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Executive Summary “Life Cycle Impact Assessment and Interpretation”

Introduction

The report at hand was elaborated within the work package “life cycle assessment” in the RENEW project (Renewable Fuels for Advanced Powertrains). The project investigates different production routes for so called biomass-to-liquid (BTL) automotive fuels made from biomass.

The LCA method aims to investigate and compare environmental impacts of products or services that occur along their supply chain from cradle to grave. The method is standardized by the International Organization for Standardization (ISO).

Within the RENEW project, different production routes for BTL-fuels[1], which are produced by gasification of biomass followed by a synthesis process, have been further developed. These are:

- Production of Fischer-Tropsch-fuel (FT) by two-stage gasification (pyrolytic decomposition and entrained flow gasification) of wood and straw, gas treatment and synthesis;
- Production of FT-fuel by two-stage gasification (flash pyrolysis and entrained flow gasification) of wood, straw and energy plants as well as CFB-gasification (circulating fluidized bed), gas treatment and synthesis;
- BTL-DME (dimethylether) and methanol production by entrained flow gasification of black liquor from a kraft pulp mill, gas treatment and synthesis. Biomass is added to the mill to compensate for the withdrawal of black liquor energy;
- Bioethanol production by different processes from different feedstock.

This report elaborates on the life cycle impact assessment (LCIA) and the interpretation of the life cycle assessment.

Goal of the study

The goal of the LCA is to compare different production routes of BTL-fuels (FT-diesel and dimethylether) from an environmental point of view. The environmental impacts of different conversion routes developed in the RENEW project are investigated for that purpose. The different conversion concepts are compared based on the delivery of one MJ fuel to the tank. Emissions from using the fuel are not taken into account in this analysis. A comparison with fossil fuels is not made here. A detailed description of the goal and scope definition of this LCA can be found in a separate report of this project (Jungbluth et al. 2007a).

Scenarios

Two different scenarios are considered in the modelling of the process chains. These scenarios are defined in cooperation with other work packages of SP5 in the RENEW project (SP5-Partners 2007).

Starting point calculation

The so-called “starting point calculation” addresses the possible production route in the near future. Average data representing agricultural and harvesting technology of today are used for these production systems. Farms with very small production volumes, which are not supplied to the market, are not

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[1] In this project, we name all fuels derived via gasification of biomass resources as BTL-fuels and not only those fuels synthesised in Fischer-Tropsch synthesis.

considered in the assessment. The inventory of the conversion processes is based on the actual development state of the different technologies. In a nutshell this means “assuming we would erect such a plant today, what would the plant look like?” In this scenario the operation of the biomass to biofuel plant is self-sufficient, which means that the plant uses energy only out of biomass. Thus, no direct external electricity or other non-renewable energy supply is considered in the process models.

Scenario 1

In scenario 1 a modelling of a maximized fuel production is made. The supply chain is supposed to be as efficient as possible regarding biofuel production. One of the highest criteria of the evaluation is the ratio of biofuel production to needed agricultural land. The use of hydrogen improves the carbon/hydrogen-ration and thus leads to a higher conversion rate of biomass to fuel. External conventional electricity input into the production system is used in most of the conversion concepts for providing the necessary hydrogen.

A quite crucial point in scenario 1 is the assumption on the hydrogen supply for the biomass conversion. The way in which the electricity for the water electrolysis is produced has important consequences for the costs and the environmental performance of the conversion concept. Here we assume that the external electricity is provided with wind power plants. This is assumed by the project team one option for a maximized fuel production based on renewable energy.

It is not realistic to get such a renewable electricity supply until 2020 for more than a small number of conversion plants, but this scenario describe a direction that might be worth going. Only if there would be the possibility in 2020 for hydrogen from wind power, the conversion rate biomass to fuel could be increased in the way modelled here. Due to the limited production capacity until 2020, this scenario does not describe a general improvement option, but an option for special locations. The influence of using the average electricity in Europe is shown in a sensitivity analysis.

For biomass production, it is assumed that inputs of fertilizers and pesticides are higher than for today. In addition, the yield are higher than today.

Life cycle inventory

The inventory includes all process stages from well-to-tank for BTL-fuels. This includes resource extraction or biomass production, transportation, storage, fuel conversion and distribution. All conversion concepts are investigated on a scale of 500 MW biomass input. Many data for the conversion processes have been directly provided by the RENEW partners. The data were cross-checked by technology experts from WP 5.4.

The functional unit for the comparison of BTL-fuel production routes is defined as the energy content expressed as the “lower heating value (MJ) of the fuel delivered to the tank”. The full life cycle inventory of all conversion processes is reported in a separate public report of this project (Jungbluth et al. 2007b). Data of the production of ethanol were not available in due time. Thus, this pathway has been excluded from further investigation in the life cycle assessment. CHEMREC did not provide data for scenario 1. Thus, this process is only evaluated in the starting point calculation.

Category indicators

The life cycle impact assessment covers several impact category indicators. These indicators characterise and summarize the contribution of individual emissions or resource uses to a specific environmental problem. The higher the figure, the higher is the potential environmental impact resulting from emissions and resource uses over the life cycle of the investigated product. There is no weighting used within the category indicators. Thus, all indicators are assumed to have the same relevance in the comparison.

The inclusion or exclusion of category indicators was discussed within the project team. The main clauses for the choice of category indicators were the reliability and acceptance of the existing LCIA methods by all partners.

Besides the LCIA results, two cumulative results of elementary flows are presented. The water use sums up all demands of water in the life cycle excluding turbine water. For land competition, all surface land uses are summed up as square metre used over one year.

Table 1 Category indicators investigated in this study

Category indicator	Abbreviation	Description of the problem and relevance for the processes investigated
Cumulative energy demand	CED	The cumulative energy demand of biomass, other renewable, fossil and nuclear energy resources is characterised and summed up with the reference unit MJ-eq (mega joule equivalents).
Abiotic depletion	ADP	Important is the use of non-renewable energy resources. The depletion of other abiotic resources is included in this indicator as well. The use of uranium for electricity generation is included with a smaller characterisation factor compared to the CED.
Global warming	GWP	Contribution to the problem of climate change evaluated with the global warming potential. Main reason for promotion of BTL-fuels.
Photochemical oxidation, non-biogenic	POCP, non biogenic	Evaluation of potential contribution to the formation of summer smog. The production processes and agriculture have some relevance. It has to be noted that only a small part of NMVOC gets a characterisation factor according to the CML methodology. All unspecified NMVOC are not assessed. Here we do not evaluate biogenic emissions from plant growing, but other biogenic emission, e.g. CO from biomass burning.
Acidification	AP	Emission of acid substances contributing to the formation of acid rain. Relevant are air emissions from agriculture and fuel combustion in transport processes.
Eutrophication	EP	Overfertilization of rivers and lakes due to human-made emissions. High relevance for the use of fertilizers in agricultural processes.
		Inventory results
Water use		Water is a scare resource especially in Southern European countries. The indicator includes all types of water use including rain falling on the agricultural area, irrigation water and direct uses of water in conversion processes.
Land competition		Land area is the most important resource for production of biomass and there are differences between different biomass types. It is recorded in m2a (square metre occupied for one year).

Limitations of the study

Environmental impacts due to the use of pesticides and the emissions of heavy metals in agricultural production are not assessed with the category indicators used in this study. These substances have toxicological effects on animals, plants and human beings.

With regard to the category indicators for toxicological effects there was no consensus in the project group whether or not the requirements of ISO 14044, 4.4.2.2.3 are fulfilled by LCIA methods published for such impacts. Indicators therefore are not included in the study and the importance of this decision for the comparison of the conversion routes has not been evaluated.

The exclusion of certain category indicators might be quite important regarding the ranking of different conversion processes. The authors of this study consider the exclusion of toxicity impacts as a major shortcoming of this study. Such effects should be taken into account especially if it comes to a comparison between fuels made from biomass and fossil fuels. Further research about the definition of reliability within the ISO standards and a consensus finding process for the best available methodologies for toxicological effects is necessary.

Analysis of results for category indicators in the starting point calculation

The main drivers regarding all environmental category indicators are analysed in the study. Here we explain the results for the more realistic starting point calculation. Detailed results related to the scenario 1 can be found in the full study.

The major elementary flow regarding the cumulative energy demand is the energy bound in harvested biomass. Thus, the biomass production process accounts for 80%-90% of the cumulative energy demand in the starting point calculation.

Crude oil (50%-60%) and natural gas use are the major contributions to abiotic depletion. The use of uranium has only a small contribution with this category indicator. The resource extraction takes place in many different unit processes of the life cycle.

Carbon dioxide (50%-70%) and dinitrogen monoxide (20%-40%) are the major elementary flows with respect to global warming. Methane from off-gases and emissions of the internal power plant in the conversion plant accounts for up to 15% of the total greenhouse gas emissions.

A range of different substances is important with regard to the photochemical oxidation. The most important ones are sulphur dioxide, carbon monoxide and different NMVOC. Dimethylether emissions are relevant in the distribution of BTL-DME.

Acidification is caused by ammonia, sulphur dioxide and nitrogen oxides in about equal shares. The emissions of acidifying substances can be attributed to the biomass production, direct air emissions of these conversion process that release off-gases and emissions from the internal power plant. The operation of transport devices and tractors is also an important source of such emissions.

Eutrophication is caused by nitrates, phosphates, ammonia and nitrogen oxides. A share of more than 50% of the release of eutrophication emissions can be attributed in most cases directly to the agricultural production process. Other important sources of emissions are the direct air emissions from the conversion process and power plant. The production of fertilizers contributes in smaller amounts.

The water use is fully dominated by rainwater used in agriculture. Other water uses e.g. in the conversion plant or for irrigation are not very important.

The results for land competition are dominated by the agricultural biomass production, which accounts for about 90% of all land uses. For the conversion routes based on straw, this share is reduced to 80%. Because of the allocation procedure, only a marginal part of the land used for wheat cultivating is accounted for straw. Several wood-consuming background processes, e.g. storage facilities, get a share of up to 20% in these straw-conversion routes.

Comparison of the starting point calculation

In the following, the category indicator results of different conversion concepts are compared from well to tank.

The ranking of the different processes is visualized in the following table. The process with the lowest environmental impacts is set to 100% in this evaluation. The table shows the environmental impacts of all processes in comparison to the process with the lowest impacts. In addition, processes with just 15% higher environmental impacts are ranked "lowest". Processes with 16% to 50% higher impacts than the optimum are ranked as "low impacts" processes. Different colours help to see the levels.

Many category indicators like acidification, eutrophication, water use and land competition show an absolute dominating influence of the agricultural production of biomass. Thus, the type of biomass and the conversion rate are important in the comparison.

The conversion rate plays a major role in the formation of air emissions from the conversion plant. It is assumed that the higher the conversion rate, the lower is the share of biogenic carbon dioxide and thus also other pollutants which are released to the ambient air. Therefore, the improvement of the conversion rates and the reduction of the environmental burdens of the biomass production itself are the main drivers for further environmental improvements of the BtL-chains, within the same scenario.

The conversion processes cEF-D[2] and BLEF-DME have the lowest environmental impacts in the assessment with regard to the environmental indicators cumulative energy demand, global warming, photochemical oxidation, acidification, eutrophication and abiotic resource depletion. They are followed by CFB-D and dEF-D process. The ICFB-D process shows the highest environmental impacts due to a process design with a considerably high amount of electricity production and thus a lower biomass to fuel conversion rate.

In the case of the conversion of wood, the cEF-D process has between 15% and 30% higher impacts than the production of dimethylether with regard to the category indicators cumulative energy demand, abiotic depletion, global warming, eutrophication, water and land use. This can be explained mainly with the higher conversion rate of the BLEF-DME process. However, the cEF-D process has 35% lower impacts for the category indicator photochemical oxidation, because the emissions in the dimethylether distribution are higher. CFB-D has more than 65% higher impacts than cEF-D and BLEF-DME. The ICFB-D process has a rather low conversion rate and thus has higher impacts for all category indicators except photochemical oxidation, which does not include biogenic emissions.

The comparison of processes based on wood or straw depends not only on the type of biomass, but also on the difference in the conversion rate. The CFB-D process based on wood perform slightly better than processes based on straw regarding the category indicators cumulative energy demand, abiotic depletion, global warming potential and eutrophication potential. For the cEF-D concept, the process with straw has lower environmental impacts than the conversion of wood.

In the case of straw conversion, the cEF-D process has the lowest impacts for all category indicators followed by the dEF-D and the CFB-D process. There is only one conversion process using miscanthus (ICFB-D). Thus, a direct comparison with other conversion concepts is not possible.

Table 2 Starting point calculation. Ranking of the different conversion concepts with respect to the category indicators based on the energy content of the fuel delivered to the tank

	Biomass	Miscanthus	Straw	Straw	Straw	Wood	Wood	Wood	Wood
	Process	Allothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Centralized Entrained Flow Gasification	Entrained Flow Gasification of Black Liquor for DME-production
	Code	ICFB-D	CFB-D	dEF-D	cEF-D	CFB-D	ICFB-D	cEF-D	BLEF-DME
	Company	TUV	CUTEC	FZK	UET	CUTEC	TUV	UET	CHEMREC
Category indicator	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-DME
cumulative energy demand	MJ-Eq	*252%*	*186%*	147%	115%	*169%*	*263%*	128%	100%
abiotic depletion	kg Sb eq	*255%*	*260%*	*155%*	121%	*165%*	*257%*	128%	100%
global warming (GWP100)	kg CO2 eq	*226%*	*252%*	128%	104%	*171%*	*224%*	116%	100%
photochemical oxidation, non-b	kg C2H4	*244%*	*361%*	*258%*	100%	*292%*	*245%*	104%	141%
acidification	kg SO2 eq	*256%*	*192%*	*190%*	100%	*181%*	*289%*	130%	133%
eutrophication	kg PO4--- eq	*453%*	*207%*	*162%*	106%	*176%*	*300%*	117%	100%
water use	m3	*780%*	*151%*	127%	100%	*672%*	*1034%*	*508%*	*396%*
land competition	m2a	*631%*	*155%*	139%	100%	*610%*	*959%*	*458%*	*358%*

	Min	Max
Lowest impacts	100%	115%
Low impact	116%	150%
High impact	*151%*	*250%*
Highest impacts	*251%*	

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[2] cEF-D stands for centralized entrained flow gasification, BLEF-DME stands for entrained flow Gasification of Black Liquor for DME (dimethylether)-production. See Table 2 for further abbreviations.

Analysis of sub-processes in biomass conversion

The data of biomass conversion have been investigated in detail for different sub-processes of the process. The aim was to compare also different sub-processes and to see the relative share of sub-processes for the total environmental impacts.

In general, many category indicators results for the sub-processes of the conversion process are quite dependent on the biomass input. For the cumulative energy demand, water use and land competition the share of biomass production and provision is in most cases higher than 90%. The second most important factor are the air emissions with off-gases or due to the energy production in the on-site power plant. This is especially important for the release of substances contributing to photochemical oxidation. Thus, the sub-processes using more heat and electricity are more important for the total environmental impacts.

In scenario 1, the importance of process steps is influenced largely by the external electricity input. The process stage, which uses hydrogen produced with external electricity, is more important concerning the environmental indicators that are influenced by the electricity production. The biomass input stage is relevant for these category indicators, like land use, which are dominated by impacts from agriculture.

The detailed analysis shows that it is difficult to compare different conversion concepts based on the detailed results for single process stages, because the allocation of environmentally relevant streams within the plant might be quite different. Thus, the importance of the different sub-processes might be quite different even if the overall results are quite similar.

Sensitivity analysis

The allocation criterion between straw and wheat grains has quite an important influence on the total impacts of all processes that use straw as an input. Allocation by energy content results in up to three times higher environmental impacts per MJ of fuel produced from straw as compared to allocation by actual market prices.

A sensitivity analysis of the ICFB-D process was made. Heat and electricity produced simultaneously are accounted for as equal products to liquid fuels according to their exergy content. The results of different category indicators are reduced by 10% to 30%, if the wood input for the ICFB-D process is reduced by about 30% according to the exergy shares of fuel, heat and electricity production.

Fuel yields per hectare

The fuel yield per hectare is an important yardstick for comparing different types of biomass and different process routes. The calculation includes the full life cycle from seed to tank, e.g. also biomass losses during storage and land occupation for other processes than biomass production. All land uses (not only the agricultural land area) are included in this calculation.

The fuel yield for energy crops per hectare is between 860 to 2300 kg oil equivalents. Processes based on straw show a fuel yield up to 8200 kg oil equivalents per hectare, if the agricultural land is allocated to the straw based on its share of the today revenue of wheat production. The yield of processes based on straw is only 1300 to 1900 kg oil equivalents per hectare if the allocation is based on the energy content of grains and straw.

These results for the fuel yield highlight that it is preferable to use by-products, such as straw or wastes, for biofuel production. Nevertheless, it has to be taken into account that their potential is limited and that a rising demand will lead to higher prices, and, because of the allocation criterion, also to higher environmental impacts.

Comparison for scenario 1

The main idea of scenario 1 is an increase of the fuel yield per hectare. The use of hydrogen produced by electrolysis is considered an interesting option for the conversion process. Most conversion concepts use an amount of electric energy in the same amount like the direct biomass input. CHEMREC has not provided data for BLEF-DME in scenario 1.

All processes show a considerable increase of the fuel yields per hectare of between 60% and 200% if hydrogen is used in the process. A fuel yield between 2100 and 4100 kg oil equivalent per hectare is possible when using miscanthus and wood.

The cEF-D process using wood has the lowest impacts of all investigated concepts with respect to several category indicators except for the cumulative energy demand, water use and land competition. This can be explained by with the highest conversion rate of all processes. Because of the lower environmental impacts of straw production in water use and land competition, the dEF-D process has a lower impact for these category indicators. The ICFB-D concept is modelled without an input of external energy. Thus, it has the lowest cumulative energy demand. The dEF-D process with straw has the lowest impacts for eutrophication potential, water use and land competition.

Comparing straw based processes, the process of FZK (dEF-D) shows the lowest impacts except the cumulative energy demand, which is highest. This can be explained mainly by the higher conversion rate of the dEF-D process compared with the CFB-D concept.

Comparing wood based processes, the cEF-D of UET shows the lowest impacts except cumulative energy demand, where the ICFB-D process of TUV has a lower impact because it does not use external electricity.

A clear overall ranking with regard to the use of different biomass resources cannot be made. In addition, a clear ranking of the different conversion processes is not possible, because results show trade offs between the different category indicators. A formal weighting between category indicators, which would bridge these trade-offs, shall not be used according to the ISO standards for comparative LCA studies.

Table 3 Scenario 1 with wind power used in hydrogen production. Ranking of the different conversion concepts with respect to the category indicators based on the energy content of the fuel delivered to the tank

	Biomass	Miscanthus	Straw	Straw	Wood	Wood	Wood
	Process	Allothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Centralized Entrained Flow Gasification
	Code	ICFB-D	CFB-D	dEF-D	CFB-D	ICFB-D	cEF-D
	Company	TUV	CUTEC	FZK	CUTEC	TUV	UET
Category indicator	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT
cumulative energy demand	MJ-Eq	100%	*219%*	*292%*	*207%*	112%	*218%*
abiotic depletion	kg Sb eq	101%	*257%*	*160%*	*257%*	134%	100%
global warming (GWP100)	kg CO2 eq	119%	*261%*	133%	*254%*	*151%*	100%
photochemical oxidation, non-b	kg C2H4	139%	*238%*	*170%*	*226%*	*155%*	100%
acidification	kg SO2 eq	125%	*163%*	118%	*209%*	*175%*	100%
eutrophication	kg PO4--- eq	*336%*	*212%*	100%	*237%*	*212%*	102%
water use	m3	*573%*	*163%*	100%	*929%*	*959%*	*489%*
land competition	m2a	*331%*	147%	100%	*611%*	*622%*	*319%*

	Min	Max
Lowest impacts	100%	115%
Low impact	116%	150%
High impact	*151%*	*250%*
Highest impacts	*251%*	

Sensitivity analysis with European electricity mix

A sensitivity analysis was performed for the use of average European electricity instead of wind power. The ICFB-D process (by TUV) does not use an external hydrogen production and thus not electricity from the grid. Thus, it shows a better performance in this analysis than the other processes with regard to the global warming potential, cumulative energy demand and photochemical oxidation. On the other side, it has higher impacts for category indicators directly related to biomass production (eutrophication, water and land use).

The CFB-D process (by CUTEC) using straw has lower or about the same results as the process of dEF-D (by FZK) for the category indicators cumulative energy demand, abiotic depletion, global warming potential, POCP and AP. For eutrophication, land and water use, it has slightly higher impacts. So there is no clear overall ranking among the conversion concepts.

Among the two processes converting wood and using hydrogen (cEF-D and CFB-D process), the cEF-D process (by UET) has slightly higher impacts for the electricity dominated indicators abiotic depletion, global warming, POCP and AP due to the higher external electricity demand of the cEF-D process. The CFB-D concept (by CUTEC) has slightly higher impacts for category indicators related to biomass production (cumulative energy demand and eutrophication).

The electricity mix changes some of the results of the comparison quite significantly. The ranking according to the cumulative energy demand, photochemical oxidation, eutrophication, water and land competition remains about the same. Regarding abiotic depletion and global warming, the differences between the process routes get more significant.

Producing hydrogen with electricity will only make sense if renewable energy, e.g. wind power, is available in very large capacities and with a secure supply. Generally, the use of hydrogen produced via electrolysis and using the today electricity mix would be a clear disadvantage for most of the evaluated category indicators. Because the necessary capacities for wind power will not be available at many conversion plant locations, this scenario does not describe the average situation of BTL-production in the year 2020.

Improvement options

Different improvement options are identified. The most important one is the increase of the biofuel yield from a given amount of biomass. This reduces the input of biomass and decreases the losses. e.g. in form of air pollutants or effluents on the other. A linear relationship between carbon losses and following emissions to air accompanying the biogenic CO_2 emissions is assumed.

Another conclusion is to improve the environmental profile of the biomass production itself, because this analysis shows that the biomass production has a dominating influence on most of the environmental indicators. Using wastes and by-products is therefore preferable for some category indicators, but not always possible. Possibilities for such an improvement have not been evaluated in detail. Detailed studies of agricultural production show that improvements are not easy to achieve. Different influencing factors as e.g. fertilizer and pesticide use, diesel consumption and level of yields have to be balanced out to find an optimum solution.

The use of after treatment technologies to reduce the emissions to air has not been studied in detail. It is assumed that all conversion plants have to meet the legal emissions limits, but do not further reduce the emissions. Such an after treatment might reduce the direct emissions, but might lead to higher indirect impacts e.g. due to surplus energy use or necessary auxiliary materials. Further research would be necessary to identify the optimum solutions.

For some processes, auxiliary inputs, e.g. quicklime, are found to be an important contribution to some category indicators. Thus, further focus should be put on reducing the necessary input. In addition, a separate refinery treatment of Fischer-Tropsch raw products can increase the environmental impacts slightly.

Nutrients, which are bound in the biomass, such as phosphorous, are lost with the disposal of ashes, sludge, slag or effluents. Recovering these nutrients and recycling them for a use in agriculture might be another option to improve the overall performance.

All conversion concepts are investigated on a scale of 500 MW biomass input. Some conversion concepts might be improved by increasing the plant size to up to 5 GW. This has not been considered in this study.

Outlook

In general, this study confirms the knowledge already gained in several LCA studies for biofuels. The type of biomass input and the conversion rate to the final fuel are quite important with respect the environmental evaluation of all types of biofuels.

The starting point calculation highlights the differences in environmental impacts caused by different conversion concepts and of different types of biomass inputs. Scenario 1 can be used to evaluate the possible maximized fuel yields if large quantities of surplus electricity are available to produce hydrogen for the process.

This life cycle assessment study compares different concepts of BTL-fuel production based on the status of technology development in the year 2006. Further improvement can be expected for all technologies. Thus, this study is only valid for the moment and it might be possible that the ranking of different conversion concepts must be revised in future. The results of the study should be reconsidered as soon as updated data are available or first commercial plants are in operation.

Abbreviations and Glossary

a	annum (year)
AP	acidification potential
BLEF-DME	Entrained Flow Gasification of Black Liquor for DME-production
BLG	black liquor gasification
BLGMF	black liquor gasification with motor fuel production
BTL	biomass-to-liquid fuel including FT-fuel, methanol and DME produced from synthesis gas
CED	cumulative energy demand
cEF-D	Centralized Entrained Flow Gasification
CFB	circulating fluidized bed
CFB-D	Centralized Autothermal Circulating Fluidized Bed Gasification
CFBR	Circulating-Fluidized-Bed-Reactor
dEF-D	Decentralized Entrained Flow Gasification
DME	dimethylether
E-1	Exponential description of figures. The information 1.2E-2 has to be read as 1.2 * 10-2 = 0.012
EP	Eutrophication potential
FICFB	Fast internal circulating fluidized bed (Güssing plant)
FT	Fischer-Tropsch (synthesis)
GHG	green house gas
GWP	global warming potential
HHV	higher (upper) heating value
ICFB-D	Allothermal Circulating Fluidized Bed Gasification
ISO	International Organization for Standardization
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
LHV	lower heating value
LTV	low temperature gasifier
n.a.	not available
PM	particulate matter
POCP	photochemical ozone creation potential (summer smog)
RENEW	Renewable Fuels for Advanced Powertrains
RER	Country code for Europe
RME	rape seed oil methyl ester
SETAC	Society of Environmental Toxicology and Chemistry
SP	Sub-Project in RENEW. SP5 deals with the assessment of different BTL-fuel production processes
toe	tonnes oil equivalent with 42.6 MJ/kg
U	Label for unit process in the LCA software, shown in figures calculated with information from this software, but no specific relevance in the context.

UCTE	Union pour la Coordination du Transport de l'Electricité
WP	Work package
WP5.1	Biomass potential assessment
WP5.2	Life cycle assessment for BTL-fuel production routes
WP5.3	Economic assessment of BTL-fuel production
WP5.4	Technical assessment
WP5.5	Analysis of gasification processes for gaseous fuels

Contents

1 Introduction

1.1 Background

The study at hand has been elaborated within the project RENEW – Renewable Fuels for Advanced Powertrains. On January 1st, 2004 a consortium with partners from industry, universities and consultants started to investigate production routes for automotive fuels made from biomass. The production of BTL-fuels by gasification of biomass followed by a synthesis process is investigated and a life cycle assessment (LCA) of several technologies is performed.

Representatives of 32 institutions from 9 countries work together. Automotive and mineral oil companies, energy suppliers, plant builders and operators joined a consortium together with universities, consultants and research institutes. Supported by the European Union and Swiss federal authorities, the partners will contribute to increase the use of BTL-fuels made from biomass.

ESU-services Ltd., Switzerland is responsible for a work package where different production routes for biomass-to-liquid (BTL) fuels are investigated in an LCA from well to tank. Different scenarios for the BTL-fuel chains are considered in the LCA. The aim of the LCA is to compare and improve the different production routes dealt within the project.

The LCA is one work package (WP5.2) out of five in the subproject 5 (SP5). Work package 1 (WP5.1) investigates the potentials of biomass supply in Europe. WP5.3 investigates economic aspects of the BTL-fuel production. A further technical assessment of the different supply routes including also use aspects of the fuels is elaborated in WP5.4. The production of gaseous fuels from biomass via gasification is investigated in WP5.5.

1.2 Reading guide

The report forms the last step of a series of reports within WP5.2 of the RENEW project. As a first step in an LCA, a goal and scope definition has been elaborated (Jungbluth et al. 2007a). Based on the system boundaries described in that report, life cycle inventory data have been collected and summarized (Jungbluth et al. 2007b).

This report presents the life cycle impact assessment (LCIA) and the interpretation of the results. All calculations are based on ecoinvent data v1.3 used as background database (ecoinvent Centre 2006) and the data investigated within this project (Jungbluth et al. 2007b).

Chapter 1 gives an introduction to this report. The following chapters deal with the life cycle impact assessment. In chapter 2 the biomass production is analysed. In chapters 3 and 4 we compare the different conversion routes in the starting point scenario and scenario 1, respectively. Chapter 5 analyses these conversion processes and its environmental impacts in detail. Different sensitivity analyses are presented in chapter 7. Conclusions based on these results are elaborated in the final chapter 8.

1.3 Scenarios investigated

Data of biomass production and conversion are investigated for two different cases according to the common project document (SP5-Partners 2007):

Today	Starting point of scenario definitions with description of today’s production systems
Sc1	Scenario 1 (Maximized biofuel production) describing production technology with highest conversion rate that can be achieved using hydrogen produced with electricity .

Scenario 2 (self-sufficient production) has been excluded from the analysis because it has been considered by the conversion plant developers to be very similar to the starting point scenario.[3]

The project team has further elaborated the necessary assumptions for the consideration of the scenarios. The following assumptions were crucial for the investigation of biomass production and conversion.

1.3.1 Starting point

The so-called "starting point calculation" addresses the possible production route in the near future. For these production systems, average data for agricultural and harvesting technology of today are used. Farms with very small production volumes that is not available for the market, are not considered in the assessment. Biomass is the major energy carrier for the supply of internal energy and for the production of the fuel. The inventory for the conversion processes is based on the actual development state of the different technologies. In a nutshell this means "assuming we would erect such a plant today, what would the plant look like?" In this scenario the operation of the biomass to biofuel plant is self-sufficient which means that the plant produces all electricity, energy and necessary inputs out of biomass. Thus, no direct external electricity supply is considered for the modelling.

1.3.2 Scenario 1

In scenario 1 a modelling for a maximized fuel production is made. The supply chain is supposed to be as efficient as possible regarding biofuel production. One of the highest criteria of the evaluation is the biofuel production to needed surface area for biomass production ratio. External conventional electricity input into the production system is used in most of the conversion concepts. The use of hydrogen improves the carbon/hydrogen-ration and thus lead to a higher conversion rate of biomass to fuel.

A quite crucial point for scenario 1 is the assumption for the hydrogen supply for the biomass conversion. The way in which the electricity is produced has important consequences for the costs and the environmental performance of the conversion concept. Here we assume that the external electricity is provided with wind power plants. It is not realistic to get such a renewable electricity supply until 2020 for more than a very small number of conversion plants, but this scenario describes a direction that might be worth going. Only if there would be the possibility in 2020 for hydrogen from wind power, the conversion rate biomass to fuel could be increased. Due to the limited production capacity until 2020 this will not lead to a considerable share of biofuel production. Therefore this scenario does not describe a general improvement option, but an option for special locations or lucky circumstances.

It is probable that inputs of fertilizers and pesticides are higher than for today biomass production. In addition, the yield should be higher than today. Possible improvements in the production of items like fertilizers or conventional diesel until 2020 have not been investigated in the analysis.

1.4 Scope of the life cycle impact assessment

The results of the life cycle impact assessment are investigated for several category indicators. These indicators characterise and summarize the contribution of single emissions or resource uses for a specific environmental problem. The higher the figure, the higher is the potential environmental impact resulting from emissions and resource uses over the life cycle of the investigated product.

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[3] Decision of the RENEW Coordination Committee, Stuttgart, March 2006.

The inclusion or exclusion of category indicators has been discussed within the project team (Jungbluth et al. 2007a). The main clauses for the choice of category indicators were the reliability and acceptance of the existing LCIA methods. The relevance of further indicators for the product systems of interest was not assessed because no agreement could be achieved on the reliability of possible methodologies. The last column of Tab. 1.1 shows the LCIA methodologies to be applied.

Further category indicators can be assessed in more detail in external studies. The data collection facilitates the use of different methods. This makes it possible to take into account the latest scientific developments and to use the most suited methods than agreed on in this project.

In all cases, different characterisation models are available. The methods are chosen according to the baseline proposal from Guinée *et al.* (2001).

Biogenic NMVOC emissions from plants are so far only rarely treated in LCIA. There are some uncertainties for the correct modelling. In the base case, such emissions are excluded from the assessment by setting the characterisation factor of "isoprene, low population area" to zero in this adapted method. There is no characterisation factor given by Guinée *et al.* (2001) for (mono-)terpene, the other NMVOC emission investigated in the LCI for biomass production. A sensitivity analysis is performed, considering the isoprene emissions.

The CML category indicator for photochemical oxidation does not take into account several NMVOCs. The methodology EDIP will be used for sensitivity analysis as this can be used to characterize all NMVOCs (Hauschild & Wenzel 1997).

All LCIA methods are linked to the elementary flows in the inventory data according to the implementation rules defined for the ecoinvent database (Frischknecht et al. 2004b). New elementary flows will be assessed according to the factors provided in the original method and the implementation rules described for ecoinvent data.

Within the ecoinvent database, all emissions are further distinguished concerning compartments (e.g. air, water, soil) and subcompartments (e.g. fresh, salt or groundwater). Within this evaluation, we only show the detailed results for subcompartments, if this is considered to be important or necessary for the further interpretation. Otherwise, emissions in different subcompartments are summed up to one indicator.

The differentiation between biogenic and fossil carbon compounds is important, because biogenic CO_2 does not contribute to the problem of climate change as it is renewable and the same amount of carbon has been taken up by the plants during growing.

Besides the LCIA results, two cumulative results for the inventory analysis are presented. The water use sums up all demands of water in the life cycle excluding turbine water. For land competition, all surface land uses are summed up as square metre used over one year. Both results are further on referred to also as category indicators.

A formal weighting between category indicators, which would bridge trade-offs in case of bidirectional results, shall not be used according to the ISO standards for comparative LCA studies.

We describe the results of the life cycle impact assessment in the following chapters. These chapters show information about the contribution of certain emissions to a respective impact category. We also describe the contribution of certain parts of the product system to a respective impact category.

Tab. 1.1 Category indicators used in this report

Category indicator	**Abbreviation**	**Relevance for the processes investigated**	**Assessed**
Cumulative energy demand	CED	The cumulative energy demand of biomass, other renewable, fossil and nuclear energy resources is characterised and summed up with the reference unit MJ-eq. For agricultural products, the energy content in the harvested biomass is considered for this indicator.	(Frischknecht et al. 2004b)
Abiotic depletion	ADP	Important is the use of energy resources. The depletion of other abiotic resources is included in this indicator as well.	(Guinée et al. 2001)
Global warming	GWP	Contribution to the problem of climate change evaluated with the global warming potential. Main reason for promotion of BTL-fuels.	(Guinée et al. 2001, 100 years time frame for integration)
Photochemical oxidation, non-biogenic	POCP, non-b	Production processes and agriculture have some relevance. It has to be noted that only a small part of NMVOC gets a characterisation factor according to the CML methodology. All unspecified NMVOC are not assessed. This method does not evaluate biogenic emissions from plant growing, but other biogenic emission, e.g. CO from biomass burning.	(Guinée et al. 2001, high NO_x POCP) excluding isoprene, low population area
Photochemical oxidation	POCP	Sensitivity analysis including isoprene emissions from plant growing. Important because of air emissions from plant growing.	(Guinée et al. 2001, high NO_x POCP)
Photochemical smog		Methodology covering a larger range of substances that are important for photo oxidant formation. This method is applied in a sensitivity analysis.	Sensitivity analysis (Hauschild & Wenzel 1997)
Acidification	AP	Relevant for air emissions from agriculture and fuel combustion in transport processes.	(Guinée et al. 2001, average European AP)
Eutrophication	EP	High relevance due to use of fertilizers in agricultural processes.	(Guinée et al. 2001, generic EP)

		Inventory results	
Water use		Water is a scare resource especially in Southern European countries. The indicator includes all types of water use including rain falling on the agricultural area, irrigation water and direct uses of water in conversion processes.	No LCIA method. Amount will be quantified as LCI result.
Land competition		Most important resource for production of biomass and important differences between different biomass types.	No accepted LCIA method. Assessment on the level of inventory data on land competition (Guinée et al. 2001).

