potentials, the biofuel usage in Germany is currently about 0.8 % and about 0.3 % in the EU (JRC 2004). Before the production technologies for new biofuels are available, the potentials of biofuels depend mainly on the political conditions, the competing land use, and biomass usages. These factors are also not foreseeable for the future.

- **Competing land use.** The potentials of biofuels from cultivated biomass depends foremost on the land area available, while the potentials from organic residues do not depend on land area. The land area for the production of biofuels can compete with the area for foodstuff production and the area for natural conservation. The IFEU study (2004) shows that for Germany, the technical potentials for biofuels are reduced considerably due to the observance for natural conservation aspects (including surface water and soil conservation). There are no such studies for the other reference locations.
- **Competing biomass usages.** The DLR study (2004) has shown that competing biomass usages affect the potentials of biofuels greatly. The potentials of biofuels in Germany were reduced to one quarter in 2050 when one assumes that the biomass potentials are more used in stationary sectors than in transport sector. There are no detailed potentials estimations of biofuels that consider the competing usages of biomass available for the remaining reference areas (EU and the world). In the other studies, it is assumed that the total available biomass to be used in the fuel sector.
- **Further research need.** For EU and the world, there are thus far no potentials estimations for biofuels that consider the competing land use from natural conservation aspect and the biomass potentials of competing biomass usages.

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Appendix

There is an extensive appendix in this report, in some parts mentioned in the text. This appendix is only available in German language and can be requested from the authors. In the following, a brief description of the content of each chapter in the Appendix is documented:

A 1 Analysis parameters of the studies examined (10 pages)

Appendix A 1 lists the parameters contained in the publications considered in this study. The parameters are categorized into: energy balance, greenhouse gases (CO_2, CH_4, and N_2O), further emissions (NO_X, SO_X, NMHC, CO, etc.), potential estimation and cost estimation. For the sake of clarity, “further emissions” are not listed individually. Rather, only the number of further emissions considered in individual studies is documented.

A 2 Energy and greenhouse gas balance of biofuels (93 pages)

In Appendix A 2.1 – A 2.3, each energy and greenhouse gas balance prepared by individual authors for a single biofuel from the same raw material is presented. The differences and their reasons are shown and spectrums are derived. Furthermore, the comparison of individual biofuels (e.g. bioethanol) from different energy crops is available. A complete documentation is found in Appendix A 2.4, which contains the results of energy and greenhouse gas balances that are not presented in the main report.

A 3 Further environmental impacts of biofuels (10 pages)

Appendix A 3 illustrates the advantages and disadvantages in further environmental impacts (acidification, eutrophication, photosmog, ozone depletion) of biofuels compared to their fossil fuel counterparts discussed in the analysed studies.

A 4 Costs of fossil fuels and biofuels (21 pages)

The cost differences between the results by individual authors on the various fuels – categorized according to the raw materials – are presented in Appendix A 4. Also, the reasons for these differences are shown and spectrums are derived.

A 5 Publications not further analysed in this study (8 pages)

Appendix A 5 contains the publications not analysed for the following reasons:

a) No primary data were presented in the publication. The findings are based on a detailed study that itself is considered in this investigation.
b) More recent publications of the same authors are available.
c) The publication considers exclusively data from other authors, rather than primary data.
d) The publication is no longer up-to-date (1995 and earlier).
e) There are other reasons which are listed separately.

A 6 Complete References (arranged alphabetically according to authors) (13 pages)

List of Abbreviations

ADEME	French Environment and Energy Management Agency
BTL	Biomass-To-Liquid
CFC	Chlorofluorocarbon
CNG	Compressed Natural Gas
CONCAWE	Conservation of Clean Air and Water in Europe
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DfT	Department for Transport
DIREM	French Direction of the Energy and Mineral Resources
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DME	Dimethylether
DPF	Diesel particulate filters
EEA	European Environmental Agency
EIA	Energy Information Administration
Enerstrat	Energy Strategies
EST	Energy Saving Trust
ETBE	Ethyl Tertiary Butyl Ether
EtOH	Ethanol
ETSU	Energy Technological Support Unit
EUCAR	European Council for Automotive R&D
FAT	Eidgenössische Forschungsanstalt für Agrarwirtschaft und Landtechnik (Swiss Federal Research Station for Agricultural Economics and Engineering
FC	Fuel Cell
FfE	Forschungsstelle für Energiewirtschaft (Research Institute for Energy Economy
FVV	Forschungsvereinigung Verbrennungskraftmaschinen (Research Association for Combustion Engines)
GH2	Gaseous hydrogen
GJ	Gigajoule
GM	General Motors
Gt	Gigatonne (a thousand million metric tonnes, 10^{12} kg)
GWP	Global-Warming-Potential
ha	Hectare
HTU	Hydro Thermal Upgrading
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEEP	Institute for European Environmental Policy
IFEU	Institute for Energy and Environmental Research Heidelberg
IfE	Institut für Energetik und Umwelt (Institute for Energy and Environment)
IFO	Institut für Wirtschaftsforschung (Institute for Economic Research)
IPCC	Intergovernmental Panel on Climate Change
ISVS	Institut für Straßen- und Verkehrswesen der Universität Stuttgart (Institute for Road and Transportation Science at the University of Stuttgart)
JRC	Joint Research Centre
L, l	Litre (0.001 m^3)
LCA	Life Cycle Assessment
LBST	Ludwig-Bölkow-Systemtechnik
LH2	Liquid hydrogen
LHV	Lower Heating Value
MJ	Megajoule
MTBE	Methyl Tertiary Butyl Ether
MeOH	Methanol
NMHC	Non-methane hydrocarbons
NREL	National Renewable Energy Laboratory
NSCA	National Society for Clean Air and Environmental Protection
PAH	Polycyclic aromatic hydrocarbons
RME	Rapeseed Methyl Ester
t	Tonne (metric ton)
TTW	Tank-to-Wheel
UBA	Umweltbundesamt (Federal Environmental Agency)
USDA	U.S. Department of Agriculture
VITO	Vlaamse instelling voor technologisch onderzoek
WBGU	Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (German Advisory Council on Global Change)
WTT	Well-to-Tank
WTW	Well-to-Wheel

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