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4F CROPS:

Future Crops for Food, Feed, Fiber and Fuel

Life cycle analyses (LCA)

Final report on Tasks 4.2 & 4.3

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Abbreviations

Abbreviation	Explanation
1,3-PDO	1,3-propanediol
BtL	Biomass-to-Liquid; thermochemical process yielding liquid biofuels from biomass
C_2H_4	Ethylene
CFC-11	Trichlorofluoromethane (freon-11 / R-11); ozone-depleting chlorofluorocarbon
CH_4	Methane
CHP	Combined heat and power (plant)
CO_2	Carbon dioxide
DDGS	Distillers' Dried Grains with Solubles; co-product of distillation used as animal feed
eq.	Equivalent
EtOH	Ethanol; biofuel / biochemical made from sugar, starch or lignocellulosic crops
EU27	All countries that are currently part of the European Union
FAME	Fatty Acid Methyl Ester; biodiesel
FT (diesel)	Fischer-Tropsch (diesel); chemical process yielding liquid biofuel from syngas
GHG	Greenhouse gas(es)
GJ	Gigajoule (10^9 Joule)
ha	Hectare (10^4 m^2)
HC	Hydrocarbons
HVO	Hydrogenated Vegetable Oil; liquid biofuel made by hydrotreatment of vegetable oil
IE	inhabitant equivalent, yearly environmental impact of an average European (EU27)
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis / Life Cycle Assessment
LUC	Land-use change
N_2O	Nitrous oxide (Dinitrogen monoxide)
NO_X	Generic term for nitrogen oxides
PM10	Particulate matter; fine particles with a diameter of < 10 µm, linked to health hazards
PO_4	Phosphate
POCP	Photochemical Ozone Creation Potential
RE	Renewable Energy
RME	Rapeseed oil Methyl Ester; biodiesel made from rapeseed oil
SO_2	Sulphur dioxide
SVO	Straight Vegetable Oil; can be used as biofuel in technically modified diesel engines
t	(Metric) tonne (10^6 g)
UCTE	Union for the Co-ordination of Transmission of Electricity; association of electricity distribution network operators in Continental Europe.
WP	work package
yr	year

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1 Introduction

Background

The production and use of biomass for non-food purposes plays an increasing role in the European Union. The Renewable Energy Directive (2009/28/EC) fosters the use of biomass for energy in order to reduce greenhouse gas emissions, to increase the security of energy supply and to provide opportunities for employment and regional development /CEC 2009/. In addition, the use of biomass for bio-based materials or chemicals will gain in importance. In the absence of a European regulation, Germany has recently launched a national action plan on the increased use of biomass for non-food-non-energy purposes /BMELV 2009/.

However, the agricultural area within the European Union is limited. Therefore, an additional biomass production in order to meet the above mentioned goals puts more pressure on this limited area and increases the competition between the production of food, feed, fiber and fuel. In order to mitigate this competition and potential negative side-effects such as deforestation, land use efficiency in the agricultural sector needs to be increased.

On this background the EU-funded project "4F CROPS – Future Crops for Food, Feed, Fiber and Fuel" has been initiated. The overall goal of this project is to analyse parameters that play an important role in establishing successful non-food cropping systems in the EU27. Within the project, work package 4 (WP 4) focuses on environmental parameters by investigating the environmental impacts associated with the production and use of future non-food crops which were selected in WP 2. Two assessment techniques were applied: environmental impact assessment (EIA) and life cycle assessment (LCA), the latter of which is in the focuses of this report.

In literature, hundreds of LCA studies on bioenergy and bio-based products can be found, covering a wide range of products (see e.g. review studies on biofuel LCAs by /Quirin et al. 2004/, /Larson 2006/, /von Blottnitz & Curran 2007/, /Menichetti & Otto 2009/). Usually, either different products originating from a certain crop or a certain product originating from different crops is investigated, but rarely a multitude of crops *and* products at the same time. Moreover, the results of different LCA studies for the same product are known to vary quite substantially, among others due to differences in accounting for co-products, in system boundaries or in basic data /Gnansounou et al. 2009/, /Cherubini et al. 2009/. Therefore, the assessment in WP 4 could not be based on a literature review but required own calculations in order to ensure unbiased comparisons. For this purpose, the crops selected in WP 2 were amended with conversion paths and products by IFEU taking into account important studies on the energy and / or material use of biomass such as /Patyk et al. 2000/, /Quirin et al. 2004/, /Werpy et al. 2004/, /Scheurlen et al. 2005/, /Patel et al. 2006/, /Bozell et al. 2007/, /Oertel 2007/, /Reinhardt et al. 2007/ and /van Beilen et al. 2007/.

This deliverable (D 13) covers the results of the screening life cycle analyses (LCA) performed under task 4.2 as well as the results of the modelling of dependencies and sensitivities under task 4.3. These results serve the basis for task 4.4 and thereby contribute to the identification of best options which are presented in a separate deliverable (D 14).

Goal and scope

The overall goal of this report is to analyse by means of screening LCAs which environmental impacts are associated with the production and use of bioenergy and bio-based materials from selected future crops and to compare them to the environmental impacts of their fossil or conventional equivalent products. Apart from that, dependencies and sensitivities are modelled and investigated using a multi-functional assessment tool.

In total, 15 future crops are assessed covering oil, fiber and sugar crops as well as woody and herbaceous lignocellulosic crops. The analysis covers seven different environmental zones within Europe and two non-food use options for the main products: their use either for bioenergy production (‘fuel’) or for producing bio-based materials (‘fiber’). The environmental impact categories to be assessed cover energy savings, greenhouse effect, acidification, eutrophication, summer smog, ozone depletion, and human toxicity.

The following main question and sub-questions are addressed in this report (D 13). Further environment-related questions will be answered in a separate report (D 14):

- What are the environmental advantages and disadvantages of bioenergy and bio-based materials made from the selected crops in comparison to their fossil or conventional equivalents?
  - Which life cycle stages make the largest contribution to the overall results?
  - Are there opportunities to improve the environmental performance of bioenergy or bio-based materials?
  - What are the effects of the choices made regarding methods and data on the results?

Approach

Within WP 4, a multi-functional assessment tool was developed by IFEU to carry out all analyses to be done under tasks 4.2, 4.3 and 4.4. First of all, this custom-made Microsoft® Excel based software tool was used to perform the life cycle assessments under task 4.2. It is able to simultaneously handle a large number of different bioenergy and biomaterial paths. The tool is linked to the continuously updated internal IFEU database /IFEU 2010/ as well as commercial databases such as /ecoinvent 2010/ and /GEMIS 2010/.

The tool was also used for the modelling of dependencies and sensitivities under task 4.3. For this purpose, the basic scenarios of task 4.2 were transferred into so-called reference scenarios by varying a number of parameters along the entire life cycle. Dozens of variations and sensitivity analyses were performed in order to identify multi-functional dependencies as well as opportunities to improve the environmental performance of products.

2 Methodology, specifications and data sources

2.1 Methodology

The life cycle analyses (LCA) in this study are carried out largely following the guidelines of the ISO standards 14040 and 14044 on product life cycle assessment /ISO 2006/. Basically, the following aspects are covered by LCAs:

- **Inputs and outputs** (biomass and other raw materials, energy and wastes, waste water, emissions etc.), which lead to
- **potential environmental impacts** (e.g. use of resources and environmental consequences of releases such as greenhouse effect or acidification),
- **throughout the product's entire life cycle** from raw material acquisition through production (including co-products), use, end-of-life treatment, recycling and final disposal ("cradle-to-grave approach").

The analyses in this study are so-called screening LCAs which follow the above mentioned ISO standards except for a) the level of detail of documentation, b) the quantity of sensitivity analyses and c) the mandatory critical review. Nevertheless, the results of these screening LCAs are quite reliable due to the close conformity with the standards. They describe basic interrelationships regarding selected environmental impact categories and give a conclusive overview. For more specific questions, they can be extended to a full LCA.

The basic feature of LCAs is the so-called life cycle comparison: for example, the entire life cycle of a bioenergy carrier is compared to the entire life cycle of non-renewable (fossil) energy carrier (see example in Fig. 2-1).

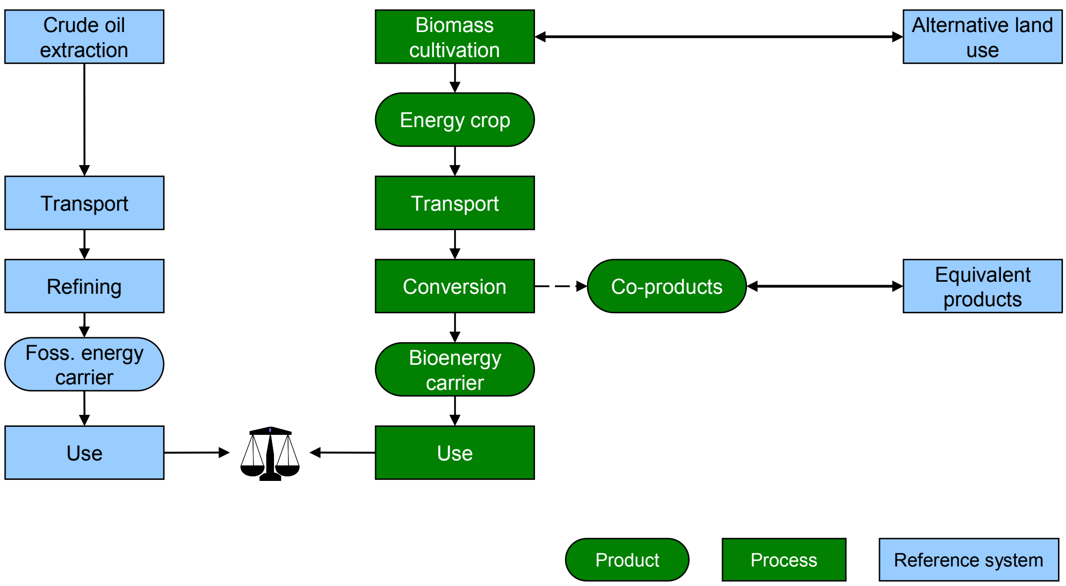

Fig. 2-1 Exemplary schematic life cycle comparison between a bioenergy carrier and a non-renewable (fossil) energy carrier

With that, LCAs provide comprehensive information on environmental impacts, both for single production stages as well as for the life cycle as a whole. By means of variations and sensitivity analyses, multi-functional dependencies as well as opportunities to improve the environmental performance of products can be identified. Finally, interpretations and recommendations relevant for decision-makers in industry, government or non-government organisations can be derived from the results.

2.2 Specifications

2.2.1 General specifications in this study

- **System to be studied:** This study covers the cultivation and use of 15 crops for non-food purposes in seven environmental zones within Europe covering five crop groups (oil, fiber, lignocellulose from woody and herbaceous biomass, sugar). It assesses the production and use of these crops for both bioenergy and biomaterial production replacing non-renewable (fossil) energy and conventional products, respectively. Fig. 2-1 shows such a schematic life cycle comparison, exemplified for bioenergy versus fossil energy.
- **Agricultural reference system:** The agricultural reference system is an essential part of LCAs for agricultural products. It defines what the agricultural land would be used for if the investigated crop was not cultivated. In this study, fallow / set-aside land is taken as the default agricultural reference system. Further background information can be found in /Jungk et al. 2000/. More detailed descriptions on agricultural reference systems and variations thereof are given in chapter 2.2.2 and 3.4.1, respectively.
- **Functional unit:** With agricultural land becoming increasingly scarce and land-use competitions between food / feed production and non-food applications aggravating, land-use efficiency is becoming a very relevant parameter /Reinhardt & Zemanek 2000/. Therefore, in this project the functional unit is defined as ‘useful output per hectare in an average year’. The results will be referred to this unit.
- **Co-product allocation:** In the standard scenarios, allocation is avoided by expanding the system boundaries as stipulated by the ISO standards 14040 and 14044 /ISO 2006/. Instead, the substitution method is applied where avoided environmental impacts due to the co-product use – which substitutes for a conventional product – are credited to the main product. For more details, see /Borken et al. 1999/ and chapter 3.4.2.
- **Environmental impact categories:** The environmental impact categories covered in this study are energy savings, greenhouse effect, acidification, eutrophication, summer smog, ozone depletion as well as human toxicity. In order to increase the comparability between the categories, the results are normalised and displayed as ‘inhabitant equivalent’ (IE) per 100 hectares (ha). For further specification, see chapter 2.2.3.
- **Time-related coverage:** In this study, the cropping systems are related to current conditions (2008). In order to cover future developments regarding yields the results are also calculated for 2020 and 2030 by means of a sensitivity analysis (see chapter 3.4.1).

- **Geographical coverage:** The geographical area covered in this study is the EU27. For an easier handling and in order to ensure the coverage of a wide range of environmental conditions (e.g. regarding climate and soil), the area is subdivided into representative regions. As in WP 2, the approach suggested by /Metzger et al. 2005/ is followed. Out of 13 environmental zones of Europe, seven zones were chosen: Atlantic Central (ATC), Atlantic North (ATN), Continental (CON), Lusitanian (LUS), Mediterranean North (MDN), Mediterranean South (MDS) and Nemoral (NEM). For more details, see chapter 3.1.
- **Infrastructure:** Infrastructure comprises all production and processing equipment, vehicles such as tractors, buildings and streets connected with the crop's production and use. In many LCAs assessing bioenergy systems or conventional energy production systems it was shown that infrastructure accounts for less than 10 % of the overall results (see /Nitsch et al. 2004/, /Fritsche et al. 2004/ and /Gärtner 2008/). Therefore, in this project, infrastructure is not included.

2.2.2 Agricultural reference system

The agricultural reference system is an essential part of LCAs for agricultural products. It defines the alternative land use, i.e. what the cultivation area would be used for if the crop under investigation was not cultivated /Jungk et al. 2000/. By definition, the agricultural reference system also comprises any change in land use or land cover induced by the cultivation of the investigated crop (energy crop or industrial crop). In literature, two different cases are distinguished, of which the first one is commonly referred to as land-use change (LUC), whereas the second one is called land-cover change (LCC):

1. LUC: The cultivation area is situated on existing cropland which either lay fallow / was set aside or was used for other crops, e.g. for food and / or feed crops
2. LCC: The cultivation area is situated on land which was transformed from grassland, forest land or wetland to cropland

Most often, both processes are subsumed under the term land-use change (LUC). In LCAs, such changes in land use have to be accounted for in two respects: first, land-use changes lead to an alteration of existing processes and the environmental impacts caused by them. For example, if wheat production is replaced, the same amount of wheat has to be produced elsewhere leading to respective expenditures; second, changes in site quality are induced in terms of carbon stocks. For example, a decline in above-ground and below-ground carbon stock leads to greenhouse gas emissions which have to be included in the greenhouse gas balance. Land-use changes also have considerable effects on biodiversity; however, to date no method exists to include these effects in LCAs.

Land-use changes involve both direct and indirect effects. Direct land-use changes (dLUC) comprise any change in land use or land cover which is directly induced by the cultivation of the crop under investigation. This crop can either be cultivated on existing cropland (replacing fallow / set-aside land or grassland) or on land which was transformed from (semi-)natural ecosystems such as grassland, forest land or wetland into cropland. Especially the transformation of the latter can lead to considerable emission of greenhouse gases.

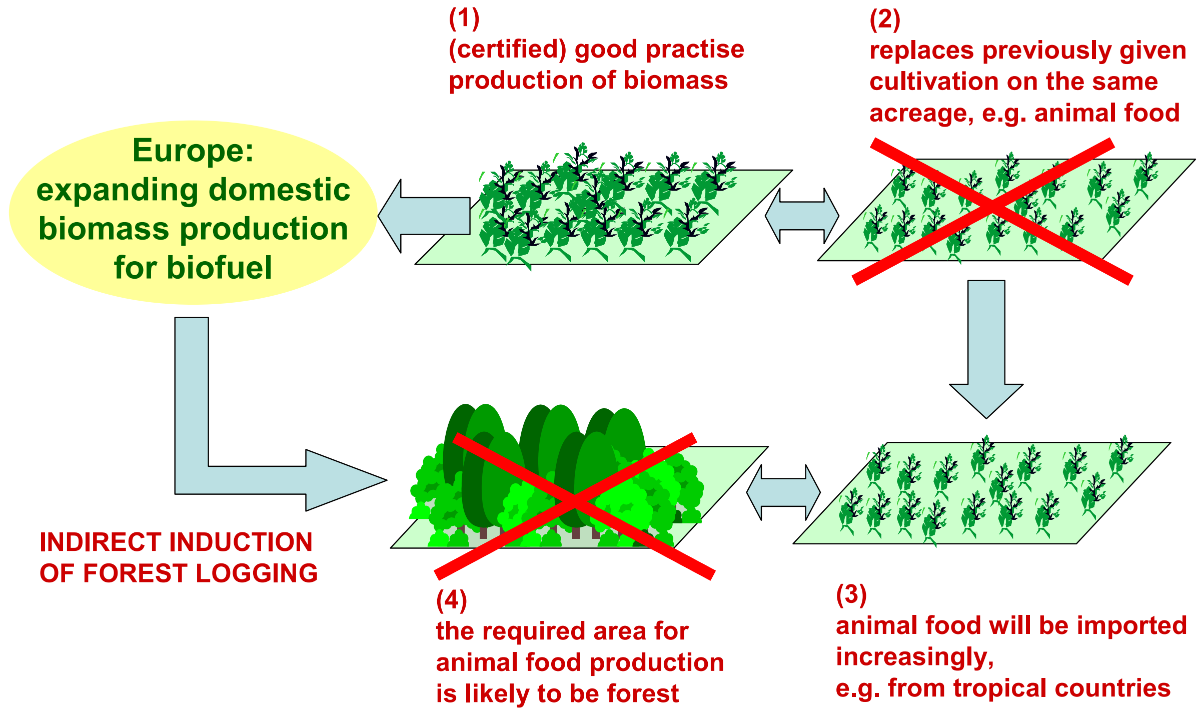

Fig. 2-2 Exemplary mechanism of indirect land-use change due to biomass for bioenergy production in Europe (/Fehrenbach et al. 2008/)

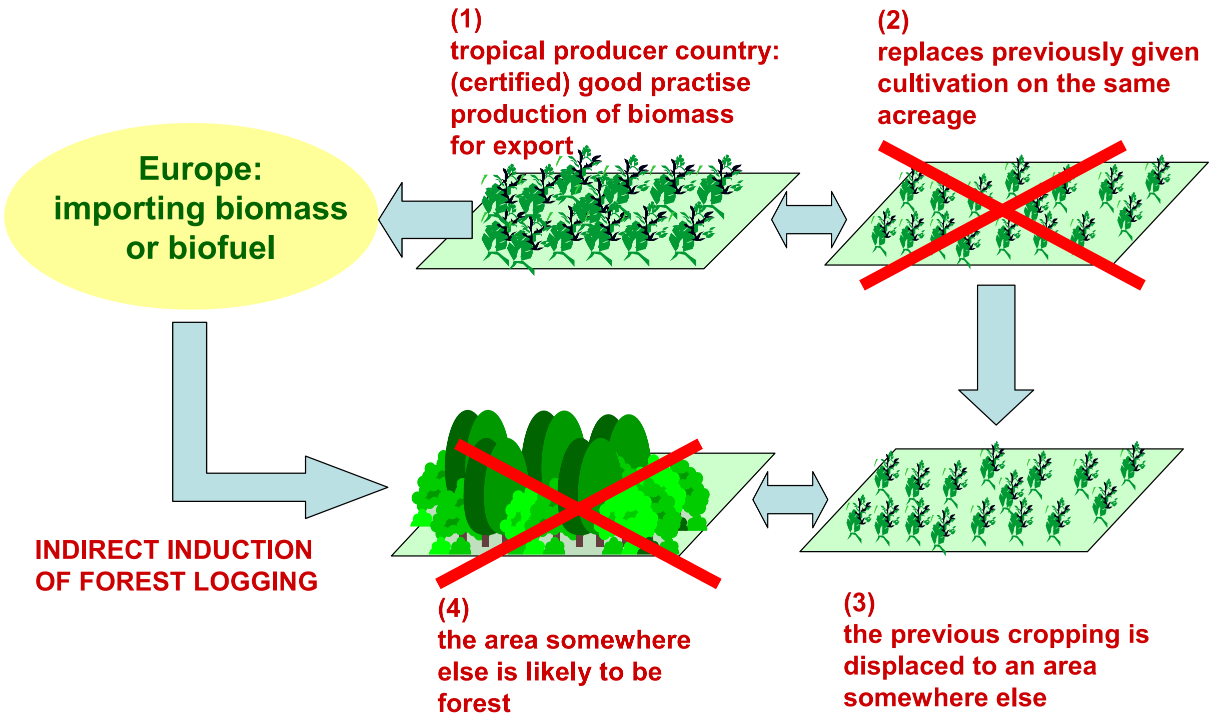

Fig. 2-3 Exemplary mechanism of indirect land-use change due to biomass for bioenergy import to Europe (/Fehrenbach et al. 2008/)

As long as fallow / set-aside land or any (semi-)natural ecosystem are transformed into cropland, no further indirect effects are caused. However, if agricultural land currently used for food and feed production is used for non-food purposes, the demand for food and feed still needs to be satisfied. Consequently, food and feed production is displaced to another area where unfavourable land-use changes might occur. This phenomenon is called indirect land-use change (iLUC), leakage effect or displacement and is demonstrated in Fig. 2-2. Also here, high carbon emissions can be caused if ultimately natural forests, savannahs, grasslands or peatlands are transformed into cropland.