2 Biomass production

2.1 Comparison for category indicators results

Tab. 2.1 shows the results according to the category indicators listed in Tab. 1.1. The results are further analysed in the following figures.

Throughout this report, the different products are labelled with the type of product (e.g. wheat straw), the stage in the life cycle (e.g. at intermediate storage), the functional unit (e.g. kg) and the location (e.g. RER for Europe). The "U" stands for unit process data in the used database.

It has to be noted that it is principally not possible to compare different biomass resources at this stage with the aim to identify the best biomass inputs for a conversion process. The characteristics of these processes depend on the biomass input and are not a linear function of the biomass mass nor energy content.

Tab. 2.1 Category indicators per kg of dry matter biomass at intermediate storage

Impact category	Unit	bundles, short-rotation wood, at intermediate storage/kg/RER U	bundles, short-rotation wood, scenario 1, at intermediate storage/kg/RER U	miscanthus-bales, at intermediate storage/kg/RER U	miscanthus-bales, scenario 1, at intermediate storage/kg/RER U	wheat straw, bales, at intermediate storage/kg/RER U	wheat straw, bales, scenario 1, at intermediate storage/kg/RER U
cumulative energy demand	MJ-Eq	21.6	21.3	21.1	20.2	19.5	18.7
abiotic depletion	kg Sb eq	0.00061	0.00067	0.00063	0.00045	0.00050	0.00033
global warming (GWP100)	kg CO2 eq	0.147	0.170	0.154	0.131	0.114	0.084
photochemical oxidation, non-b	kg C2H4	0.0000215	0.0000239	0.0000195	0.0000168	0.0000144	0.0000122
acidification	kg SO2 eq	0.00120	0.00136	0.00096	0.00085	0.00071	0.00059
eutrophication	kg PO4--- eq	0.00073	0.00069	0.00132	0.00127	0.00066	0.00042
water use	m3	0.867	0.752	0.667	0.480	0.172	0.121
land competition	m2a	1.098	0.972	0.723	0.551	0.241	0.206
energy content of biomass	MJ/kg	18.4	18.4	18.8	18.8	17.2	17.2

Fig. 2.1 shows the relative comparison of the different biomass products with the category indicators used in this project. In general it has to be taken in mind that life cycle inventory data and thus also LCIA results for agricultural products show an uncertainty in the range of 15% - 30% (Nemecek et al. 2005). The main reasons are the large variability e.g. in terms of yields per hectare and actual energy use between single farms. Thus, smaller differences between different types of crops cannot be regarded as important.

The results for the cumulative energy demand show only little variation because most of the demand stems from the energy bound in the biomass. Differences for the abiotic depletion, global warming, POCP (non-biogenic) and acidification are higher with the lowest figures for straw and the highest for short rotation wood (willow-salix or poplar). Category indicator results for eutrophication are highest for the production of miscanthus. Wheat straw shows quite lower figures for some category indicators due to the allocation approach used in this study. This changes if another allocation approach is chosen as analysed in a sensitivity analysis in chapter 7.1.

Wheat straw shows the highest yields of dry matter per year and hectare due to the allocation between straw and grains. Only a small part of the land use for the wheat field is allocated to the straw and the rest is allocated to the wheat grains. Miscanthus has higher yields than short-rotation wood and thus a lower result for the land competition (see figures for land competition in Tab. 2.1).

These results and the influencing factors are further analysed in the following chapters.

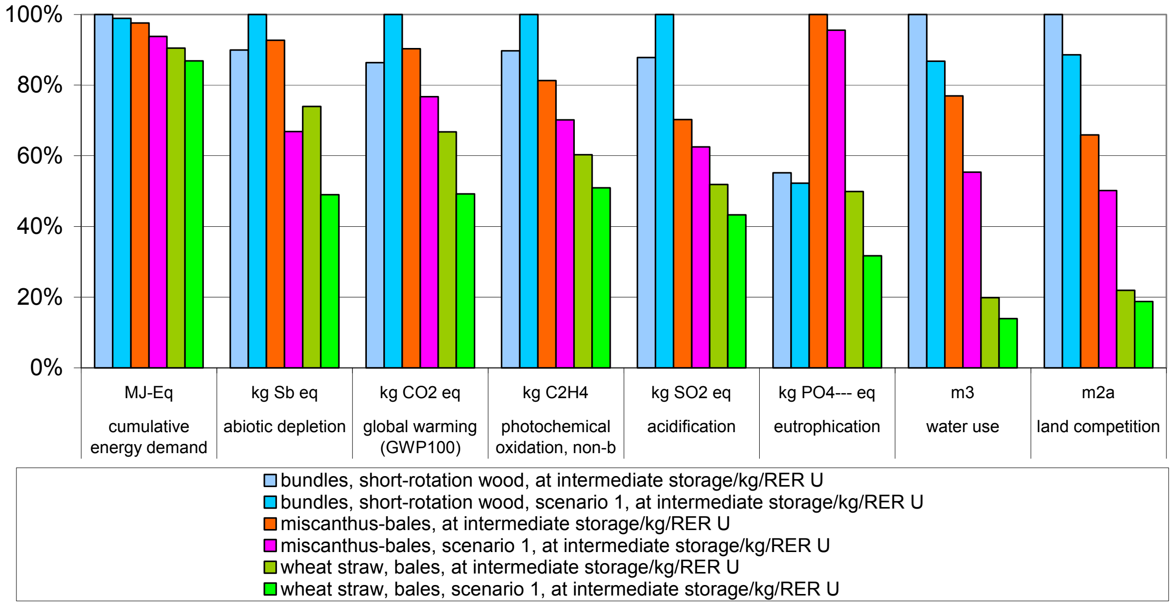

Fig. 2.1 **Relative comparison of biomass resources for the category indicators (basis kg dry matter of harvested biomass)**

Tab. 2.2 shows the same results per MJ of energy content of the biomass. In order to produce one MJ of biomass 9% to 17% of additional energy input are required. The table shows also the theoretical energy yield per square metre and year. Straw has the highest yields with about 70 to 80 MJ/m2a while short rotation wood has a quite lower yield of 17 to 19 MJ/m2a. But, it has to be noted that the high yield of straw is rather an effect of the allocation procedure and not a real yield per m^2.

Tab. 2.2 **Category indicators per MJ energy content in the biomass**

	Unit	bundles, short-rotation wood, at intermediate storage/kg/RER U	bundles, short-rotation wood, scenario 1, at intermediate storage/kg/RER U	miscanthus-bales, at intermediate storage/kg/RER U	miscanthus-bales, scenario 1, at intermediate storage/kg/RER U	wheat straw, bales, at intermediate storage/kg/RER U	wheat straw, bales, scenario 1, at intermediate storage/kg/RER U
cumulative energy demand	MJ-Eq	1.17E+00	1.16E+00	1.12E+00	1.08E+00	1.14E+00	1.09E+00
abiotic depletion	kg Sb eq	3.29E-05	3.67E-05	3.33E-05	2.40E-05	2.90E-05	1.92E-05
global warming (GWP100)	kg CO2 eq	8.00E-03	9.26E-03	8.19E-03	6.95E-03	6.62E-03	4.88E-03
photochemical oxidation, non-b	kg C2H4	1.17E-06	1.30E-06	1.04E-06	8.93E-07	8.39E-07	7.08E-07
acidification	kg SO2 eq	6.50E-05	7.40E-05	5.09E-05	4.53E-05	4.11E-05	3.43E-05
eutrophication	kg PO4--- eq	3.97E-05	3.76E-05	7.04E-05	6.73E-05	3.84E-05	2.44E-05
water use	m3	4.71E-02	4.09E-02	3.55E-02	2.55E-02	1.00E-02	7.02E-03
land competition	m2a	5.97E-02	5.28E-02	3.85E-02	2.93E-02	1.40E-02	1.20E-02

energy yield	MJ/m2a	16.8	18.9	26.0	34.1	71.5	83.5

Fig. 2.2 shows also a relative comparison of the biomass products based on the energy content harvested. The relative importance of the different types of biomass changes only slightly due to the very small differences in the energy contents of the biomass. Wheat straw has in many categories the lowest impact factor because the economic allocation gives a low share to this low value product. This changes if another allocation approach is chosen as analysed in a sensitivity analysis in chapter 7.1. Miscanthus ranges for most aspect in the middle of the three types of biomass while short rotation wood shows the highest impacts for most category indicators per MJ harvested.

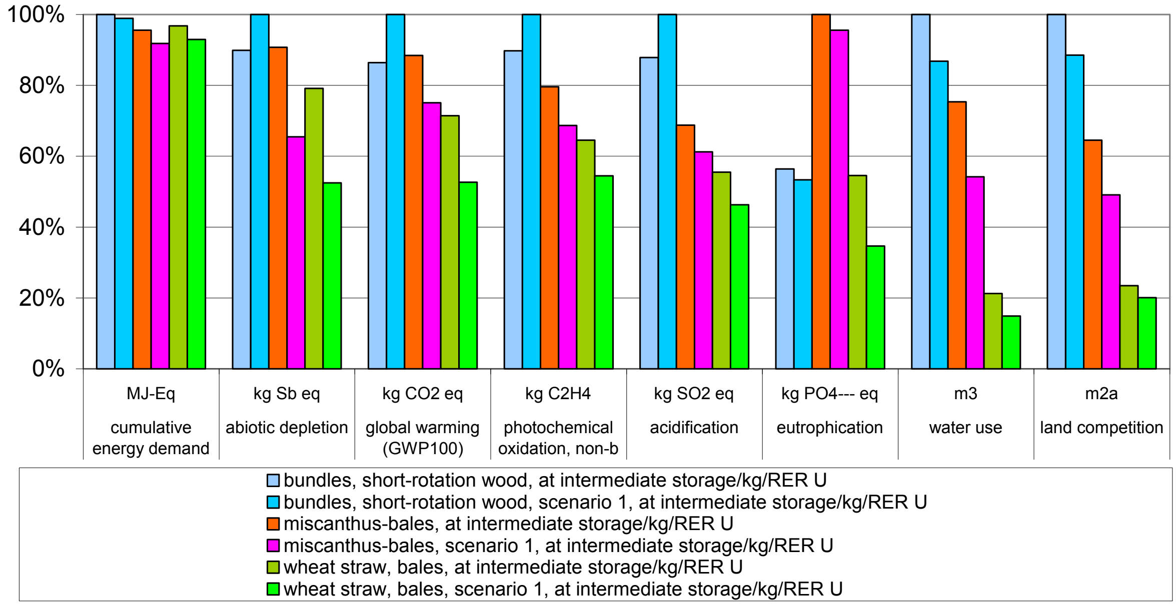

Fig. 2.2 Relative comparison of biomass resources for different category indicators (basis MJ of harvested biomass)

2.2 Analysis for the contribution to category indicators

2.2.1 Cumulative energy demand

The results for the cumulative energy demand are dominated with more than 90% by the direct input of biomass energy. Crude oil, natural gas and other energy resources are used to produce machinery, fertilizers, pesticides and fuels. The shares are rather similar for the different types of biomass products.

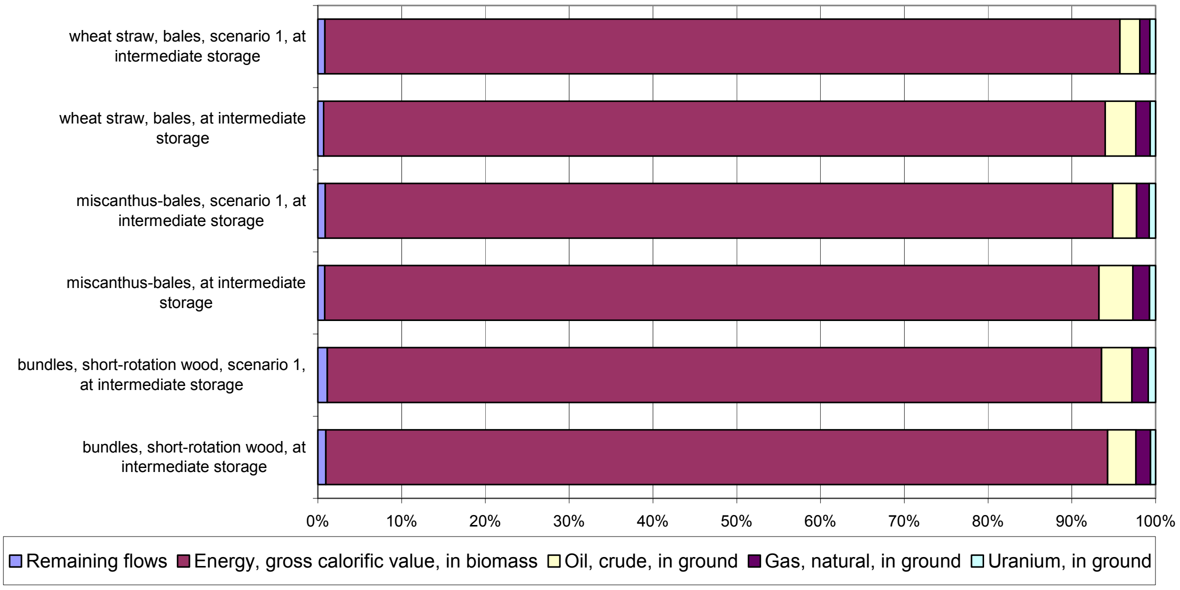

Fig. 2.3 Contribution of individual elementary flows to the total cumulative energy demand

2.2.2 Abiotic depletion

Fossil resources are the main elementary flows for the depletion of abiotic resources. Crude oil and natural gas account together for about 80% of the total impacts.

A detailed analysis of these flows shows the following. The use of diesel in agricultural machinery accounts for about 50% of the abiotic depletion. Input of N-fertilizers is also quite important. Oil and gas use are the major contributions to abiotic depletion.

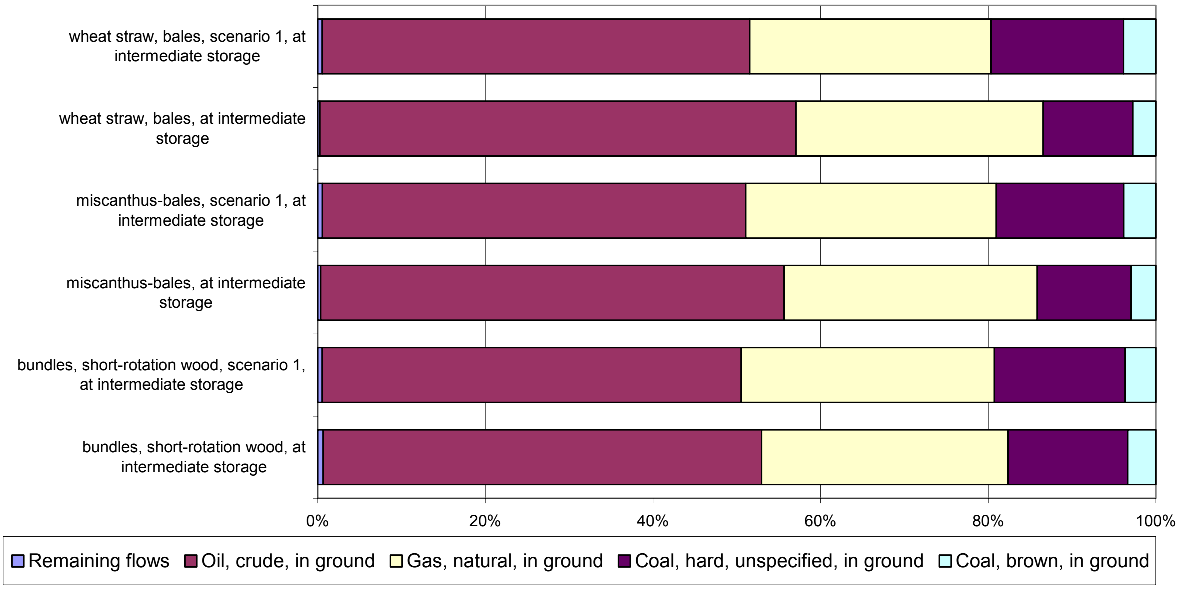

Fig. 2.4 Contribution of individual elementary flows to the total abiotic depletion

2.2.3 Global warming

In agricultural production N_2O is, besides CO_2, one very important greenhouse gas, which can contribute to more than 50% to the overall global warming potential as shown in Fig. 2.5. Together they account for 95% of the greenhouse gas emissions. About 60% of the N_2O emissions, are due to the agricultural production while 40% are released during the production of fertilizers. It has to be noted that the model used for N_2O emissions from agriculture takes into account secondary emissions due to nitrate emissions to rivers, which are than transformed partly to N_2O which amount to about 35% of the total N_2O emissions. Studies that do not take into account this effect will show a lower contribution of N_2O from agriculture. The model for the N_2O emissions takes also into account the surplus of nitrogen in the nitrogen balance. So far there is only limited experience for the nitrogen uptake of the new agricultural crops short-rotation wood and miscanthus. Furthermore, improvements can be expected concerning the N_2O emissions during fertilizer production. Thus, these emissions should be reduced in future in order to reduce also the global warming potential for all types of biofuels.

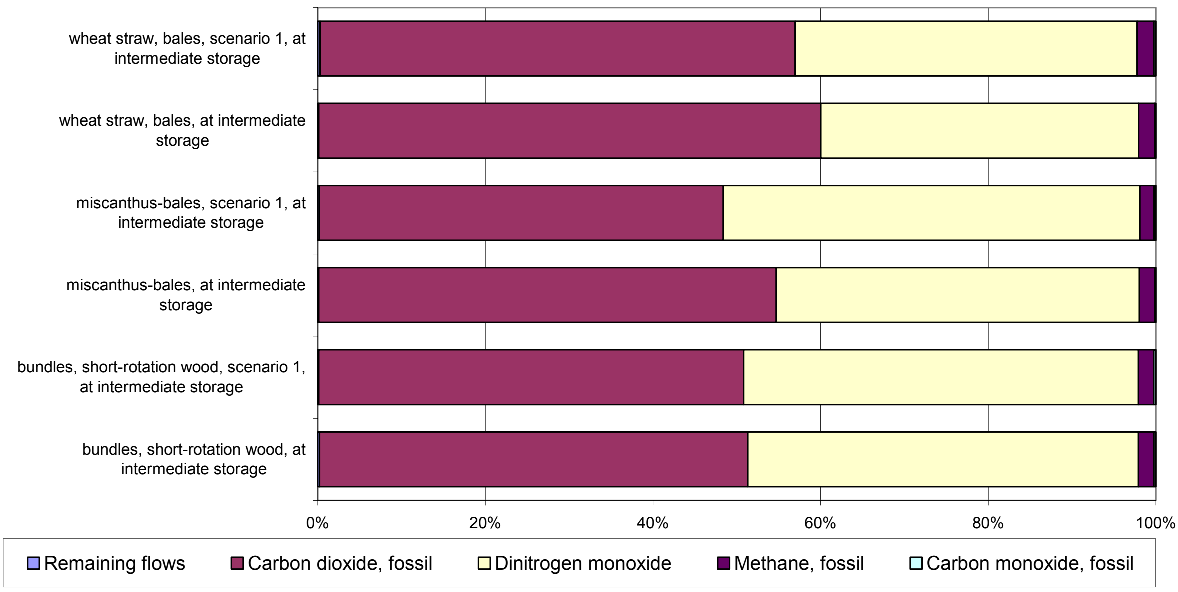

Fig. 2.5 **Contribution of individual elementary flows to the total global warming potential**

2.2.4 Photochemical oxidation, non-biogenic

The following figure evaluates the results for photochemical oxidation (non-biogenic). A detailed analysis showed that emissions of SO_x and CO, are important with regard to non-biogenic photo-oxidant formation. They are emitted in several different processes in the life cycle. An important input is the use of tractors, which includes the emissions from the supply of the fuel and from producing the tractor.

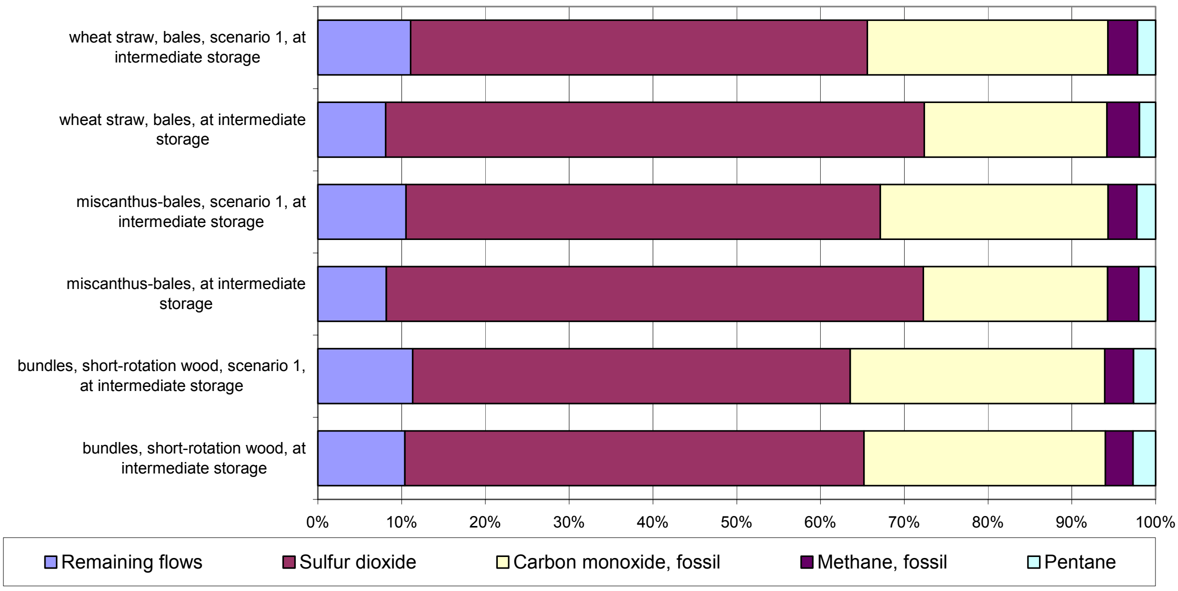

Fig. 2.6 **Contribution of individual elementary flows to the total photochemical oxidation, non-biogenic**

2.2.5 Acidification

Direct field emissions of NH_3 (40%-50%) and emissions from fuel combustion (NO_x) are important contributors to the acidification potential. Thus, emissions are quite dependent on the fertilizer use.

Sulphur dioxide is another important pollutant released in different stages and processes of the life cycle.

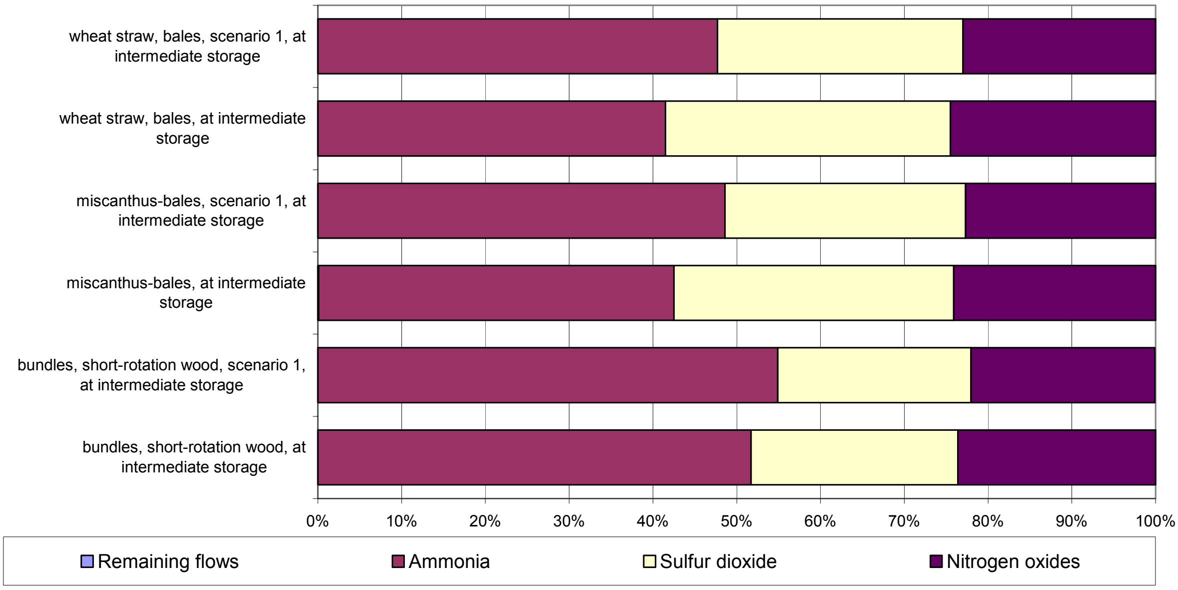

Fig. 2.7 Contribution of individual elementary flows to the total acidification

2.2.6 Eutrophication

Nitrate (30%-70%) and phosphate (10%-50%) are important emissions for eutrophication. They depend directly on the application of fertilizers. The specific emissions are lowest in scenario 1 because this scenario has higher yields in relation to the fertilizer inputs. The emissions of miscanthus production are higher, due to a more disadvantageous ratio between fertilizer consumption, N-deposition and N-uptake of the plants. But, it has to be noted that the models used for calculating such emissions are unsure (Jungbluth et al. 2007b:chapter 2.2.5). The methods can only be improved with direct field measurements on the cultivation of these crops. So far, such data are not available for these new types of agricultural products. The absolute impacts for ammonia are quite similar for the different crops, but the share varies with the importance of other emissions such as nitrate and phosphate.

So far it has not been considered that technical progress in fertilizer application and management might in future result in lower emissions than investigated here for scenario 1.

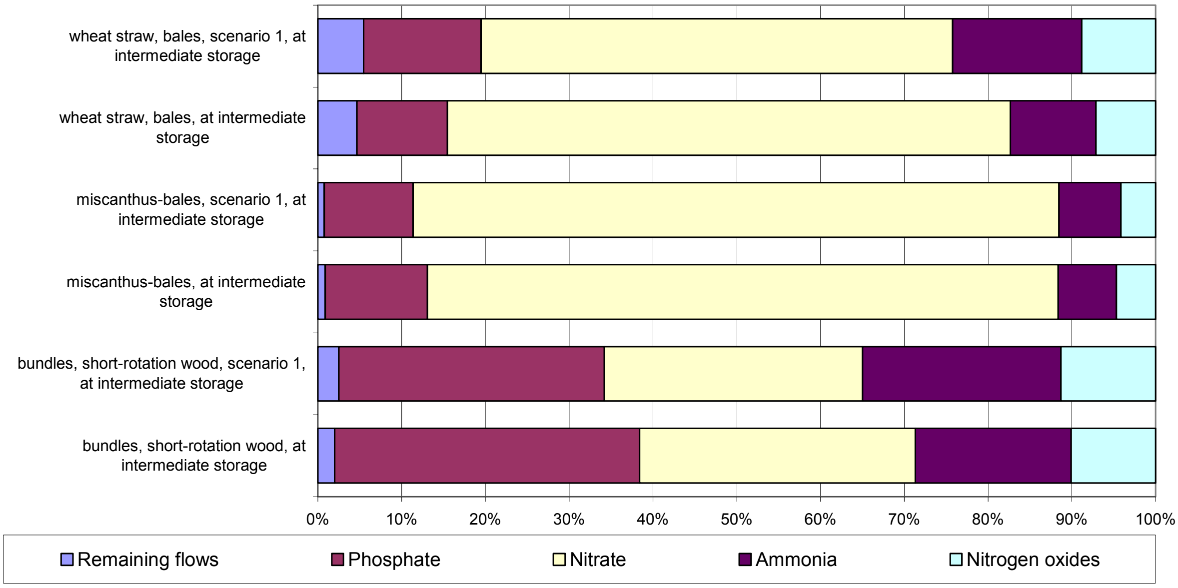

Fig. 2.8 **Contribution of individual elementary flows to the total eutrophication**

2.2.7 Water use

Rainwater is the main resource accounting for about 95% of the total water use. Water from rivers is also used for irrigation. Indirect water uses in the life cycle, e.g. in the conversion plant, account for less than 1%. The water use is quite dependent on the land competition and the area on which rain is falling. Uses in scenario 1 are lower due to the higher productivity. Further information can be found in the inventory analysis (Jungbluth et al. 2007b:2.2.4).

2.2.8 Land competition

The cumulative use of land area is mainly depending on the direct land competition and thus on the biomass yield per hectare. The indirect land competition in the life cycle (e.g. for roads or conversion plants) accounts for less than 1% of the total land competition.

3 BTL pathways, starting point calculation

3.1 Comparison for category indicators

For each BtL-pathway the ratio biomass input to BtL-fuel output based on energy is provided in the inventory analysis (Jungbluth et al. 2007b). We summarize these key figures for the starting point calculation in Tab. 3.1. The CHEMREC[4] process has the highest conversion rate followed by the UET process. The TUV process has rather low conversion rate (biomass to fuel) because it produces large amounts of electricity as a by-product. The electricity is only burdened with the direct air emissions from the power plant, but not with the production of biomass. This, is a worst-case assumption for the production of the biofuels. A sensitivity analysis on this issue is performed in chapter 7.4. The table shows also the capacity in MW biomass input for the different conversion concepts.

Tab. 3.1 Key figures of conversion processes for the ratio between biomass input and BTl-fuel output in terms of mass and energy, starting point calculation

	Biomass	Wood	Straw	Wood	Straw	Straw	Wood	Miscanthus	Wood
	Process	Centralized Entrained Flow Gasification	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Allothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Entrained Flow Gasification of Black Liquor for DME-production
	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-DME
	Code	cEF-D	cEF-D	CFB-D	CFB-D	dEF-D	ICFB-D	ICFB-D	BLEF-DME
	Developer	UET	UET	CUTEC	CUTEC	FZK	TUV	TUV	CHEMREC
conversion rate (biomass to all liquids)	energy	53%	57%	40%	38%	45%	26%	26%	69%
capacity biomass input (MW)	power	499	462	485	463	455	52	50	500
all liquid products (diesel, naphtha, DME)	toe/h	22.5	22.3	16.6	15.0	17.5	1.1	1.1	29.0

toe tonnes oil equivalent with 42.6 MJ/kg

Fig. 3.1 shows a relative comparison of the fuel products based on the energy content. The comparison is presented on a relative scale (0-100%). Tab. 3.2 shows the absolute figures. Both presentations show the life cycle from well to tank. Thus, "at service station" means that all relevant inputs and outputs until the supply to the tank are taken into account.

Green colour in Tab. 3.2 indicates the processes with the lowest results for a specific biomass input (wood or straw) and a specific category indicator. Bold figures indicate the lowest environmental impacts of all processes. An orange colour indicates the highest environmental impacts for a specific fuel.

For the conversion of wood, the UET process has between 15% and 30% higher impacts than the CHEMREC process for the category indicators CED, abiotic depletion, global warming, eutrophication, water and land use. However, it has 35% lower impacts for the category indicator photochemical oxidation. CUTEC has more than 70% higher impacts for all aspects investigated than UET and CHEMREC. The TUV process shows rather low conversion rate and thus has higher impacts for all category indicators except photochemical oxidation not including biogenic emissions.

The comparison of processes based on wood or straw depends not only on the type of biomass, but also on the difference in the conversion rate. The CFB-D process based on wood perform slightly better than processes based on straw regarding the category indicators cumulative energy demand, abiotic depletion, global warming potential and eutrophication potential. For the cEF-D concept, the process with straw has lower environmental impacts than the conversion of wood.

The process with the lowest environmental impacts for POCP, acidification water use and land competition is the UET process with straw. The UET process has the lowest environmental impacts in the

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[4] In order to facilitate the reading of this report, the Developer-Code was used instead of the Process-Code, e.g. the name of "TUV" stands for the process of "ICFB-D". See Tab. 3.1 for further abbreviations.

ranking for the conversion of straw followed by the FZK and the than CUTEC process for all category indicators.

There is only one conversion process using miscanthus (TUV). Thus, a direct comparison with other conversion concepts is not possible, because the environmental impacts are quite dependent on the type of biomass. There is no clear recommendation for the use of miscanthus or straw if one compares the results for the two inputs to the TUV process.

Tab. 3.2 shows also the final fuel energy yield per square metre of land used for one year. The fuel yield for energy crops per hectare is between 860 to 2300 kg oil equivalents. Processes based on straw show a fuel yield up to 8200 kg oil equivalents per hectare if the agricultural land is allocated to the straw based its share for the today revenue for wheat production. Only a small part of the total land occupation for the wheat field is allocated to the by-product straw. The yield for processes based on straw is only 1300 to 1900 kg oil equivalents per hectare if the allocation procedure is based on the energy content of the grains and straw.

The processes designed by TUV have higher environmental impacts than the other processes. This is partly due to the specific design of the process, which aims to produce larger amount of heat and electricity together with BTL-FT fuels. In chapter 7.4 a sensitivity analysis is made for the allocation of a part of the wood input to the produced heat and electricity. This reduces the environmental impacts by about 30%.

The results are further analysed in the following chapters.

Tab. 3.2 Category indicator results per MJ of BTL-fuel delivered to the tank, starting point calculation and fuel yield per hectare and year

Impact category	Unit	BTL-fuel, miscanthus, at service station/MJ/TUV U	BTL-fuel, straw, at service station/MJ/CUTEC U	BTL-fuel, straw, at service station/MJ/FZK U	BTL-fuel, straw, at service station/MJ/UET U	BTL-fuel, wood, at service station/MJ/CUTEC U	BTL-fuel, wood, at service station/MJ/TUV U	BTL-fuel, wood, at service station/MJ/UET U	dimethylether, black liquor, at service station/MJ/Chemrec U
cumulative energy demand	MJ-Eq	5.32	3.92	3.10	2.44	3.57	5.55	2.70	**2.11**
abiotic depletion	kg Sb eq	0.000269	0.000274	0.000163	0.000128	0.000173	0.000270	0.000134	**0.000105**
global warming (GWP100)	kg CO2 eq	0.0579	0.0646	0.0328	0.0265	0.0437	0.0572	0.0296	**0.0256**
photochemical oxidation, non-b	kg C2H4	0.0000296	0.0000438	0.0000313	**0.0000121**	0.0000355	0.0000298	0.0000126	0.0000171
acidification	kg SO2 eq	0.000466	0.000350	0.000346	**0.000182**	0.000330	0.000528	0.000237	0.000243
eutrophication	kg PO4--- eq	0.000402	0.000184	0.000144	0.000094	0.000156	0.000267	0.000104	**0.000089**
water use	m3	0.158	0.031	0.026	**0.020**	0.136	0.209	0.103	0.080
land competition	m2a	0.180	0.044	0.040	**0.028**	0.174	0.273	0.130	0.102
energy yield	MJ/m2a	5.6	22.7	25.3	35.1	5.8	3.7	7.7	9.8
fuel yield	toe/ha/a	1.3	5.3	5.9	8.2	1.4	0.86	1.8	2.3

toe tonnes oil equivalent with 42.6 MJ/kg

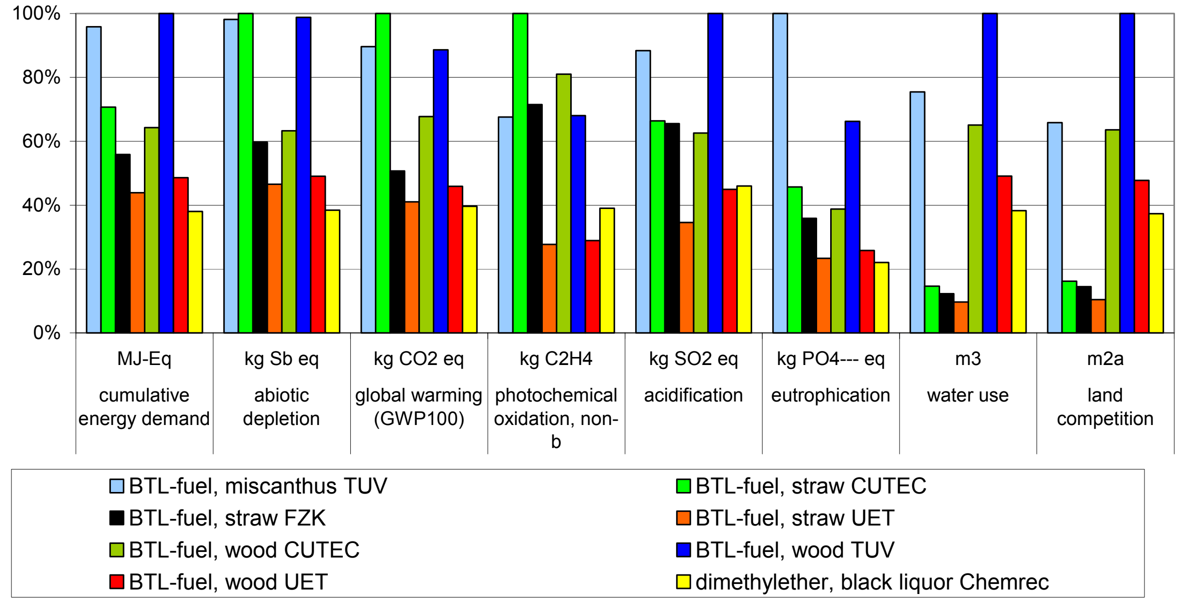


Fig. 3.1 **Relative comparison of fuels using different category indicators (basis MJ of fuel delivered to the tank)**

3.2 Analysis for the contribution to category indicators

3.2.1 Cumulative energy demand

The major elementary flow for the cumulative energy demand is the input of energy bound in the biomass when it is harvested. Thus, the biomass production process accounts for 80%-90% of the cumulative energy demand in the starting point calculation.

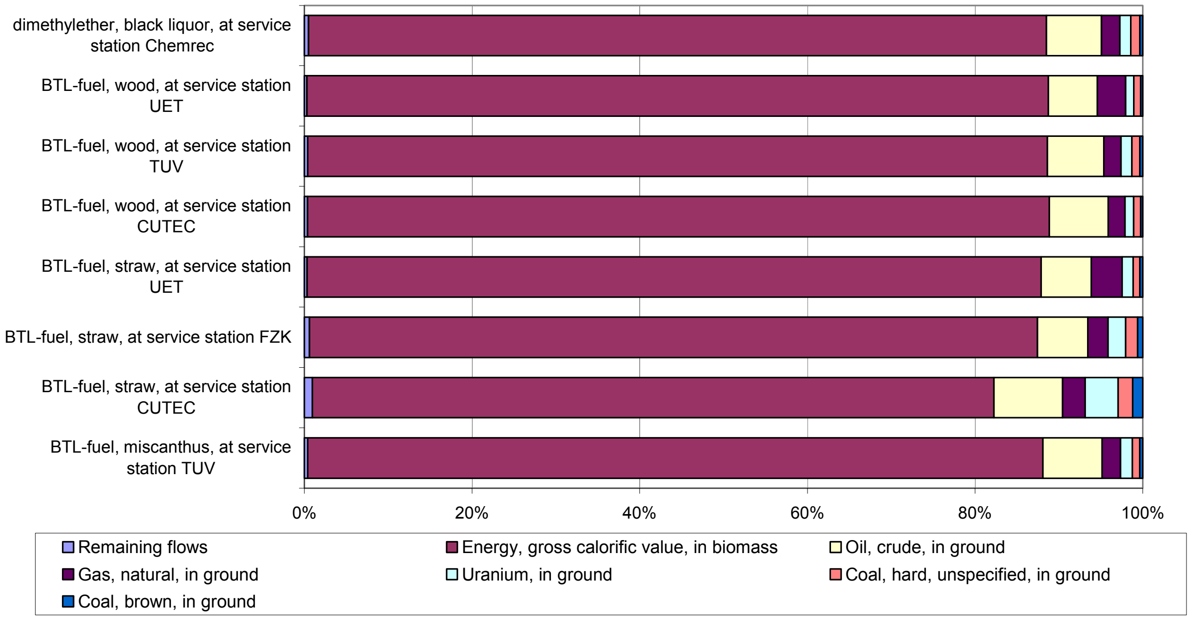
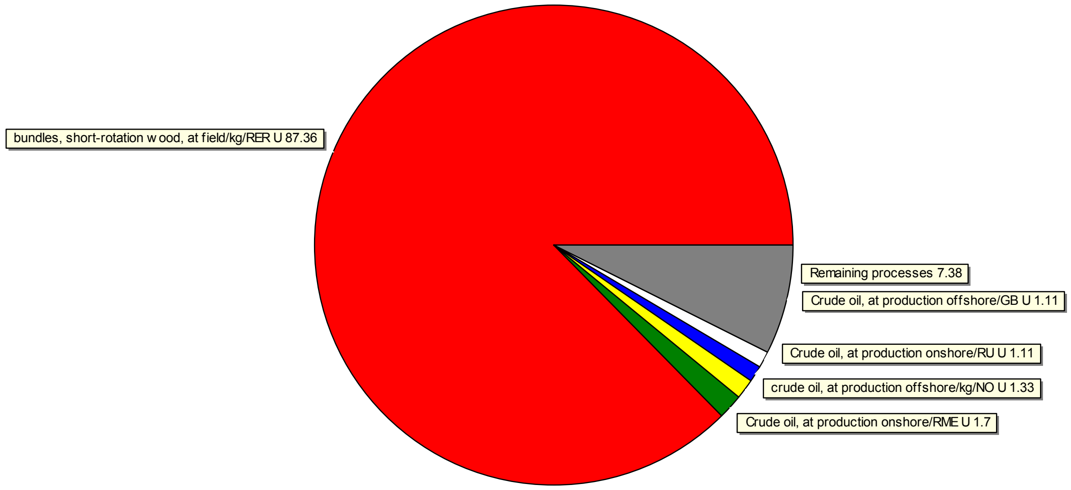


Fig. 3.2 **Contribution of individual elementary flows to the total cumulative energy demand**

The cumulative energy demand of different unit processes is evaluated in Fig. 3.3 for one conversion technology. The figure shows the names of the process involved and the percentage direct contribution to this category indicator. Direct contribution means that only elementary flows directly accounted for this unit process are taken into account while upstream flows are shown with the processes were they are accounted for.

In this example, about 87% of the cumulative energy demand can be attributed to the extraction of biomass energy during biomass production. This is equal to the higher heating value of the harvested biomass product (short-rotation wood in this example). Fossil energy demand is also accounted for at the process of extraction, thus e.g. crude oil production in Middle East (RME – region middle east) accounts for 1.7% of the total.

This type of figures is not shown for all conversion processes and all category indicators, because this would mean a lot of repetitive information. Only some interesting examples are chosen. Results for other processes are outlined in the text if they differ considerable from these examples.



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 3.3 Contribution of individual unit processes in the product system to the total cumulative energy demand, example for TUV process with wood

3.2.2 Abiotic depletion

Oil (50%-60%) and gas use are the major contributions to abiotic depletion. It has to be noted, that the use of uranium has only a small contribution with this category indicator, and is thus not shown in the figure.

The resource extraction takes place in many different unit processes of the life cycle. A major part can be attributed to crude oil extraction processes that take in different countries. In addition, processes for the extraction of other energy resources are important. Fig. 3.5 shows an example. There are no general differences between the different processes investigated.

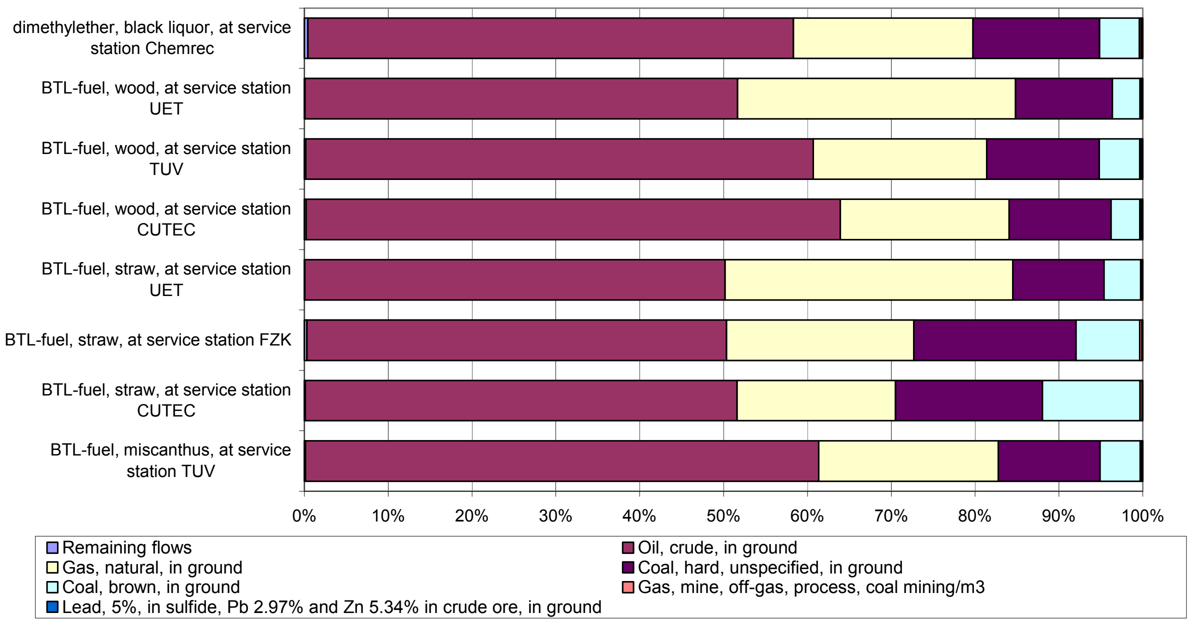


Fig. 3.4 **Contribution of individual elementary flows to the total abiotic depletion**

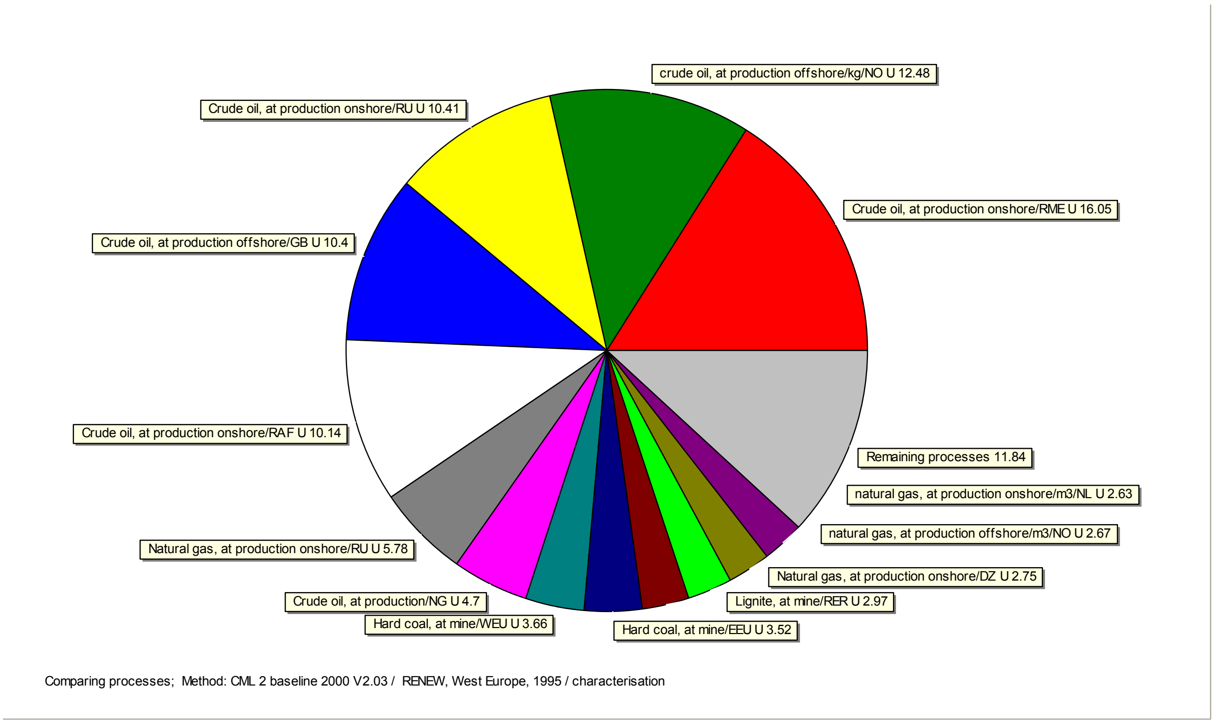


Fig. 3.5 **Contribution of individual unit processes in the product system to the total abiotic depletion, example for CUTEC process with wood**

3.2.3 Global warming

Carbon dioxide (50%-70%) and dinitrogen monoxide (20%-40%) are the major elementary flows with respect to global warming. Methane from biomass combustion in the conversion plant accounts for up to 15% of the total emissions. In addition, the release of off-gases from the gas cleaning prior to the synthesis process is important. The data for the methane content of off-gases and the emissions of power plants used in the conversion are based on single measurements and do not distinguish for the different technologies. For process improvement from an environmental point of view, such emissions should be reduced to a minimum. This is even more important than in the case of fossil based power plants and combustion processes where fossil CO_2 is normally the most important greenhouse gas.

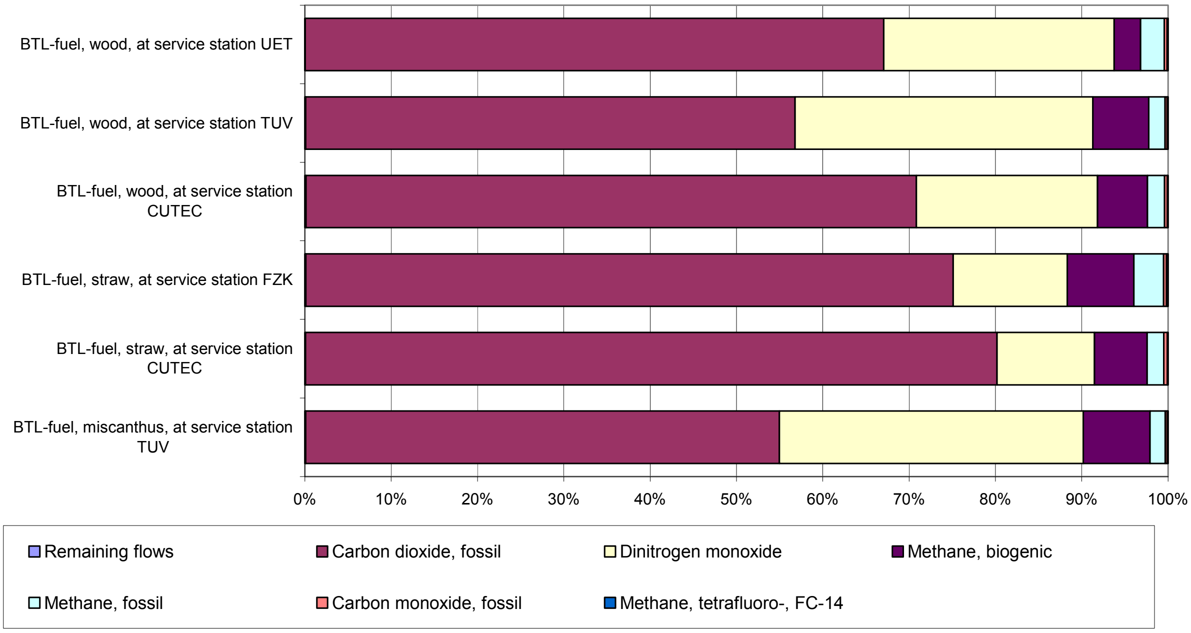


Fig. 3.6 Contribution of individual elementary flows to the total global warming potential

The detailed analysis reveals some differences between the conversion routes. In principle, the following types of processes are important for the releases of greenhouse gases: biomass production, fertilizer production (ammonia steam reforming and nitric acid production), transport and tractor processes, off-gases and emissions from the power plant (examples in Fig. 3.7 to Fig. 3.9).

About 15% of the emissions from the CHEMREC process are directly related to the release of off-gases.

In the UET process for wood, releases due to biomass production (17%) and the off-gases from the conversion process (13%) are most important process stages for direct emissions contributing to the indicator global warming potential.

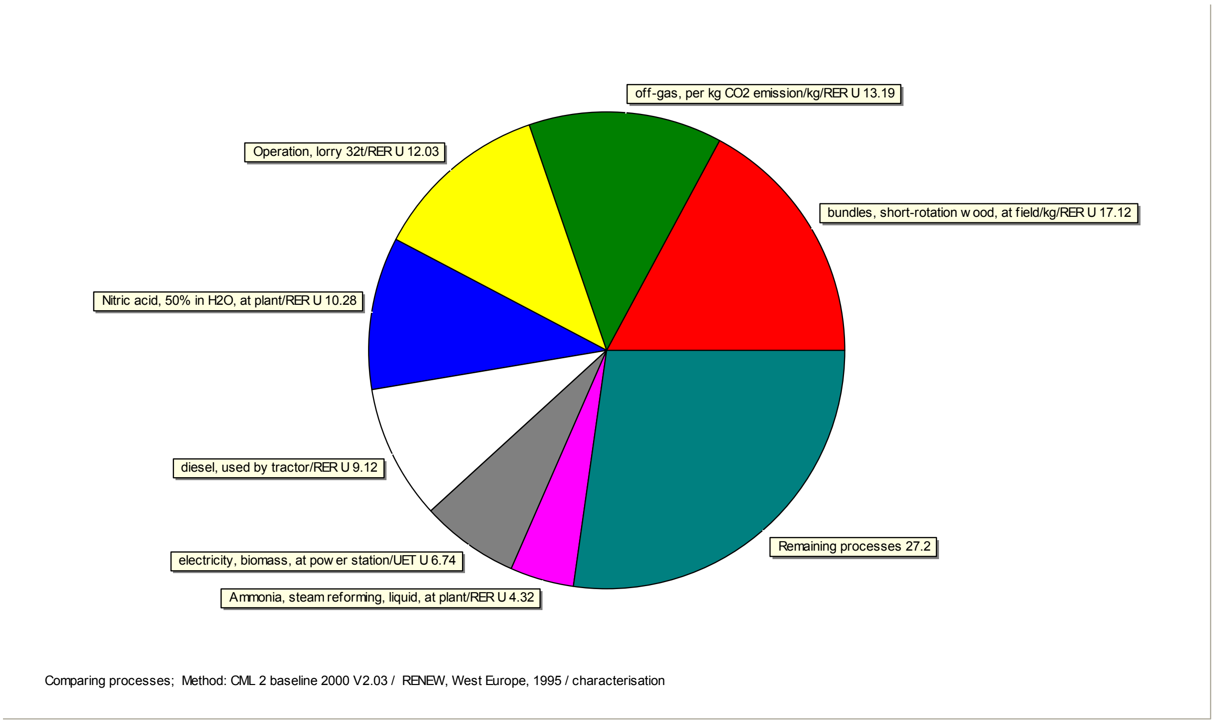


Fig. 3.7 **Contribution of individual unit processes in the product system to the total global warming potential, UET-process, wood**

The TUV processes show a relatively low share of biogenic methane emissions because a large part of the emissions from the power plant is allocated to the part of the electricity that is delivered to the grid. Emissions from the use of fossil chemicals in the production process form an important part.

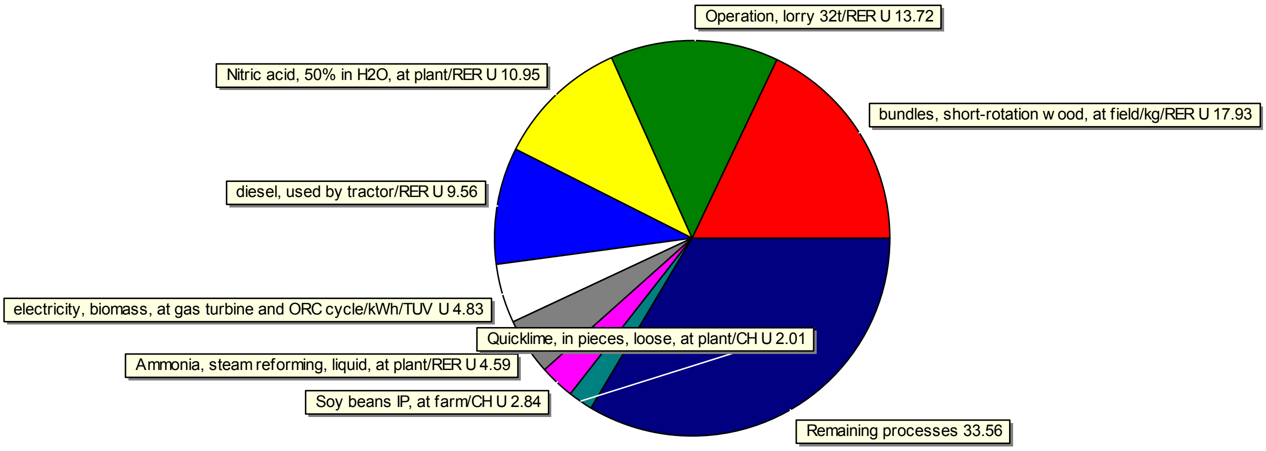


Fig. 3.8 **Contribution of individual unit processes in the product system to the total global warming potential, wood, TUV-process**

In the CUTEC process, the production of quicklime for CaO, which is used as a catalyst, is responsible for about 19% of the greenhouse gas emissions in the case of straw input. The plant developer already discus the possibilities for the recycling of this material from the ashes of this process. Thus the use of less or alternative materials is an important improvement option. An important part of the emissions arises at the power plant.

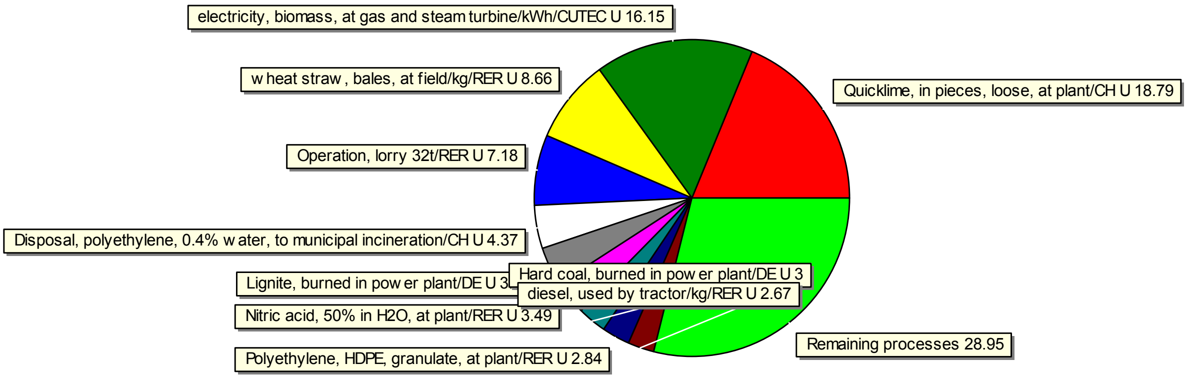


Fig. 3.9 Contribution of individual unit processes in the product system to the total global warming potential, straw, CUTEC-process

3.2.4 Photochemical oxidation, non-biogenic

A range of different substances is important for the photochemical oxidation. The most important one in this study are sulphur dioxide, carbon monoxide and different NMVOC. Dimethylether emissions are relevant in the distribution of DME.

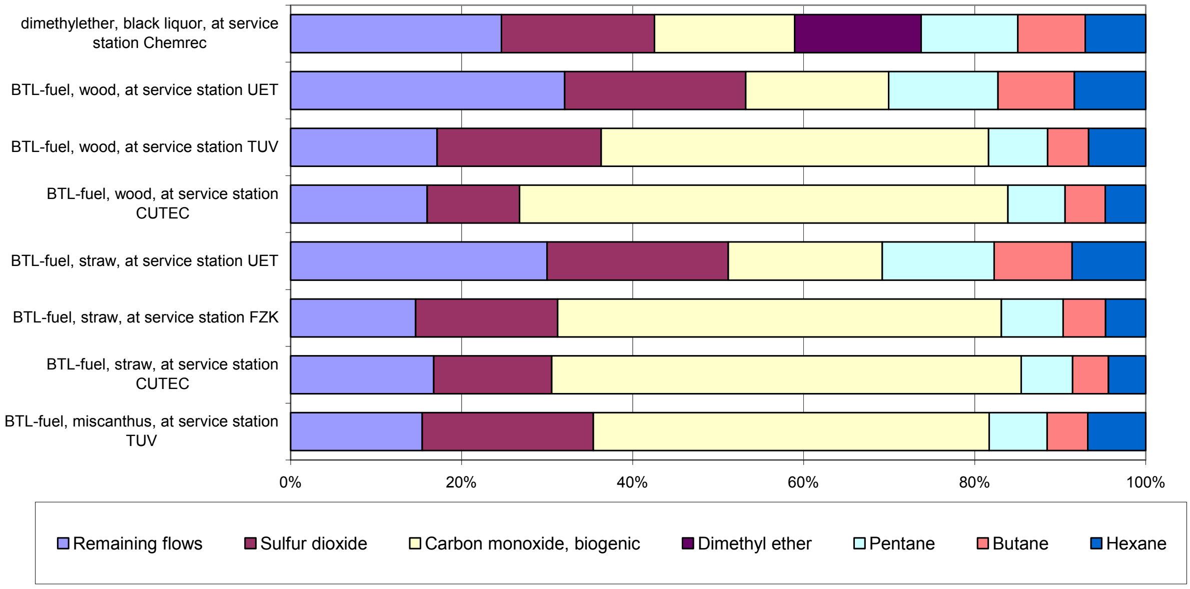


Fig. 3.10 Contribution of individual elementary flows to the total photochemical oxidation, non-biogenic

The most important processes are direct releases of photo oxidants from the conversion process, e.g. with off-gases, with process emissions and from the power plant. They account for more than 50% of the total emissions. The emission profile and the actual amount of these releases are based on expert guesses and not on measurements. Another important source of such emissions is the production of rare metals (e.g. palladium) used in the catalysts. The amount and actual composition of the catalysts is based on literature data and not on data from the conversion plants. Thus, the catalyst used actually for the different conversion processes might vary in the composition and in the amount used. Due to these uncertainties, comparisons based on the POCP should be done with care.

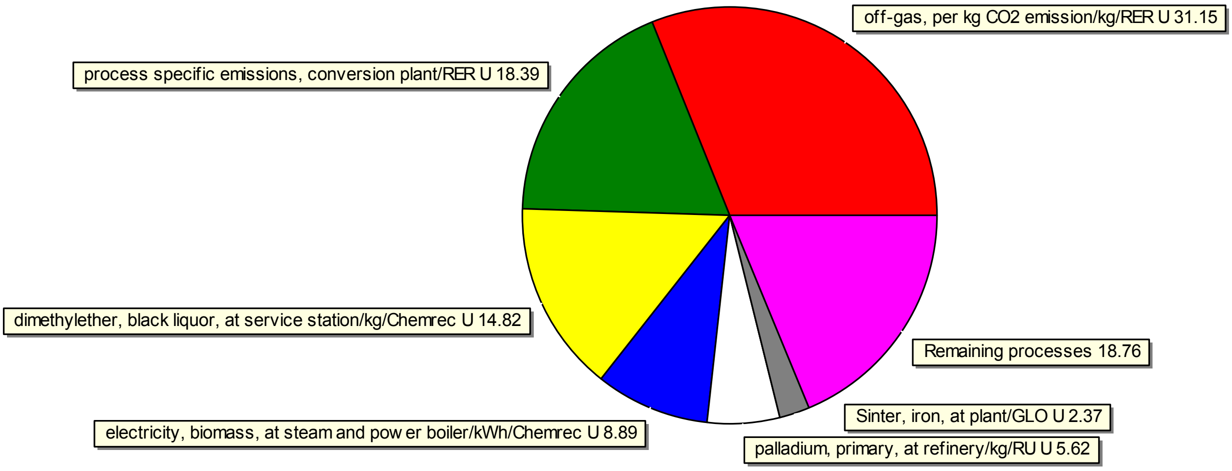


Fig. 3.11 **Contribution of individual unit processes in the product system to the total photochemical oxidation, non-biogenic, CHEMREC, wood**

3.2.5 Acidification

Acidification is caused by ammonia, sulphur dioxide and nitrogen oxides in about equal shares for the fuel products investigated in this study.

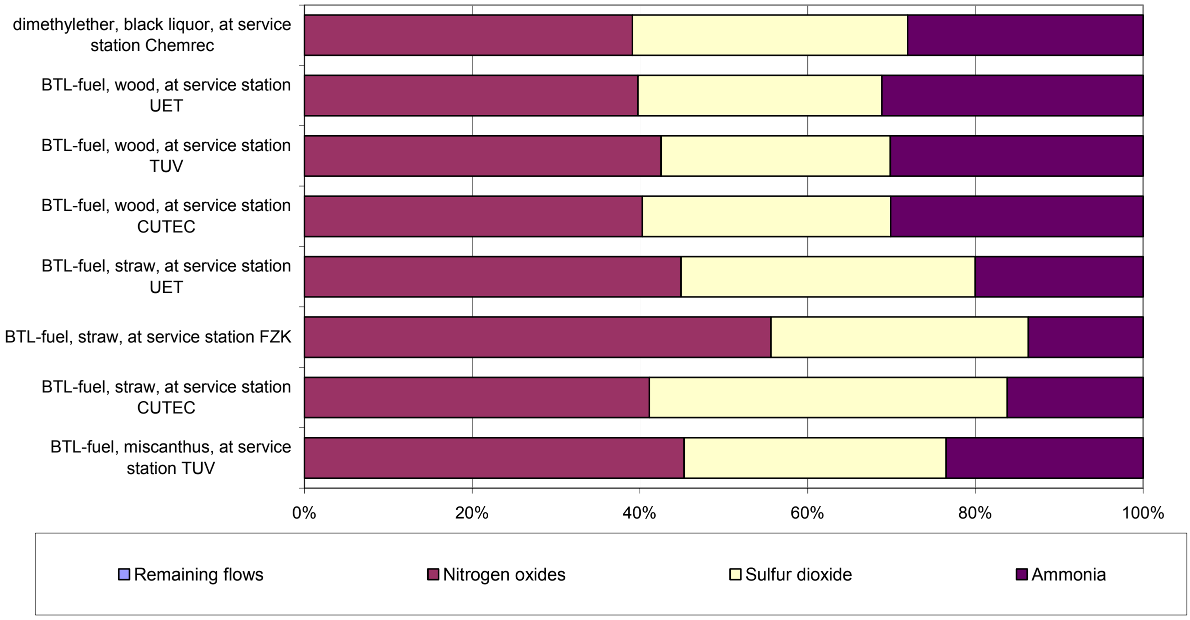


Fig. 3.12 **Contribution of individual elementary flows to the total acidification**

The emissions of acidifying substances can be attributed to the biomass production and direct air emissions of the conversion process with off-gases and from the power plant. The operation of transport devices and tractors is also an important source of such emissions.

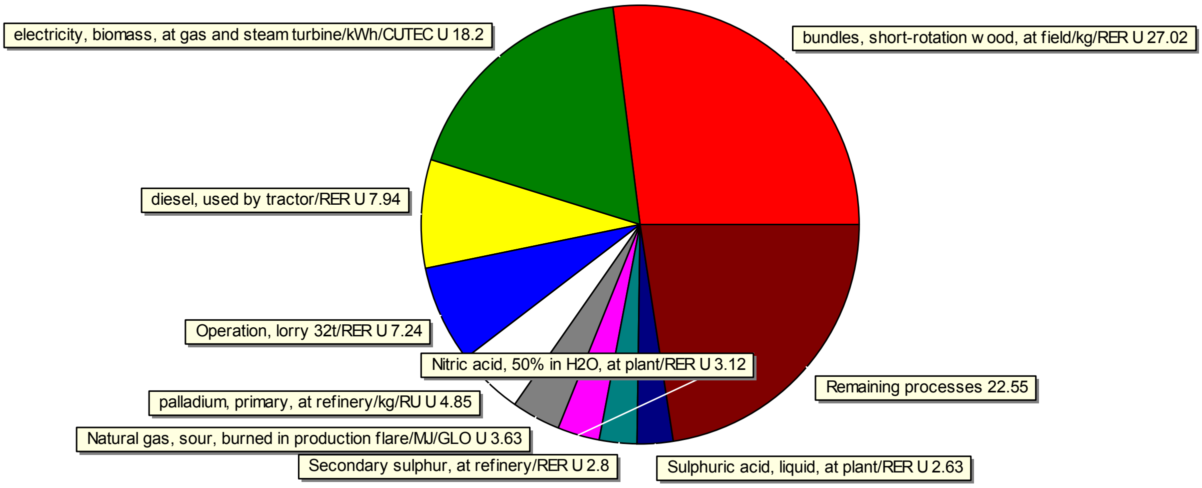


Fig. 3.13 Contribution of individual unit processes in the product system to the total acidification, CUTEC-process, wood

3.2.6 Eutrophication

Eutrophication is caused by nitrates, phosphates, ammonia and nitrogen oxides.