Not only the production of energy crops in Europe leads to indirect land-use changes elsewhere in the world. Also the import of biomass or biofuel into Europe has such effects. This mechanism is shown in Fig. 2-3. In the producing country good practice and the absence of direct land-use change may be certified. However, the required area now being used by the new crop is no longer available for the previous food or feed production. As a result, food or feed production is displaced to other areas where in turn land-use changes may occur.

Indirect land-use change effects are difficult to verify empirically: they occur at global level and they are linked to the cultivation of energy crops (e.g. in Europe) via economic market mechanisms. In contrast to direct land-use changes, these indirect effects cannot be exactly allocated to the cultivation of a specific energy crop. This makes the positioning of affected areas and the quantification of these effects very challenging. Therefore, several studies use partial and / or general equilibrium models to quantify the iLUC effect of different non-food biomass expansion scenarios. These are sometimes linked to biophysical models covering different thematic focuses such as biodiversity, soil (erosion) and water (see e.g. /Fehrenbach et al. 2009/ for more details). Despite all efforts, up to date there is no commonly accepted method on how to quantify iLUC effects, let alone integrate indirect land-use changes in life cycle assessments. Therefore, in this study these effects can only be exemplified using scenarios.

In order to evaluate the effects of different agricultural reference systems including direct and indirect land-use changes on the greenhouse gas balances, a sensitivity analysis is performed covering fallow and the displacement of food crops (cereals) and feed (grassland on organic soils). As has been noted, indirect effects are difficult to quantify. Since it is outside the scope of this study to apply models for analysing land-use dynamics, the scenarios regarding land-use change are subjectively chosen. Therefore, the results obtained are only exemplary, indicating at most the order of magnitude of these effects. Further details of the scenarios are provided in chapter 3.4.1.

2.2.3 Environmental impact categories

The environmental impact categories analysed in this study are described in detail in Table 2-1. The related category indicators, life cycle inventory (LCI) parameters and characterisation factors are shown in Table 2-2.

Table 2-1 Environmental impact categories and their description

Impact category	Description
Energy savings	Consumption of non-renewable energy carriers, i.e. fossil fuels such as crude oil natural gas and different types of coal as well as uranium ore. The procedures and general data for the calculation are documented in detail in /Borken et al. 1999/.
Greenhouse effect	Global warming as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide originating from the combustion of fossil energy carriers, a number of other trace gases – among them methane and nitrous oxide – are included.
Acidification	Shift of the acid/base equilibrium in soils and water bodies by acid forming gases (keyword 'acid rain'). Emissions of sulphur dioxide, nitrogen oxides, ammonia, and hydrogen chloride are recorded.
Eutrophication	Input of nutrients into soils and water bodies (keyword 'algal bloom'). Nitrogen oxides and ammonia are recorded.
Summer smog (POCP)	Formation of specific reactive substances e.g. ozone, in presence of solar radiation in the lower atmosphere (keyword 'ozone alert'). Hydrocarbons are considered.
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases like CFCs or nitrous oxide (keyword 'ozone hole').
Human toxicity	Toxic potential to individuals from substances, e.g. the possibility of carcinogenic, mutagenic, teratogenic, or only sensitising effects. Particulate matter, sulphur dioxide, nitrogen oxides, hydrocarbons and ammonia are taken into account.

Presentation of results

In chapter 4.3, covering variations and sensitivity analyses, most results are displayed only for the first four environmental impact categories: energy savings, greenhouse effect, acidification, and eutrophication. This is because on the one hand, the presentation of results should be as concise as possible, aiming at the most relevant aspects only. On the other hand, the methodologies for summer smog, ozone depletion and human toxicity are less well developed and still subject to scientific discussions.

As far as summer smog is concerned, hydrocarbons and nitrogen oxides are contributing to its formation. In this study, the most widespread category indicator, the so-called photochemical ozone creation potential (POCP) is used. However, this category indicator only includes hydrocarbons and neglects the effect of nitrogen oxides. For many years, the so-called nitrogen-corrected POCP (NcPOCP) was discussed as an alternative, but due to drawbacks regarding its calculation, it never became commonly accepted. In summary: since there is no commonly accepted indicator describing the cause-effect relationship of both hydrocarbons and nitrogen oxides, the informative value of the POCP results given in this study is limited.

Regarding ozone depletion, an ODP factor for nitrous oxide was always lacking. Only recently, a study by /Ravishankara et al. 2009/ reported a first value, which is not commonly accepted yet. Nevertheless, it is used in this study. At the same time, emission factors for nitrous oxide emissions from fertiliser application are still disputed in the scientific community.

The environmental impact category human toxicity covers a wide range of potentially harmful impacts on human health. Therefore, thousands of substances causing carcinogenic, mutagenic or teratogenic effects would have to be included. Up to now, there is no commonly accepted category indicator available. Moreover, it is very difficult to determine quantitative characterisation factors because the causal relationships between noxious substances and the damage to human health are not fully understood yet. In this study, only the human toxicity potential of particulate matter (PM10) is regarded, which of course gives an incomplete picture of this environmental impact category.

Table 2-2 Indicators, LCI parameters and characterisation factors for the respective impact categories (/CML 2004/, /IPCC 2007/, /Klöpffer & Renner 1995/, /Leeuw 2002/, /Ravishankara et al. 2009/, /IFEU 2010/ on the basis of /IPCC 2007/)

Impact category	Category indicator	Life cycle inventory parameter	Formula	Character. factor
Energy savings	Cumulative primary energy demand from non-renewable sources	Crude oil Natural gas Hard coal Lignite Uranium ore	—	—
Greenhouse effect	CO_2 equivalent (carbon dioxide equivalent)	Carbon dioxide fossil	CO_2	1
		Nitrous oxide	N_2O	298
		Methane biogenous	CH_4	25
		Methane fossil*	CH_4	27.75
Acidification	SO_2 equivalent (sulphur dioxide equivalent)	Sulphur dioxide	SO_2	1
		Nitrogen oxides	NO_X	0.7
		Ammonia	NH_3	1.88
		Hydrochloric acid	HCl	0.88
Eutrophication	PO_4 equivalent (phosphate equivalent)	Nitrogen oxides	NO_X	0.13
		Ammonia	NH_3	0.346
Summer smog (POCP)	C_2H_4 equivalent (ethylene equivalent)	Non-methane hydrocarbons	NMHC	0.416
		Methane	CH_4	0.007
Ozone depletion	CFC-11 equivalent ($CFCl_3$ equivalent)	Trichlorofluoromethane	$CFCl_3$	1
		Nitrous oxide	N_2O	0.017
		Other CFCs, HFCs, FCs, …	various	various
Human toxicity	PM10 equivalent	Particulate matter	PM10	1
		Sulphur dioxide	SO_2	0.54
		Nitrogen oxides	NO_X	0.88
		Non-methane hydrocarbons	NMHC	0.012
		Ammonia	NH_3	0.64

* including CO_2 effect after CH_4 oxidation in the atmosphere

Normalisation

Normalisation is an optional element in LCAs. Hereby, the magnitude of the category indicator results relative to some reference information is calculated. The aim of the normalisation is to better understand the relative magnitude of the results for the different environmental impact categories. Normalisation transforms an indicator result by dividing it by a selected reference value, e.g. the total inputs and outputs for a given area (global, regional, national or local) on a per capita basis.

In this study, the environmental advantages and disadvantages of bioenergy and biomaterials are put into relation with the environmental situation in the EU27. The reference information is the yearly average energy demand and the average emissions of various substances per inhabitant in Europe, the so-called inhabitant equivalent (IE). The reference values are presented in Table 2-3 for all environmental impact categories.

For example, each EU27 inhabitant causes yearly average GHG emissions of 11 tons (=1 IE). The production and use of rapeseed biodiesel (FAME) from 100 ha of agricultural land in the Continental zone leads to emission savings of 19.1 IE or 21.4 t CO_2 eq. / (ha*yr).

Table 2-3 Emissions in the environmental impact categories and the resulting inhabitant equivalent related to inhabitant and year (base year: 2005) (/IFEU 2010/ based on /Eurostat 2007/ and /CML 2009/). Inhabitants EU27 2005: 491,153,644 /Eurostat 2010/.

Impact category	Unit	EU27 inhabitant equivalent
Primary energy	GJ / yr	82
Greenhouse effect	t CO_2 equivalent / yr	11
Acidification	kg SO_2 equivalent / yr	49
Eutrophication	kg PO_4 equivalent / yr	6
Summer smog (POCP)	kg C_2H_4 equivalent / yr	20
Ozone depletion	kg CFC-11 equivalent / yr	0.069
Human toxicity	kg PM10 equivalent / yr	40

2.3 Data sources

The data used for the life cycle analyses can be divided into different categories:

- Data on the cultivation of the crops
- Data on the upstream process of ancillary products (e.g. fertilisers, tractor fuel, pesticides etc.), data on transport processes as well as data on provision and use of fossil energy carriers and conventional products
- Data on the conversion of biomass into bioenergy or bio-based materials

Regarding crop cultivation, data on yields and irrigation related to the different environmental zones were provided by /UNICT 2009/ and cross-checked by IFEU. All other data on cultivation, e.g. the amount of fertiliser input stem from IFEU's internal database which is continuously updated /IFEU 2010/.

The data for the second category are mostly taken from IFEU's internal database which is continuously updated /IFEU 2010/. Where necessary, these data are supplemented by data from external databases such as /ecoinvent 2010/.

Data on the conversion of biomass are also taken from IFEU's internal database. They were obtained, validated and updated during the years in the course of different life cycle assessment studies (/Müller-Sämann et al. 2002/, /Gärtner & Reinhardt 2003/, /Gärtner & Reinhardt 2005/, /Gärtner et al. 2006/, /Reinhardt et al. 2006/, /Reinhardt et al. 2007/, /Rettenmaier et al. 2008/, /Köppen et al. 2009/). Where necessary, they are adjusted to the project-specific needs regarding system boundaries.

Yields and irrigation

In order to account for yield differences due to soil quality and level of agronomic input (e.g. fertiliser input and irrigation), three yield levels were introduced by /UNICT 2009/:

- Minimum (Min): cultivation on marginal land and low input
- Average (Avg): cultivation on agricultural land and low input
- Maximum (Max): cultivation on agricultural land and high input

Irrigation is necessary only for four crops in two environmental zones. The amount of irrigation water required is related to the yields and is displayed in Table 2-4.

Table 2-4 Irrigation water required in relation to the yields

[m³ / (ha*yr)]		Poplar	Eucalyptus	Giant reed	Sweet sorghum
MDN	Min				
	Avg				
	Max	5,000		5,000	5,000
MDS	Min		2,500		2,500
	Avg		2,500		2,500
	Max		5,000		5,000

Table 2-5 Yields for all crops and all environmental zones for 2008 /UNICT 2009/

[t / ha]		NEM	ATN	ATC	CON	LUS	MDN	MDS
Rapeseed	Min	1.0	1.5	1.8	1.2	0.9		
@ 9 % water content	Avg	1.8	2.3	3.2	2.7	1.9		
	Max	2.8	3.2	4.8	4.4	2.7		
Sunflower	Min						2.3	
@ 10 % water content	Avg						3.0	
	Max						3.5	
Ethiopian mustard	Min							0.8
@ 10 % water content	Avg							1.9
	Max							3.0
Hemp	Min	0.3	0.5			0.8	0.8	
@ 14 % water content	Avg	0.5	0.8			1.0	1.1	
	Max	0.5	1.0			1.2	1.2	
Flax	Min			0.9	1.4			0.9
@ 9 % water content	Avg			1.2	1.8			1.2
	Max			1.4	2.0			1.5
Poplar	Min	5.1		5.1			8.5	
@ 50 % water content	Avg	7.5		6.0			12.0	
	Max	10.0		8.5			15.0 *	
Willow	Min		5.1		4.3	5.1		
@ 50 % water content	Avg		6.8		6.8	6.8		
	Max		8.5		7.5	8.5		
Eucalyptus	Min							6.8 *
@ 50 % water content	Avg							10.5 *
	Max							14.5 *
Reed canary grass	Min	10.0						
@ 23 % water content	Avg	11.5						
	Max	13.0						
Miscanthus	Min		10.5	23.5	21.0	27.0		
@ 35 % water content	Avg		13.0	26.0	25.0	34.0		
	Max		16.0	29.0	28.0	41.0		
Switchgrass	Min		7.0	10.0				
@ 15 % water content	Avg		10.0	15.0				
	Max		14.0	19.0				
Giant reed	Min						42.5	
@ 50 % water content	Avg						51.0	
	Max						64.5 *	
Cardoon	Min							16.0
@ 35 % water content	Avg							18.5
	Max							22.0
Sugar beet	Min			62.0	66.0			
@ 75 % water content	Avg			80.0	78.0			
	Max			92.0	90.0			
Sweet sorghum (grains)	Min					4.0	4.1	5.4 *
@ 18 % water content	Avg					5.8	6.4	8.5 *
	Max					7.3	7.7 *	10.0 *

* irrigation necessary

3 System description and scenarios

Chapter 3.1 presents the selection of the crops assessed in this project as well as their allocation to seven environmental zones in Europe. In chapter 3.2 the use of the different crops is presented. For almost each crops both the use for bioenergy production as well as for biomaterials is assessed. In chapter 3.3, the life cycles for each of the crop uses and the respective equivalent systems are depicted. Based on these basic scenarios, different variations are investigated by means of sensitivity analyses. They are presented in chapter 3.4.

3.1 Selection of crops and environmental zones

As stated in the previous chapters, the environmental advantages and disadvantages of the main products from energy crops and industrial crops are compared to their respective fossil and conventional equivalents by means of a life cycle analysis.

In WP 2, 15 crops were chosen for analysis covering five groups – according to the main product to be used: oil, fiber, lignocellulose from woody and herbaceous biomass, and sugar. In each of these crop groups, the crops are allocated to one of the seven environmental zones (see chapter 2.2 and Fig. 3-1). Table 3-1 gives an overview of the selected crops and the zones they are allocated to.

Table 3-1 Investigated crops arranged by the main products and allocated to the environmental zones in which they are cultivated: ATC=Atlantic Central, ATN=Atlantic North, CON=Continental, LUS=Lusitanian, MDN=Mediterranean North, MDS=Mediterranean South, NEM=Nemoral

Common name	Scientific name	NEM	ATN	ATC	CON	LUS	MDN	MDS
Oilseed rape	*Brassica napus* L.	●	●	●	●	●		
Sunflower	*Helianthus annuus* L.						●	
Ethiopian mustard	*Brassica carinata* A. Braun							●
Hemp	*Cannabis sativa* L.	●	●			●	●	
Flax	*Linum usitatissimum* L.			●	●			●
Poplar	*Populus spp.*	●		●			●	
Willow	*Salix humilis* Marsh.		●		●	●		
Eucalyptus	*Eucalyptus spp.*							●
Reed canary grass	*Phalaris arundinacea* L.	●						
Miscanthus	*Miscanthus × giganteus*		●	●	●	●		
Switchgrass	*Panicum virgatum* L.		●	●				
Giant reed	*Arundo donax* L.						●	
Cardoon	*Cynara cardunculus* L.							●
Sugar beet	*Beta vulgaris* L.			●	●			
Sweet sorghum	*Sorghum bicolor* L. Moench					●	●	●

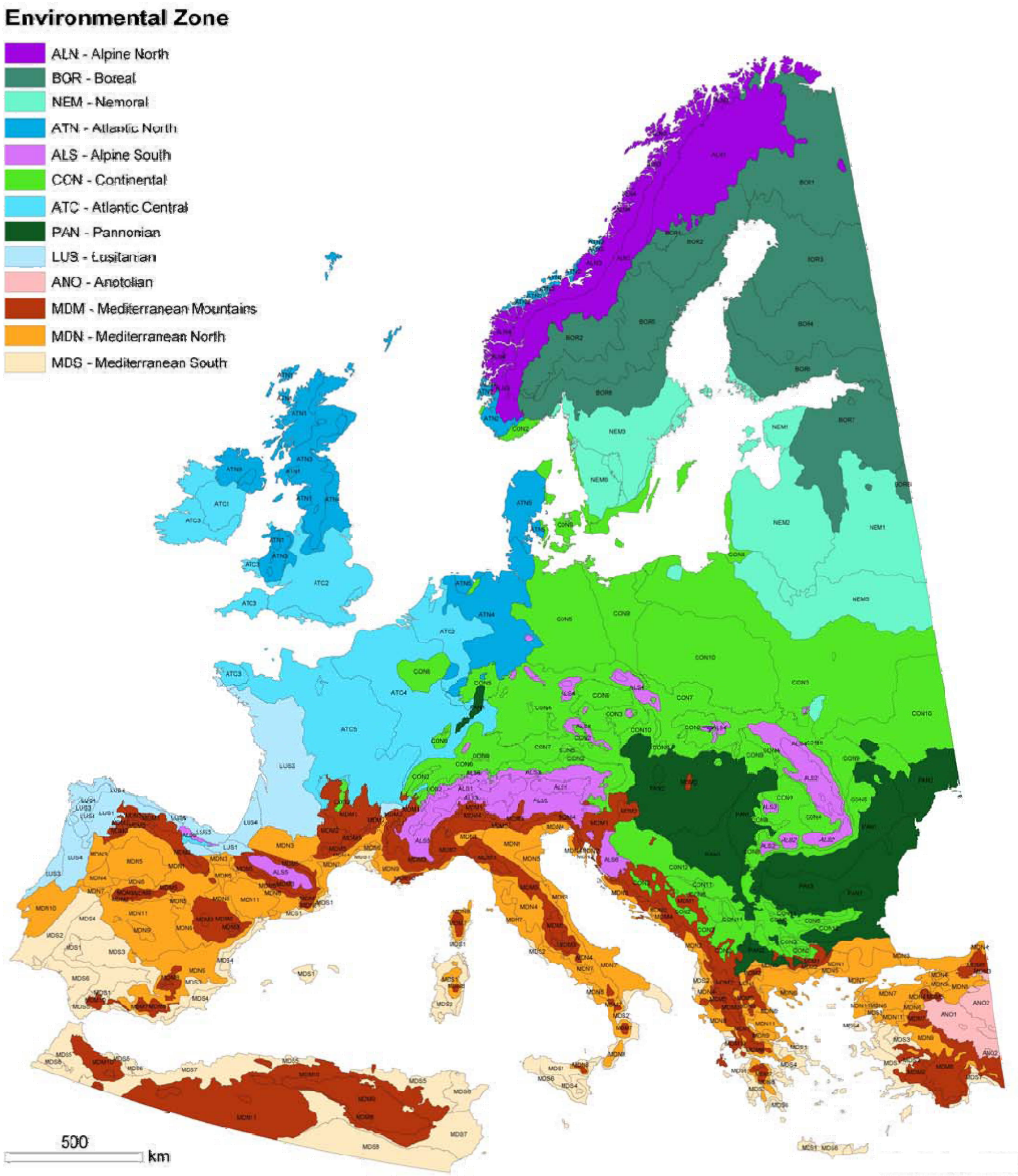

Fig. 3-1 Environmental zones of Europe /Metzger et al. 2005/

3.2 Selection of conversion paths and products

In each crop group selected for assessment, a great range of different bioenergy and biomaterial use options are possible. In various studies assessing the energy and material use of biomass, relevant use options were identified, e.g. /Quirin et al. 2004/, /Werpy et al. 2004/, /Scheurlen et al. 2005/, /Patel et al. 2006/, /Bozell et al. 2007/, /Oertel 2007/, /Reinhardt et al. 2007/, /van Beilen et al. 2007/ and /Carus et al. 2010/. Taking into account these findings, IFEU has selected representative conversion paths and products for each crop group. For bioenergy, mainly the uses for heat and / or power production as well as for transport fuels are covered. For biomaterial, the use in the chemical industry as well as in other industrial sectors (e.g. building industry) is included. For almost all crop groups both the use for energy production and the use as bio-based material are assessed. One exception is the fiber crops – here only the use as bio-based material is analysed. It has to be noted that each crop is either used for energy production or as bio-based material, i.e. combinations are excluded. The conversion paths and main products chosen for each crop group are presented in Table 3-2.

In the following chapter, detailed life cycle comparisons are depicted featuring all main products and the most important co-products.

Table 3-2 Overview of the conversion paths and main products selected for each crop group

Crop group	Conversion path	Main product	Use
Oil crops	Direct combustion	Heat and power	Bioenergy
		Heat	
		Power	
	Transesterification	Biodiesel (FAME)	
	Hydrogenation	HVO	
	Refining	Lubricant	Biomaterial
	Transesterification & hydrogenation	Surfactant	
Fiber crops	Fleece production	Fiber composite	Biomaterial
		Insulation mat	
Lignocellulosic crops (woody and herbaceous biomass)	Direct combustion	Heat and power	Bioenergy
		Heat	
		Power	
	Gasification & synthesis	FT diesel	
		Ethylene	Biomaterial
	Hydrolysis & fermentation	Fuel ethanol	Bioenergy
		Chemical ethanol	Biomaterial
		1,3-PDO	
		Ethylene	
Sugar crops	Fermentation	1,3-PDO	Biomaterial
	Fermentation	Fuel ethanol	Bioenergy
		Chemical ethanol	Biomaterial
		Ethylene	

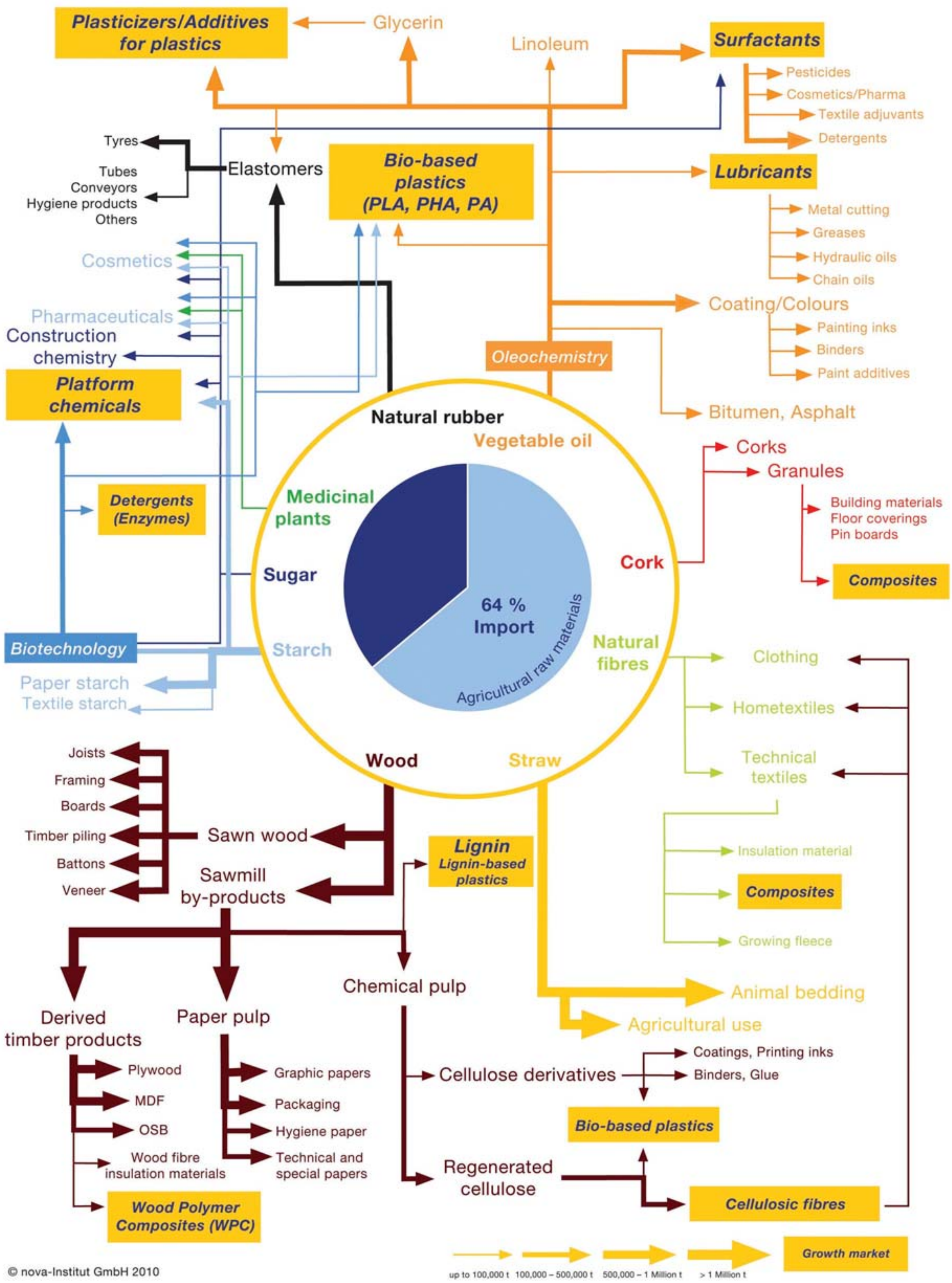

Fig. 3-2 Overview on biomaterial use options of renewable raw materials in Germany /Carus et al. 2010/. The yellow circle in the centre comprises different main products, according to which the crops are grouped, e.g. oil, fiber, sugar and woody lignocellulosic crops.

3.3 Basic scenarios

In the following subchapters, the life cycles for all crop groups to be assessed are depicted. Where applicable the life cycle scheme is the same for all crops in one group. The figures show all main and co-products and their respective conventional equivalents. For all basic scenarios, the default agricultural reference system (alternative land use) is fallow. Regarding electricity inputs and outputs, the European average power mix (UCTE mix) is taken into account.

3.3.1 Oil crops

Rapeseed and the seeds from sunflower and Ethiopian mustard contain oil that can be used for energy or for producing bio-based materials. Fig. 3-3 depicts the resulting life cycles.

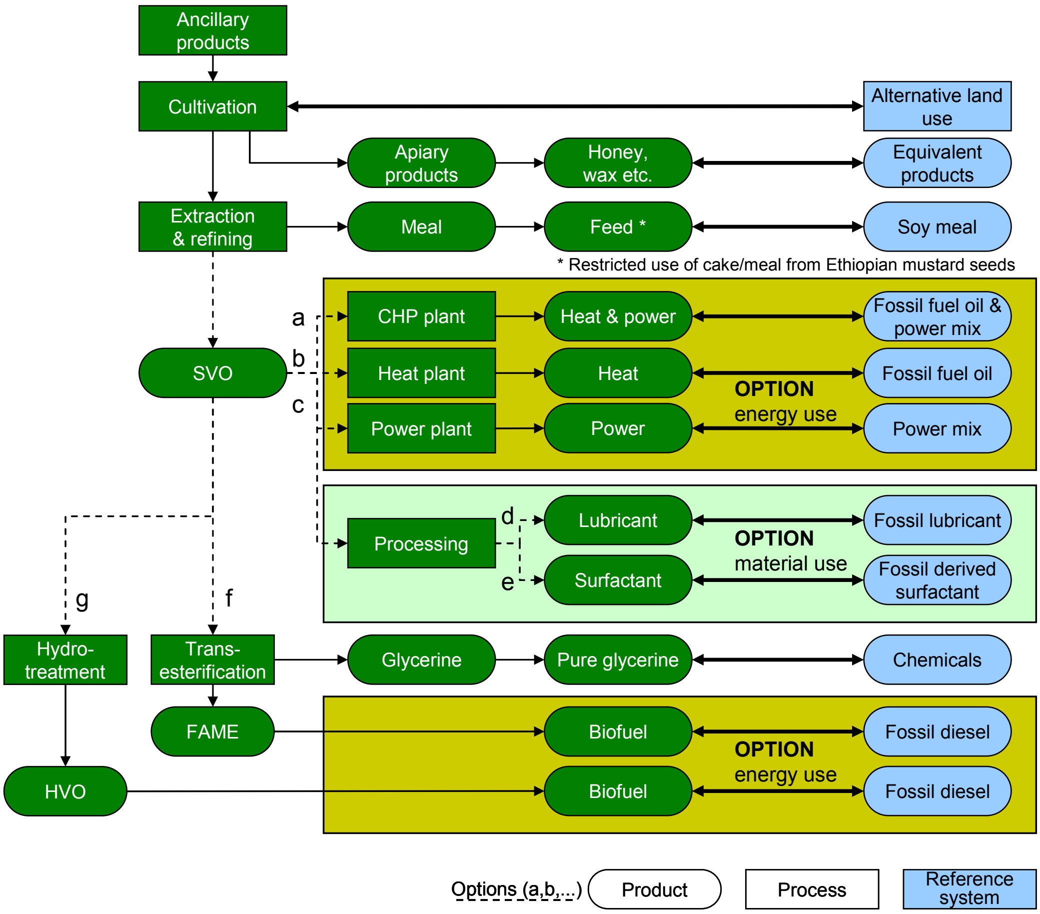

Fig. 3-3 Schematic life cycle comparison of bioenergy and bio-based materials from rapeseed, sunflower and Ethiopian mustard oil and their conventional equivalents. Options indicate if the respective main product is used for energy purposes or for bio-based materials; dashed lines show different use possibilities of products within one option.

As the seed cake of Ethiopian mustard contains high amounts of glucosinate it is not suitable as feed /Carlsson 2009/ and thus excluded from this use. Three energy use pathways are considered: the straight vegetable oil (SVO) can be directly combusted in order to produce heat and / or power (a - c). The second and third possibility would be its transesterification to biodiesel (FAME, f) or its hydrogenation to hydrogenated vegetable oil (HVO, g). The material use covers the application as bio-based lubricant (d) or surfactant (e).

3.3.2 Fiber crops

The use options for hemp and flax are depicted in Fig. 3-4. Here, only the use of their fibers as bio-based material is investigated. The energy use of the oil of both crops is currently not a viable option and is therefore not included. The use as bio-based material comprises their use as fiber composite (a) or as insulation mat (b).

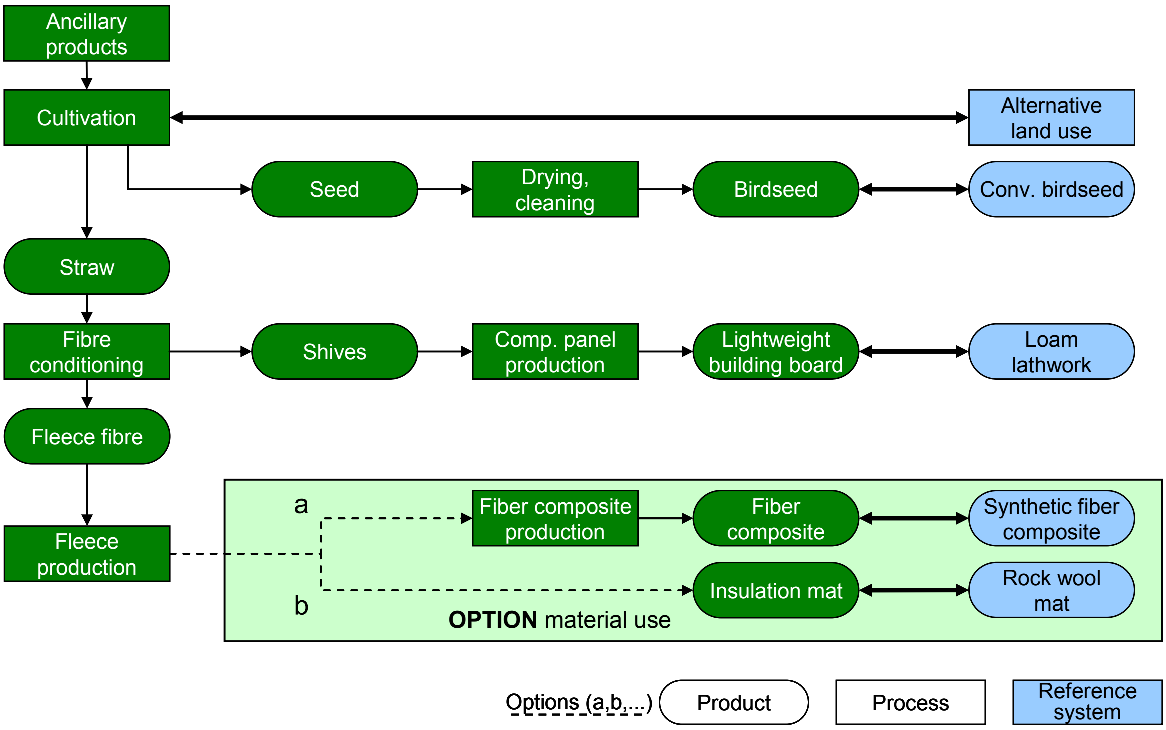

Fig. 3-4 Schematic life cycle comparison for bio-based materials produced from hemp and flax and their conventional equivalents.

3.3.3 Woody and herbaceous lignocellulosic crops

Woody and herbaceous lignocellulosic crops are combined into one group since the lignocellulosic material can be processed in a similar way. Woody lignocellulosic crops include poplar, willow and eucalyptus, cultivated as short-rotation coppice. The herbaceous group consists of reed canary grass, Miscanthus, switchgrass, giant reed, and cardoon. Two different approaches are assessed for both groups: gasification and subsequent processing of the syngas (thermochemical conversion; see Fig. 3-5) and the chemical disintegration of lignocellulosic material into sugar and its fermentation in a biorefinery (biochemical conversion; see Fig. 3-6). For both groups, also the direct combustion of the biomass for heat and / or power production is assessed.

Thermochemical conversion

In Fig. 3-5 the use options for lignocellulosic feedstock are depicted which are based on biomass gasification. In a first step, the biomass is gasified for obtaining a syngas. This gas can either be used for energy production via the synthesis of biofuels (d) or it can be used as biobased material in the chemical industry (e). As with the plant oil, the biomass also can be directly combusted in order to obtain heat and / or power (a, b, c).

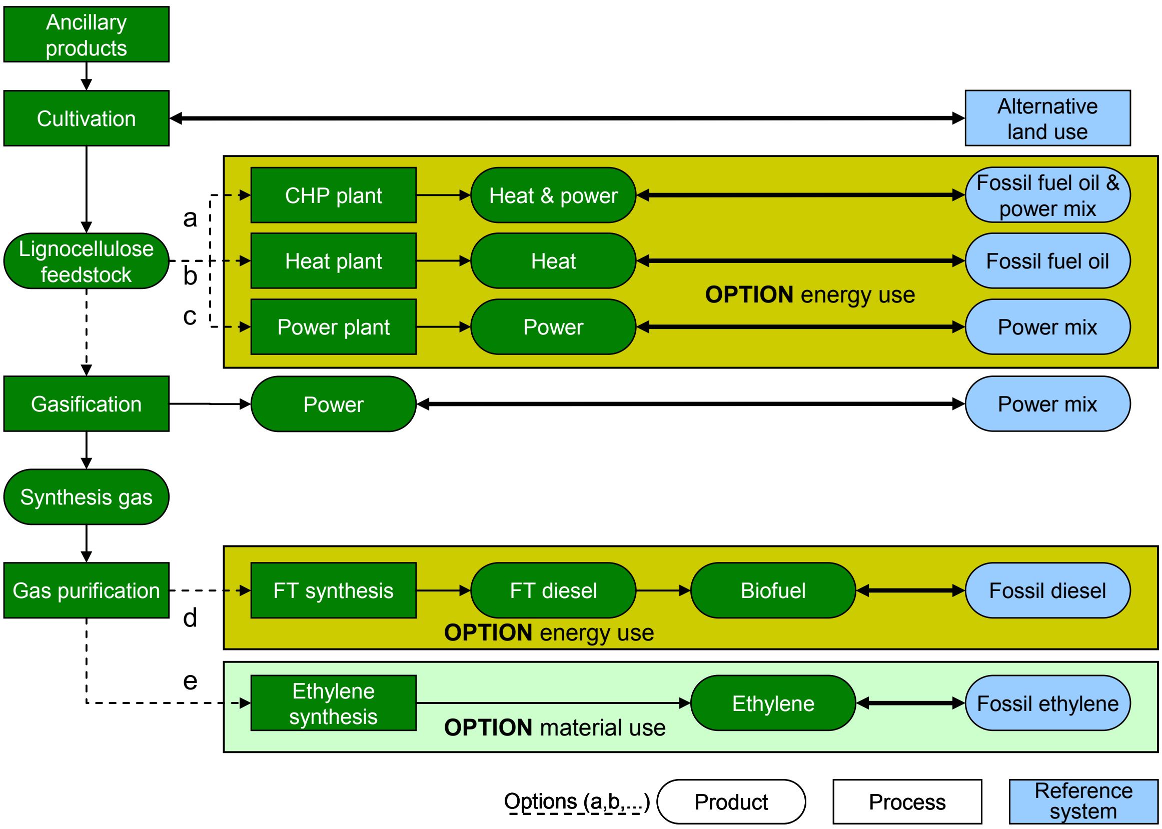

Fig. 3-5 Schematic life cycle comparison of bioenergy and bio-based materials produced from lignocellulosic crops (woody and herbaceous) and their conventional equivalents; in this case, the biomass is processed thermochemically

Biochemical conversion

Fig. 3-6 shows all use option for lignocellulosic biomass in a biorefinery. Also here the alternative use option is the direct combustion of the biomass for energy production (a, b, c). In a lignocellulosic feedstock (LCF) biorefinery, the biomass is disintegrated into its main components. Among them are cellulose and hemicellulose which are further disintegrated into sugar. The sugar can either be directly used as a raw material in the chemical industry (d) or processed further into bioethanol. The latter can serve as biofuel (e) or as renewable raw material in the chemical industry (f, g).