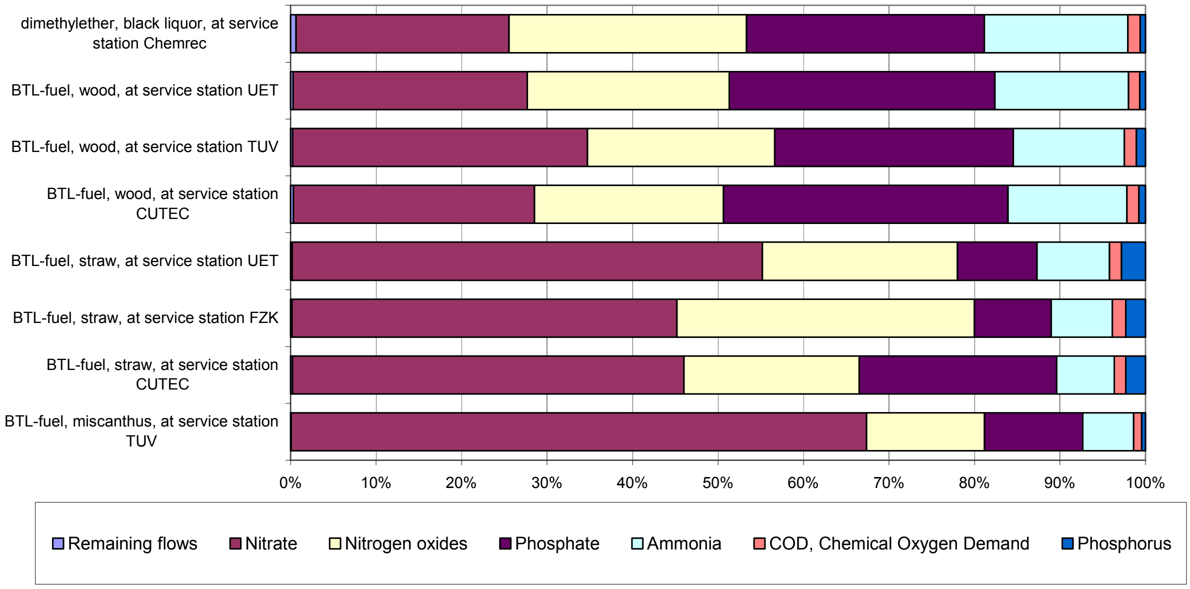


Fig. 3.14 Contribution of individual elementary flows to the total eutrophication

A share of more than 50% for the release of eutrophication emissions can be attributed in most cases directly to the agricultural production process. Other important sources of emissions are the direct air emissions from the conversion process and power plant. The production of fertilizers contributes in smaller amounts.

The TUV process uses rape oil methyl ester as an input. This has been approximated with soya oil. The emissions originating from this production process are important, however as the RME is later on burned for power generation in the process, this cannot be considered as a major disadvantage of this process type.

The disposal of ashes from the biomass combustion has some relevance in the case of the CHEMREC process.

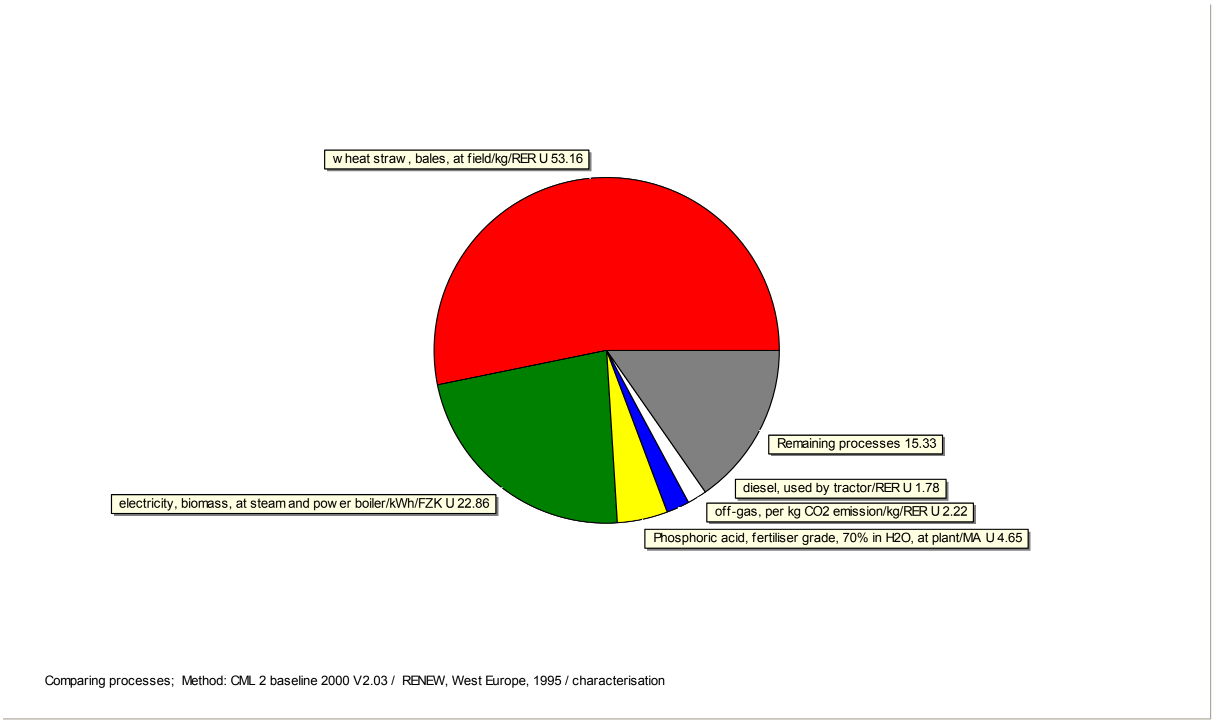


Fig. 3.15 Contribution of individual unit processes in the product system to the total eutrophication, straw, FZK-process

3.2.7 Water use

The water use is fully dominated by rainwater used in agriculture. Other water uses e.g. in the conversion plant or for irrigation are not very important. In the moment, there is no LCIA methodology available for characterising different types of water uses. Water use and water scarcity is an important issue especially in Southern European countries. On a regional scale, this should be taken into account for the assessment of different types of biomass resources used for biofuel production.

3.2.8 Land competition

Land competition is dominated by agricultural types of land competition, which are directly due the biomass production and account for about 90% of all land uses. Background processes, e.g. storage facilities that are constructed with wood, get a share of up to 20% in the conversion routes based on straw. This is because of the allocation of a larger part of the land used for wheat growing to the wheat grains. Thus, the direct land use assigned to the straw is smaller than for other crops.

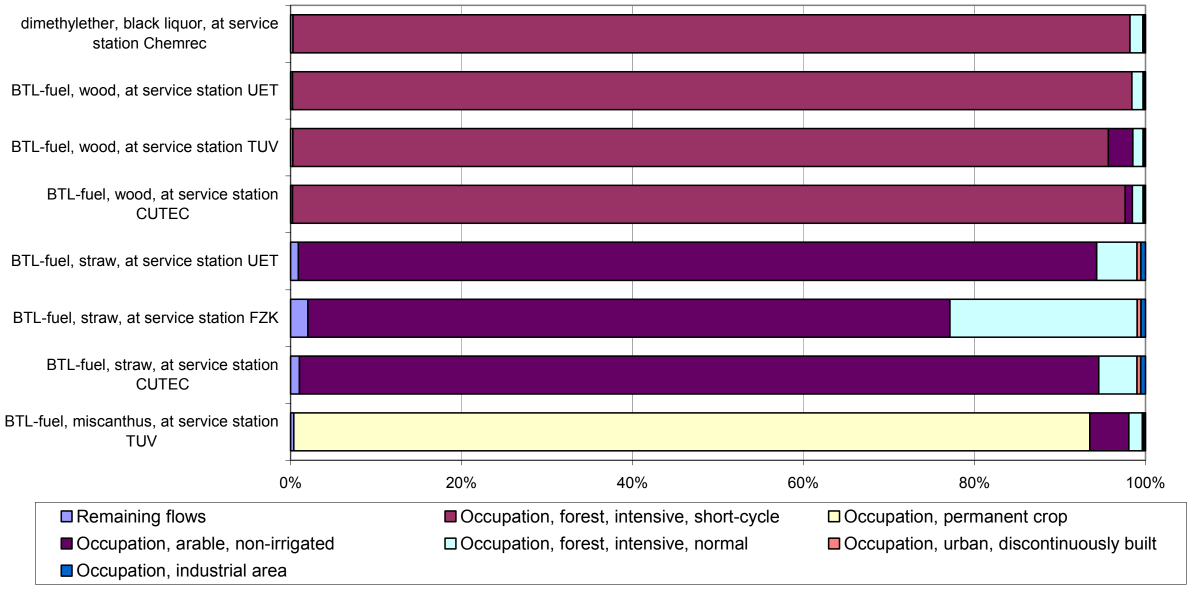


Fig. 3.16 Contribution of individual elementary flows to the total land competition

3.3 Summary

Many category indicators like acidification (25%), eutrophication (more than 50%), water use and land competition (both about 99%) show an absolute dominating influence of the agricultural production of biomass. Thus, only the conversion ratio and the type and production patterns of biomass are important when comparing different conversion routes.

It is assumed that carbon losses are released as biogenic CO_2 to the air. With these emissions, other pollutants as NO_x are modelled based on a linear relationship, because the legal limits prescribe the concentration of pollutants in the flue gases. The conversion rate thus plays a major role in the formation of air emissions from the conversion plant. The higher the conversion rate, the lower the share of carbon and thus also other pollutants which are released to the ambient air. The most important processes for the POCP are direct releases of photo oxidants from the conversion process, e.g. with off-gases, with process emissions and from the power plant. They account for more than 50% of the total emissions. Another important source of such emissions is the production of rare metals (e.g. palladium) used in the catalysts.

The conversions processes designed by UET and CHEMREC have the lowest environmental impacts in the assessment with the choice of category indicators investigated in this survey. They are followed by the CUTEC process. The TUV process shows the highest impacts due to a process design with a considerable high amount of electricity production and thus a lower biomass to fuel conversion rate. A sensitivity analysis, which considers the higher electricity production, is performed in chapter 7.4.

4 BTL pathways, scenario 1

4.1 Comparison for category indicators

For each BtL-pathway the conversion ratio biomass input to BtL-fuel output based on mass and energy is provided in the inventory analysis (Jungbluth et al. 2007b). We summarize these key figures for scenario 1 in Tab. 4.1.

The conversion rates vary quite a lot between the different processes. Data for the TUV process are in the range of the figures presented by other plant operators for the starting point calculation. There is no external hydrogen input for this conversion process. Conversion rates for other processes are higher than 100% because the process is operated with a large energy input from the electricity grid. This is not accounted for in the conversion rate biomass to liquids because it is not a biomass energy input.

According to the data provided and used, the UET process has the highest conversion rate. The process of CUTEC has a similar conversion rate as the TUV process, but with quite different amount of hydrogen input. CHEMREC has not provided data for scenario 1.

The demand for external electricity ranges between 135 and 515 MW. The differences and reasons for the technical differences are further analysed in WP5.4 of the RENEW project.

Tab. 4.1 Key figures of conversion processes. Ratio biomass input to BTL-fuel output in terms of mass and energy and hydrogen input, scenario 1

	Biomass	Wood	Wood	Straw	Straw	Wood	Miscanthus
	Process	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Allothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification
	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT
	Code	cEF-D	CFB-D	CFB-D	dEF-D	ICFB-D	ICFB-D
	Developer	UET	CUTEC	CUTEC	FZK	TUV	TUV
conversion rate (biomass to all liquids)	energy	108%	57%	56%	91%	55%	57%
capacity biomass input (MW)	power	499	485	464	455	518	498
external electricity, including H2 production	MW	489	135	149	515	-	-
hydrogen input conversion	kg/kg product	0.24	0.13	0.13	0.34	-	-
all liquid products (diesel, naphtha, DME)	toe/h	45.6	23.4	21.9	34.9	24.1	24.0

toe tonnes oil equivalent with 42.6 MJ/kg

Fig. 4.1 shows a relative comparison of the fuel products based on the energy content. All comparisons are presented on a relative scale (0-100%). Tab. 4.2 shows the corresponding absolute figures. In general, one can see quite large differences between the processes for individual category indicators. However, there is no clear trend in the ranking if all category indicators are assessed together.

Green colour in Tab. 4.2 indicates the process with the lowest environmental impacts for a specific biomass input (wood or straw). Bold figures indicate the lowest environmental impacts of all process. An orange colour indicates the lowest performance for a specific biomass input.

The main idea of scenario 1 is an increase of the fuel yield per hectare. As one can see in Tab. 4.2 a fuel yield of 3900 kg oil equivalents per hectare is possible for the use of miscanthus if hydrogen can be used in the process. For the use of wood, a yield in the range of 2100kg to 4100kg can be reached.

It seems to be quite unrealistic in Europe to achieve the necessary electricity demand with wind power plants, if one looks at the necessary capacity. The electricity demand of the different processes in scenario 1 is in the range of 135 MW to 560 MW. With an installed capacity of 1.5 MW per wind power plant, this would mean that a wind park with 100 to 400 wind power plants would be necessary for one conversion plant.

All renewable sources for electricity do normally not guarantee a stable and constant power supply because e.g. of dependence on whether conditions. Thus it has to be noted that the production of biofuels in such a remote plant would be quite dependent on the actual supply situation and thus needs to be flexible in terms of hydrogen supply.

The other possibility for guarantying a 24-hour availability of electricity would be the supply of electricity from the grid. Such a back-up system with electricity supply from the grid would demand the installation of according transmission capacities for the supply of electricity. But, in return, installing a link to the electricity grid would also be competitive to the use of green electricity in the conversion plant.

Neither an additional storage, nor a backup system to the grid has been considered in the life cycle inventories of the processes using external electricity for hydrogen production.

The cEF-D process has the lowest impacts of all investigated concepts for several category indicators if wood is used. But, for the cumulative energy demand, water use and land competition other processes show lower impacts. The ICFB-D concept has been modelled without an input of external energy. It has the lowest environmental impacts for the CED. The use of straw in dEF-D has the lowest impacts for eutrophication, water use and land competition.

The process of FZK (dEF-D) has for many category indicators the lowest results if only processes based on straw are compared with each other. But, the cumulative energy demand is highest in this case.

The cEF-D of UET has for many category indicators the lowest impacts comparing the processes based on wood. But, also here the ICFB-D process of TUV has a lower impact for the CED because it does not use external electricity.

A clear overall ranking with regard to the use of different biomass resources cannot be made. In addition, a clear ranking of the different conversion processes is not possible, because results show trade offs between the different category indicators. A formal weighting between category indicators, which would bridge these trade-offs, shall not be used according to the ISO standards for comparative LCA studies.

Quantitative information about the modelling uncertainty is not available. A statement about a clear ranking of a conversion concept should consider this. Due to these difficulties, a clear ranking is currently not possible.

The impacts of the different conversion concepts are further analysed in the following chapters.

Tab. 4.2 Scenario 1 with wind power. Category indicator results per MJ of BTL-fuel and fuel yield per year and hectare

Impact category	Unit	BTL-fuel, miscanthus, at service station/MJ/TUVU	BTL-fuel, straw, at service station/MJ/CUTECU	BTL-fuel, straw, at service station/MJ/FZKU	BTL-fuel, wood, at service station/MJ/CUTECU	BTL-fuel, wood, at service station/MJ/TUVU	BTL-fuel, wood, at service station/MJ/UETU
cumulative energy demand	MJ-Eq	**2.29**	5.02	6.68	4.74	2.57	5.00
abiotic depletion	kg Sb eq	0.000098	0.000250	0.000156	0.000250	0.000130	**0.000097**
global warming (GWP100)	kg CO2 eq	0.0218	0.0477	0.0244	0.0465	0.0277	**0.0183**
photochemical oxidation, non-b	kg C2H4	9.48E-06	1.62E-05	1.16E-05	1.54E-05	1.06E-05	**6.82E-06**
acidification	kg SO2 eq	0.000173	0.000225	0.000163	0.000288	0.000241	**0.000138**
eutrophication	kg PO4--- eq	0.000153	0.000097	**0.000046**	0.000108	0.000097	0.000046
water use	m3	0.0516	0.0147	**0.0090**	0.0837	0.0864	0.0441
land competition	m2a	0.0595	0.0265	**0.0180**	0.1100	0.1120	0.0575
energy yield	MJ/m2a	16.8	37.7	55.6	9.1	8.9	17.4
fuel yield	toe/ha/a	3.9	8.9	13.0	2.1	2.1	4.1

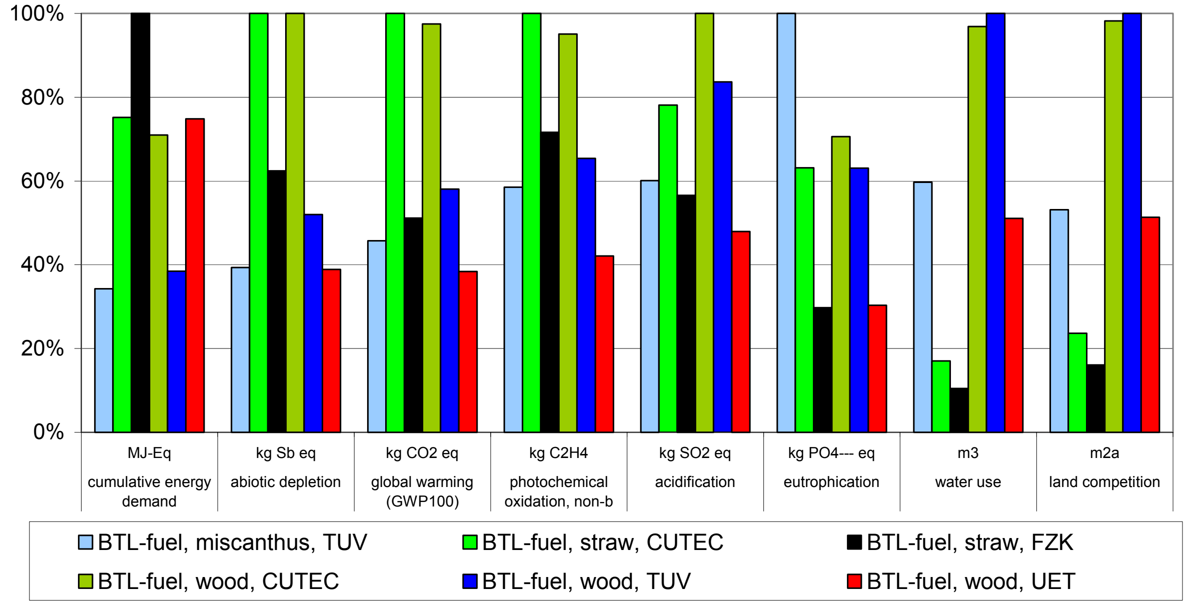


Fig. 4.1 Scenario 1 with wind power. Relative comparison of fuels using different category indicators (basis MJ of fuel delivered to the tank)

4.2 Analysis of results for category indicators

4.2.1 Cumulative energy demand

Energy bound in biomass is also in scenario 1 a major input for the cumulative energy demand that accounts for 20% to 90% of the energy input. Now also other types of energy resources get importance due to the use of electricity from wind power plants. They account for up to 75% of the total cumulative energy demand. Thus, most of the energy input is still from renewable sources.

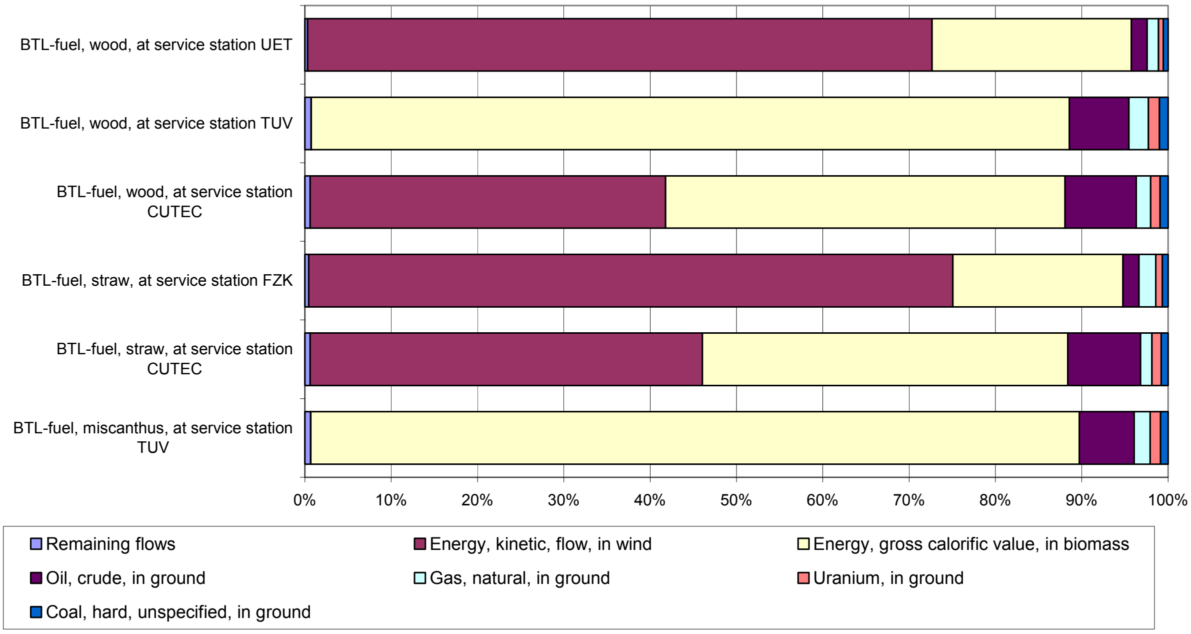
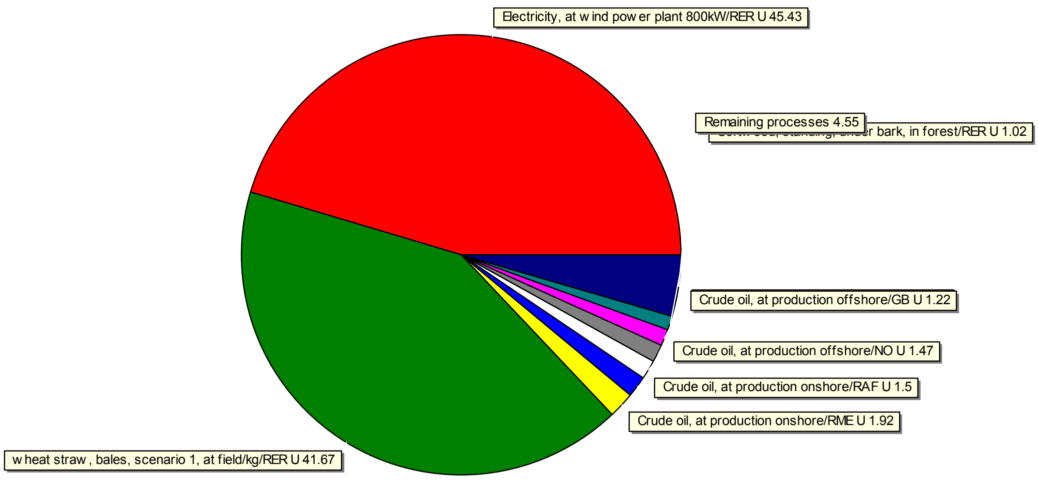


Fig. 4.2 Contribution of individual elementary flows to the total cumulative energy demand

Besides the biomass production, the kinetic energy for the wind power plant is mainly responsible for the results of this indicator.



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.3 Contribution of individual unit processes in the product system to the total cumulative energy demand, straw, CUTEC-process

4.2.2 Abiotic depletion

Coal, oil and gas use are the major contributions to abiotic depletion. Different shares of these inputs are mainly due to a different amount of electricity consumption in the production process. Coal inputs are mainly dominated by the use of electricity while crude oil is finally used as fuels e.g. in transport processes.

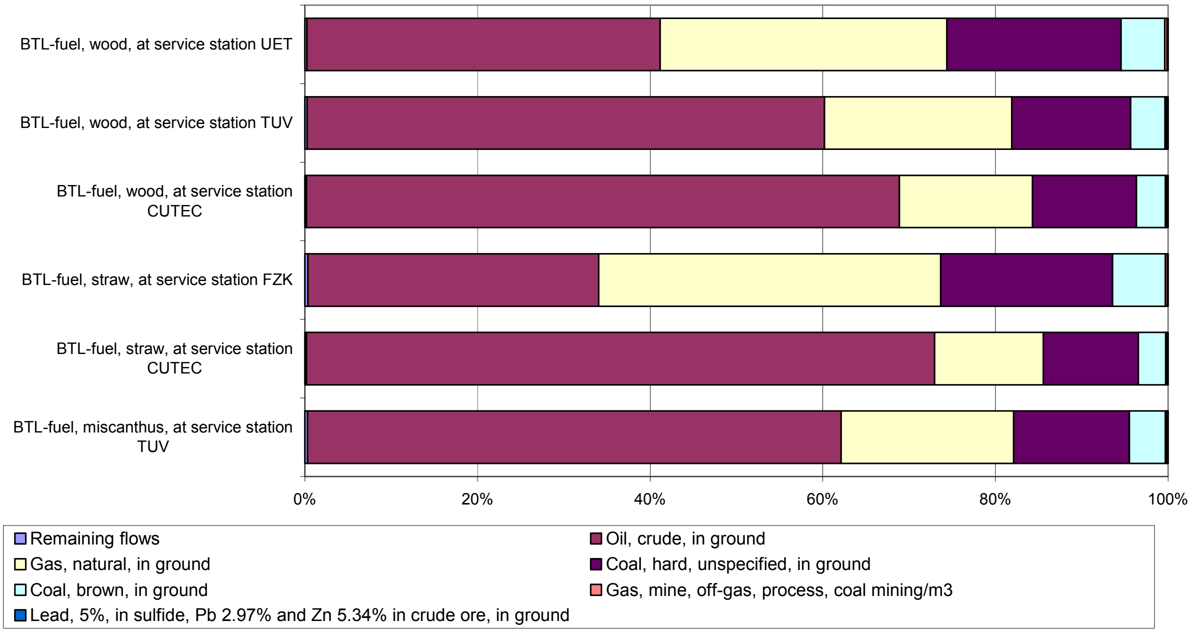
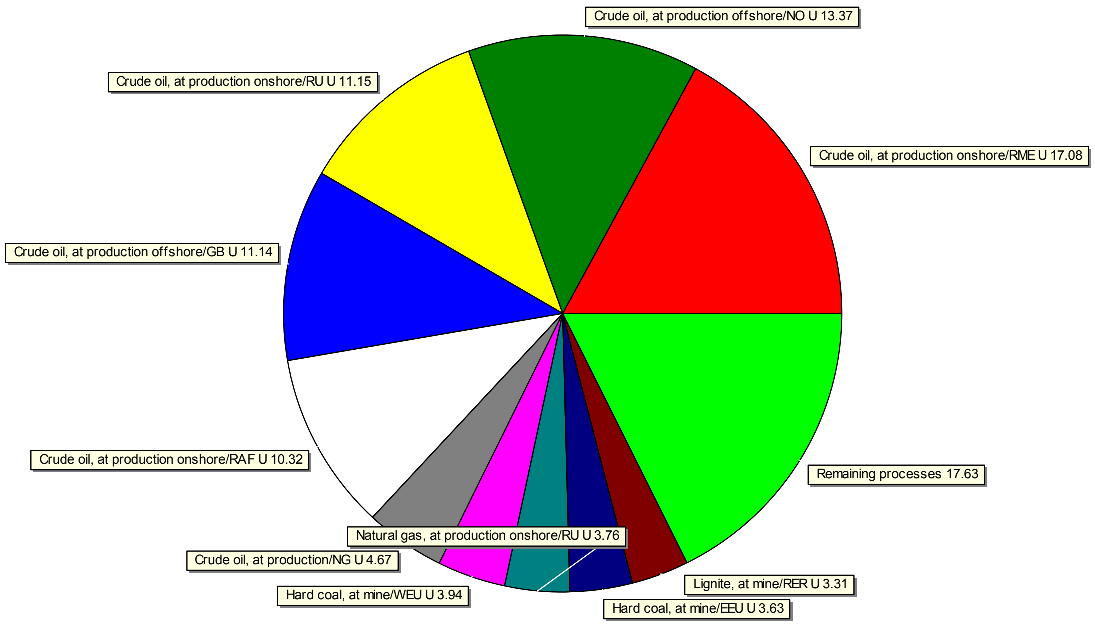


Fig. 4.4 Contribution of individual elementary flows to the total abiotic depletion

The resource extraction takes place in many different stages of the life cycle. A major part can be attributed to the extraction processes for the fossil resources. Fig. 4.5 shows an example. There are no particular differences between the different processes investigated.



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.5 **Contribution of individual unit processes in the product system to the total abiotic depletion, example for CUTEC process with wood**

4.2.3 Global warming

Carbon dioxide accounts for 55% to 80% of the emissions contributing to global warming. Dinitrogen monoxide (10% to 30%) and methane (5%-10%) from biomass combustion are the other elementary flows contributing to global warming.

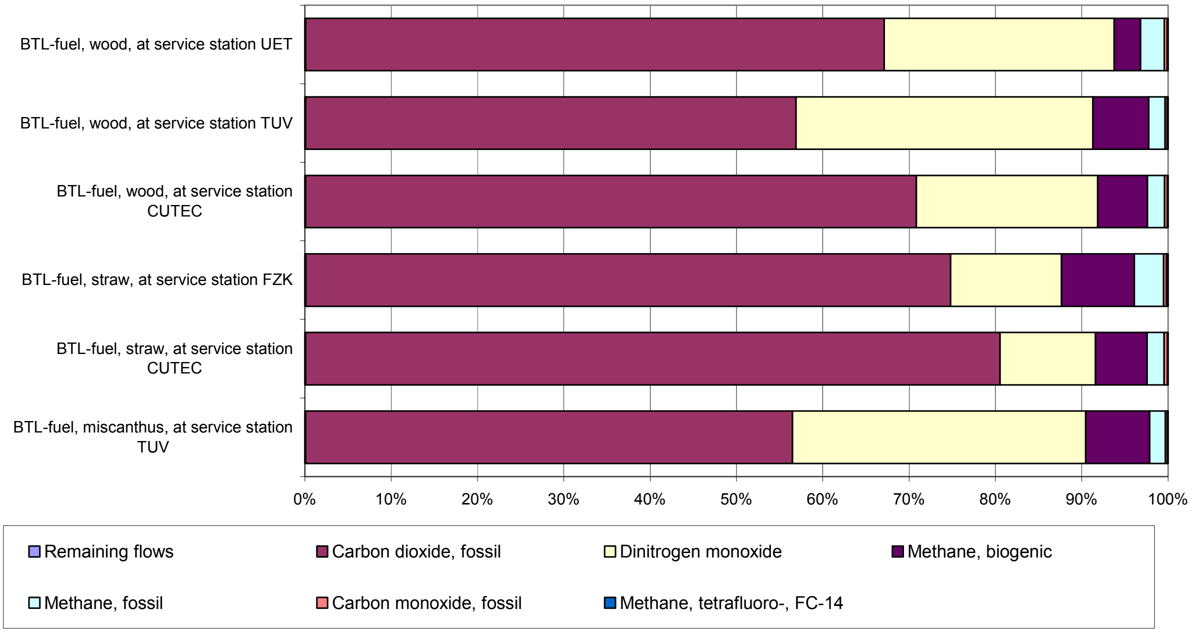
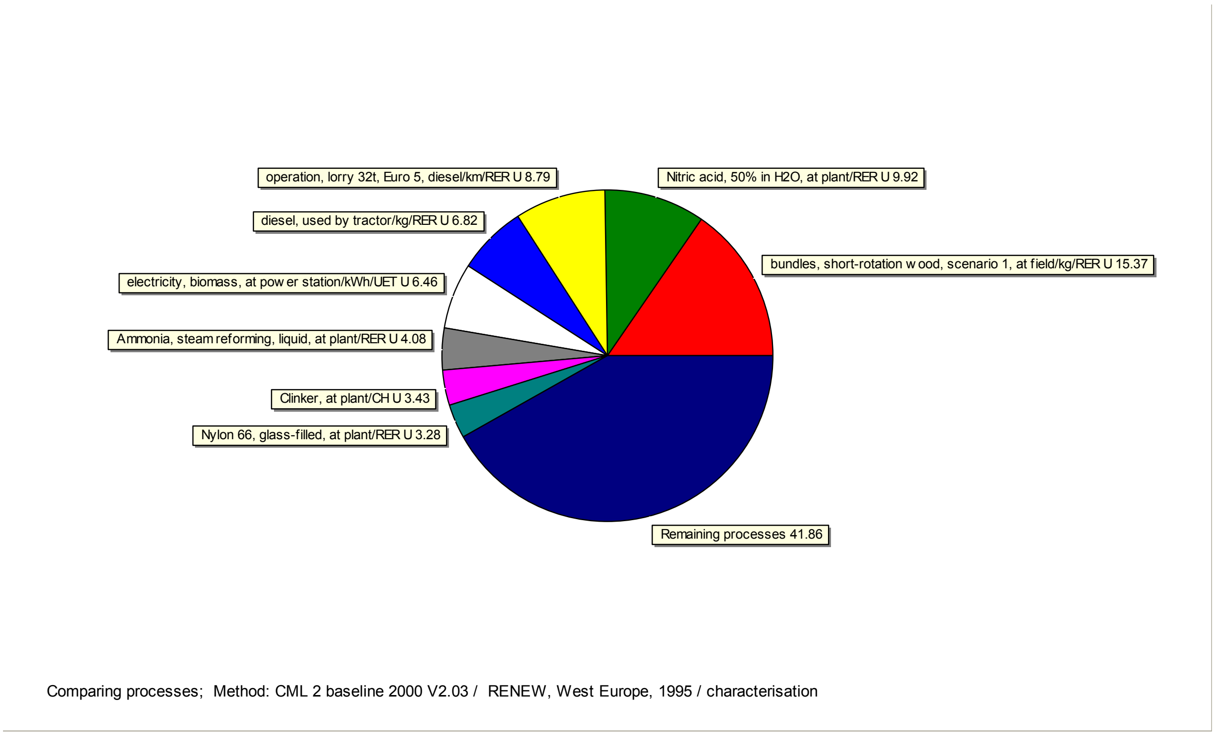


Fig. 4.6 **Contribution of individual elementary flows to the total global warming potential**

In general, the following types of processes are important for the releases of greenhouse gases: biomass production, fertilizer production, transport and tractor processes, off-gases and emissions from power plants for external and internal electricity supply (example in Fig. 4.7).



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.7 Contribution of individual unit processes in the product system to the total global warming potential, wood, UET-process

4.2.4 Photochemical oxidation, non-biogenic

A range of different substances is important for the formation of summer smog. The most important are sulphur dioxide (25% - 35%), carbon monoxide (10%-20%) and different NMVOC.