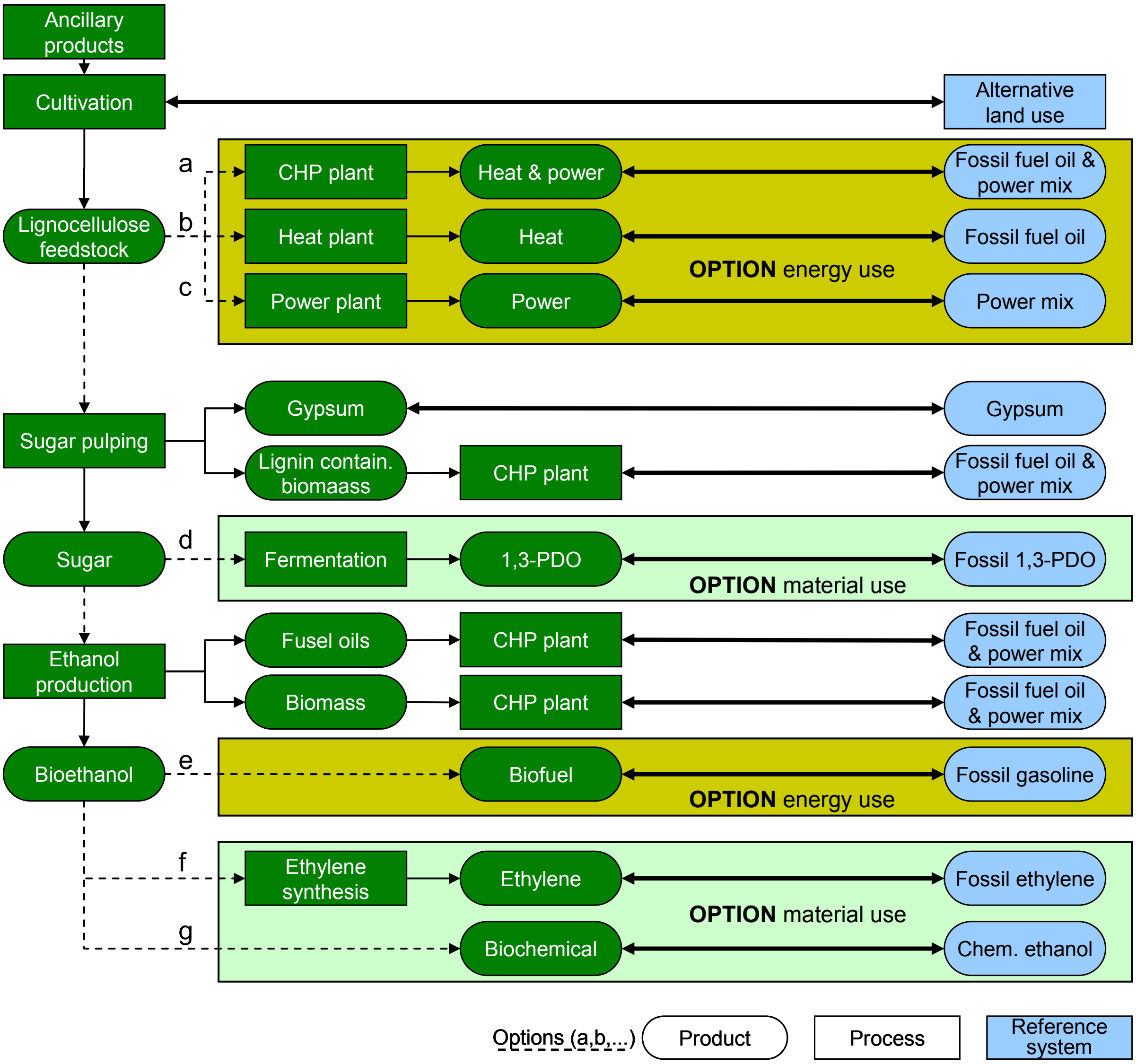

Fig. 3-6 Schematic life cycle comparison of bioenergy and bio-based materials produced from woody and herbaceous lignocellulosic crops and their conventional equivalents; in this case, the biomass is processed biochemically

3.3.4 Sugar crops

The two sugar crops that are investigated are sugar beet and sweet sorghum. Since the production of bioenergy and bio-based materials from these crops differs substantially, separate schematic life cycles for each crop are presented in Fig. 3-7 and Fig. 3-8. Both production processes differ also in number and type of co-products that are generated.

The syrup obtained from **sugar beet** can be refined into purified sugar that serves as a raw material in the chemical industry (a). As a second option, it can be fermented into bioethanol which can serve either as biofuel (b) or as a renewable raw material in the chemical industry (c, d).

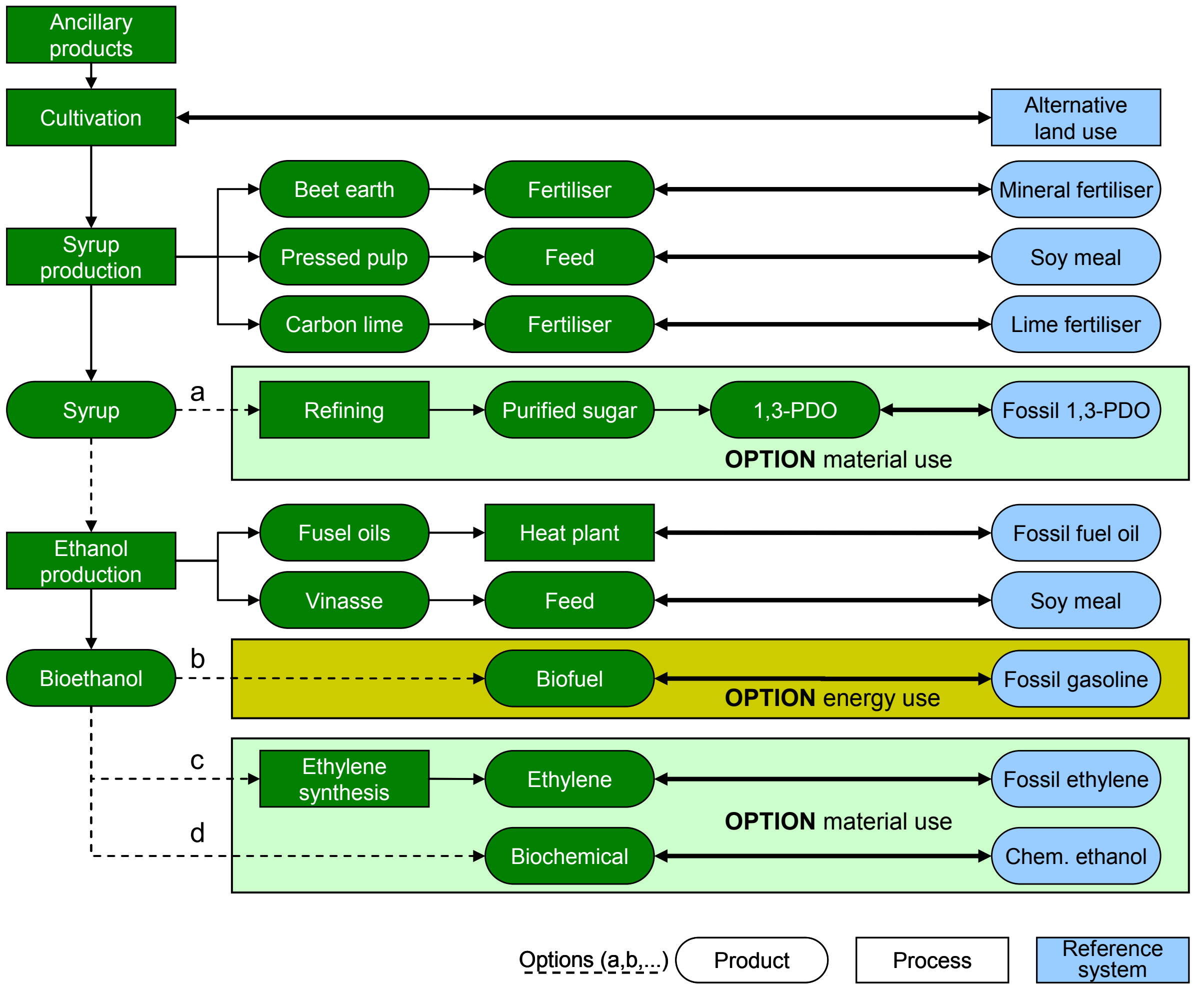

Fig. 3-7 Schematic life cycle comparison of bioenergy and bio-based materials produced from sugar beet and their conventional equivalents

From **sweet sorghum**, different crop parts are obtained which can serve different purposes (Fig. 3-8). The stems contain a sugary juice which can either be used to produce 1,3-PDO for the chemical industry (a) or further transformed into bioethanol – analogous to sugar beet. Furthermore, the starch containing grains can also be used to produce ethanol. Both types of ethanol – from the juice and from the grains – can either serve as a biofuel (b) or as a renewable raw material in the chemical industry (c, d).

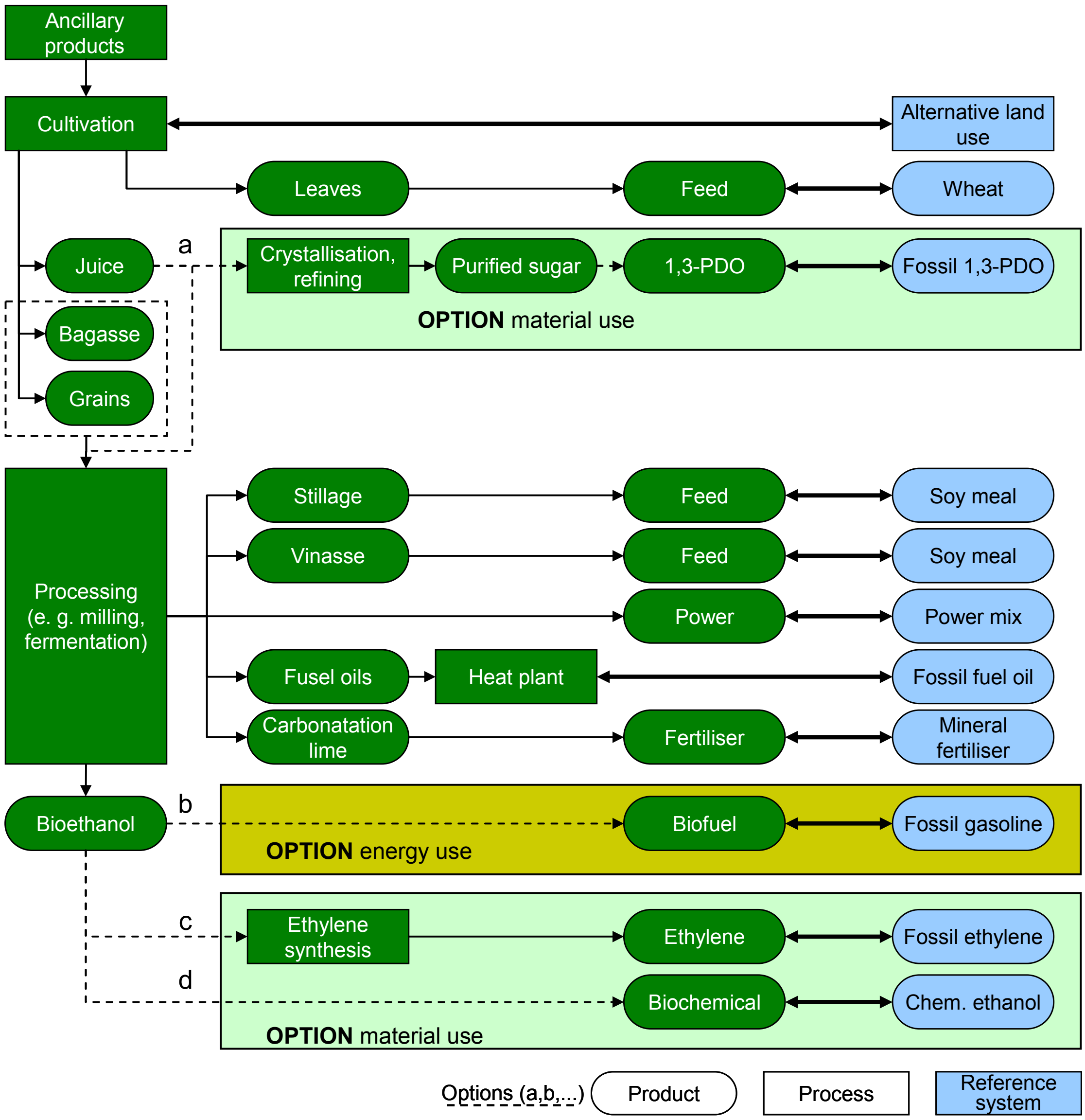

Fig. 3-8 Schematic life cycle of production of bioenergy and bio-based materials produced from sweet sorghum and their conventional equivalents

Since from sweet sorghum, two different products are obtained (juice and grains) that can be used in different ways, there are several possibilities for combining the products. All combinations assessed in this study are shown in Table 3-3.

Table 3-3 Overview on the use combinations of sweet sorghum juice and grains

		Grains		
		Fuel EtOH	Chem. EtOH	Ethylene
Juice	Fuel EtOH	X		
	Chem. EtOH		X	
	Ethylene			X
	1,3-PDO		X	X

3.4 Reference scenarios: Variations and sensitivity analyses

A multi-functional assessment tool is applied to scrutinise life cycle stages having a significant influence on the results as well as to identify dependencies on various parameters. This tool uses correlations based on functional dependencies, e.g. CO_2 equivalent savings as a function of yields (spatial and temporal), co-product uses or substituted power mixes.

In the following, a number of variations and sensitivity analyses are shortly presented. Their results are displayed in chapter 4.3. If not indicated otherwise, all variations and sensitivity analyses are based on current (2008) average (avg) yields. The default agricultural reference system (alternative land use) is fallow and for electricity inputs and outputs, the European average power mix (UCTE mix) is taken into account.

3.4.1 Crop cultivation

Agricultural reference system

As described in chapter 2.2.2, the agricultural reference system (alternative land use) is an essential part of LCAs for agricultural products. By definition, the agricultural reference system also comprises any change in land use or land cover induced by the cultivation of the investigated crop. This sensitivity analysis aims at evaluating the effects of different alternative land uses, including direct and indirect effects on the greenhouse gas balances. For further background information on land-use change dynamics, see chapter 2.2.2.

All scenarios assessed in this sensitivity analysis are displayed in Fig. 3-9. The scenarios are divided into scenarios which only consider direct effects (referred to as ‘a’) and others which also take into account indirect effects (referred to as ‘b’).

In the basic scenarios of this study, the default agricultural reference system is fallow (scenario Ia). This choice is substantiated by the results of an assessment of surplus land potentially available for non-food cropping systems within EU25, indicating that more agricultural land will be available than is needed to satisfy the demand for food and feed. This is in line with the assumptions of the land availability assessment in WP 1. Since only surplus land (i.e. land which is not needed for food and feed production) is used for energy and industrial crop cultivation, no crops are displaced, which does not lead to any indirect land-use changes. With carbon stock change set at zero, a land-use change from fallow (still remaining agricultural land, i.e. not subject to natural succession) to cropland does not involve any GHG emissions. The latter also applies to scenario Ib, but in this case, indirect land-use effects due to co-product use are taken into account.

Scenario II and III refer to the replacement of food crops (wheat) as well as of feed (grassland on organic soils). In contrast to the use of fallow, the displacement of food and feed production due to energy crop cultivation in Europe induces indirect land-use changes: wheat production is displaced to US prairie and feed production is substituted by soy production on former Brazilian forest land. The displacement of feed, i.e. the substitution of forage by soy is calculated based on the protein contents. Therefore, using one hectare of grassland for non-food purposes does not necessarily mean that exactly one hectare of new land will be used for the displaced feed crops. This is also the case for wheat displacement since different wheat yields might apply for Europe and the USA, respectively. However, for simplification in this study the same yields are used.

According to the division into ‘direct’ and ‘indirect’ versions, the scenarios IIa and IIIa only include expenditures for the additional production of food and feed crops. Scenarios IIb and IIIb additionally include greenhouse gas emissions from indirect land-use changes and indirect land-use effects due to co-product use.

In order to illustrate the indirect effects caused by the use of co-products, the sensitivity analysis is performed for two different crops: for 1st generation bioethanol produced from sugar beet and for 2nd generation bioethanol from Miscanthus. In the case of sugar beet, a co-product is obtained which can be used as feed (DDGS) and thereby leads to a positive indirect effect, as it reduces the overall land use. If DDGS substitutes for Brazilian soy meal, the carbon stock of the released land could increase and thereby lead to GHG savings. At least, the former soy cultivation area would turn into grassland (conservative assumption), at best, it becomes a secondary forest. No such co-product is obtained from Miscanthus processing. It again has to be noted that all scenarios related to indirect effects are not based on modelling but are exemplary. In reality, effects might be quite different.

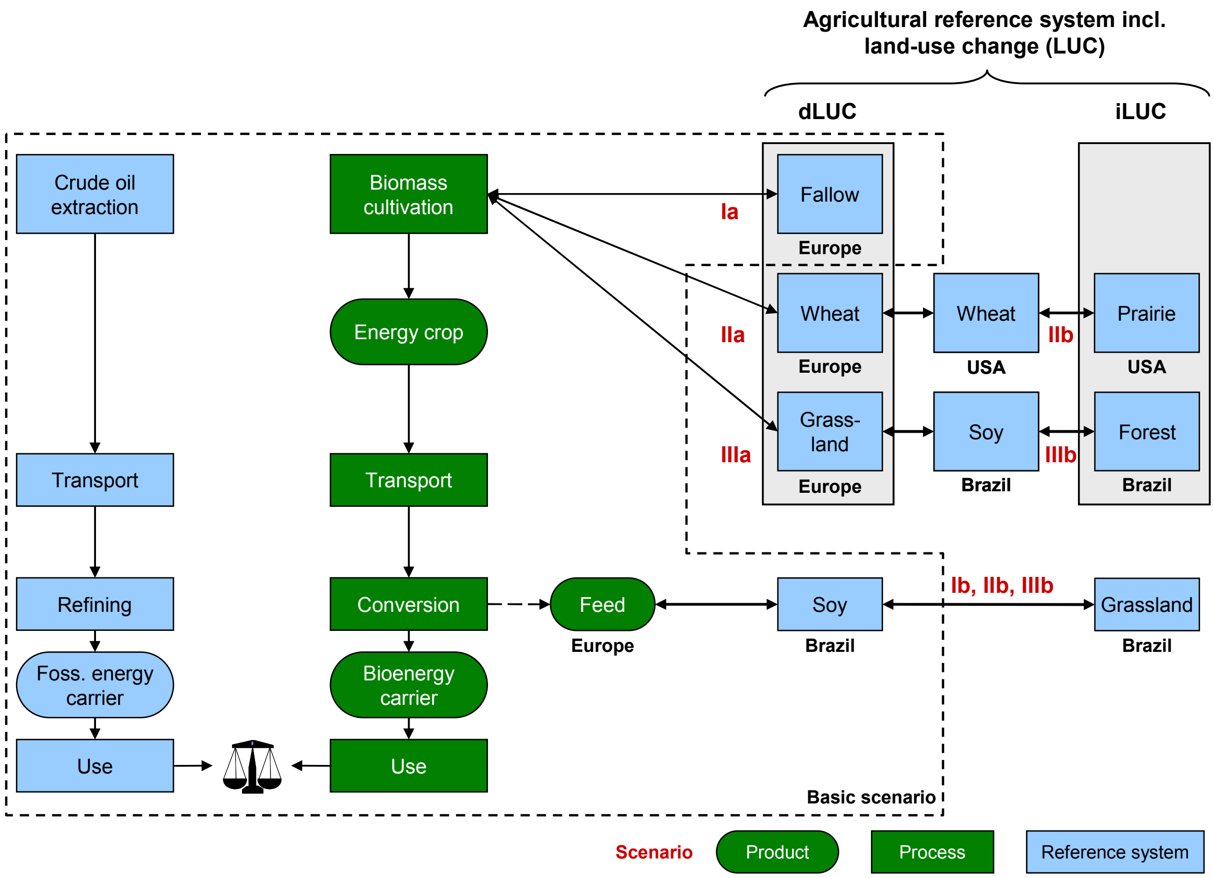

Fig. 3-9 Overview on the different agricultural reference systems assessed

In Table 3-4, all six scenarios including the respective carbon stock changes are summarised. The numbers in the second column are also displayed in the flow chart (Fig. 3-9). The names in the first column can be found in the graph in the results chapter 4.3.1.

All carbon stock changes caused by land-use changes are calculated following IPCC's stock-difference method, except for the soil organic carbon stock changes and N_2O emissions due to the conversion of grassland on organic soils (/UBA 2009/). Greenhouse gas emissions from land-use changes can either result from discrete events (e.g. clear-cutting a forest) or from continuous processes (e.g. peat oxidation) that prevail for many years after land conversion. Emissions from discrete events require an annualisation, which is applied by dividing total emissions equally over 20 years.

Table 3-4 Overview on all scenarios related to the agricultural reference system for sugar beet and Miscanthus. DLUC = direct land-use change, iLUC = indirect land-use change.

Name	N°	Carbon stock changes & GHG emissions due to crop cultivation (Miscanthus & sugar beet)	Carbon stock changes due to co-products (only sugar beet)
Fallow dLUC	I a	Replacing fallow: ±0 t C / ha	Land release not considered
Fallow iLUC	I b	Replacing fallow: ±0 t C / ha	Land release in Brazil: +10 t C / ha
Cereals dLUC	II a	Replacing cereals in Europe: ±0 t C / ha	Land release not considered
Cereals iLUC	II b	Replacing cereals in Europe: ±0 t C / ha Displacing cereal production to US prairie: -10 t C / ha	Land release in Brazil: +10 t C / ha
Grassland dLUC	III a	Replacing grassland on organic soil in Europe: –13 t C / ha Continuous GHG emissions from organic soil: 6 t C / (ha*yr)	Land release not considered
Grassland iLUC	III b	Replacing grassland on organic soil in Europe: –13 t C / ha Continuous GHG emissions from organic soil: 6 t C / (ha*yr) Displacing feed production to Brazilian forests: -160 t C / ha	Land release in Brazil: +10 t C / ha

Yields within each environmental zone

For covering different environmental and management conditions, three yield classes are regarded: minimum, average, and maximum (see chapter 2.3). The respective yields are depicted in Table 2-5.

Yields between environmental zones

Some of the crops assessed are cultivated in different environmental zones. Due to differences in the biophysical conditions, different yields are achieved in the zones. In order to capture the influence of the yields on the results, they are varied in a sensitivity analysis. The yields are depicted in Table 2-5.

Time-related coverage

Yields not only vary between the environmental zones but will also change in future. In the next decades, they are likely to increase due to progress in crop breeding. In order to capture this development, the results related to current yields are compared to those related to expected yields in 2020 and 2030, respectively. The average yields are shown Table 3-5 and Table 3-6.

Table 3-5 Yields for all crops and all environmental zones for 2020 /UNICT 2009/

[t / ha]		NEM	ATN	ATC	CON	LUS	MDN	MDS
Rapeseed	Avg	2.1	2.5	3.5	3.1	2.1		
Sunflower	Avg						2.9	
Ethiopian mustard	Avg							2.1
Hemp	Avg	0.5	0.8			0.9	1.1	
Flax	Avg			1.2	1.9			1.2
Poplar	Avg	9.6		7.3			12.1	
Willow	Avg		8.3		8.8	6.8		
Eucalyptus	Avg							10.4 *
Reed canary grass	Avg	14.7						
Miscanthus	Avg		15.9	31.8	32.3	33.8		
Switchgrass	Avg		12.2	18.4				
Giant reed	Avg						51.3	
Cardoon	Avg							20.3
Sugar beet	Avg			88.4	90.9			
Sweet sorghum (grains)	Avg					5.8	6.4	8.4 *

* irrigation necessary

Table 3-6 Yields for all crops and all environmental zones for 2030 /UNICT 2009/

[t / ha]		NEM	ATN	ATC	CON	LUS	MDN	MDS
Rapeseed	Avg	2.4	2.8	3.8	3.6	2.3		
Sunflower	Avg						2.8	
Ethiopian mustard	Avg							2.3
Hemp	Avg	0.5	0.8			0.9	1.1	
Flax	Avg			1.2	2.0			1.1
Poplar	Avg	11.8		8.7			12.1	
Willow	Avg		9.8		10.8	6.7		
Eucalyptus	Avg							10.4 *
Reed canary grass	Avg	18.1						
Miscanthus	Avg		18.8	37.6	39.9	33.6		
Switchgrass	Avg		14.5	21.7				
Giant reed	Avg						51.6	
Cardoon	Avg							21.9
Sugar beet	Avg			96.0	103.2			
Sweet sorghum	Avg					5.7	6.5	8.4 *

* irrigation necessary

3.4.2 Co-product use and allocation

Variation of co-product use

Along the life cycles of the crops under concern, different co-products are obtained. They can be used in different ways resulting in different conventional products to be replaced. Fig. 3-10 shows selected co-products obtained in different crop groups and their alternative use options. For oil crops, the seed meal can either be used as animal feed, fertiliser or as solid biofuel producing heat and power (Variation I). Regarding hemp and flax, the shives that are obtained in fiber extraction can be used as material for lightweight building board production or as animal bedding (Variation II). In the lignocellulosic feedstock (LCF) biorefinery, the lignin containing biomass can either be directly combusted in a CHP to generate process energy or used as raw material for plastics production (Variation III). When processing sweet sorghum into bioethanol, bagasse and stillage are obtained which can be used as follows (Variation IV): the bagasse can either be combusted internally and returned to the production process as process energy, or it can be processed to second generation bioethanol. One option to use stillage, a residue from fermentation, is its direct use as feed. It can also can be further dried and pelletised and used as feed in form of Distillers' Dried Grains with Solubles (DDGS). The advantage of the latter product is that it can be stored and transported and thus may be sold on the feed market.

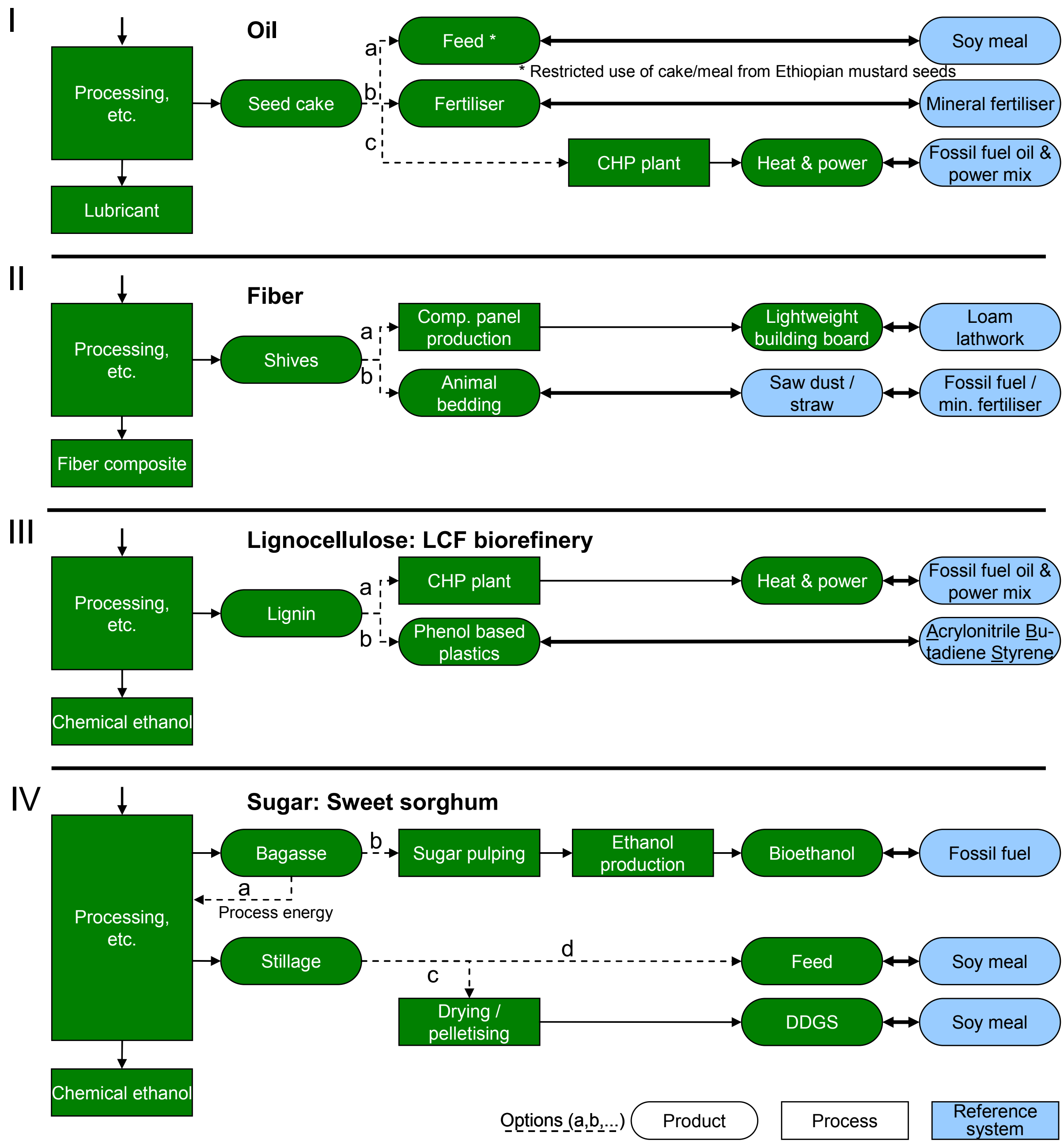

Fig. 3-10 Alternative co-product use in production of bioenergy and bio-based materials from different crop groups. Dashed lines indicate optional uses of co-products that are varied in sensitivity analyses; option a: calculated as standard

Variation of co-product allocation

In life cycle analyses, different methods exist to deal with the co-products such as rapeseed meal in biofuel production from rapeseed. In the substitution method the co-products substitute conventionally produced goods (e.g. rapeseed meal for soy meal) (see Fig. 3-11, left side). Thus, through the use of the co-products the environmental impacts caused by the production of the conventional pendants are avoided. These avoided environmental impacts are credited to the main product (in this case biofuel).

In the allocation method all environmental impacts (e.g. emissions) are partitioned proportionately to the different products and co-products (see Fig. 3-11, right side). Thereby, different references are possible such as economic value, mass, or energy content. The allocation method is widely required in international standards or directives such as the European renewable energy directive /CEC 2009/ for calculating greenhouse gas balances.

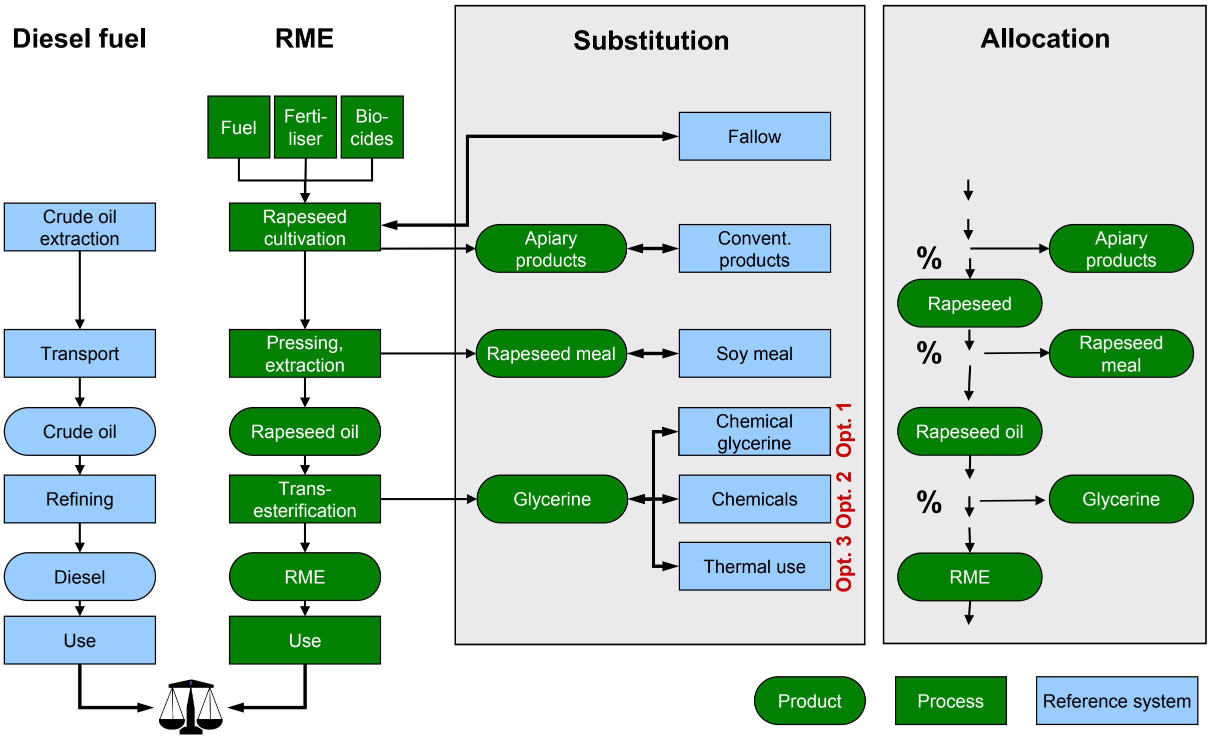

Fig. 3-11 Comparison of credit and allocation method

3.4.3 Fossil reference system

Stationary energy use

The oil and lignocellulosic crops can be used for generating power and / or heat either in combined heat and power production facilities (CHP) or in separate heat and power plants. These options are displayed in Fig. 3-3 to Fig. 3-7. Depending on the scenario, different fossil energy carrier sources are replaced: if the biomass is used in a CHP, a fossil heat plant and power from the grid are replaced. If only power or heat are produced from the biomass, either power from the grid or fossil heating plants are replaced.

Substituted power mix

In most life cycles calculated, surplus electricity is produced that substitutes power from the grid. Depending on the country where the conversion plant is built, the substituted power is composed of different energy carriers. Since the power that is replaced accounts for a big part of the credits, the composition of the power mix can have a significant influence on the results. In the standard version, the UCTE mix (average European mix) is taken. In the sensitivity analyses, the following power mixes are assessed: Sweden, France, Germany and Poland. The mixes are chosen in order to reflect a wide range of energy carriers with different characteristics such as coal, nuclear power or hydro power. Table 3-7 shows the shares of energy carriers in the power mixes.

Table 3-7 Shares of energy carriers in the power mixes in Europe (UCTE mix), Sweden, France, Germany and Poland /ecoinvent 2010/

	Fuel oil & natural gas	Coal	Uranium	Hydro	Other renewable
UCTE	19%	33%	40%	6%	2%
Sweden	2%	3%	57%	29%	8%
France	4%	7%	84%	5%	1%
Germany	10%	57%	28%	2%	3%
Poland	4%	93%	1%	1%	1%

Table 3-8 Specific non-renewable energy demand and specific emissions connected to the production of 1 kWh of electricity in Europe (UCTE mix), Sweden, France, Germany and Poland /IFEU 2010/

	$MJ_{non-ren.}$ / kWh	g CO_2 eq. / kWh	g SO_2 eq. / kWh	g PO_4 eq. / kWh
UCTE	11.7	538	2.78	0.12
Sweden	6.1	50	0.27	0.02
France	12.9	111	0.72	0.04
Germany	12.4	760	1.10	0.09
Poland	14.8	1296	10.37	0.29

4 Results

In the following, the results for the life cycle comparisons between the products of the different crops and their fossil equivalents are presented. In chapter 4.1 some results are exemplified in order to explain how the graphs are generated. In chapter 4.2 the results are presented for each crop featuring its use for energy production and as bio-based material as well as for all environmental impact categories. For each crop, one environmental zone is chosen as an example. The results for all other environmental zones can be found in the appendix (chapter 7). Chapter 4.3 presents the results of the sensitivity analyses where selected life cycle stages are varied.