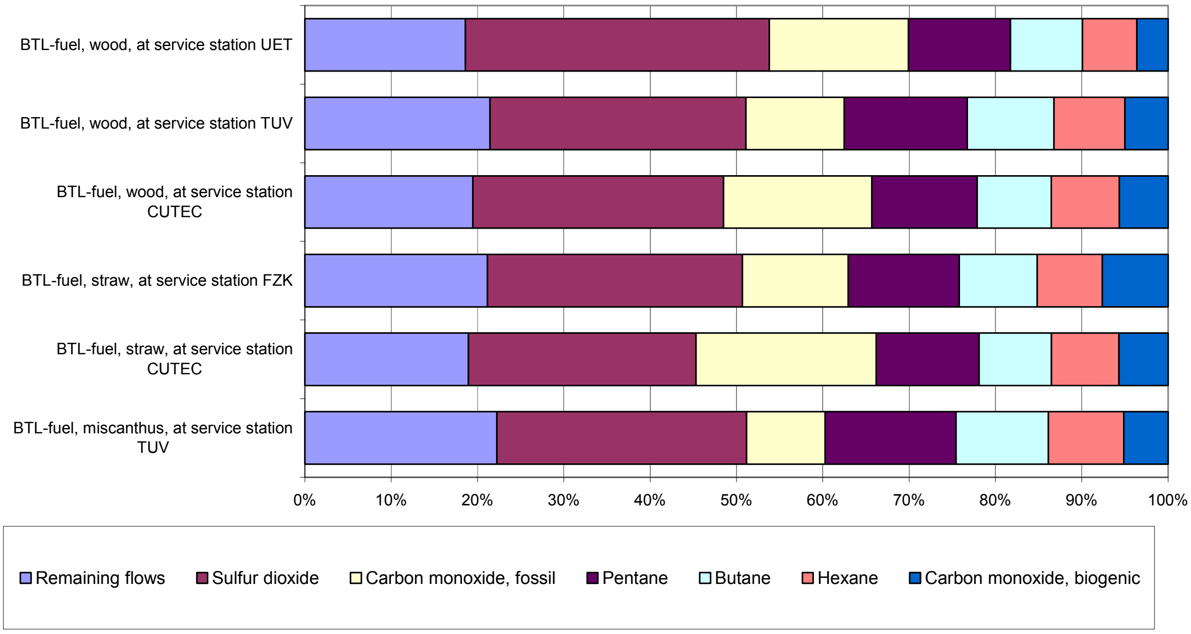
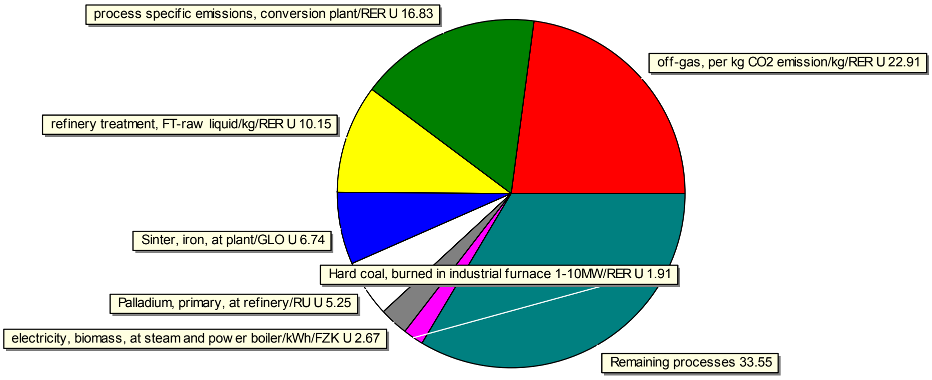


Fig. 4.8 Contribution of individual elementary flows to the total photochemical oxidation, non-biogenic

The most important single processes for the emission of photo oxidants are still direct releases from the conversion process, e.g. with off-gases, process emissions and from the power plant. In addition, a subsequent refinery treatment will emit further substances. The example in Fig. 4.9 stands for a conversion process with a relatively low shares of direct emissions and emissions from biomass.



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.9 Contribution of individual unit processes in the product system to the total photochemical oxidation, non-biogenic, straw, FZK

4.2.5 Acidification

Acidification is caused by ammonia, sulphur dioxide and nitrogen oxides. Sulphur dioxide emissions (30%-50%) are dominant for the total result.

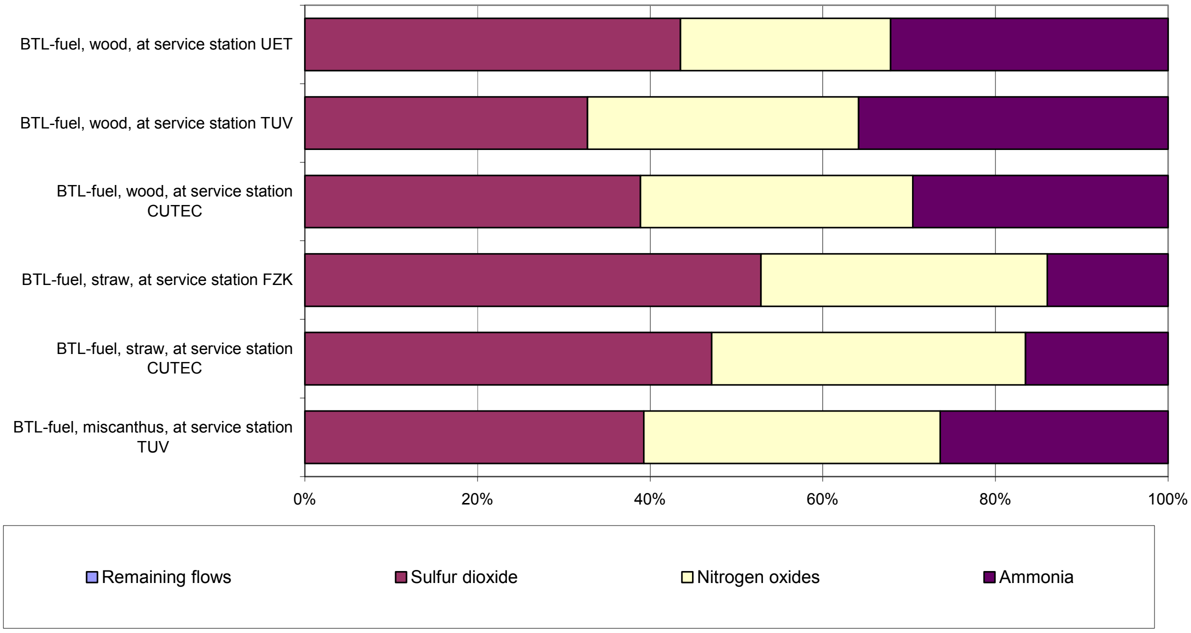
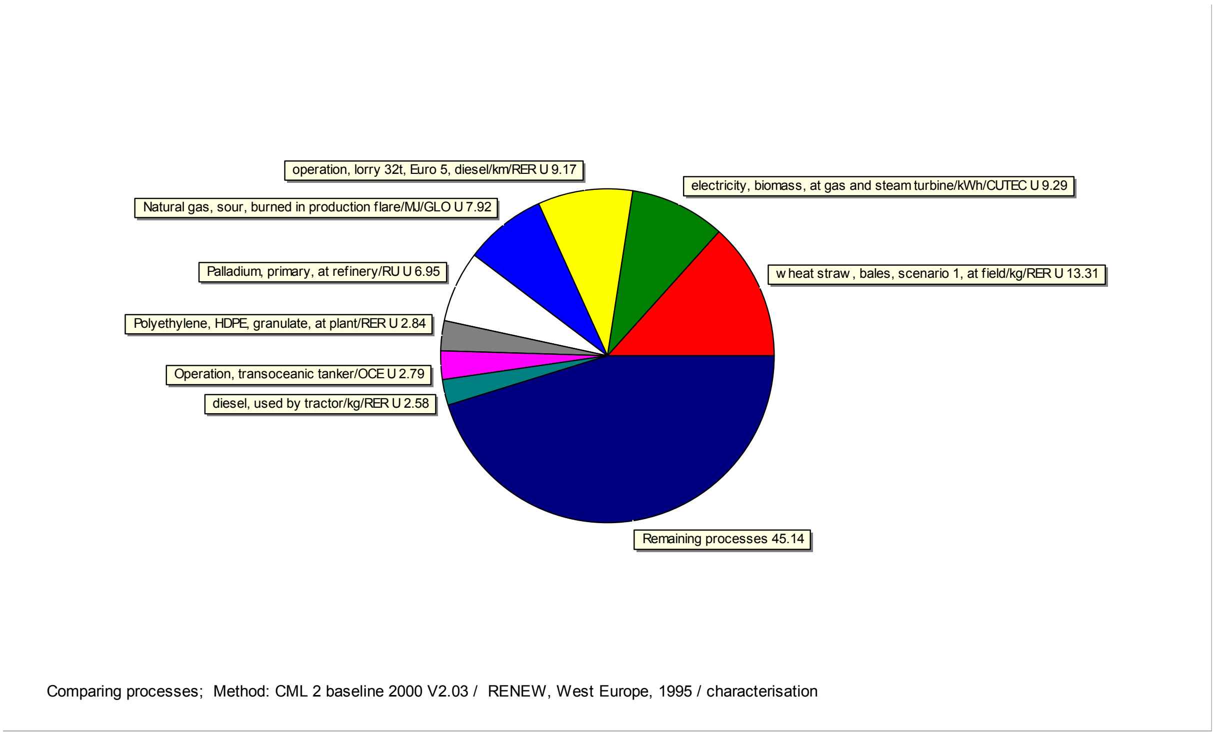


Fig. 4.10 Contribution of individual elementary flows to the total acidification

The emissions from biomass production are the most important source of emissions.



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.11 Contribution of individual unit processes in the product system to the total acidification, straw, CUTEC-process

4.2.6 Eutrophication

Eutrophication is mainly caused by nitrates and phosphates emissions to water and ammonia and nitrogen oxides emissions to air. Phosphorous describes the emission of elemental phosphor directly to the soil.

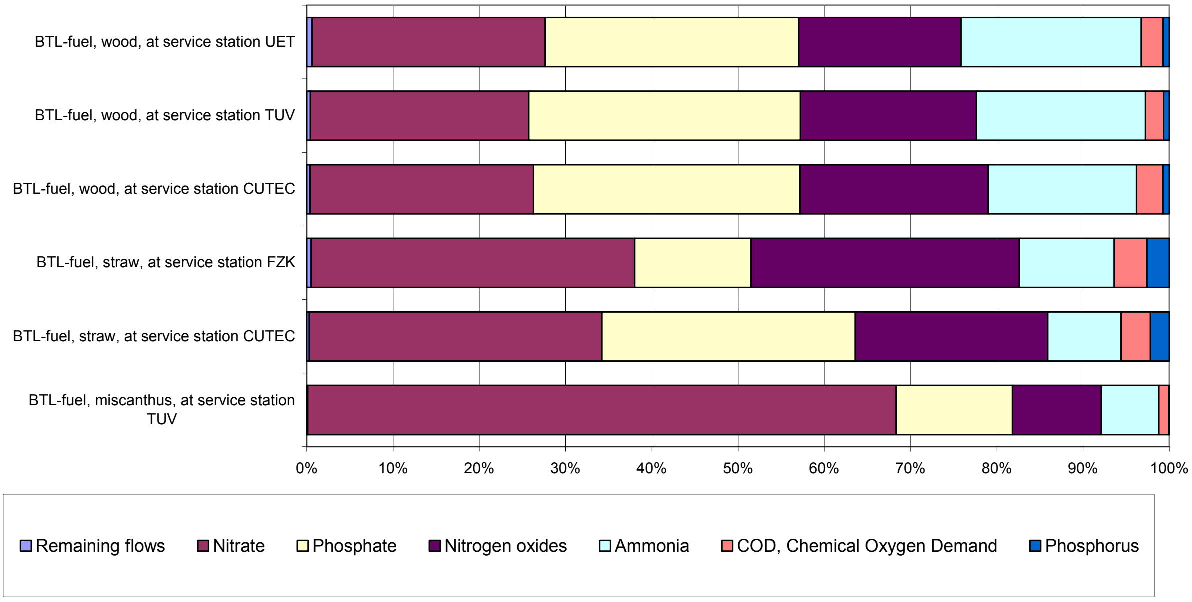
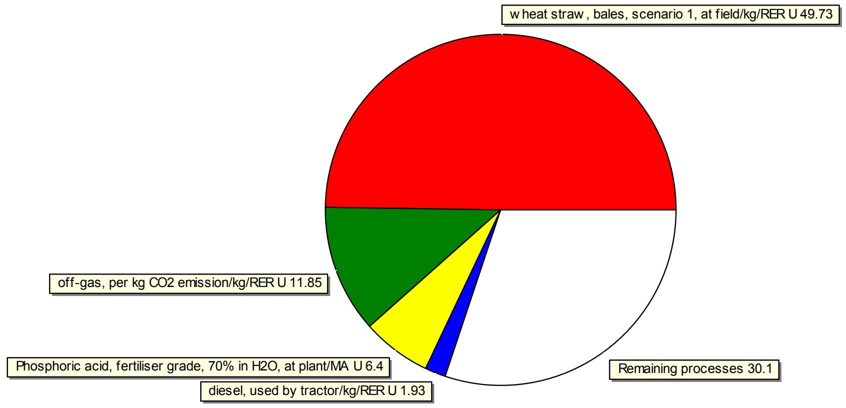


Fig. 4.12 Contribution of individual elementary flows to the total eutrophication

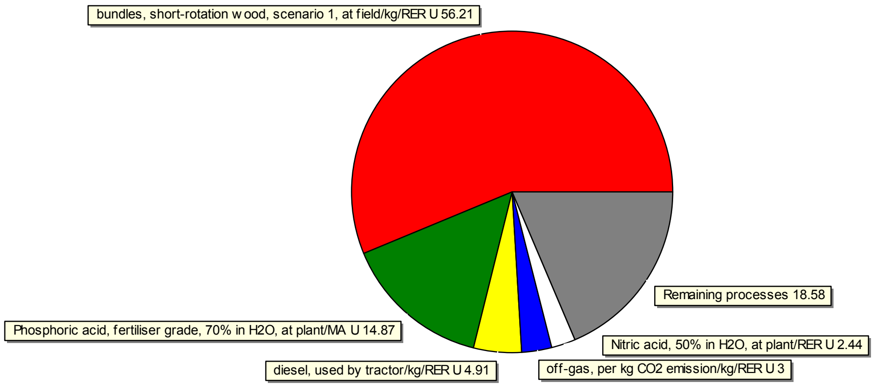
A share of about 50% of the release of eutrophication emissions can be attributed in most cases directly to the agricultural production process. Other important sources of emissions are the direct air emissions from the conversion process and power plant. The production of fertilizers contributes a smaller share.

The disposal of slag from the CUTEC conversion process makes a relevant contribution because of phosphate emissions.



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.13 Contribution of individual unit processes in the product system to the total eutrophication, straw, FZK-process



Comparing processes; Method: CML 2 baseline 2000 V2.03 / RENEW, West Europe, 1995 / characterisation

Fig. 4.14 Contribution of individual unit processes in the product system to the total eutrophication, wood, UET-process

4.2.7 Water use

The water use is fully dominated by rainwater used in agriculture. Only a small part of the water use is caused by irrigation water. The conversion plants itself use only small quantities of water compared to the use in agriculture.

4.2.8 Land competition

Land competition is dominated with a share of about 90% by agricultural types of land competition, which are directly due the biomass production. In case of straw based processes, also background processes for the storage of straw and other infrastructure buildings have a share of up to 30%. In comparison to the starting point calculation, now much more straw is stored in a closed storage and thus a higher share of this infrastructure results. Wood is used in these processes as a construction material. The production of this wood contributes to the total results for land competition. It has to be noted that for straw a lower land competition is allocated. Land occupation by the wind power plant is also included in the life cycle inventory, but it is not very important for the total sum of land uses.

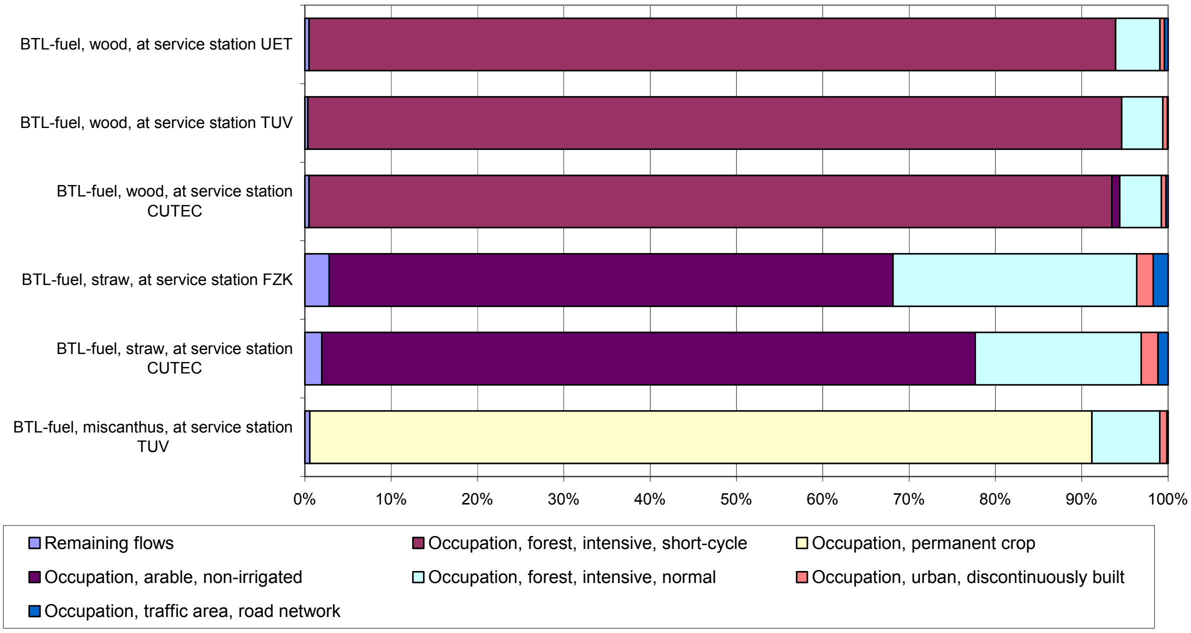


Fig. 4.15 Contribution of individual elementary flows to the total land competition

4.3 Summary

The data in scenario 1 are less certain as the data in the starting point calculation. There are large differences in the modelling results provided by the different plant developers, which cannot easily be explained (see Tab. 4.1).

In scenario 1, the amount of electricity, which is used for external hydrogen production, is a quite important factor for many category indicators. The environmental profile is quite dependent on the power plant mix actually used for the electricity generation. Thus, a sensitivity analysis is performed on this aspect in chapter 7.2. The electricity generation considered here with wind power is not available in large scale for many conversion plants.

Many category indicators show a dominating influence of the agricultural production of biomass. The share for the production and provision of biomass for the following category indicators is given in brackets: eutrophication (50%), water use (99%) and land competition (90%-95%). Thus, the conversion ratio and the type of biomass are still important in the comparison of different conversion routes.

The conversion rate also plays a role in the formation of air emissions from the conversion plant. The higher the conversion rate, the lower the share of carbon and thus also other pollutants which are released to the ambient air.

5 Analysis of sub-processes in biomass conversion

This chapter describes the analysis for the importance of different sub-processes in the conversion process. This analysis does not include the subsequent distribution of the fuel to the filling station, which makes only little differences between the different conversion routes.

5.1 Centralized Entrained Flow Gasification, cEF-D (SP1-UET)

5.1.1 Starting point calculation

Most impacts are dominated by the stage of biomass provision including storage and preparation. Thus, the environmental impacts origin mainly from the biomass production and provision chain. The only category indicator with a dominant share of other process sub-processes is the contribution to photochemical oxidation (excl. biogenic emissions). Different sub-processes have an importance mainly due to their use of electricity and heat provided by the internal power plant.

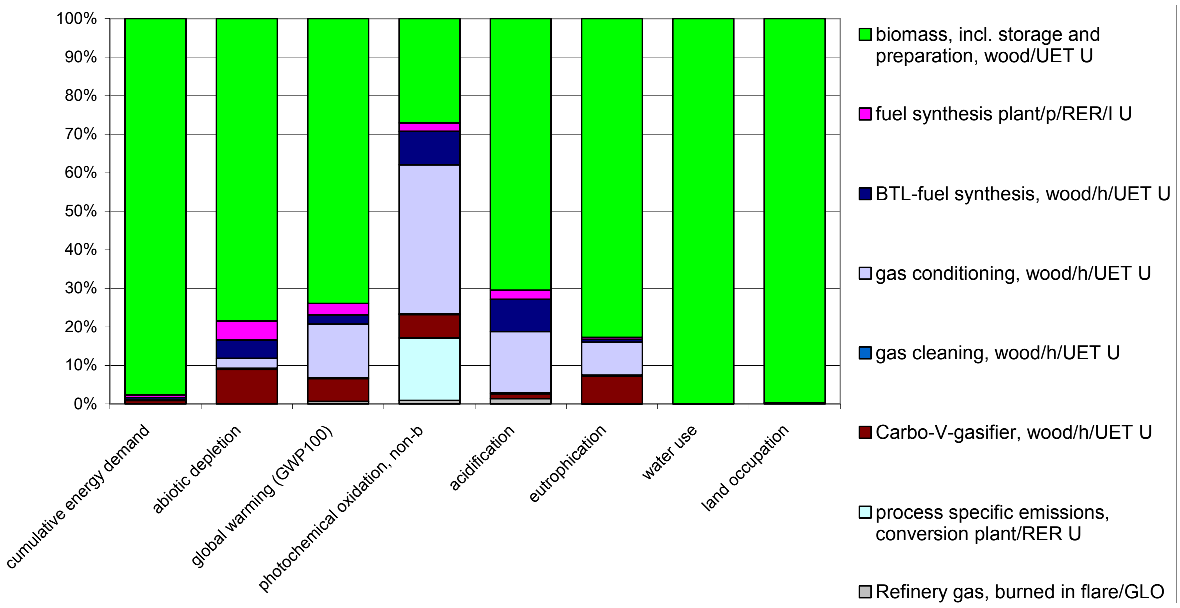


Fig. 5.1 **Contribution of different sub-processes to the total impacts, UET, wood input, starting point calculation**

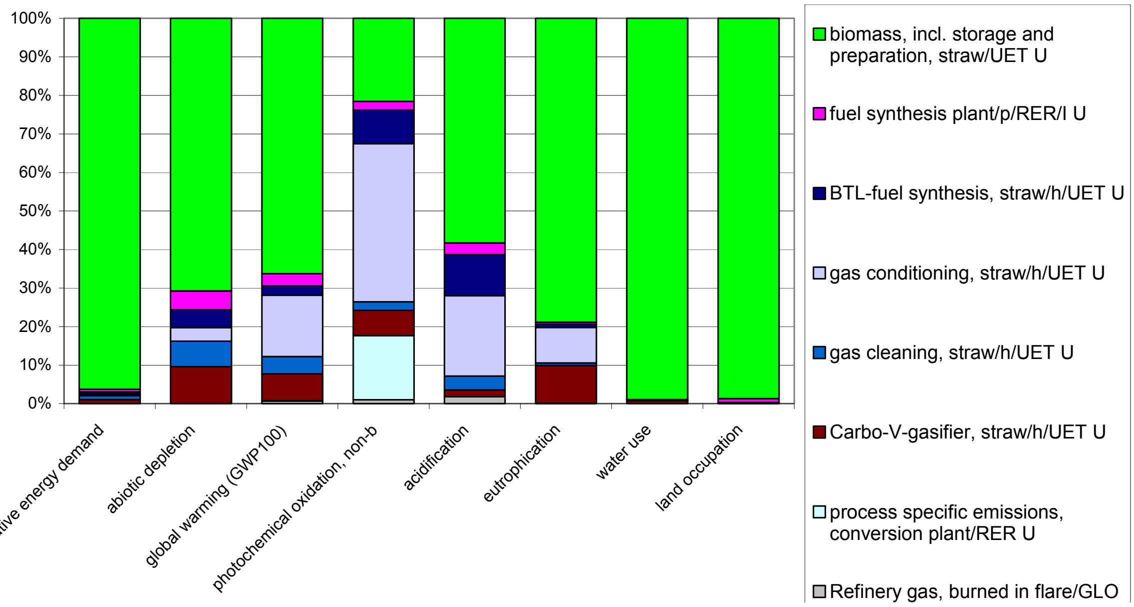


Fig. 5.2 **Contribution of different sub-processes to the total impacts, UET, straw input, starting point calculation**

5.1.2 Scenario 1

The sub-process gas conditioning bears more of the environmental burdens due to the use of external electricity for hydrogen production.

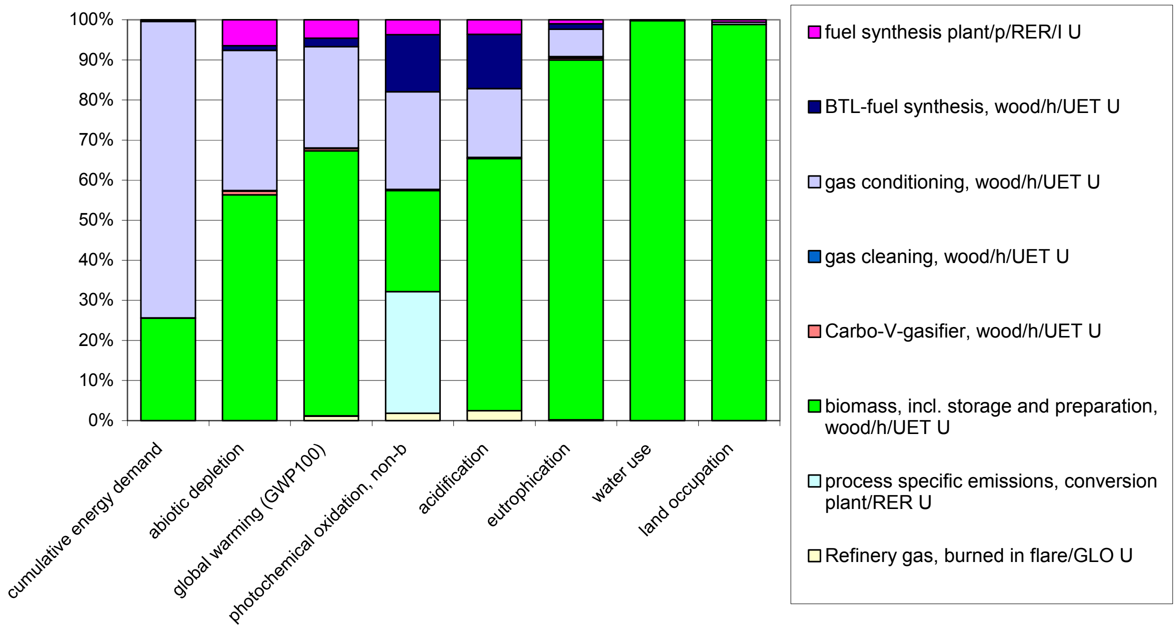


Fig. 5.3 **Contribution of different sub-processes to the total impacts, UET, wood input, scenario 1**

5.2 Centralized Autothermal Circulating Fluidized Bed Gasification, CFB-D (SP2-CUTEC)

5.2.1 Starting point calculation

In principle, impacts are dominated by the biomass input and thus by the conversion rate. Gasification and gas cleaning are the most important direct process stages. The post-conversion refinery treatment of FT-raw products has some importance concerning abiotic depletion and photochemical oxidation.

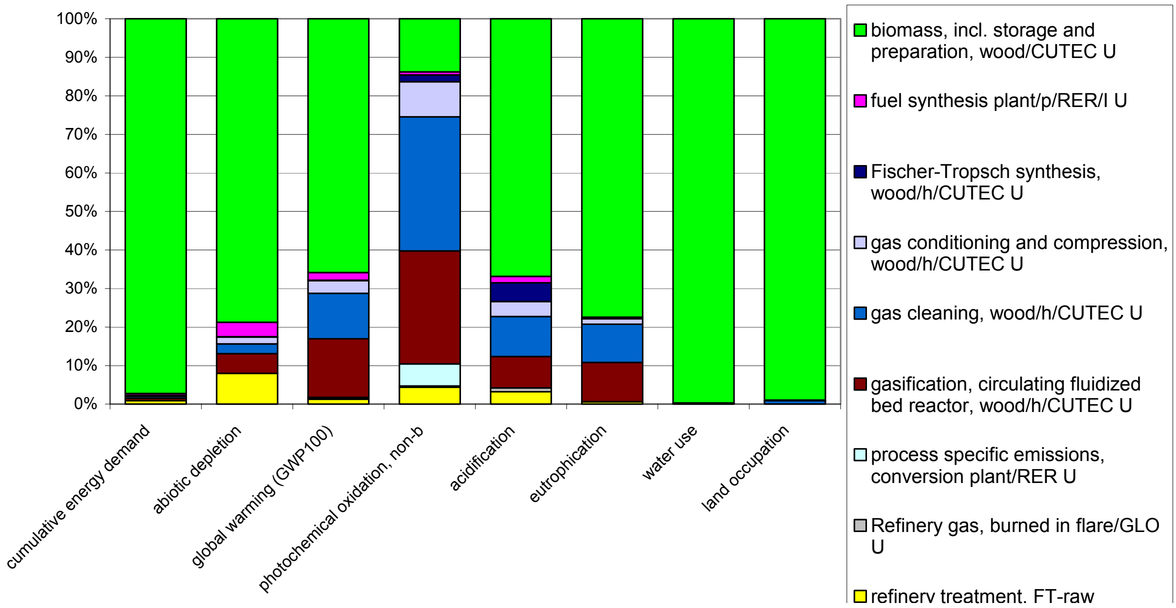


Fig. 5.4 **Contribution of different sub-processes to the total impacts, CUTEC-process, wood, starting point calculation**

5.2.2 Scenario 1

The sub-process Fischer-Tropsch synthesis bears more of the environmental burdens due to the use of external electricity for hydrogen production.

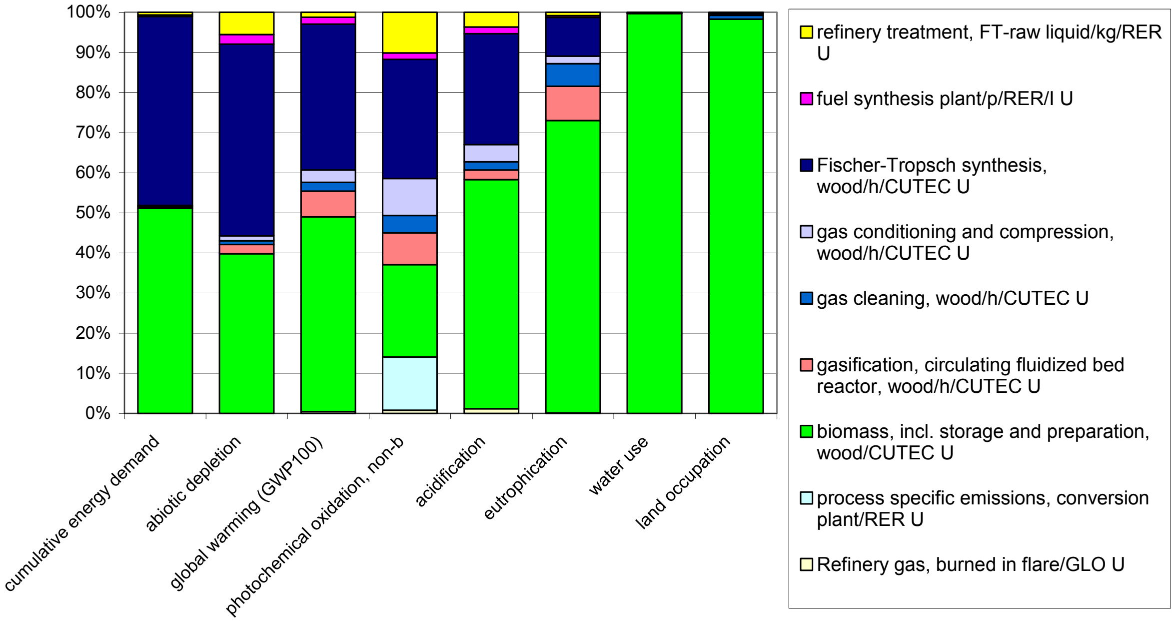


Fig. 5.5 Contribution of different sub-processes to the total impacts, CUTEC, wood input, scenario 1

5.3 Decentralized Entrained Flow Gasification, dEF-D (SP2-FZK)

5.3.1 Starting point calculation

The FZK process shows in several categories a comparably lower share of impacts caused by the biomass production and provision. This is due to the lower environmental impacts of the straw input and thus a higher contribution of direct emissions from the conversion.

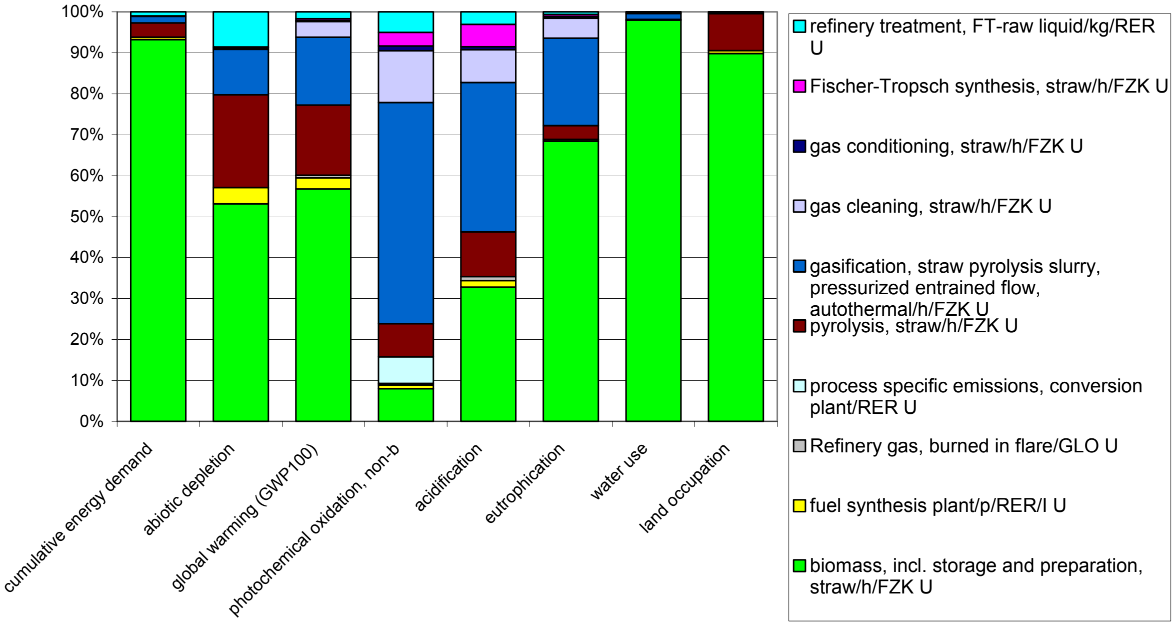


Fig. 5.6 Contribution of different sub-processes to the total impacts, FZK, straw, starting point calculation

5.3.2 Scenario 1

The sub-process Fischer-Tropsch synthesis bears more of the environmental burdens due to the use of external electricity for hydrogen production.

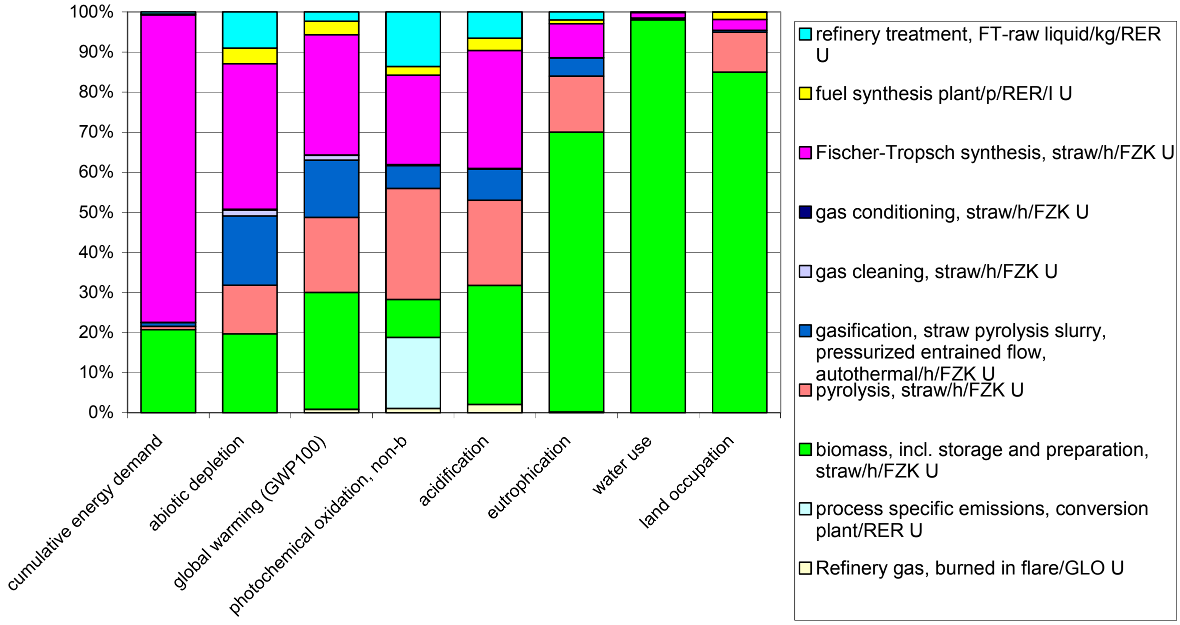


Fig. 5.7 Contribution of different sub-processes to the total impacts, FZK, straw input, scenario 1

5.4 Allothermal Circulating Fluidized Bed Gasification, ICFB-D (SP2-TUV)

5.4.1 Starting point calculation

In comparison to other processes, the TUV process has a relatively higher contribution of non-biomass related environmental impacts. The use of rape oil methyl ester in gas cleaning is important and causes a higher direct share of this process stage.

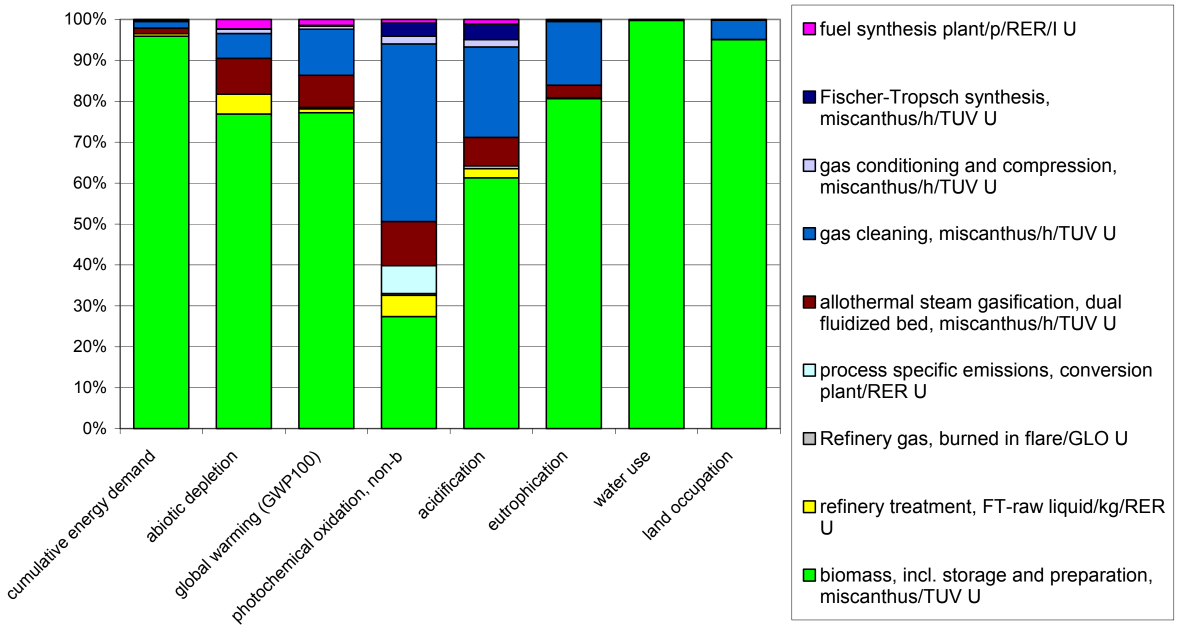


Fig. 5.8 **Contribution of different sub-processes to the total impacts, TUV process, miscanthus, starting point calculation**

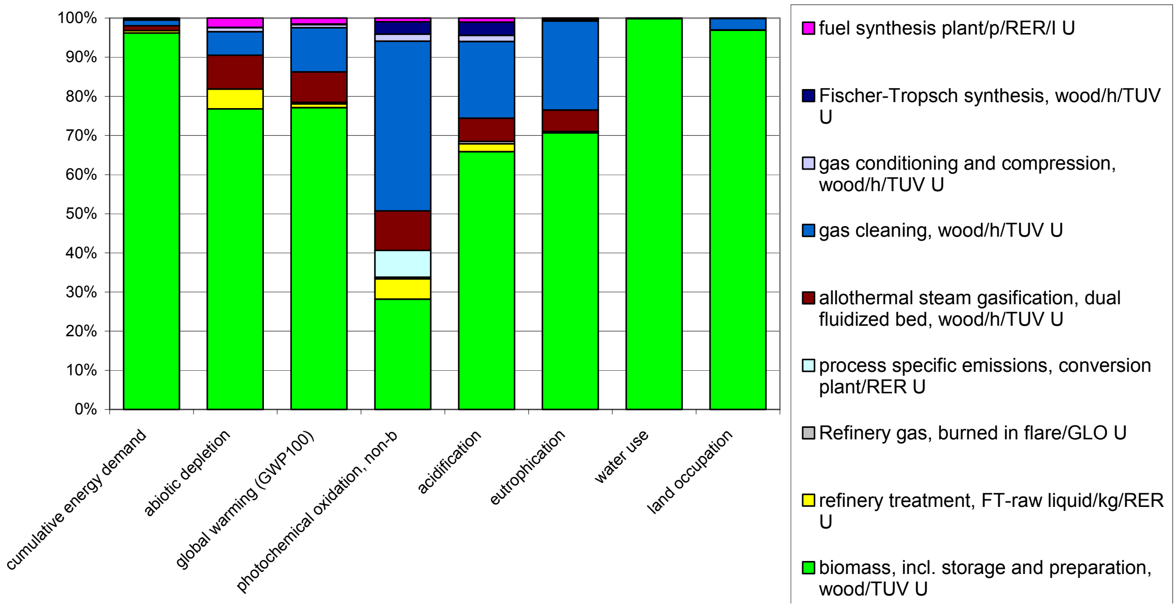


Fig. 5.9 **Contribution of different sub-processes to the total impacts, TUV process, wood, starting point calculation**

5.4.2 Scenario 1

This process uses no external hydrogen. Thus the most important sub-process is the import of biomass. The refinery treatment of FT-raw products contributes also to the total environmental impacts for different category indicators.

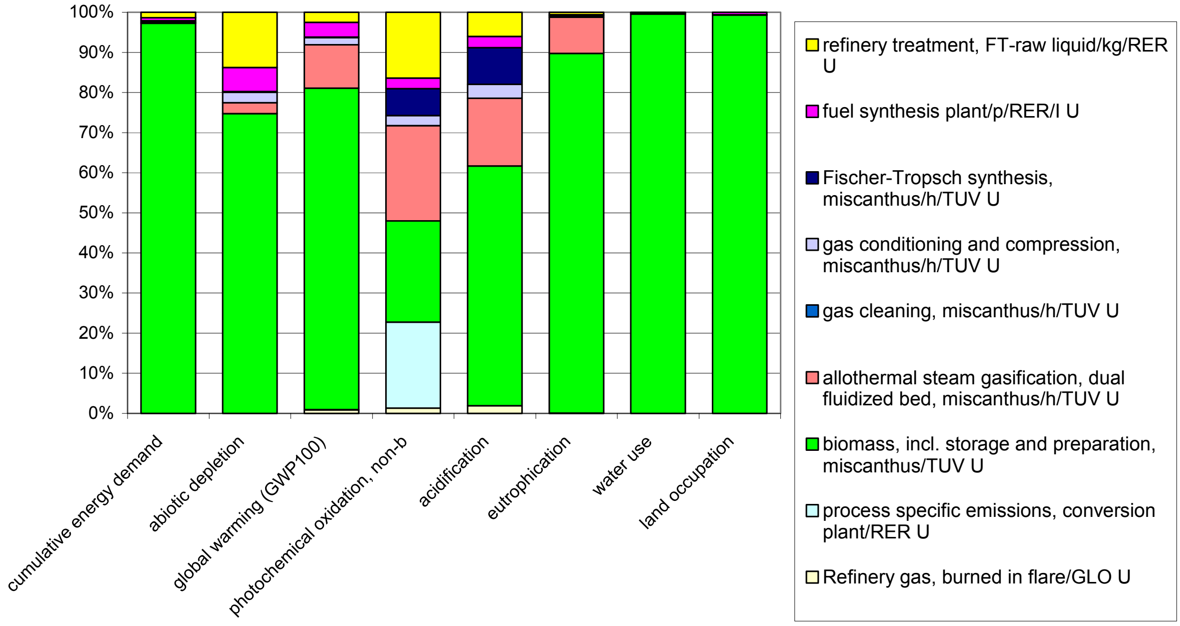


Fig. 5.10 Contribution of different sub-processes to the total impacts, TUV, miscanthus input, scenario 1

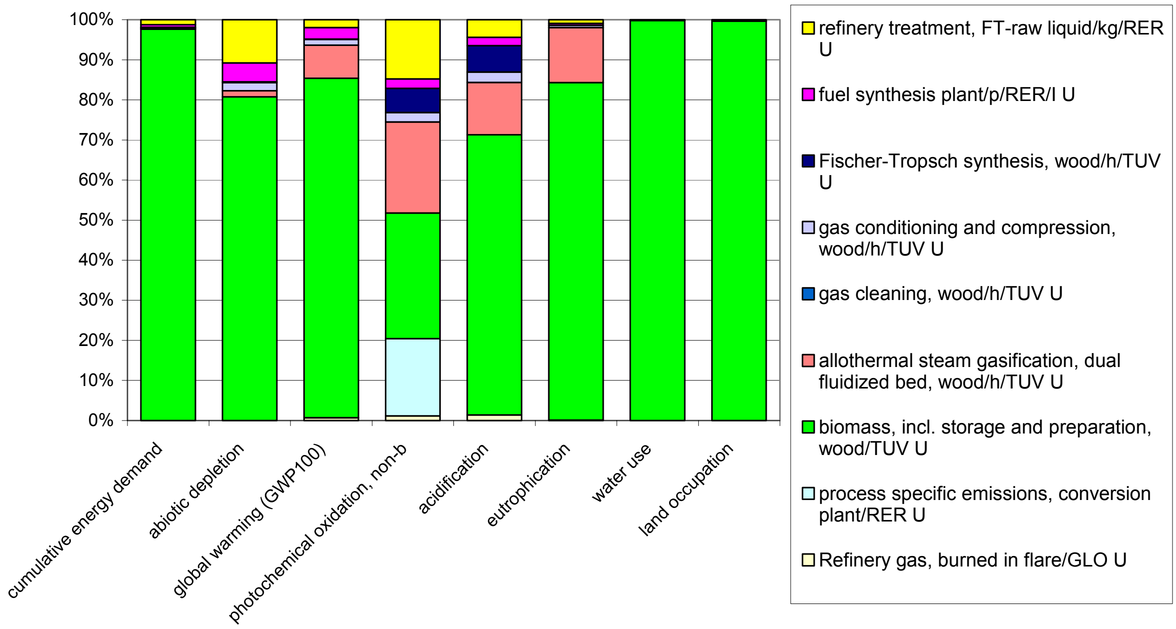


Fig. 5.11 Contribution of different sub-processes to the total impacts, TUV, wood input, scenario 1

5.5 Entrained Flow Gasification of Black Liquor for DME-production, BLEF-DME (SP3-CHEMREC)

5.5.1 Starting point calculation

The main part of the cumulative energy demand is due to the provision of biomass and its transport to the plant. About 70% of the total greenhouse gas emissions are due to the biomass production and provision. Here mainly N_2O and CH_4 emissions are relevant. Other important stages are the direct emissions of the conversion plant (power plant and off-gases). Also in this case, methane emissions are important. Biomass input is the most important sub-stage of the process for most other aspects with exception of direct releases causing photochemical oxidation.

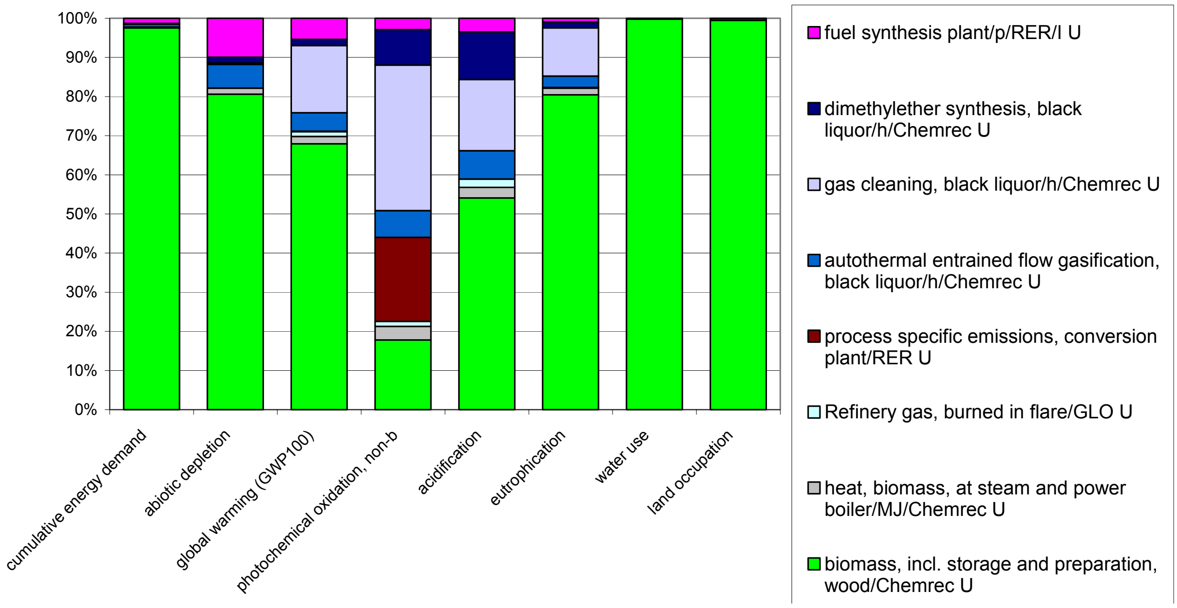


Fig. 5.12 Contribution of different sub-processes to the total impacts, CHEMREC process, wood, starting point calculation

5.6 Summary

The idea of investigating different sub-process stages was to compare also the environmental impacts in this level of detail. The detailed analysis shows that it is difficult to compare different conversion concepts based on the detailed results for single process stages, because the allocation of environmentally relevant streams within the plant might be quite different. Thus, the importance of the different sub-processes might be quite different even if the overall results are quite similar.

5.6.1 Starting point calculation

In general, many category indicators results are quite dependent on the biomass input. For the cumulative energy demand, water use and land competition the share of biomass production and provision is in most cases higher than 90%. The second most important factor are the air emission with off-gases or due to the energy production in the on-site power plant. This is especially important for the release of substances contributing to photochemical oxidation. Thus, the conversion rate is quite a crucial factor in the comparison of different BTL-concepts.

5.6.2 Scenario 1

In this scenario, the importance of process steps is influenced largely by the external electricity input. The process stage, which uses hydrogen produced with external electricity, is more important concerning the environmental indicators that are influenced by the electricity production. The biomass input stage is relevant for these indicators, like land use, which are dominated by impacts from agriculture.

6 Normalization

The normalization factor for land competition in Western Europe is 3E-13 (1/m2a/a) (Guinée et al. 2001). The annual rainfall is about 800 mm per m^2. This results in 0.8 m3 per m2a. The normalization factor is 3.8 E-13 ($1/m^3/a$).

No normalization figure is available for the cumulative energy demand (including biomass energy). In principle it can be expected that the CED would be in the same range of importance as global warming potential and abiotic depletion.

All other normalization factors are taken from the original CML report for the situation in Western Europe (Guinée et al. 2001). The normalization gives an insight into the relevance of the specific product in relation to the total environmental impacts caused in Western Europe for the specific category indicator. It has to be considered that normalization means that all environmental problems are considered to be of the same importance. Thus, the normalization does not include a weighting and category indicators with the highest result cannot per se be considered as the most relevant ones.

6.1 Starting point calculation

Fig. 6.1 compares the normalized category indicator results for the different conversion concepts. The most important category indicators are water and land use on the right side. Besides the impacts for abiotic depletion, global warming, acidification and eutrophication are in the same order of magnitude. Thus, also a normalization of the impacts does not help much for giving clear preferences for one conversion concept.

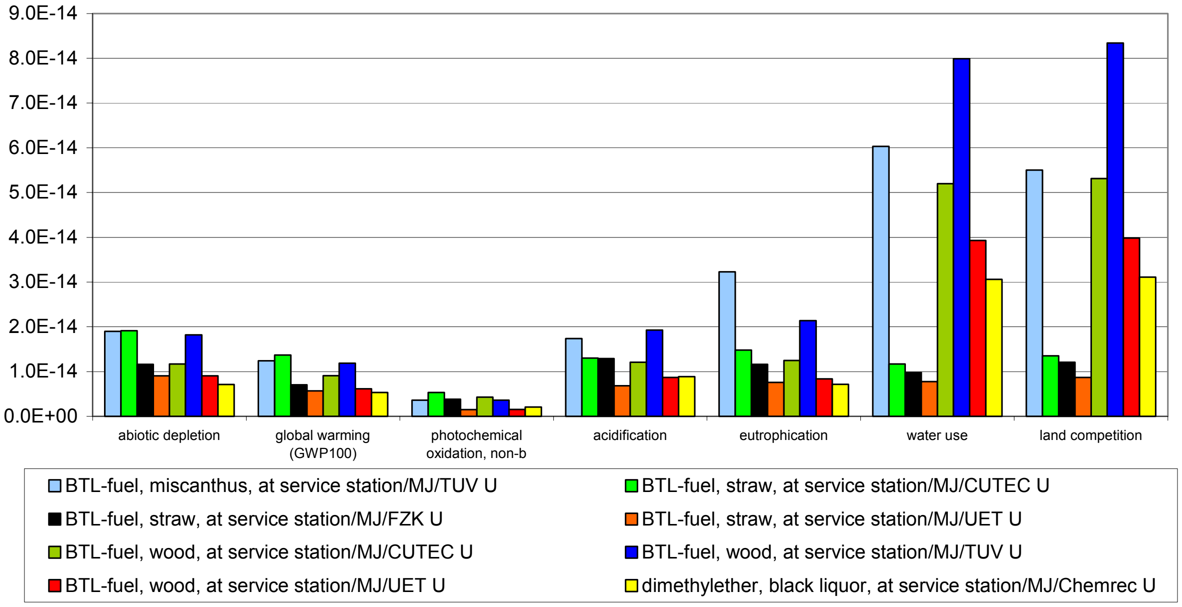


Fig. 6.1 Relative comparison of fuels using different normalized category indicators (basis MJ of fuel delivered to the tank), starting point calculation

6.2 Scenario 1

Fig. 6.2 compares the normalized category indicator results for the different conversion concepts. The most important category indicator is water use and land competition. Also the normalization figures do not give a clear picture for the ranking of different conversion concepts.

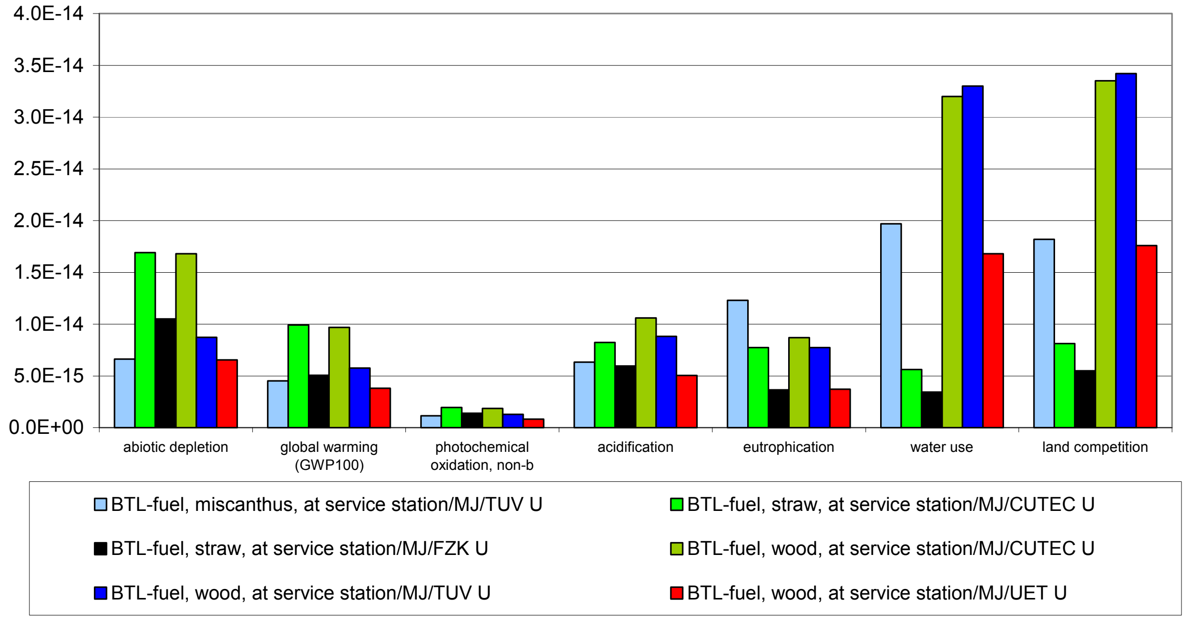


Fig. 6.2 **Relative comparison of fuels using different normalized category indicators (basis MJ of fuel delivered to the tank), scenario 1**

7 Sensitivity analyses

7.1 Allocation between wheat and straw

7.1.1 Biomass production

Fig. 7.1 shows a comparison of different biomass products. In this sensitivity analysis, the environmental impacts for wheat have been allocated between wheat grains and straw based on the energy content of these two products. This can be justified if both products are seen as a raw material with most important property being the energy content. In comparison to Fig. 2.2 the environmental impacts of wheat straw are higher compared to the two other biomasses because the allocation share is much higher.

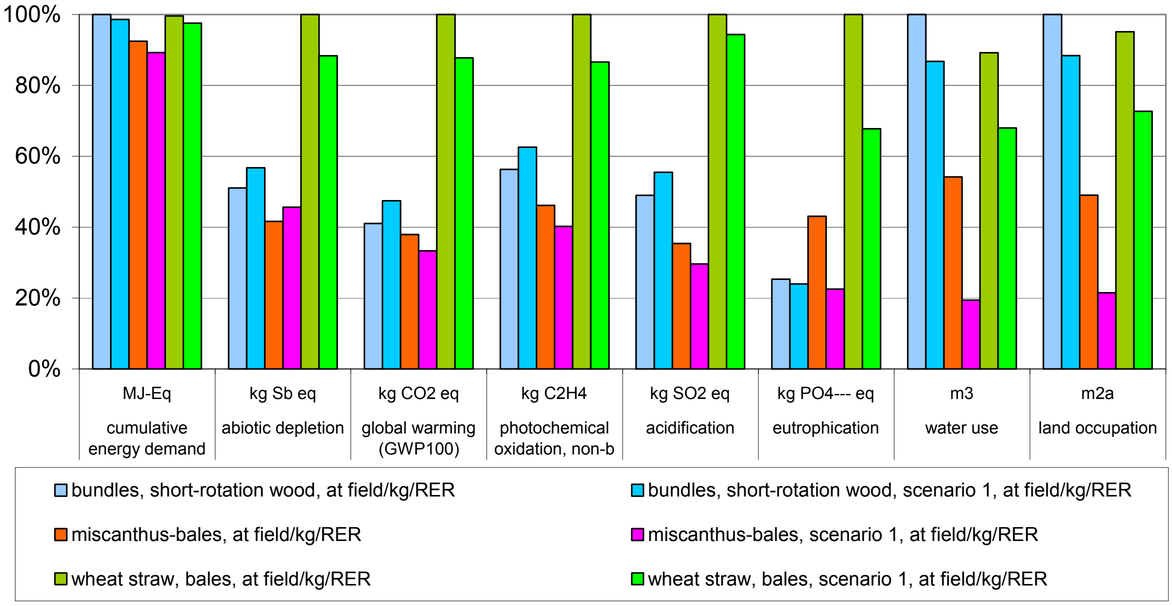


Fig. 7.1 Relative comparison of biomass resources on the basis of category indicator impacts (basis MJ of harvested biomass), sensitivity analysis for allocation by energy content of wheat grains and straw

For comparison, we show here the previous figure with an allocation based on the prices of wheat grains and straw.

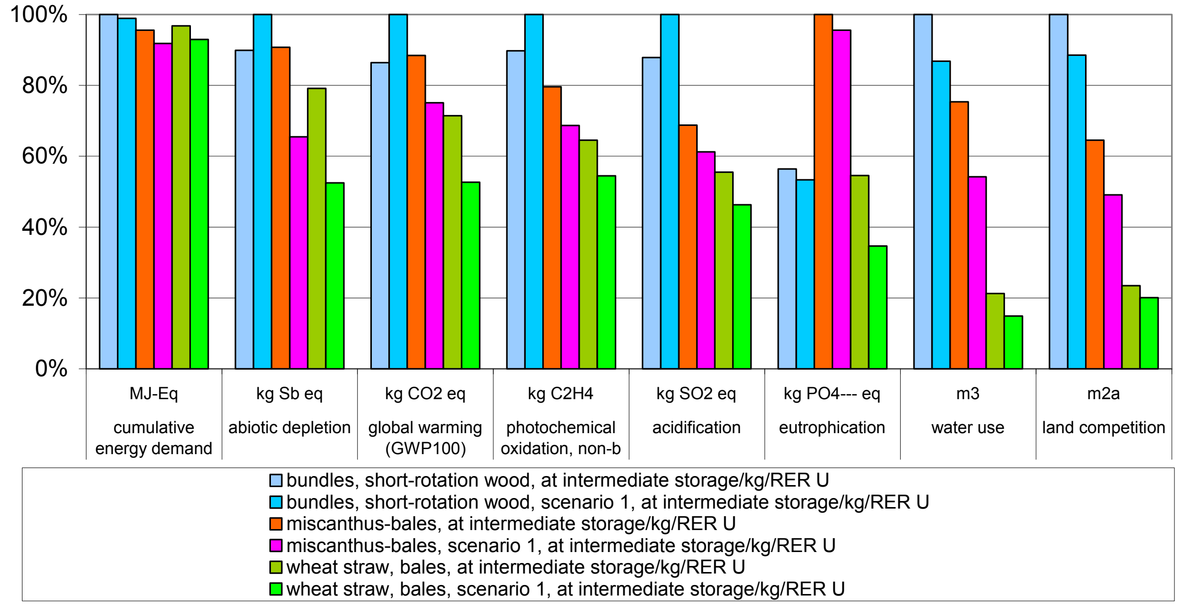


Fig. 2.2 Relative comparison of biomass resources for different category indicators (basis MJ of harvested biomass)

7.1.2 Conversion processes

Tab. 7.1 and Fig. 7.2 show the influence of the allocation criterion between wheat and straw on the impacts per MJ fuel delivered to the tank. The allocation criterion between straw and wheat grains has quite an important influence on the total impacts of all processes that use straw as an input.

The change in the allocation criterion leads to a higher amount of land occupation assigned to the straw. Thus, the calculated energy yield and fuel yield decreases. For most category indicators the impacts for the processes using straw are now higher than for the processes using wood as an input.

Tab. 7.1 Category indicator impacts per MJ of BTL-fuel, sensitivity analysis for straw allocation based on energy content. Calculation of energy yield and fuel yield

Impact category	Unit	BTL-fuel, miscanthus, at service station/MJ/TUV U	BTL-fuel, straw, at service station/MJ/CUTEC U	BTL-fuel, straw, at service station/MJ/FZK U	BTL-fuel, straw, at service station/MJ/UET U	BTL-fuel, wood, at service station/MJ/CUTEC U	BTL-fuel, wood, at service station/MJ/TUV U	BTL-fuel, wood, at service station/MJ/UET U	dimethylether, black liquor, at service station/MJ/Chemrec U
cumulative energy demand	MJ-Eq	5.32	4.32	3.43	2.7	3.57	5.55	2.7	**2.11**
abiotic depletion	kg Sb eq	0.000269	0.000423	0.000289	0.000227	0.000173	0.00027	0.000134	**0.000105**
global warming (GWP100)	kg CO2 eq	0.0579	0.111	0.0717	0.0574	0.0437	0.0572	0.0296	**0.0256**
photochemical oxidation, non-b	kg C2H4	2.96E-05	4.87E-05	3.54E-05	1.54E-05	3.55E-05	2.98E-05	**1.26E-05**	1.71E-05
acidification	kg SO2 eq	0.000466	0.000669	0.000615	0.000396	0.00033	0.000528	**0.000237**	0.000243
eutrophication	kg PO4--- eq	0.000402	0.000565	0.000466	0.00035	0.000156	0.000267	0.000104	**8.89E-05**
water use	m3	0.158	0.133	0.112	0.0887	0.136	0.209	0.103	**0.08**
land competition	m2a	0.18	0.182	0.156	0.121	0.174	0.273	0.13	**0.102**

energy yield	MJ/m2a	5.6	5.5	6.4	8.3	5.7	3.7	7.7	9.8
fuel yield	toe/ha	1.3	1.3	1.5	1.9	1.3	0.9	1.8	2.3

The allocation choice might change the ranking for the CUTEC process. It leads to higher comparative impacts for several category indicators. The UET process has now lower or about the same impacts than all other processes using straw.

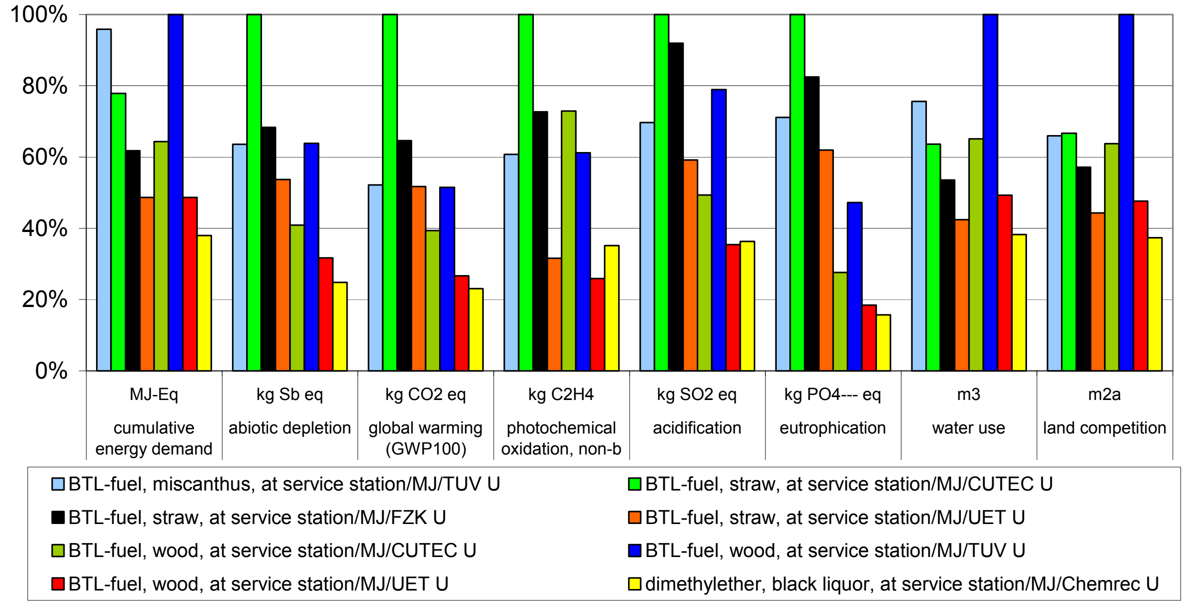


Fig. 7.2 **Relative comparison of fuels using different category indicator impacts, sensitivity analysis for straw allocation based on energy content (basis MJ of fuel delivered to the tank)**

Here we show a repetition of Fig. 3.1 for comparison.

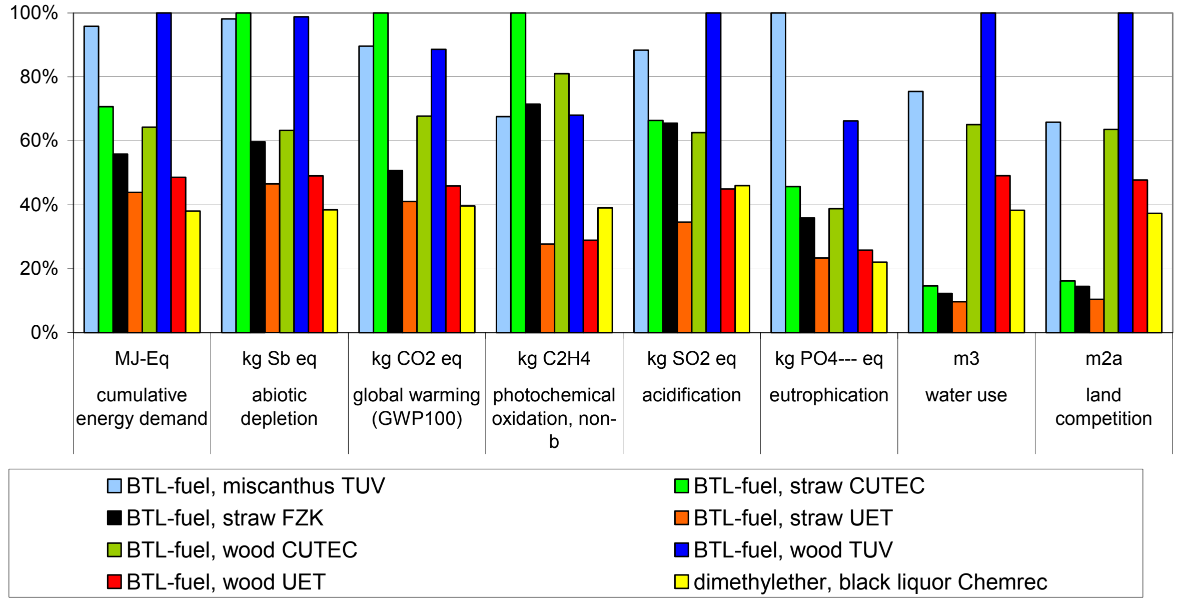


Fig. 3.1 **Relative comparison of fuels using different category indicators (basis MJ of fuel delivered to the tank)**

Fig. 7.3 evaluates the influence of the allocation choice between straw and grains on the impacts. Allocation by energy content results in up to three times the environmental impacts per MJ of fuel as compared to allocation by price (base case described in chapter 3.1, see Fig. 3.1). The CED is not affected, because the input of biomass energy is allocated in all cases based on physical relationship. Thus, the life cycle inventory shows the measured energy content of the straw and the wheat grains.