4.1 Exemplification of results

Fig. 4-1 shall serve as an example to explain how the graphs in the following chapters are generated. It shows the life cycle comparison between bioethanol produced from sugar beet and conventional gasoline. The first bars in the upper part of the chart show on the right side all expenditures necessary for the production of bioethanol (e.g. cultivation, conversion of the juice into bioethanol). To the left all credits are depicted which are obtained from the use of co-products (here: vinasse). The second bars in each category show the expenditures related to the production and use of the conventional gasoline which is replaced by bioethanol. The lower part of the graph depicts the balances for each environmental impact category. They are calculated as follows: the credits for the bioethanol production and the expenditures for the fossil equivalent are summed up and subtracted from the expenditures for the bioethanol production. The balances thus quantify for instance the net primary energy or greenhouse gas savings due to the use of bioethanol instead of conventional gasoline. In the following chapters, only these balances will be depicted.

Results

- The energy and greenhouse gas balances for bioethanol produced from sugar beet show advantages, i.e. substituting conventional fuel by bioethanol helps saving fossil energy resources and greenhouse gas emissions. Regarding summer smog, the balances are advantageous, too.
- In contrast, the balances show disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicology. In these cases the expenditures that occur during the production of bioethanol cannot be compensated by the credits obtained due to the co-product use and due to the replacement of fossil fuel.
- The extent to which each life cycle stage contributes to the overall balance varies between the environmental impact categories:
  - the **conversion** stage, i.e. the use of fossil energy carriers for process energy generation, has the largest influence on energy and greenhouse gas balances. In contrast, conversion is of only minor importance for other environmental impact categories.

- the **cultivation** stage is most important in terms of acidification, eutrophication and ozone depletion, which are dominated by nitrogen fertiliser-related field emissions like N_2O (greenhouse effect and ozone depletion) or NH_3 (acidification and eutrophication).
- the **utilisation** stage has a considerable impact on acidification and eutrophication, mainly through NO_X emissions.
- transports and the provision of specific ancillary products only have a minor influence.

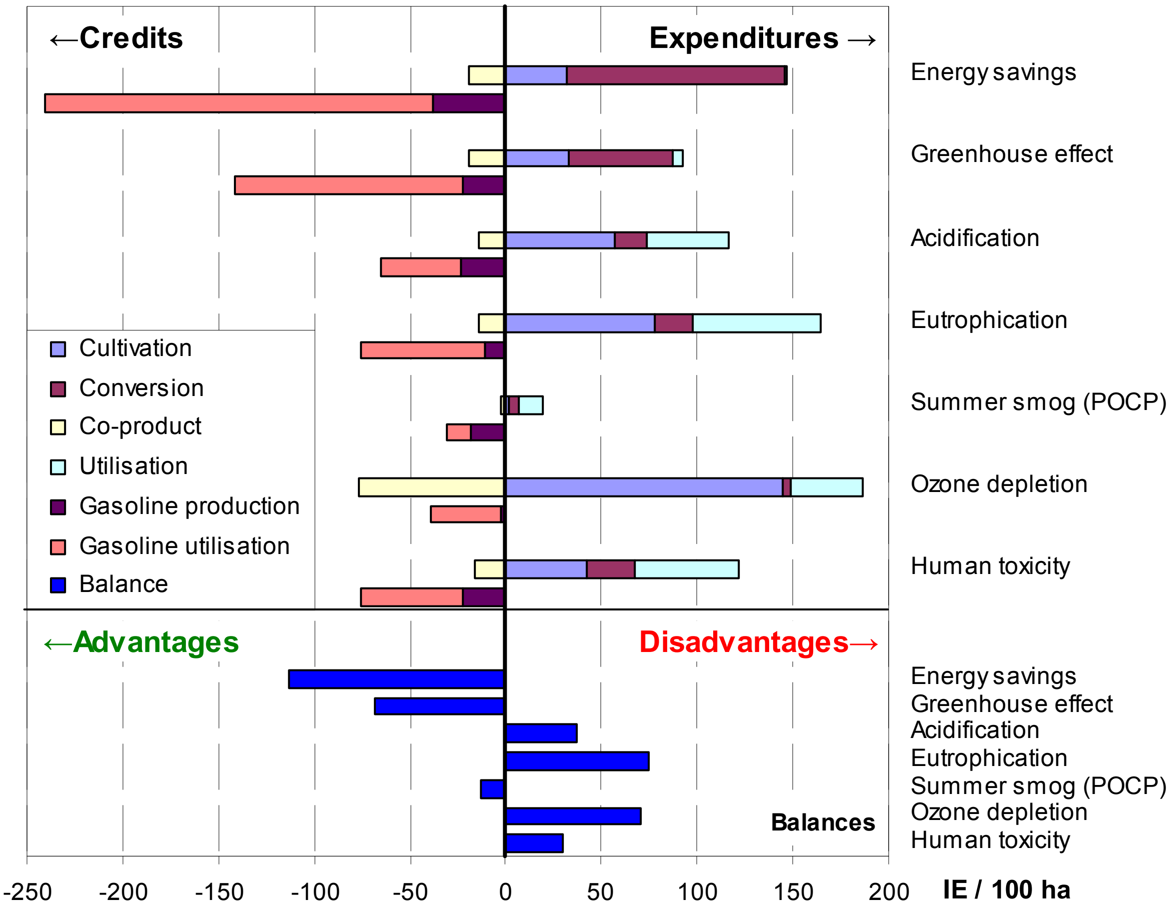

Fig. 4-1 Results of the life cycle comparison between bioethanol produced from sugar beet and conventional gasoline.

Reading the diagram – exemplification for the first bars 'energy savings'

The first bar in the upper part of the graph shows that the energy needed for the production of bioethanol from 100 hectares of sugar beet equals the yearly energy demand of 147 in-habitants. The amount of energy credited due to the use of the co-product vinasse equals the yearly energy demand of about 20 inhabitants. The second bar shows the amount of energy that can be saved by replacing conventional fuel with bioethanol (equivalent to the yearly energy demand of 241 Europeans).

In the balances section below all credits and expenditures are set off against each other. As a result, if conventional fuel is replaced by bioethanol produced from sugar beet, the energy savings per 100 hectares equal the yearly energy demand of 114 inhabitants.

4.2 Basic scenarios

This chapter presents the results of the life cycle comparisons for all 15 crops. The underlying life cycles are shown in chapter 3.3. The results are aggregated into oil crops, fiber crops, woody lignocellulosic crops, herbaceous lignocellulosic crops and sugar crops. For each crop, results are shown only for one exemplary environmental zone. The results for all other investigated environmental zones are depicted in the appendix (chapter 7). The bandwidths refer to the minimum and maximum yields, respectively (see chapter 2.3).

4.2.1 Oil crops

For the bioenergy pathway, only one of the three possibilities presented in chapter 3.3.1 is depicted: the direct combustion of the biomass in combined heat and power plants (CHP). The other two options (the production of either heat or power) are presented in chapter 4.3.4. For each crop, the abbreviation of the environmental zone is indicated in the chapter title.

4.2.1.1 Rapeseed (CON)

Results: bioenergy

- If rapeseed oil is combusted in a CHP for heat and power production, or processed into hydrogenated vegetable oil (HVO) or biodiesel (FAME) it helps saving fossil energy resources and reducing greenhouse gas emissions compared to the fossil counterparts. In contrast, all bioenergy pathways clearly show disadvantageous environmental impacts regarding acidification, eutrophication, ozone depletion, and human toxicity. Summer smog is clearly disadvantageous for CHP and shows no clear results for HVO and FAME.
- The use of rapeseed oil in a CHP helps saving more fossil energy resources and greenhouse gas emissions than its use for the production of HVO and FAME. However, it shows more disadvantages regarding acidification, eutrophication, summer smog, and human toxicity. HVO and FAME show almost equal results. In these four categories, FAME shows slightly more advantages and slightly less disadvantages. Regarding ozone depletion, all use options perform similarly disadvantageously (see Fig. 4-2).

Results: biomaterials

- Both the use of rapeseed oil for producing biogenic lubricant and surfactant helps saving fossil energy carriers and reducing greenhouse gas emissions as well as summer smog in comparison to their conventional equivalents. In contrast, both bio-based materials clearly show disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity. This pattern is quite similar to the one for bioenergy production from rapeseed oil (see Fig. 4-2).
- In most categories, the use as surfactant performs slightly better by saving slightly higher amounts of energy resources and greenhouse gases than lubricants and showing fewer disadvantages regarding most other environmental impact categories. For summer smog and ozone depletion, both biomaterials show about the same results.

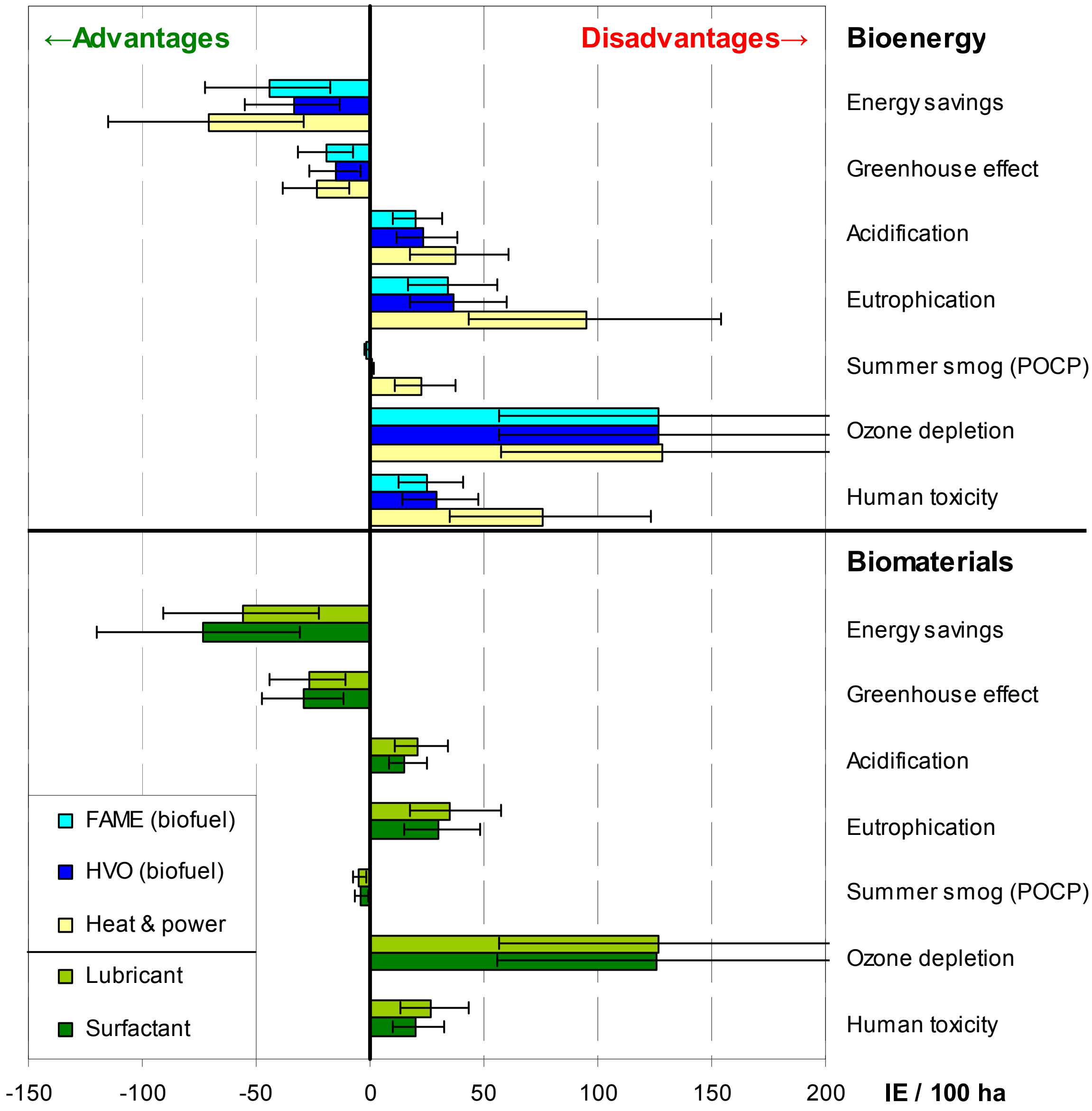

Fig. 4-2 Results of the life cycle comparison of bioenergy and biomaterials produced from rapeseed oil with their conventional equivalent products for the Continental (CON) zone (FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Reading the diagram – exemplification of 1st bar 'energy savings' for bioenergy

The first bar shows that by replacing conventional diesel with biodiesel (FAME) produced from rapeseed, the energy savings per 100 hectares are equivalent to the yearly energy demand of about 44 Europeans.

4.2.1.2 Sunflower (MDN)

Results: bioenergy

- The production of biofuels (FAME, HVO) as well green power and heat in a CHP from sunflower oil shows advantages with regard to energy savings and greenhouse effect. Regarding acidification, eutrophication, ozone depletion, and human toxicity all bioenergy products show clear disadvantages compared to their respective fossil equivalents. Regarding summer smog, the use of the sunflower oil in a CHP shows clear disadvantages whereas its use as FAME or HVO shows ambiguous results (see Fig. 4-3).
- On the one hand, the use of sunflower oil in a CHP shows higher advantages regarding fossil energy and greenhouse gas savings; on the other hand, disadvantages in the categories acidification, eutrophication, summer smog and human toxicity are much higher than for the use as transport fuel.
  Within the transport fuels, FAME performs slightly better than HVO: it shows higher advantages regarding energy savings and greenhouse effect and fewer disadvantages regarding the other environmental impact categories. However, the difference between both biofuels is only small. Regarding ozone depletion, all three energy use options perform equally disadvantageously.

Results: biomaterials

- The use of sunflower oil to produce bio-based lubricants and surfactants shows advantages regarding energy savings, greenhouse effect, and summer smog compared to their conventional counterparts. Regarding acidification, eutrophication, ozone depletion, and human toxicity, disadvantages occur if sunflower oil is used for the production of bio-based materials (see Fig. 4-3).
- Surfactant produced from sunflower oil shows higher advantages than lubricant regarding energy savings and greenhouse effect and less disadvantages regarding acidification, eutrophication, and human toxicity. For summer smog and ozone depletion, both bio-based materials show nearly the same results.

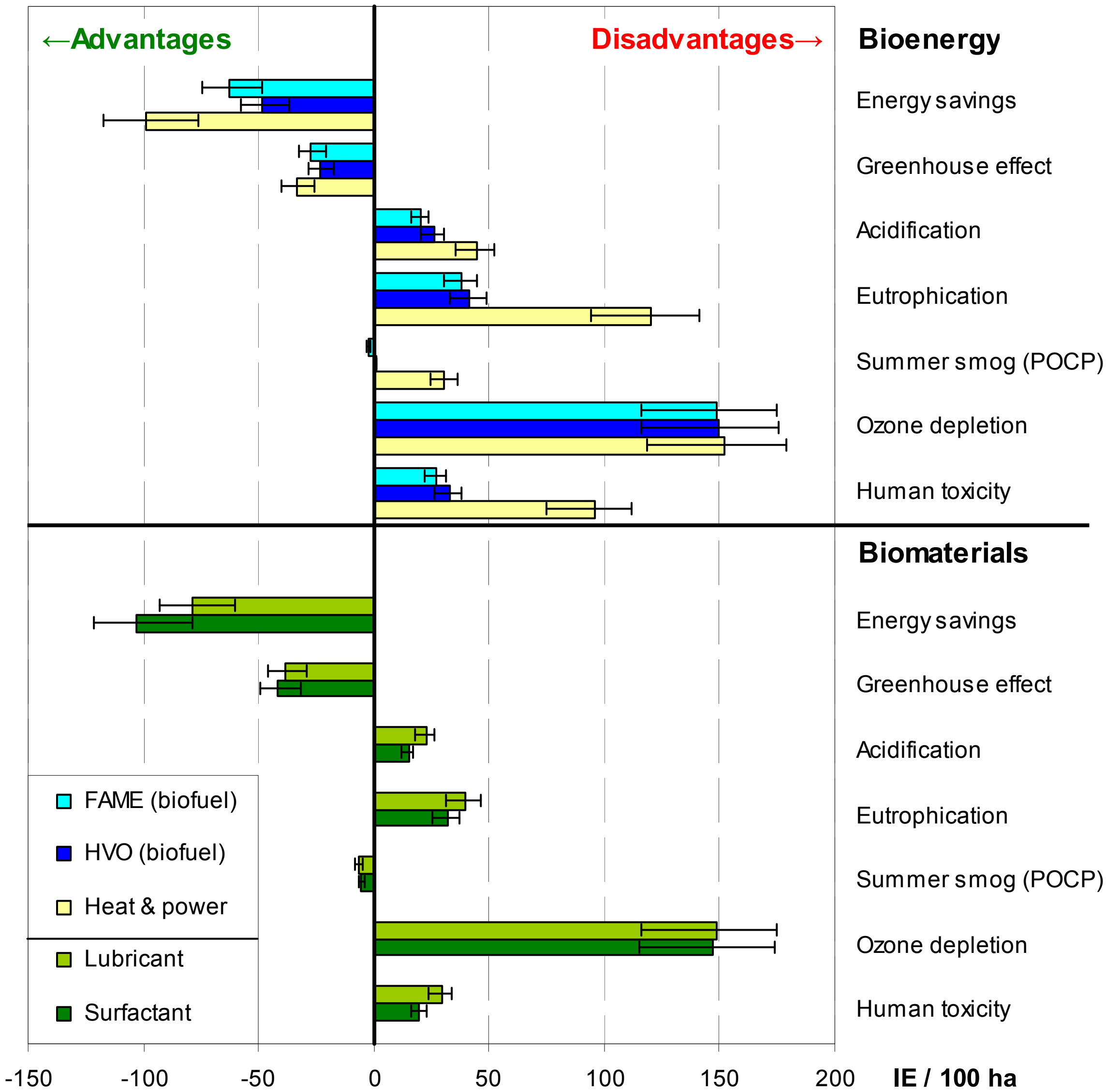

Fig. 4-3 Results of the life cycle comparison of bioenergy and biomaterials produced from sunflower oil with their conventional equivalent products for the Mediterranean North (MDN) zone (FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Reading the diagram – exemplification of 4th bar 'greenhouse effect' for bioenergy

If sunflower oil from 100 hectares is used to produce biodiesel (FAME) that replaces conventional diesel as transport fuel, the amount of greenhouse gases savings equals the amount which is emitted each year by 28 Europeans.

4.2.1.3 Ethiopian mustard (MDS)

Results: bioenergy

- Fossil energy can be saved and greenhouse gas emissions can be reduced if the biofuels HVO or FAME are produced from Ethiopian mustard oil or if the oil is used in a CHP for heat and power production. All these bioenergy use options, however, show disadvantages regarding acidification, eutrophication, summer smog, ozone depletion, and human toxicity (see Fig. 4-4).
- The use of Ethiopian mustard oil in a CHP shows far higher advantages regarding energy savings and greenhouse effect than if it was used to produce HVO or FAME. These advantages, however, come along with higher disadvantages with regard to acidification, eutrophication, summer smog, and human toxicity.
  The difference between HVO and FAME are small. HVO performs slightly better than FAME: it shows slightly more savings of energy and greenhouse gases and slightly less disadvantages regarding most other environmental impact categories. Regarding summer smog, there are no clear results for either of the biofuels. Regarding ozone depletion, there are no differences between the stationary use of the oil (in a CHP) and its mobile (HVO or FAME).