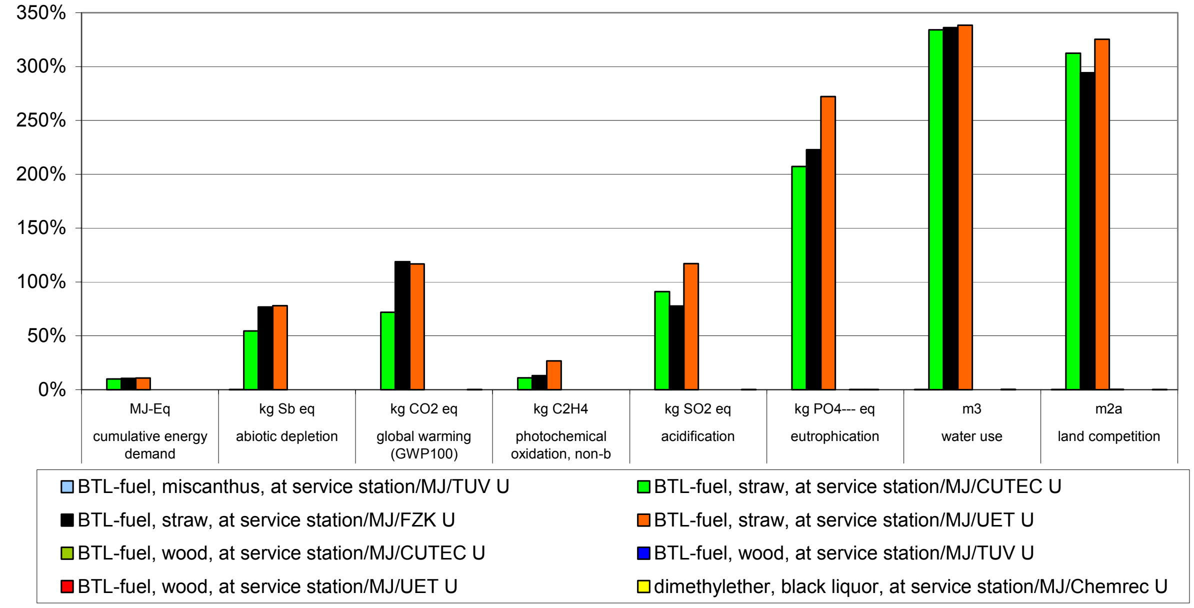


Fig. 7.3 Change of impacts due to the straw allocation based on its energy content (basis MJ of fuel delivered to the tank)

7.2 CML method for photochemical oxidation

Here we make a sensitivity analysis with the CML 2001 method, which is not changed regarding the characterisation of biogenic NMVOC emissions.

7.2.1 Biomass production

Isoprene emissions are by far the most dominant emissions accounting for about 99 % of the cumulative photochemical oxidation potential if they are included in the assessment. For POCP there are advantages for the use of straw and miscanthus that emit lower amounts during growing.

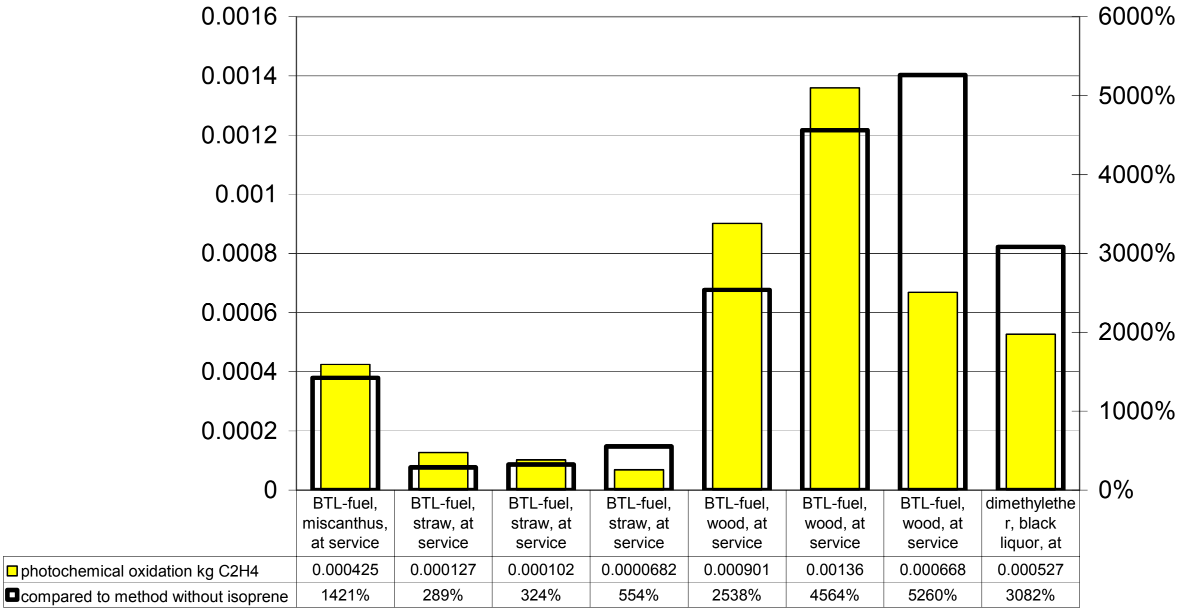
7.2.2 Starting point calculation

Fig. 7.4 shows the absolute figures for the new results (left scale) and the percentage change compared to the method used here without accounting for isoprene emissions.

The air emission of pollutants contributing to summer smog (high concentrations of ozone) is absolutely dominated by the biomass production. The impacts are up to 53 times higher than for the method excluding the biogenic emissions. The conversion ratio and the type of biomass use are quite important. Only for processes based on straw, other types of emissions get some relevance because of the lower isoprene emissions.

Processes, based on straw or miscanthus, have a clear advantage in comparison to processes based on wood. This should be taken into account even if the inventory for these substances might still have an uncertainty of about factor 2.

In any case, it has to be taken into account that the formation of summer smog depends not only on the amount of NMVOC in the atmosphere, but also on other pollutants, e.g. NO_x. Thus, it is quite difficult to model a clear relationship in the LCIA between the NMVOC in agricultural areas and the formation of summer smog.

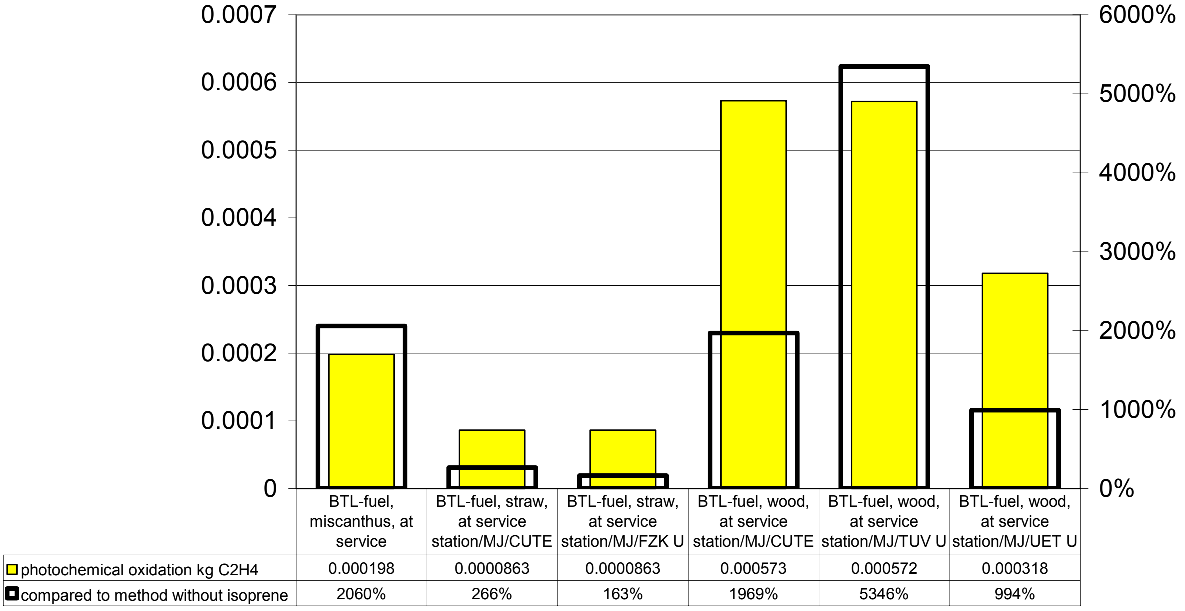


	BTL-fuel, miscanthus, at service	BTL-fuel, straw, at service	BTL-fuel, straw, at service	BTL-fuel, straw, at service	BTL-fuel, wood, at service	BTL-fuel, wood, at service	BTL-fuel, wood, at service	dimethylether, black liquor, at
🟨 photochemical oxidation kg C2H4	0.000425	0.000127	0.000102	0.0000682	0.000901	0.00136	0.000668	0.000527
▢ compared to method without isoprene	1421%	289%	324%	554%	2538%	4564%	5260%	3082%

Fig. 7.4 **Change of results due to the impact assessment with the original CML method for photochemical oxidation (basis MJ of fuel delivered to the tank), starting point calculation, kg C2H4-eq/MJ**

7.2.3 Scenario 1

The air emission of pollutants contributing to photochemical oxidation (summer smog with high concentrations of ozone) is dominated by the biomass production. The conversion ratio and the type of biomass use are quite important. For processes based on straw, other types of emissions get some relevance because of the lower isoprene emissions. The absolute change is quite smaller compared to the starting point calculation because of a higher importance of remissions resulting from the electricity use.



	BTL-fuel, miscanthus, at service	BTL-fuel, straw, at service station/MJ/CUTE	BTL-fuel, straw, at service station/MJ/FZK U	BTL-fuel, wood, at service station/MJ/CUTE	BTL-fuel, wood, at service station/MJ/TUV U	BTL-fuel, wood, at service station/MJ/UET U
🟨 photochemical oxidation kg C2H4	0.000198	0.0000863	0.0000863	0.000573	0.000572	0.000318
▢ compared to method without isoprene	2060%	266%	163%	1969%	5346%	994%

Fig. 7.5 **Change of results due to the impact assessment with the original CML method for photochemical oxidation (basis MJ of fuel delivered to the tank), scenario 1, kg C2H4-eq/MJ**

7.3 EDIP method for photochemical smog

In Fig. 7.6 and Fig. 7.7 we perform a sensitivity analysis on the category indicator photochemical smog (Hauschild & Wenzel 1997). Fig. 7.6 can be compared with the share of pollutants investigated according to the CML method used in Fig. 3.10. Isoprene emissions from biomass production are dominant. Unspecified NMVOC, which are not accounted for in the CML methodology, are important for the processes based on straw input. On the other side sulphur dioxide is not accounted for by this method.

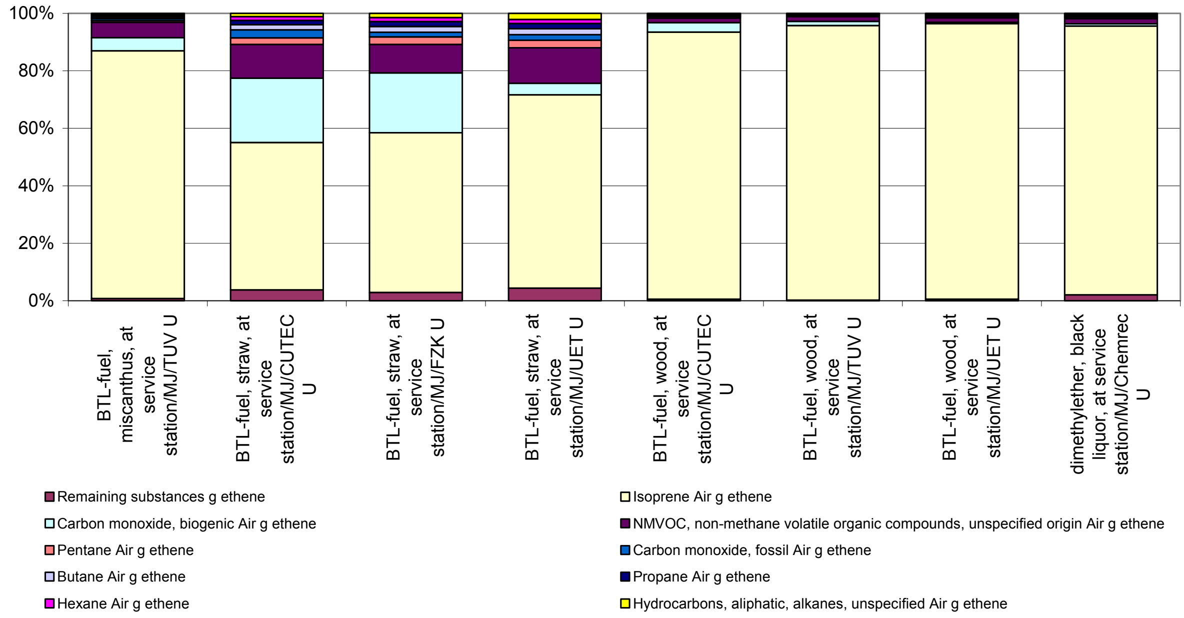


Fig. 7.6 **Contribution of individual elementary flows to the total photochemical smog, EDIP methodology, starting point calculation**

Fig. 7.7 makes also a direct comparison of the conversion routes. This can be compared with the results presented in Fig. 3.1 and Fig. 7.4. The ranking of the different processes is not much influenced by the choice of this LCIA method and the exclusion or inclusion of some individual emissions. Thus no further sensitivity analyses are performed on this aspect.

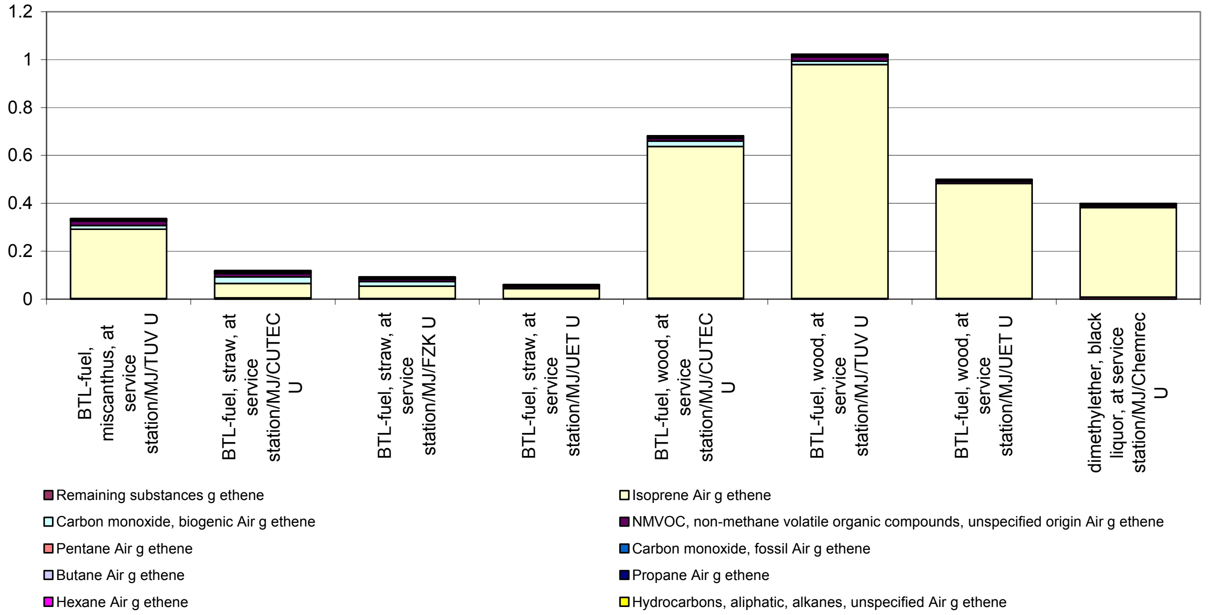


Fig. 7.7 **Comparison of process routes, photochemical smog EDIP methodology (g ethene equivalents per MJ of fuel delivered to the tank, starting point calculation**

7.4 Use of wood in the TUV process

Here we perform a sensitivity analysis that considers that also a part of the wood input should be allocated to the electricity production and thus the environmental impacts allocated to the fuel production should be lower (for details see Jungbluth et al. 2007b: Tab. 3.55).

Fig. 7.8 shows that the impacts for different category indicators are reduced between 10% to 30% if the wood input is reduced by about 30% according to the exergy share of fuel and electricity production. The approach for an allocation by exergy is also explained in the above cited inventory report.

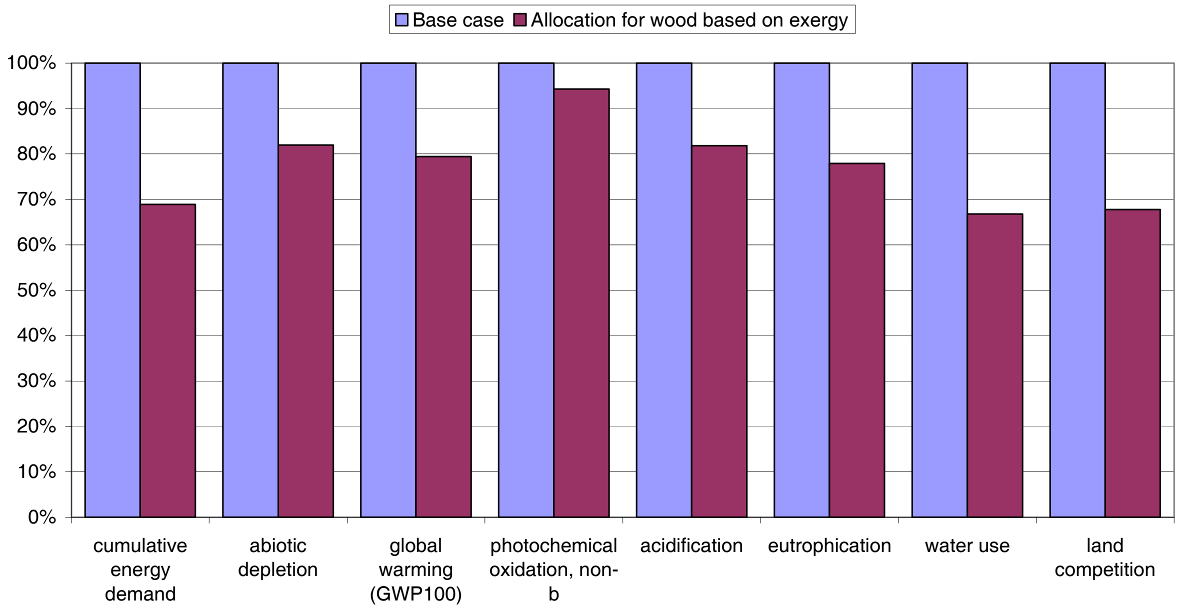


Fig. 7.8 **Influence of modelling assumptions for the allocation of wood input in the TUV process (basis MJ of fuel delivered to the tank)**

7.5 European electricity mix for hydrogen production in scenario 1

The use of external electricity for the production of hydrogen that is used for the conversion process can increase the fuel yield per hectare considerable. In the basic calculation, we assumed the use of wind power, which is quite unrealistic as a general solution in future. Tab. 7.2 and Fig. 7.9 show a relative comparison of the fuel products based on the energy content, calculated with the average European electricity mix used for hydrogen production in scenario 1. The figure can directly be compared with the results in Tab. 4.2 and Fig. 4.1, respectively.

The TUV (ICFB-D) process does not use an external hydrogen production. Thus it shows a better performance in this analysis than the other processes for the aspects which are influenced by the external electricity use from the grid (e.g. global warming, energy demand, photochemical oxidations). On the other side, it has higher impacts for category indicators directly related to biomass production (eutrophication, water and land use).

The CUTEC (CFB-D) process using straw has lower or about the same results as the process of FZK (dEF-D) for the category indicators CED, abiotic depletion, GWP, POCP and AP. For eutrophication, land and water use, it has slightly higher impacts. So there is no clear overall ranking among the conversion concepts.

Among the two processes converting wood and using hydrogen (cEF-D and CFB-D process), the (UET) cEF-D process has slightly higher impacts for the electricity dominated indicators abiotic depletion, global warming, POCP and AP due to the higher external electricity demand of the cEF-D process. The CUTEC (CFB-D) concept has slightly higher impacts for category indicators related to biomass production (CED and eutrophication).

The electricity mix changes some of the results of the comparison quite significantly. The ranking according to the cumulative energy demand, photochemical oxidation, eutrophication, water and land competition remains about the same. For abiotic depletion and global warming, the differences between the process routes get more significant.

Based on the assumption of an average electricity input, the process of TUV has many advantageous results because it does not use external electricity.

Tab. 7.2 Sensitivity analysis with average European electricity mix for hydrogen production. Category indicator results per MJ of BTL-fuel

Impact category	Unit	BTL-fuel, miscanthus, at service station/MJ/TUV U	BTL-fuel, straw, at service station/MJ/CUTEC U	BTL-fuel, straw, at service station/MJ/FZK U	BTL-fuel, wood, at service station/MJ/CUTEC U	BTL-fuel, wood, at service station/MJ/TUV U	BTL-fuel, wood, at service station/MJ/UET U
cumulative energy demand	MJ-Eq	**2.29**	4.54	5.62	4.33	2.57	4.23
abiotic depletion	kg Sb eq	**9.83E-05**	0.000792	0.00134	0.000712	0.00013	0.000954
global warming (GWP100)	kg CO2 eq	**0.0218**	0.123	0.189	0.111	0.0277	0.137
photochemical oxidation, non-b	kg C2H4	**9.48E-06**	3.22E-05	4.63E-05	2.90E-05	1.06E-05	3.20E-05
acidification	kg SO2 eq	**0.000173**	0.000633	0.00105	0.000636	0.000241	0.000783
eutrophication	kg PO4--- eq	0.000153	0.000115	8.64E-05	0.000124	9.65E-05	**7.61E-05**
water use	m3	0.0516	0.0154	**0.0105**	0.0843	0.0864	0.0451
land competition	m2a	0.0595	0.0276	**0.0204**	0.111	0.112	0.0593
energy yield	MJ/m2a	16.8	36.2	49.0	9.0	8.9	16.9
fuel yield	toe/ha	3.9	8.5	11.5	2.1	2.1	4.0

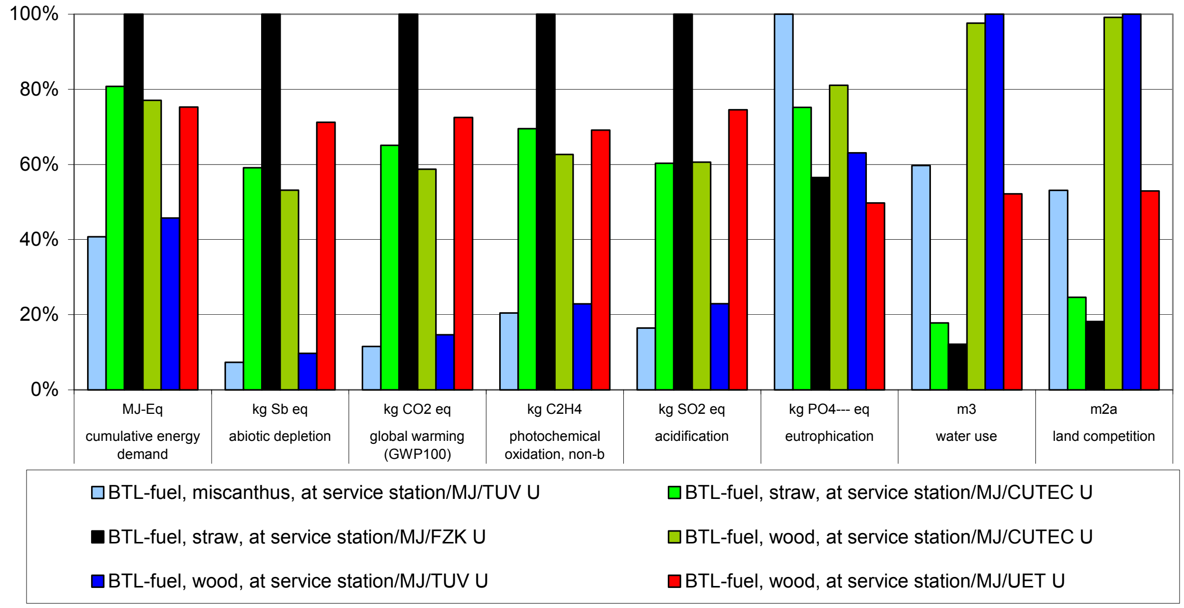


Fig. 7.9 **Relative comparison of fuels using different category indicators (basis MJ of fuel delivered to the tank), sensitivity analysis with average European electricity mix for hydrogen production**

Here we show a repetition of Fig. 4.1 for comparison.

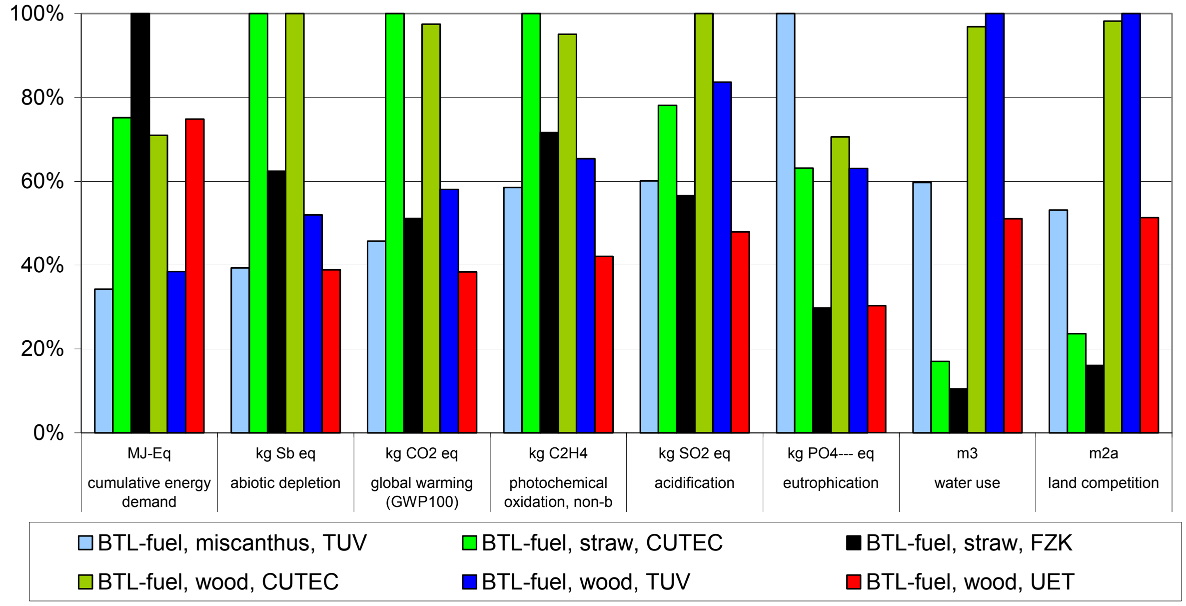


Fig. 4.1 **Scenario 1 with wind power. Relative comparison of fuels using different category indicators (basis MJ of fuel delivered to the tank)**

Fig. 7.10 shows the relative change of category indicator results due to the realistic assumption that the UCTE mix is used for electricity supply. Impacts for TUV remain the same because no external electricity is used. The use of average electricity would increase the environmental impacts considerable. Only the cumulative energy demand would be decreased slightly for the concerned processes. The use of the UCTE mix worsens especially the relative performance of the FZK and UET process. For photochemical oxidation (excl. biogenic) and acidification, the use of UCTE electricity makes the differences between the process routes larger.

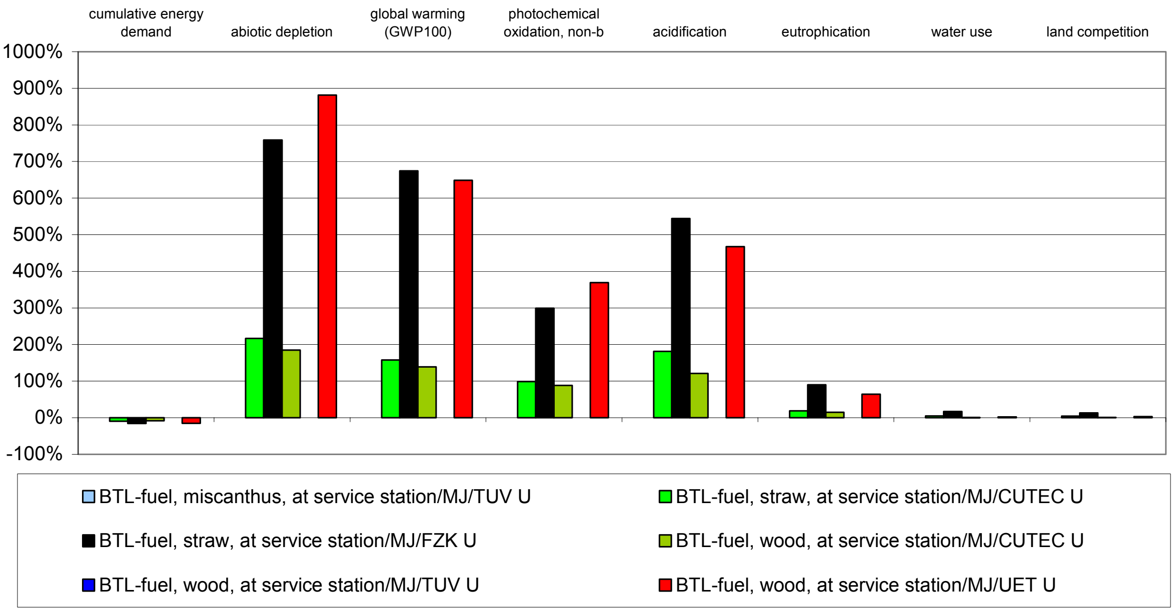


Fig. 7.10 **Change of results due to the use of average UCTE electricity instead of the unrealistic assumption that wind power can be used (basis MJ of fuel delivered to the tank)**

7.6 Comparison of starting point calculation with scenario 1

The idea for the scenario 1 is to produce a maximum of fuel output. Thus, it has been modelled that the fuel yield per hectare is increased due to the use of external electricity and hydrogen and due to further process improvements. An important question for the evaluation of scenario 1 is if the increased fuel yield makes also sense from an environmental point of view or if the use of hydrogen produced from external electricity increases the environmental impacts. In Fig. 7.11 we compare scenario 1 with the starting point calculation.

The last column shows the increase in MJ of fuel produced per hectare. All processes show a considerable increase of the fuel yields per hectare between 60% and 200% if externally produced hydrogen is used in the process.

The TUV process uses no external electricity, but shows an improved conversion rate. Thus, all category indicator results are lower. But, it has to be noted that the performance of this process in the starting point calculation was relatively low.

External hydrogen input increases the results for many category indicators considerable. It has small advantages only for eutrophication, water and land competition. The use of the today European electricity mix (UCTE) results in distinctly higher impacts for abiotic depletion, global warming, eutrophication, photochemical oxidation and acidification. The increase of fuel yields per hectare by using electricity from the grid makes only limited sense from an environmental point of view.

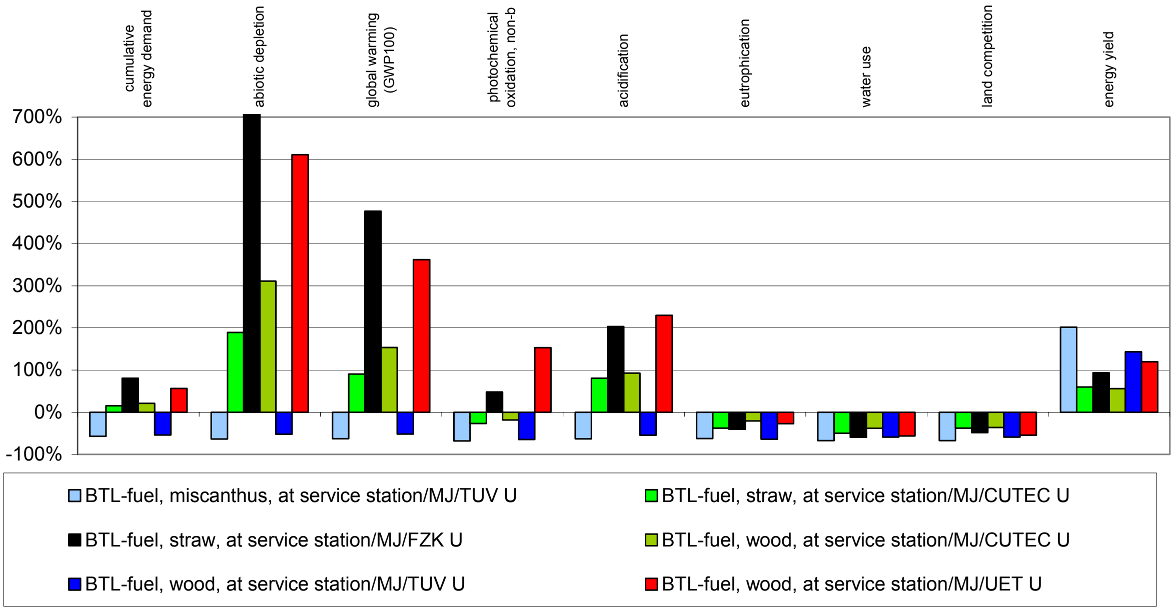


Fig. 7.11 **Relative comparison of the impacts for starting point calculation and scenario 1, UCTE power mix**

The situation for the use of external hydrogen is more favourable, if it would be possible to use electricity from wind power plants. Fig. 7.12 evaluates the relative change of impacts in comparison to the starting point calculation. The use of wind power together with improved process design would lead to lower impacts for most category indicators and most conversion concepts.