Results: biomaterials

- Fossil energy as well as greenhouse gas emissions can be saved by using lubricants and surfactants produced from Ethiopian mustard oil instead of the respective conventional equivalents. However, they increase acidification, eutrophication, ozone depletion, and human toxicity in comparison to their conventional equivalent products. Regarding summer smog, there are no clear results (see Fig. 4-4).
- The use of Ethiopian mustard oil for producing surfactants helps saving more energy and greenhouse gas emissions than lubricants. At the same time, surfactants show less disadvantages regarding acidification, eutrophication, and human toxicity. Regarding summer smog and ozone depletion, the results do not show significant differences.

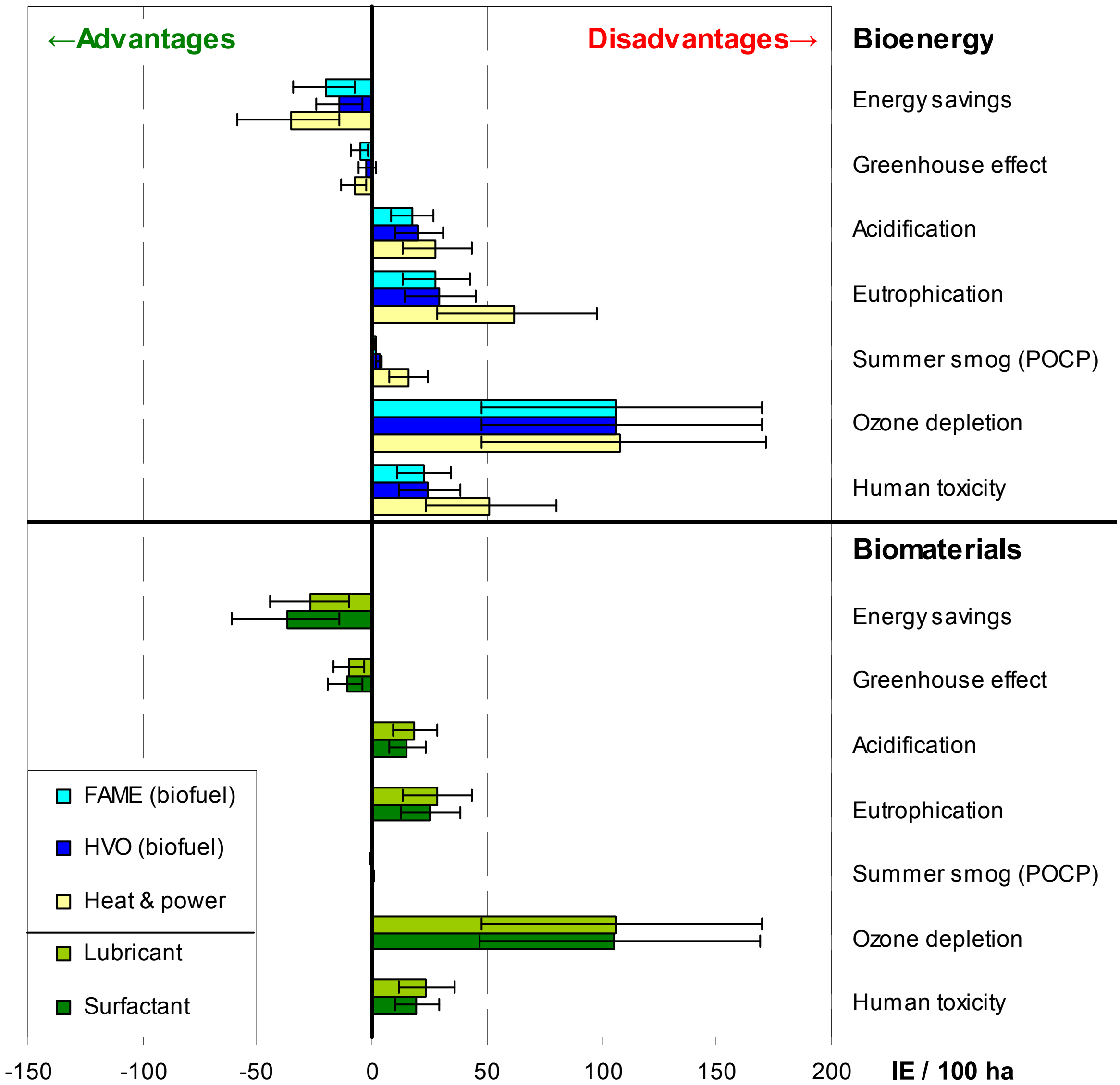

Fig. 4-4 Results of the life cycle comparison of bioenergy and biomaterials produced from Ethiopian mustard oil with their conventional equivalent products for the Mediterranean South (MDS) zone (FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Reading the diagram – exemplification of 2nd bar 'energy savings' for bioenergy

If Ethiopian mustard oil produced on 100 hectares is converted into HVO which replaces conventional diesel as transport fuel, the energy savings equal the yearly energy demand of 14 Europeans.

4.2.2 Fiber crops

As stated in chapter 3.3.2, only bio-based materials are analysed for fiber crops, since the energy use of flax and hemp is not a viable option at present. For each crop, the abbreviation of the respective environmental zone is indicated in the chapter title.

4.2.2.1 Flax (CON)

Results: biomaterials

- Fiber composites produced from flax fibers show advantages regarding energy savings, greenhouse effect, acidification, and human toxicity. Regarding summer smog, the results are ambiguous, whereas for eutrophication and ozone depletion, the balances are disadvantageous (see Fig. 4-5).
- Also insulation mats produced from flax fibers help saving energy and reducing greenhouse gas emissions. Regarding acidification, eutrophication, ozone depletion, and human toxicity, the results are disadvantageous whereas for summer smog, no clear results are obtained.
- Fiber composites show much higher environmental advantages than insulation mats regarding energy savings, greenhouse effect, acidification, summer smog, and human toxicity and less disadvantages regarding eutrophication. Regarding ozone depletion, both biomaterials perform about equally.

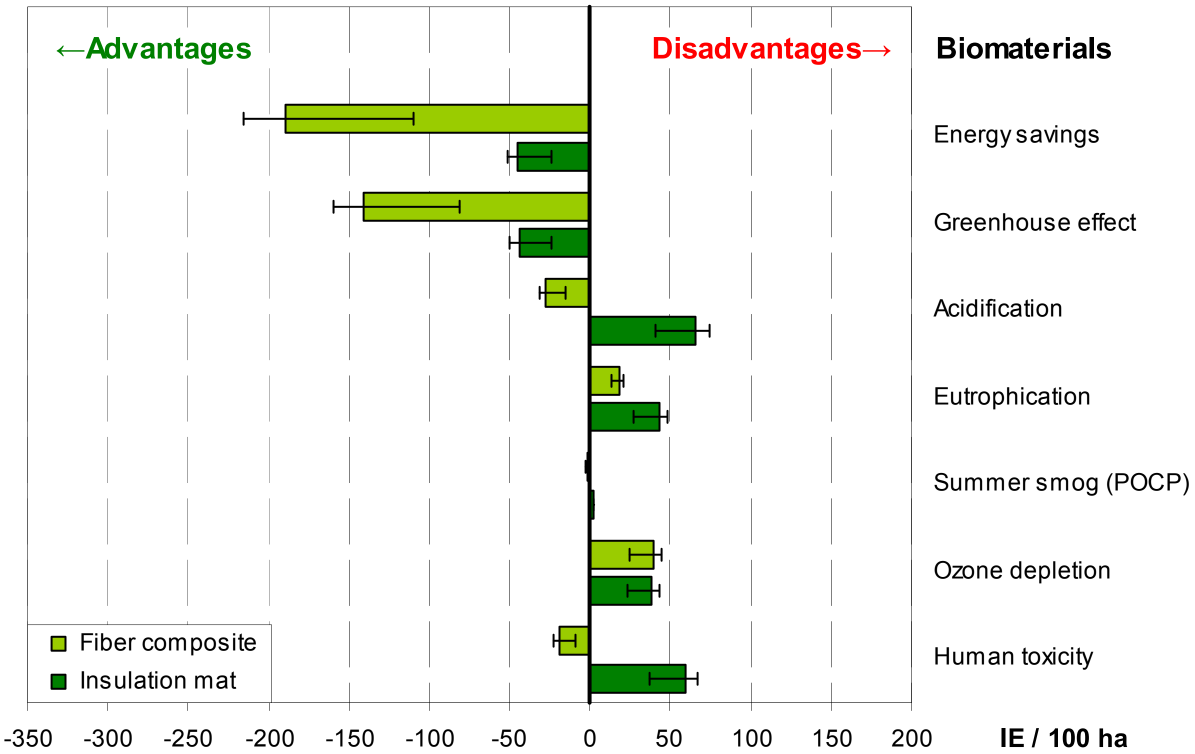

Fig. 4-5 Results of the life cycle comparison of biomaterials produced from flax fibers grown in the Continental (CON) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Reading the diagram – exemplification of 1st bar 'energy savings'

If flax fibers are used for the production of fiber composites that replace conventionally produced synthetic fiber composites, the energy savings per 100 hectares equal the yearly energy demand of 190 inhabitants.

4.2.2.2 Hemp (ATN)

Results: biomaterials

- By using fiber composites made from hemp fibers instead of conventionally produced synthetic fiber composites, fossil energy resources can be saved and greenhouse gas emissions can be reduced (see Fig. 4-6). On the contrary, the biomaterial option clearly show environmental disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity. Regarding summer smog, results are inconclusive.
- Also insulation mats produced from hemp fibers show advantages regarding energy savings and greenhouse effect whereas for acidification, eutrophication, ozone depletion, and human toxicity, they show disadvantages compared to conventionally produced rock wool mats. For summer smog ambiguous results are obtained.
- Fiber composites perform better than insulation mats. They show far higher advantages regarding energy savings and greenhouse effect and perform much better regarding acidification, eutrophication, summer smog, and human toxicity. Regarding ozone depletion, both biomaterials show almost the same amount of disadvantages.

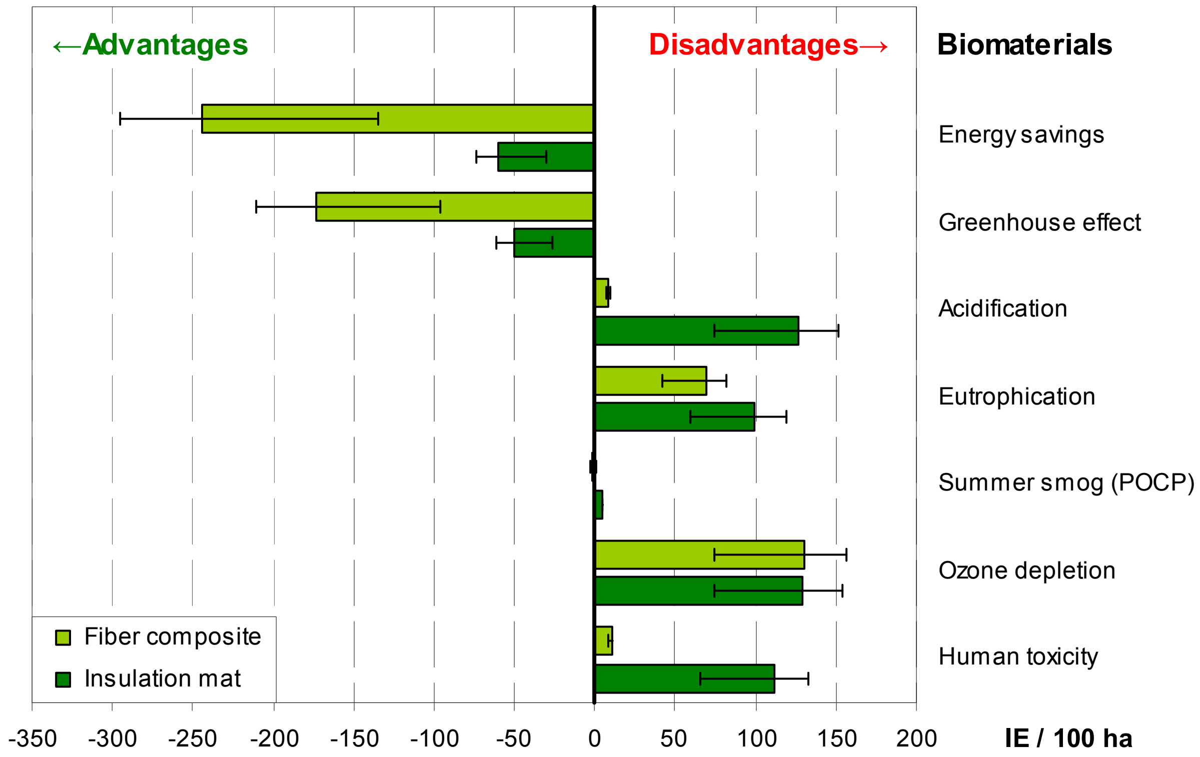

Fig. 4-6 Results of the life cycle comparison of biomaterials produced from hemp fibers grown in the Atlantic North (ATN) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Reading the diagram – exemplification of 1st bar 'energy savings'

If hemp fibers are used for the production of fiber composites that replace conventionally produced synthetic fiber composites, the energy savings per 100 hectares equal the yearly energy demand of about 244 inhabitants.

4.2.3 Woody lignocellulosic crops

This chapter presents the results of the life cycle comparisons for woody lignocellulosic crops. As described in chapter 3.3.3, three different pathways are assessed for each crop: 1) direct combustion in a CHP, 2) gasification, and 3) processing in a biorefinery. For bioenergy, only one of the three options presented in chapter 3.3.3 is depicted: the direct combustion in a CHP. The other options are presented in chapter 4.3.4. The pathways are indicated in the legends behind the respective main products and for each crop the abbreviation of the respective environmental zone is indicated in the chapter title.

4.2.3.1 Poplar (ATC)

Results: bioenergy

- If poplar is used in a CHP for heat and power production or for producing FT diesel or fuel ethanol, it shows advantages regarding energy savings and greenhouse effect and disadvantages regarding eutrophication, ozone depletion, and human toxicity. For acidification, both biofuels are disadvantageous whereas for the use in a CHP the results are ambiguous. The same applies for summer smog: no clear results are obtained for the use of the wood in a CHP and for FT diesel whereas fuel ethanol production shows clear advantages (see Fig. 4-7).
- If poplar wood is used to produce heat and power in a CHP, most energy and greenhouse gases can be saved, followed by fuel ethanol and FT diesel. Regarding acidification, eutrophication, ozone depletion, and human toxicity, CHP and FT diesel perform quite similar and show less disadvantages than fuel ethanol. If summer smog is to be avoided, fuel ethanol is the best use option.

Results: biomaterials

- Most of the bio-based materials assessed show the following pattern: advantages regarding energy savings and greenhouse effect and disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity. As an exception, 1,3-PDO shows (very small) advantages regarding acidification and human toxicity. In these impact categories, the disadvantages for chemical ethanol are only small, too. For summer smog, chemical ethanol and 1,3-PDO show advantages whereas both ethylene pathways show inconclusive results (see Fig. 4-7).
- Of all bio-based materials assessed, 1,3-PDO shows the best results regarding energy savings, greenhouse effect and summer smog, followed by chemical ethanol, ethylene produced in a biorefinery, and ethylene produced via biomass gasification. Regarding acidification, eutrophication, and human toxicity, 1,3-PDO and chemical ethanol show similar results – just as do both ethylene pathways. The latter show much more disadvantages than chemical ethanol and 1,3-PDO. Regarding ozone depletion, there are no significant differences between the biomaterials.

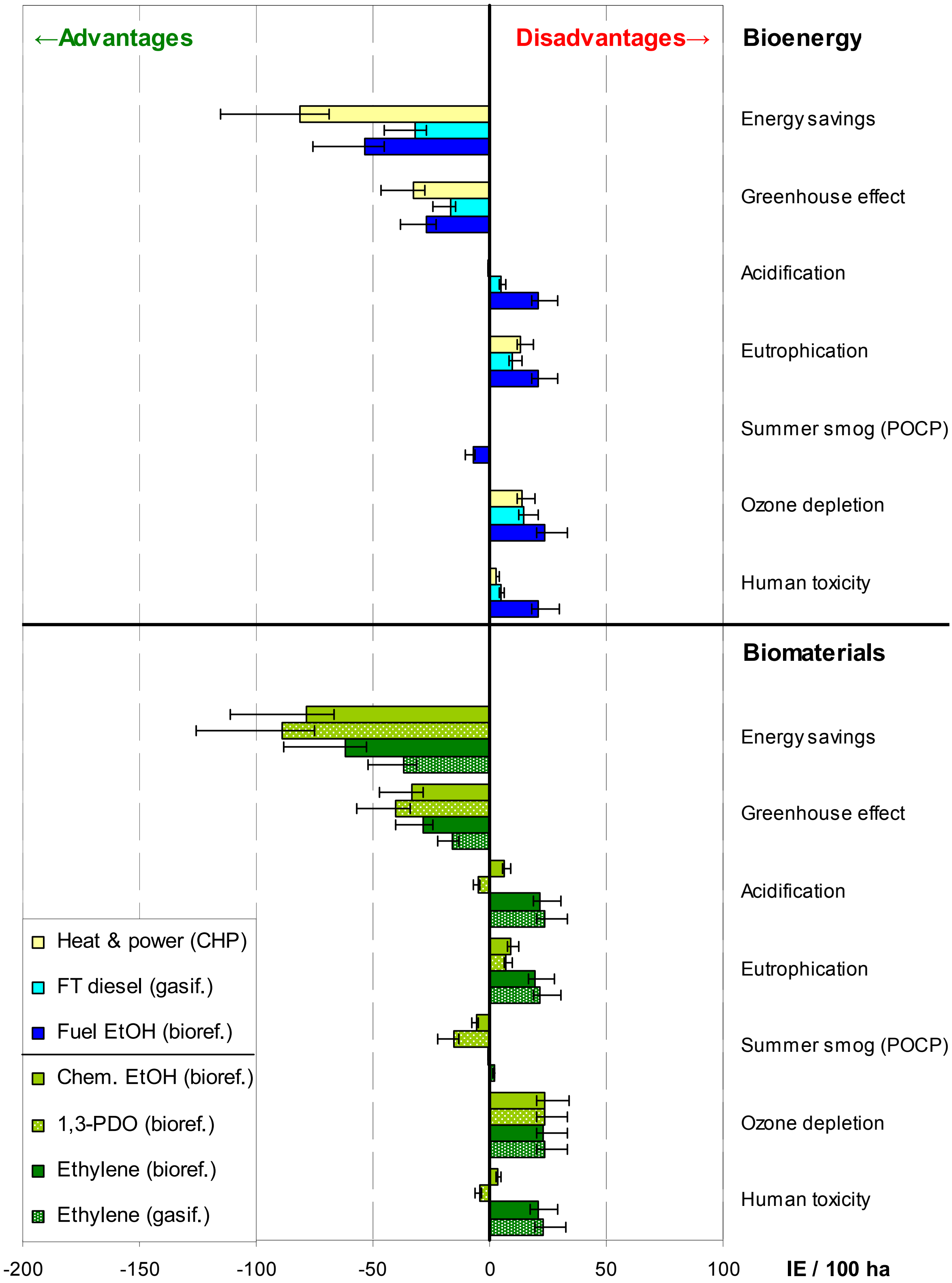

Fig. 4-7 Results of the life cycle comparisons for bioenergy and biomaterials obtained from poplar via direct combustion ('CHP'), gasification ('gasif.'), and in a biorefinery ('bioref.') for the Atlantic Central (ATC) Zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.3.2 Willow (CON)

Results: bioenergy

- The production of power and heat in a CHP from willow wood as well as of FT diesel and fuel ethanol helps saving energy and greenhouse gases. Fuel ethanol also shows advantages regarding summer smog. In contrast, many bioenergy use options show disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity. As an exception from this pattern, the use of wood in a CHP or as FT diesel does not lead to any clear results regarding acidification, summer smog and human toxicity (see Fig. 4-8).
- The direct combustion of the wood in a CHP leads to more savings in energy and greenhouse gases than the use for fuel ethanol or FT diesel production. Regarding acidification, eutrophication, ozone depletion, and human toxicity, the use in a CHP and for fuel ethanol production performs almost equally and both use options show far less disadvantages than FT diesel. Regarding summer smog, by far the best option is to produce fuel ethanol.