It is not possible to evaluate in this case the importance of the process improvement and the importance of the external hydrogen input for these favourable impacts.

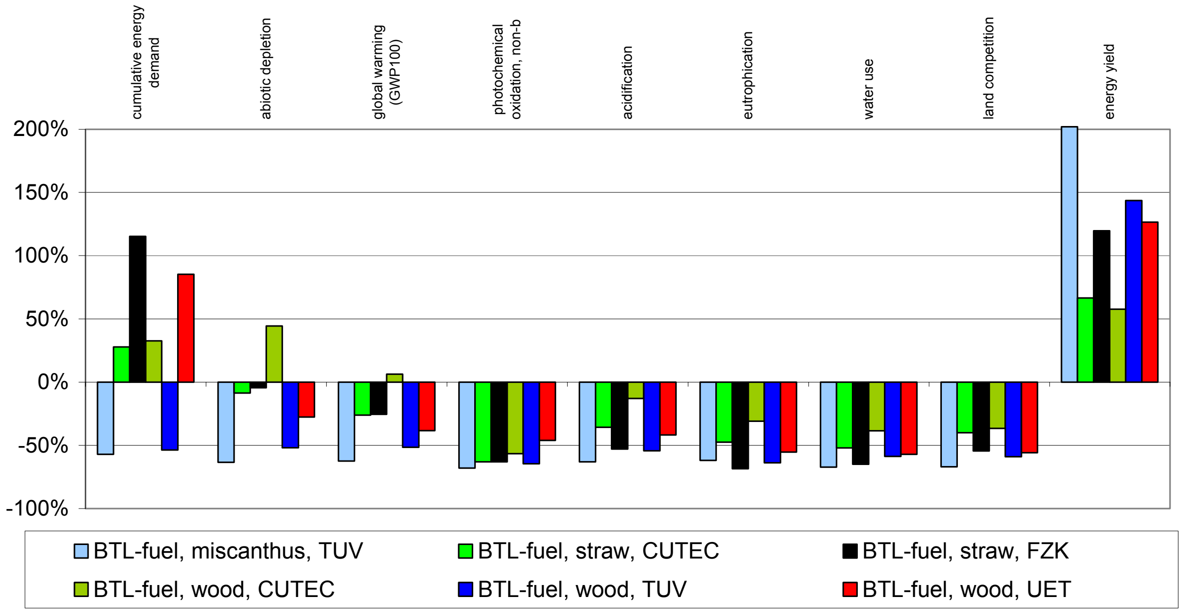


Fig. 7.12 **Relative comparison of the impacts for starting point calculation and scenario 1, wind power**

8 Conclusions

The main conclusions that can be drawn from the life cycle impact assessment and the interpretation of the results are summarized in this chapter.

8.1 Data basis

The data used for the comparison of the different conversion processes are based on models provided by the conversion plant developers. Many important parameters are based on literature data or modelling assumptions and not on real plant data (Jungbluth et al. 2007b:3.11).

These process concepts represent different development status. This might result in a different quality and reliability of the calculated LCA results. The data investigated for this study represent the status of BtL technology in the year 2006. Further technology progress may strongly influence the LCI data. Therefore, it is recommended to use updated data in future studies or to approve the data by the respective technology partner.

The most important aspect in the evaluation of the different conversion concepts is the conversion rate from biomass to final fuel. This conversion rate determines how much biomass is required. On the one hand, many environmental impacts are directly related to the amount of biomass used. On the other hand, the conversion rate has influences the emissions from the conversion process, because nearby all losses of the process are emitted to the air.

Within the LCA, it was not possible to verify the data provided by the plant owners and thus the conversion rates calculated from these data. This task is executed in a separate working package of this project, the so-called “technical assessment” (Vogel 2007; Vogel et al. 2007). All conclusions based on the comparison are only valid under the pre-condition that the provided conversion rates are correct.

All background data have been investigated in the ecoinvent database with the same methodological background as used in this study (Frischknecht et al. 2004a). Thus, they can be assumed consistent with the data investigated within this project. As all processes use similar inputs the background data do also not have a relevant influence for the comparison of the processes.

8.2 Limitations of the life cycle impact assessment

The life cycle impact assessment evaluates the environmental impacts using a selection of category indicators that was chosen based on relevance and reliability. Not all environmental impacts relevant for the investigated production systems are accounted for due to lack of data or uncertainties in the impact assessment methods (Jungbluth et al. 2007a: chapter 4.7).

Environmental impacts due to the use of pesticides and the emissions of heavy metals in agricultural production are not assessed with the category indicators used in this study. These substances have toxicological effects on animals, plants and human beings. Several methodologies are available for characterising the toxicological effects of pesticides and heavy metals (e.g. Goedkoop & Spriensma 2000; Guinée et al. 2001; Jolliet et al. 2003; Wenzel et al. 1997).

A group of LCA specialists has discussed the possible problems for LCIA of non-ferrous metals in a workshop (Apeldoorn Declaration 2004). They concluded that a number of issues in the toxicity assessment of these substances are imperfectly dealt with and that it is thus necessary to consider these shortcomings in the interpretation of the LCIA results. Furthermore they outlined that sensitivity analysis might be necessary in case that certain metals have a dominating influence on the total results. A recent evaluation of the different methodologies is published (Larsen & Hauschild 2007).

Another important issue is the change in land competition patterns. Different methodologies for characterising land occupation and transformation were published in the recent past (Köllner & Scholz 2007; Lindeijer et al. 2001; Mila i Canals et al. 2007). Here we investigate only the occupied land surface without characterising different types of land uses.

With regard to the impact assessment methodologies and category indicators for toxicological effects there was no consensus in the project group whether or not the requirements of ISO 14044, 4.4.2.2.3 are fulfilled by LCIA methods published for such impacts. Indicators therefore are not included in the study and the importance of this decision for the comparison of the conversion routes has not been evaluated as demanded in the goal and scope definition (Jungbluth et al. 2007a:chapter 4.7).

The exclusion of certain category indicators might be quite important with regard to the ranking of different conversion processes. The authors of this study consider this a shortcoming of this study. Such effects must be taken into account especially if it comes to a comparison between fuels made from biomass and fossil fuels.

Including these aspects would even more highlight the importance of the biomass production regarding the total environmental impacts caused by the fuel provision to the tank.

Further research about the definition of reliability within the ISO standards and a consensus finding process for the best available methodologies for toxicological effects is necessary. Within the framework of the UNEP-SETAC life cycle initiative, such processes are on the way (Jolliet et al. 2004; Mila i Canals et al. 2007; Stewart et al. 2003). Important is also the application of different LCIA methodologies for the toxicological effects in LCA case studies. The data investigated for this study can provide a good basis for such an evaluation.

8.3 Comparison of conversion routes

8.3.1 Starting point calculation

The starting point calculation compares the category indicator results of different conversion concepts operated in a self sufficient plant layout. Many category indicators like acidification, eutrophication, water use and land competition show an absolute dominating influence of the agricultural production of biomass. Thus, only the conversion ratio and the type of biomass are important when comparing different conversion routes.

The conversion rate also plays a major role in the formation of air emissions from the conversion plant. The higher the conversion rate, the lower is the share of carbon and thus also other pollutants which are released to the ambient air.

The ranking of the different processes is visualized in Tab. 8.1. The process with the lowest category indicator results is set to 100%. For other processes and all category indicators, the table shows the rise of environmental impacts in comparison to the process with the lowest impacts. Different colours help to see the ranking. Processes with less than 15% higher environmental impacts are ranked “lowest impacts”. Processes with 16% to 50% higher impacts than the optimum are ranked as “low impact” processes. An exponential scheme has been used in order to classify “high impacts (151%-250%) and “highest impacts” (more than 250% of the lowest impacts). This considers that the processes classified as “lowest impacts” should be close to the process with the lowest figures of all.

The UET process based on straw is ranked “lowest” or “low” in all category indicators. The use of wood has much higher impacts regarding the use of water and land. Thus, the processes of UET and CHEMREC have the lowest environmental impacts in all category indicators except these two impacts. The ranking of processes using straw is quite dependent on the actual market price for straw. With a rising demand, this price might increase and, due to the allocation procedure, in turn lead to higher impacts for processes using straw.

For the conversion of wood, the UET process has between 15% and 30% higher impacts than the production of dimethylether in the category indicators CED, abiotic depletion, global warming, eutrophication, water and land use. But, it has 35% lower impacts in the category indicator photochemical oxidation. CUTEC has more than 65% higher impacts than UET and CHEMREC for all aspects investigated. The TUV process shows a rather low conversion rate and thus has higher impacts for all category indicators except photochemical oxidation not including biogenic emissions.

Processes based on wood show slightly lower impacts than processes based on straw regarding the category indicators CED, abiotic depletion, GWP and EP. The UET process with straw shows the lowest environmental impacts for POCP, acidification, water use and land competition.

The UET process has the lowest environmental impacts followed by the FZK and the CUTEC process regarding the conversion of straw. There is only one conversion process using miscanthus (TUV). Thus, a direct comparison with other conversion concepts is not possible.

Tab. 8.1 Starting point calculation. Ranking of the different conversion concepts with respect to the category indicators based on the energy content of the fuel delivered to the tank

	Biomass	Miscanthus	Straw	Straw	Straw	Wood	Wood	Wood	Wood
	Process	Allothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Centralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Centralized Entrained Flow Gasification	Entrained Flow Gasification of Black Liquor for DME-production
	Code	ICFB-D	CFB-D	dEF-D	cEF-D	CFB-D	ICFB-D	cEF-D	BLEF-DME
	Company	TUV	CUTEC	FZK	UET	CUTEC	TUV	UET	CHEMREC
Category indicator	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-DME
cumulative energy demand	MJ-Eq	*252%*	*186%*	147%	115%	*169%*	*263%*	128%	100%
abiotic depletion	kg Sb eq	*255%*	*260%*	*155%*	121%	*165%*	*257%*	128%	100%
global warming (GWP100)	kg CO2 eq	*226%*	*252%*	128%	104%	*171%*	*224%*	116%	100%
photochemical oxidation, non-b	kg C2H4	*244%*	*361%*	*258%*	100%	*292%*	*245%*	104%	141%
acidification	kg SO2 eq	*256%*	*192%*	*190%*	100%	*181%*	*289%*	130%	133%
eutrophication	kg PO4--- eq	*453%*	*207%*	*162%*	106%	*176%*	*300%*	117%	100%
water use	m3	*780%*	*151%*	127%	100%	*672%*	*1034%*	*508%*	*396%*
land competition	m2a	*631%*	*155%*	139%	100%	*610%*	*959%*	*458%*	*358%*

	Min	Max
Lowest impacts	100%	115%
Low impact	116%	150%
High impact	*151%*	*250%*
Highest impacts	*251%*	

The fuel yield per hectare is an important yardstick for comparing different types of biomass and different process routes. The calculation includes the full life cycle from seed to tank, e.g. also biomass losses during storage and land occupation due to other processes than biomass production.

The fuel yield of energy crops per hectare is between 860 to 2300 kg oil equivalents. Processes based on straw show a fuel yield up to 8200 kg oil equivalents per hectare, if the agricultural land is allocated to the straw based on its share of the today revenue of wheat production. The yield of processes based on straw is only 1300 to 1900 kg oil equivalents per hectare if the allocation is based on the energy content of grains and straw.

8.3.2 Scenario 1

The main idea of scenario 1 is an increase of the fuel yield per hectare. This is achieved in most conversion concepts with using an amount of electric energy for water electrolysis in the same range as the direct input of biomass energy. CHEMREC has not provided data for scenario 1.

All processes show a considerable increase of the fuel yields per hectare of between 60% and 200% if hydrogen is used in the process. A fuel yield between 2100 and 3900 kg oil equivalents per hectare is possible for the use of miscanthus and wood.

Producing hydrogen with electricity will only make sense if renewable energy, e.g. wind power, is available in very large capacities and with a secure supply for the specific conversion plant. Generally, the use of hydrogen produced via electrolysis and using the today electricity mix results in considerably higher environmental impacts. As the necessary capacities for wind power will not be available at many locations, this scenario does not describe a general possibility for BTL-production in the year 2020.

The ranking of the different processes is visualized in Tab. 8.2. Comparing all processes, the cEF-D process with wood input shows the lowest environmental impacts of all investigated concepts, except for the cumulative energy demand, water use and land competition. The ICFB-D concept has been modelled without an input of external energy. It has the lowest cumulative energy demand. The use of straw in the dEF-D process has the lowest impacts with respect to eutrophication, water use and land competition.

Comparing straw based processes, the process of FZK (dEF-D) shows the lowest results except the cumulative energy demand, which is highest.

Comparing wood based processes, the cEF-D of UET shows the lowest impacts except CED, where the ICFB-D process of TUV has a lower impact because it does not use external electricity.

A clear overall ranking with regard to the use of different biomass resources cannot be made. In addition, a clear ranking of the different conversion processes is not possible, because results show trade offs between the different category indicators. The normalization alone does not support this decision as it only shows the relevance of each single category indicator for the product system in comparison to the overall impacts, but not the difference in importance between different category indicators. A formal weighting between category indicators, which would bridge these trade-offs, shall not be used according to the ISO standards for comparative LCA studies.

Tab. 8.2 Scenario 1 with wind power used in hydrogen production. Ranking of the different conversion concepts with respect to the category indicators based on the energy content of the fuel delivered to the tank

	Biomass	Miscanthus	Straw	Straw	Wood	Wood	Wood
	Process	Allothermal Circulating Fluidized Bed Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Decentralized Entrained Flow Gasification	Centralized Autothermal Circulating Fluidized Bed Gasification	Allothermal Circulating Fluidized Bed Gasification	Centralized Entrained Flow Gasification
	Code	ICFB-D	CFB-D	dEF-D	CFB-D	ICFB-D	cEF-D
	Company	TUV	CUTEC	FZK	CUTEC	TUV	UET
Category indicator	Product	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT	BTL-FT
cumulative energy demand	MJ-Eq	100%	*219%*	*292%*	*207%*	112%	*218%*
abiotic depletion	kg Sb eq	101%	*257%*	*160%*	*257%*	134%	100%
global warming (GWP100)	kg CO2 eq	119%	*261%*	133%	*254%*	*151%*	100%
photochemical oxidation, non-b	kg C2H4	139%	*238%*	*170%*	*226%*	*155%*	100%
acidification	kg SO2 eq	125%	*163%*	118%	*209%*	*175%*	100%
eutrophication	kg PO4--- eq	*336%*	*212%*	100%	*237%*	*212%*	102%
water use	m3	*573%*	*163%*	100%	*929%*	*959%*	*489%*
land competition	m2a	*331%*	147%	100%	*611%*	*622%*	*319%*

	Min	Max
Lowest impacts	100%	115%
Low impact	116%	150%
High impact	*151%*	*250%*
Highest impacts	*251%*	

8.4 Improvement options

8.4.1 General issues

The LCA shows some important improvement options for all conversion concepts from an environmental point of view. The most important issue is the conversion rate, which influences the biomass input and air and water emissions. A linear relationship is assumed between carbon losses and emissions to air accompanying the biogenic CO_2 emissions. An increase of the yield is an important improvement option from an environmental point of view.

The emission profile is influenced by the flue gas treatment system that is installed. The reduction of air emissions, especially methane, carbon monoxide, and nitrogen oxides is an important improvement option in the planning of all conversion plants.

The use of after treatment technologies for the reduction of emissions to air is not studied in detail. For all conversion plants, it is assumed that they have to meet the legal limits, but do not further reduce the emissions. Such an after treatment might reduce the direct emissions, but might lead to higher indirect impacts e.g. due to surplus energy use or additional consumption of necessary auxiliary materials. Further research would be necessary to identify the optimum solutions.

The currently weak data basis does not allow answering the question, whether it is favourable to release the off-gases directly from the gas cleaning or whether they should be used and burned together with other gases in the power plant. Further investigations are necessary in order to determine which of the two possibilities would ensure lower absolute emissions of the most important air pollutants (methane, nitrogen oxides, carbon monoxide, NMVOC's and particles).

Refinery treatment of Fischer-Tropsch raw products increases the environmental impacts. A full integration of the upgrading in the conversion concept might be advantageous, because this would facilitate the better use of internal energy flows.

The reduction of the environmental impacts of the biomass production itself is another improvement option. This analysis shows that the biomass production has a dominating influence on most of the environmental indicators. Particular options for such an improvement have not been investigated in detail. An important aspect might be the reduction of NMVOC emissions from plants by choosing favourable types of biomass resources.

Detailed studies on agricultural production show that improvements are not easy to achieve. Different influencing factors as e.g. fertilizer and pesticide use, diesel consumption and level of yields have to be balanced out to find an optimum solution. From an environmental point of view, the optimum production cannot achieve the highest yields possible (see e.g. Kägi et al. 2007; Nemecek et al. 2005).

The results of straw based processes highlight that is preferable to use by-products such as straw or wastes for biofuel production. However, the potential is limited (see Kunikowski et al. 2006 for an assessment). A rising demand might lead to higher market prices and because of the allocation procedure also to higher environmental impacts.

For some processes, the disposal of wastes from the conversion process makes a relevant contribution to the problem of eutrophication due to the emission of phosphate. It is considered that the phosphates are washed out over a very long time after the landfill has been closed. Nutrients, which are bound in the biomass, as e.g. phosphorous, are lost with the disposal of ashes, sludge, slag or effluents. Recovering these nutrients and recycling them for use in agriculture might be another option for improving the overall performance.

The use of catalysts in the conversion process and in the refinery treatment of FT-raw products might have some relevance if rare metals are used in the production. Specific information about the actual amount and composition of the catalysts has not been provided by the plant developers. Recycling of such catalysts is a possibility for minimising the use of rare metals.

8.4.2 Centralized Entrained Flow Gasification, cEF-D (SP1-UET)

The improvement options for the process of UET are described in the previous section. The main option is the increase of the fuel yield.

8.4.3 Centralized Autothermal Circulating Fluidized Bed Gasification, CFB-D (SP2-CUTEC)

The use of quicklime, which is used as a catalyst, is responsible for about 19% of the greenhouse gas emissions in the case of straw input. The plant developer discus about possibilities of a recycling of this material from the ashes of this process. The use of less or alternative materials is an important improvement option.

8.4.4 Decentralized Entrained Flow Gasification, dEF-D (SP2-FZK)

The FZK foresees a centralised gasification of the decentralized pyrolysed biomass. The FZK process is designed for a large-scale plant on a 5 GW basis. On the small 500MW scale of the scenarios investigated here, this concept has no clear advantage in comparison to centralized concepts. Transports do not play an important role for most of the category indicators. Thus on a 500 MW scale, the reduced amount of transports does not lead to a considerable reduction of environmental impacts. On the other side, the decentralization has disadvantages concerning the energy integration and the use of heat from the pyrolysis process.

8.4.5 Allothermal Circulating Fluidized Bed Gasification, ICFB-D (SP2-TUV)

The process layout with a higher share of electricity production is a disadvantage due to the boundary conditions used in this study. If a share of wood input to the process is attributed to the electricity produced (e.g. according to the exergies of fuel, heat and electricity produced), the impacts are reduced by 10% to 30%. Externally produced hydrogen is not modelled in scenario 1. Thus, no comments on this issue are possible. The data provided by TUV for scenario 1 show the highest conversion rate of all self-sufficient conversion concepts. Such high conversion rates still lack proof in reality.

8.4.6 Entrained Flow Gasification of Black Liquor for DME-production, BLEF-DME (SP3-CHEMREC)

The fugitive emissions of dimethylether during the distribution of the fuel are likely to be higher than for diesel fuels. They contribute an important share of emissions forming photo oxidants. So far the data basis on these emissions is quite weak.

Emissions from burning wood chips directly in a steam and power boiler are higher than the emissions in other concepts using tail gases from the gasification process. It is proposed to do further research with the aim to minimise these emissions, e.g. with gasification technology for the power plant.

8.5 Outlook

In general, this study confirms the knowledge already available from several studies about biofuels (Jungbluth et al. 2004). The type of biomass and the conversion rate to the final fuel are quite important with respect to the environmental evaluation of all types of biofuels.

The starting point calculation highlights the differences in the environmental impacts caused by different conversion concepts and for different types of biomass inputs. Scenario 1 can be used to evaluate the possible maximized fuel yields, if large quantities of electricity are used to produce hydrogen for the process.

This life cycle assessment study compares different concepts of BTL-fuel production based on the status of technology development in the year 2006. Further improvement can be expected for all technologies. Thus, this study is only valid for the moment and it might be possible that the ranking of different conversion concepts must be revised in future. The results of the study should be reconsidered as soon as updated data are available or first commercial plants are in operation.

Therefore, new available studies analysing similar technologies should be taken into account, too (e.g. Felder & Dones 2007; Reinhardt et al. 2006).

Further studies should also comprise the comparison with fossil fuels including the use phase and addressing questions of availability of land, competition with food production etc. To do this, a consequential LCA might be of help. In such a comparison, existing biofuels as ethanol and bio-diesel should also be included (Jungbluth & Tuchschmid 2007).

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Critical Review

(next pages)

RENEW
Renewable fuels for advanced powertrains

Critical Review

According to ISO 14040

by

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June 2007

1 Procedural Aspects of the Critical Review

The Life Cycle Assessment (LCA) study to be reviewed is part of a larger EU-project (Sixth Framework Programme: Sustainable Energy Systems, co-financed by Switzerland) aiming at the technological feasibility of producing automotive fuels from biomaterials. The LCA has been performed by ESU-services Ltd. Uster (Switzerland), the practitioner, in collaboration with partners from European research institutes (LUND, ECBREC, CRES). The data collection and the work was co-ordinated by a consortium of European automotive manufacturers (Volkswagen, Daimler Chrysler, and Volvo) together with ESU-services. The whole RENEW consortium was coordinated by VW, Wolfsburg, Germany.

Originally it was planned (Klöpffer 2004) to review the 4 components of the LCA according to ISO 14040 (ISO 1997, 2006a) separately, starting in 2004:

- Scope and goal definition document (1st year)
- Inventory document (2nd year)
- Impact assessment document (3rd year)
- Interpretation and conclusions and final report (4th year)

The critical review was commissioned in March 2005. The official kick-off meeting took part 18th June 2005 in Berlin. The main aim of this meeting was the discussion of the Goal and Scope chapter of the LCA (delivery 5.2.2) submitted for review in March 2005. At that time it was decided that the inventory and impact assessment document (delivery 5.2.7) should be reviewed 2006 and the final Interpretation and conclusions document (delivery 5.2.10) should be reviewed 2007.

Unfortunately, due to delays in data acquisition, the inventory part could not be delivered in time, but rather – together with the final report – in March 2007. As a consequence, the critical review could not – or only partly – be performed in an interactive way, which is the preferred way to conduct a critical review (Klöpffer 2005). The critical review panel was in a position to comment the Goal and Scope part, but not the inventory part early enough to give advice for the further course of this important LCA. Actually, there was no communication between the practitioner team and the critical review panel for one and a half year. The advantage of a truly interactive critical was thus missed.

The second and final critical review meeting took part in Berlin the 14th of May 2007. The aim of this meeting was to discuss the final draft reports submitted in March 2007 and to plan the finalizing of both the LCA report and the critical review report.

This critical review is based on the three deliveries 5.2.2, 5.2.7 and 5.2.10 in their final versions, i.e. after corrections made by the practitioner according to the suggestions made by the review panel. The critical review process took place in a constructive atmosphere and under conditions of confidentiality. The resulting critical review report is consensus between the reviewers in all essential items.

2 General Impressions

The LCA-study under review is a comprehensive LCA in an emerging technological field whose political importance increased during the work to an unexpected degree. The environmental topic “Climate change” surfaced in the public awareness after years of nearly total neglect and also the second component – the limited availability of fossil resources – became a public topic (again) due to increasing oil prizes. The development of the fuels studied here is more recent compared to the established fuels bio-ethanol and bio-diesel. Originally it was planned to include bio-ethanol for comparison, but this part of the study was cancelled, because data could not be provided by the respective project partner. The Goal & Scope has been changed accordingly.

The three deliverables 5.2.2, 5.2.7 and 5.2.10, to be united into one report and containing this critical review as integral part, constitute doubtlessly an impressive work within the limits set by the goal & scope. We found the following general items worth to highlight:

- Comprehensiveness
- Transparent data format
- Use of original foreground data whenever possible (i.e. if delivered by the partners)
- Use of recent background data (ecoinvent)
- Excellent graphical presentation (except often very small letters)
- Realistic basis scenario

Less positive general items concern:

- Scenario 1 is not primarily based on environmental priorities
- The Life Cycle Impact Assessment (LCIA) using a restricted set of impact categories (no eco-toxicology) favours high efficiency models without a measure of negative ecological consequences
- "Island solution" for wind-parks delivering electrical power for hydrogen production to increase the efficiency

Despite these few restrictive items, the whole picture is a positive one. Most details which have been criticized by the reviewers in the first draft of the final report(s) have been taken into account in the final version. The study in its present form may serve as the basis of future LCAs and sustainability assessments as discussed in section 5.

3 Statements by the reviewers as required by ISO 14040

According to the LCA-framework standard ISO 14040 (ISO 1997, 2006a)

"The critical review process shall ensure that:

- *the methods used to carry out the LCA are consistent with the international Standard;*
- *the methods used to carry out the LCA are scientifically and technically valid;*
- *the data used are appropriate and reasonable in relation to the goal of the study;*
- *the interpretations reflect the limitations identified and the goal of the study;*
- *the study report is transparent and consistent."*

In the following sections 3.1 to 3.5 these items are discussed and answered to our best judgement in the light of the final report(s) and applying the international LCA-standards as the yardstick.

3.1 Are the methods used to carry out the LCA consistent with the international Standard?

During the work on this LCA-study (2004-2007), the first series of international LCA standards 14040-43 (ISO 1997, 1998, 2000a, 2000b) was replaced by a slightly modified set of two standards 14040 and -44 (ISO 2006a, 2006b). Since the new norms superseded the old ones in October 2006, they also constitute the yardstick for the final report. The actual differences are, however, so small (Finkbeiner et al. 2006) that the consequences for the critical review are minor. The critical review according to the panel method is more demanding according to new set of standards, requiring at least three experts. This is evidently fulfilled in the actual case. The structure of the LCA, which should be reflected in the structure of the study report, remained unchanged. Although the structure of the report does not follow exactly the structure of LCA, the essential components "Goal and scope definition", "Inventory analysis", "Impact assessment" and "Interpretation" are clearly recognizable and dealt with sufficient detail.

With regard to the system boundaries, which are described with enough details, we have to make the objection that no clear cut-off criteria are given; this is against the requirement set by the norm (ISO 14044, §4.2.3.3.3). Since we did not find that major processes were left out of the analysis of the systems, we think that – despite the evident lack of criteria - no significant asymmetries should occur in the systems studied.

With the exception of the points mentioned, no major deviation from the rules laid down in the standards were detected. We can therefore state **that the methods used are consistent with the international standard.**

3.2 Are the methods used to carry out the LCA scientifically and technically valid?

The methods used for collecting original data, to construct the systems and to calculate the inventory tables seem to be scientifically and technically up to date. It has to be noted, however, that the systems studied are defined from "well-to-tank" (roughly corresponding to "cradle-to-factory gate"). Systems without use and end-of-life phases are truncated and, therefore, cannot claim to analyse the systems "from cradle-to-grave". This is not claimed in the study, however, and the conclusions which can be drawn are restricted. Since only different production routes for fuels were compared on the basis of their energy content (1 MJ), this truncation can be tolerated. The results do **not** allow, however, to prove the environmental superiority of one or the other fuel during use! For such assertions, "well-to-wheel" studies have to be done in the future, corresponding to "cradle-to-grave" in ordinary LCA language. The main reason for this restriction, beyond formal requirements by the standards, is the possible formation of environmentally problematic emissions by some of the fuels during combustion in the engines.

The general framework of this LCA is the attributional (i.e. classical) one which is the basis of the guidelines and standards by SETAC (SETAC 1993) and ISO. This method is valid as long as the introduction of a new technology does not alter the economy or technosphere in such a way that other important technologies (such as food production) are not significantly altered due to the competition with the new one.

The analysis uses two scenarios (a third one foreseen originally was cancelled), a status quo scenario and a “Scenario 1” which strives for optimal efficiency and includes electrical energy produced in wind parks to produce hydrogen used for increasing the amount of fuel. This scenario describes fuel production from biomass **and** wind power. The wind parks are treated as “islands”, i.e. not connected with the European electricity grid in the main scenario. The electricity grid is used in a sensitivity analysis, however.

The impact assessment method used is essentially based on standard CML methodology (Guinée et al. 2002) using midpoint indicators (e.g. the Global Warming Potential, time horizon 100 years - GWP_{100} - for the impact category “Climate change”). A similar midpoint method, using slightly different impact indicators, EDIP (Wenzel et al. 1997; Hauschild and Wenzel 1997) was used as a sensitivity analysis in several cases. Furthermore, the Cumulative Energy Demand, CED (VDI 1997) has been used as an additional category in order to measure the total primary energy demand per MJ, the reference flow used for all fuels studied. This “impact category” does not perfectly fit into the ISO LCIA scheme (ISO 2000a, 2006b), but it is a very useful energy accounting method compatible with LCA and included in the Dutch guidelines and in the Swiss ecoinvent data base and LCA method (Guinée et al. 2002; Jungbluth & Frischknecht 2004).

The LCIA-relevant ISO standards (ISO 2000a, 2006b) do not prescribe a list of impact categories or specific indicator models, characterisation factors etc. It is only required to give the reasons for the selection of a specific set of categories and indicators. In LCA studies dealing with agriculture, forestry etc. it is advisable to include eco-toxicology as an impact category in addition to the traditional categories (e.g. acidification, eutrophication and photo-oxidation). This is not the case in this study, since no consensus was obtained in the project team. This omission is seen as a missed chance to improve LCIA and finally the results of the comparative studies. Land use is included using inventory data for land occupation (m^2 a). Since an internationally accepted method for assessing all aspects of land use is missing (Udo de Haes et al. 2002), the use of inventory data is certainly a good compromise. The same is true for the use of the resource water, which is also expressed by unweighed inventory data. Precipitation is lumped together with irrigation, however, the latter being only distinguished by the additional use of energy for pumping. The scarcity of this resource in the southern countries, in contrast to the rest of Europe, is therefore not clearly indicated.

Despite these deficiencies, the methods used are clearly within the limits of the standards and of the international practice. It can therefore be stated that **the methods used are scientifically and technically valid** within the limited framework of this study. Using modern LCIA methods (e.g. Jolliet et al. 2004) would have given signals for further, more advanced work in this area.

3.3 Are the data used appropriate and reasonable in relation to the goal of the study?

In order to assess the quality of the data used in this study it is necessary to distinguish between the foreground system, which is within the (future) producers sphere of influence and the background system which is not. Regarding to foreground, the quality of the data strongly depend of the status of development of the different methods. These data have been provided by the project partners. In some cases there are already pilot plants from which realistic extrapolations can be done; in others only small-scale (more or less laboratory-type) production is available. A third class of data consists of estimates and calculations.

Overall, data are well documented and of reasonable quality.

In general we consider the scales of the future plants (scenario 1) as realistic. What is less clear is to what extent improvement options in the whole chain have been included, both in the direct processes in the plants itself and in the indirect processes. Some examples of the latter where reasonably to be expected improvements have at least not been included

explicitly are e.g. with N_2O emissions during N-fertiliser production or with the relation between future crop yields and the amount of nitrogen required for this.
Summing up, the foreground data provided by the project partners are of differing quality.

The background data are taken from the ecoinvent data bank (Frischknecht 2005), the most advanced European data bank which is 100% compatible with the LCI method used in this LCA study.

Taking in mind the deficiencies with some foreground data, for which the practitioner cannot be blamed, it can be stated **that the data used are appropriate and reasonable in relation to the goal of the study.**

3.4 Do the interpretations reflect the limitations identified and the goal of the study?

The interpretations are in general cautious. Since no weighting is used, as required by the ISO standards for studies in which comparative assertions intended to be made available to the public are made, the results of the comparisons are often not unambiguous. There is one general result, however, namely the efficiency of the biomaterial production "at the field (or forest)" is of prime importance and seems to overrule the technical details of the different industrial production processes. Since a better efficiency is obtained with intense agriculture – as opposed to the organic one – it will be a great challenge to improve this modern agriculture in such a way that it can compete the more extensive ways of agriculture proposed with good reasons for the production food.

The main limitations of this study are the restriction to "well-to-tank" and the attributional mode of conducting the LCAs. No conclusions are drawn surpassing these limitations, e.g. by speculating about the further fate of the new production methods once they will be fully developed and contribute significantly to the European automotive fuel market.

Considering the early development status of the systems studied, it can be stated **that the interpretations reflect the limitations identified and the goal of the study.**

3.4 Is the study report transparent and consistent?

The report has been improved considerably and most comments by the reviewers were taken into account. It is well readable, illustrated with coloured diagrams and the length seems to be appropriate for the systems covered.

The four components of LCA are presented and discussed in due detail. The component "Interpretation" could be better separated from "Impact Assessment", since the report should mirror the basic structure of LCA with four components.

Although not all data could be presented, it can be said the data structure is exemplary. The results are given in great detail, using tables and figures. The letter size in the tables is too small, however.

Each of the three parts is preceded by an excellent executive summary. No major discrepancies between the different parts of the reports could be found.

Finally, it can be stated **that the report is transparent and consistent.**

4 Résumé and recommendations

First of all, we should clearly state what this LCA is **not**. Most importantly, it is not a full (cradle-to-grave or well-to-wheel) LCA, in full accordance with Goal & scope. Therefore, no conclusions can be drawn on the relative virtues of the fuels investigated **as fuels for use in automotive transport.** It is also not a comparative study of the type "fossil- versus biomass-based" fuels. Actually this topic is hardly mentioned and even the more established biofuels (bio-ethanol and bio-diesel) are not treated, although the former had been on the agenda originally. No comparative energy balances, no CO_2-balances (relative to fossil fuels). These comparisons are, of course, very interesting from the point of view "climate change" and should be done in the near future.

Within the limitations of this study, which are clearly stated, **the requirements by ISO 14040/44 are fulfilled.**

This study should not be an end in itself, but rather a starting point for more comprehensive studies aiming at the urgent questions whether or not biomass-based fuels will be able to replace at least part of the fossil fuels in Europe. This automatically leads to the next problem, since the classical ("attributive") LCA is clearly not suited for studies involving a drastic change of the economic and technological background. Will the more recent "consequential" LCA (Ekvall 1999; Weidema et al. 1999; Weidema 2002), which in principle takes into account changes brought about by a new technology, be suitable for systems of that size? Or should these problems dealt with using other instruments? The review panel cannot yet give a clear recommendation.

In future work, the LCIA should be extended in order to recognise and finally prevent problem shifting. This is the foremost duty of the instrument LCA.

It is strongly recommended that the three "deliveries" should be transformed into one final report and published without cuttings. The critical review is part the report. Practitioner and commissioner have the right to comment the critical review. These comments, if there are any, are also part of the report.

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