Results: biomaterials

- All biomaterial pathways assessed show advantages regarding energy savings and greenhouse effect. Both ethylene pathways show clear disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity. 1,3-PDO shows slight advantages regarding acidification and human toxicity and disadvantages regarding eutrophication. In these three categories, also chemical ethanol performs disadvantageously. Regarding summer smog, chemical ethanol and 1,3-PDO show advantages, whereas both ethylene pathways show ambiguous results (see Fig. 4-8).
- If the four biomaterials are compared among each other, the following results can be derived: 1,3-PDO performs best since it saves most energy and greenhouse gases and shows the highest advantages regarding summer smog. Regarding acidification, eutrophication, and human toxicity it performs similarly with chemical ethanol. Both show far less disadvantages than the two ethylene pathways. Regarding energy savings and greenhouse effect, chemical ethanol performs second best, followed by ethylene produced in a biorefinery and ethylene produced via biomass gasification. Regarding ozone depletion, there is almost no difference between the four biomaterials assessed.

Reading the diagram – exemplification of 1st bar 'energy savings' for bioenergy

If willow wood is combusted in a CHP to produce heat and power that replace conventionally produced heat and power, energy savings that can be achieved per 100 hectares equal the yearly energy demand of about 93 inhabitants.

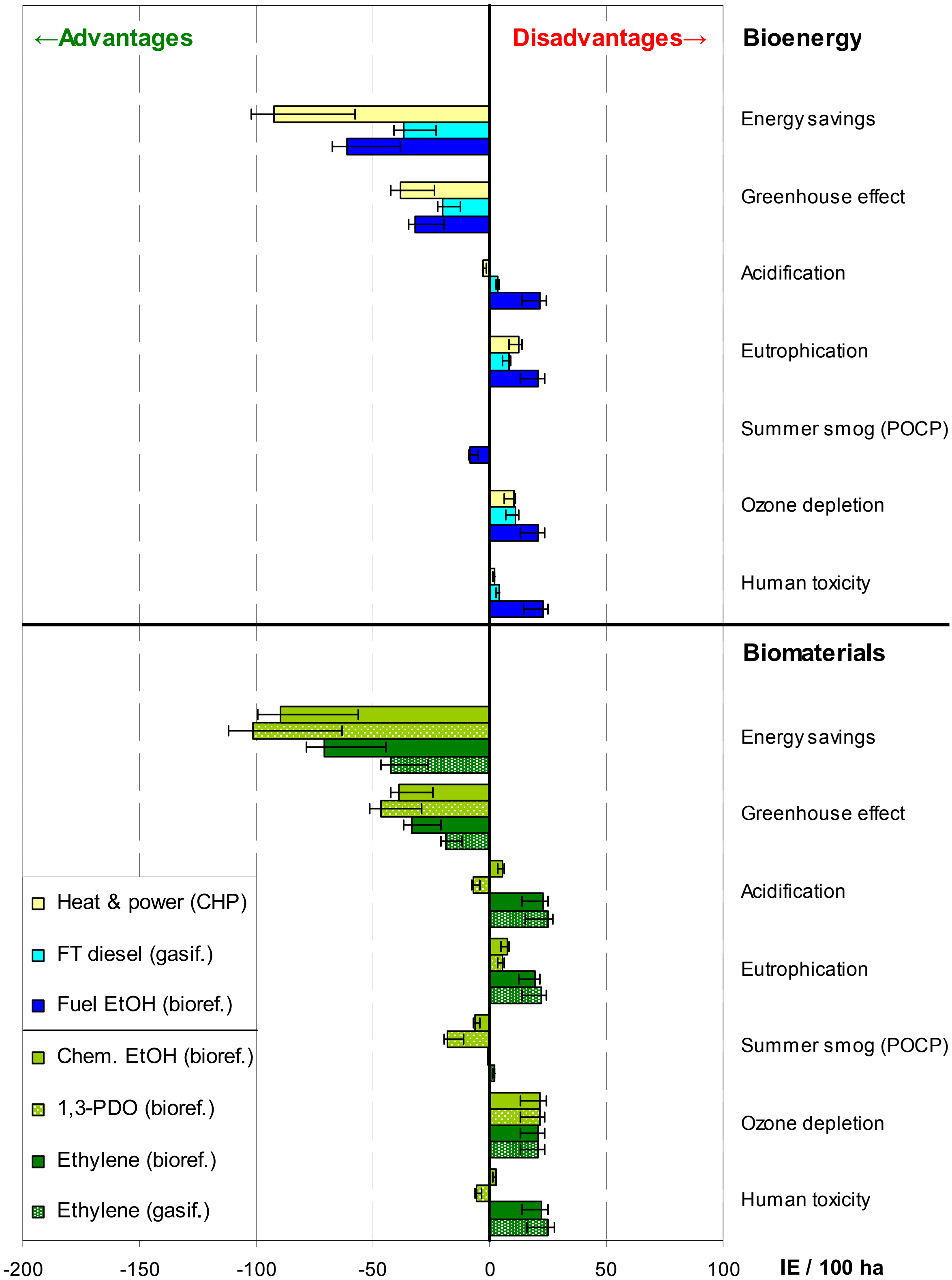

Fig. 4-8 Results of the life cycle comparison for bioenergy and biomaterials obtained from poplar via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Continental (CON) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.3.3 Eucalyptus (MDS)

Results: bioenergy

- If eucalyptus wood is used for the production of heat and power in a CHP or for the production of the biofuels FT diesel and fuel ethanol, energy and greenhouse gas emissions can be saved compared to the fossil equivalent products. However, these advantages come along with disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity for all bioenergy pathways assessed. For summer smog, fuel ethanol shows advantages whereas for the two other bioenergy no clear results are obtained (see Fig. 4-9).
- The combustion of the wood in a CHP clearly performs best in saving energy and greenhouse gases, followed by FT diesel and fuel ethanol. Regarding acidification, eutrophication, ozone depletion, and human toxicity, CHP and FT diesel perform similarly and show less disadvantages than fuel ethanol. Regarding summer smog, fuel ethanol is by far the best choice.

Results: biomaterials

- All biomaterials produced from eucalyptus wood show clear advantages regarding energy savings and greenhouse effect and clear disadvantages regarding eutrophication and ozone depletion. For acidification and human toxicity, both ethylene pathways show clear disadvantages and also chemical ethanol shows slight disadvantages whereas 1,3-PDO shows inconclusive results. For summer smog, chemical ethanol and 1,3-PDO show advantages. In this environmental impact category, both ethylene pathways show ambiguous results (see Fig. 4-9).
- By producing 1,3-PDO, most energy and greenhouse gases can be saved and most summer smog can be avoided, followed by chemical ethanol, ethylene from biomass gasification and ethylene from a biorefinery. For ozone depletion, there is no significant difference between the four biomaterial use options. For acidification, eutrophication, and human toxicity, both ethylene pathways perform similarly and show clearly higher disadvantages than chemical ethanol and 1,3-PDO – which both also show very similar results.

Reading the diagram – exemplification of 2nd bar 'energy savings' for bioenergy

If eucalyptus wood is used to produce Fischer-Tropsch diesel that replaces conventional diesel as a transport fuel, the energy savings per 100 hectares equal the yearly energy demand of about 53 inhabitants.

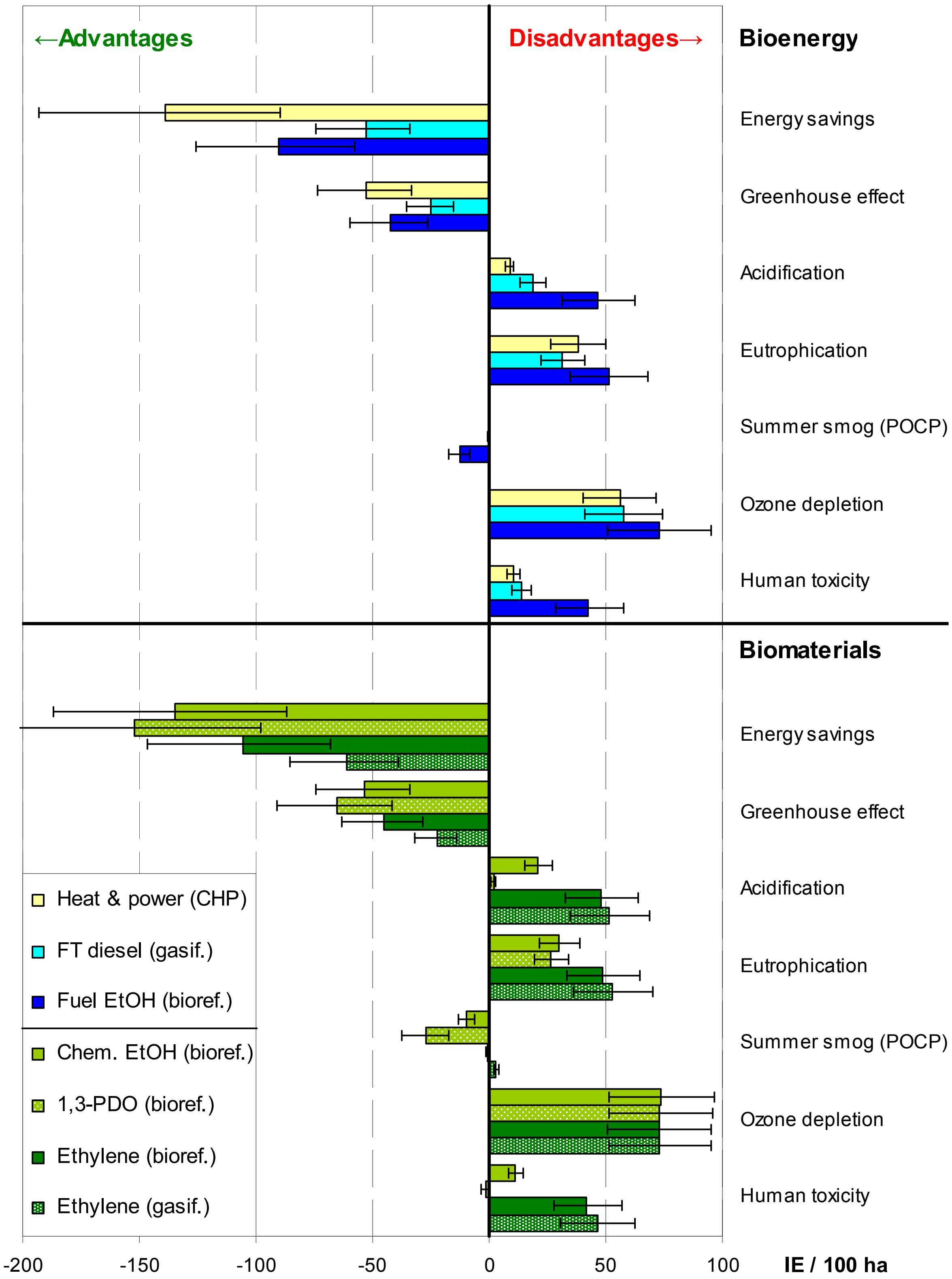

Fig. 4-9 Results of the life cycle comparison for bioenergy and biomaterials obtained from eucalyptus via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Mediterranean South (MDS) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.4 Herbaceous lignocellulosic crops

Also for herbaceous lignocellulosic crops three pathways are assessed: 1) direct combustion in a CHP, 2) gasification, and 3) processing in a biorefinery (see chapter 3.3.3). For bioenergy, only direct combustion in a CHP is depicted. The two other options named in chapter 3.3.3 are presented in chapter 4.3.4 as sensitivity analyses. The pathways are indicated in the legends and the abbreviation of the respective environmental zone is indicated in the chapter title.

4.2.4.1 Reed canary grass (NEM)

Results: bioenergy

- The production of heat and power in a CHP or of biofuels from reed canary grass helps saving energy and greenhouse gases, but shows disadvantages regarding eutrophication, ozone depletion, and human toxicity. In the latter impact category, however, disadvantages for the use in a CHP and for the production of FT diesel are very small. For acidification, fuel ethanol shows disadvantages whereas the use as FT diesel or in a CHP performs neutrally. Regarding summer smog, fuel ethanol shows advantages whereas the use in a CHP and for FT diesel is ambiguous (see Fig. 4-10).
- Of all bioenergy use options assessed, most energy and greenhouse gases can be saved if reed canary grass is combusted in a CHP for the production of heat and power. Fuel ethanol and FT diesel are second and third best, respectively. Regarding acidification, eutrophication, ozone depletion, and human toxicity, fuel ethanol shows far more disadvantages than the use in a CHP or for producing FT diesel. The latter two options perform similarly. Regarding summer smog, fuel ethanol saves most emissions.

Results: biomaterials

- All bio-based materials assessed save energy resources and greenhouse gas emissions in comparison to their fossil equivalent products. However, at the same time additional emissions leading to eutrophication and ozone depletion are caused. Also regarding acidification and human toxicity, both ethylene pathways show clear disadvantages – just as does chemical ethanol. For the latter, however, they are very small. In contrast, 1,3-PDO shows slight advantages. Regarding summer smog, chemical ethanol and 1,3-PDO help saving emissions whereas both ethylene pathways show inconclusive results (see Fig. 4-10).
- The production of 1,3-PDO from reed canary grass leads to the highest savings regarding energy, greenhouse gas emissions and the emission of photooxidants (causing summer smog) – followed by chemical ethanol, ethylene produced in a biorefinery and ethylene produced via biomass gasification. The latter performs disadvantageously regarding summer smog. Regarding acidification, eutrophication, and human toxicity, chemical ethanol and 1,3-PDO show similar results and perform better than the two ethylene pathways which also perform similarly. Regarding ozone depletion, all biomaterials show equally disadvantageous results.

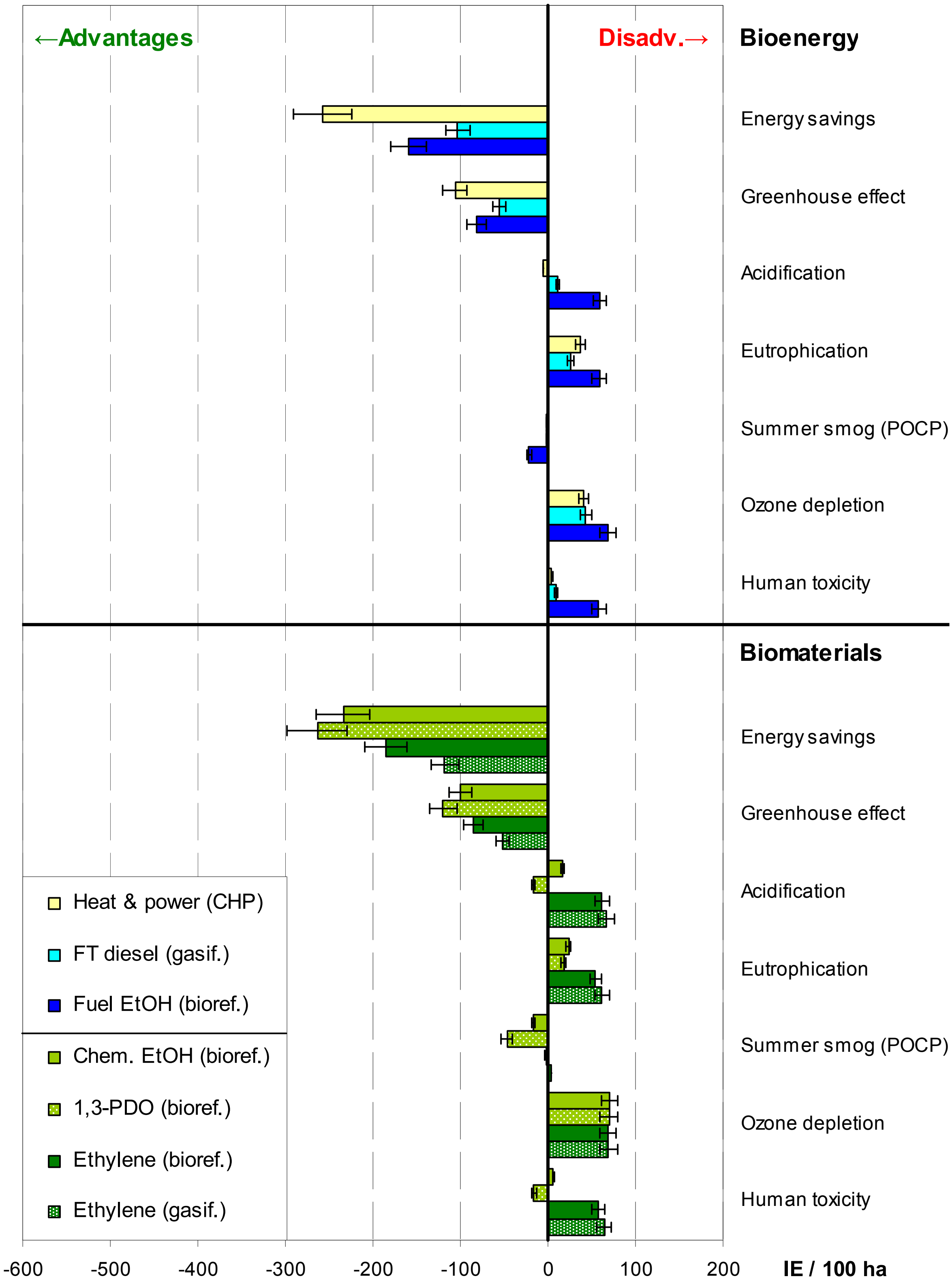

Fig. 4-10 Results of the life cycle comparison for bioenergy and biomaterials obtained from reed canary grass via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Nemoral (NEM) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.4.2 Miscanthus (ATN)

Results: bioenergy

- The use of Miscanthus in a CHP or for the production of ethanol or FT diesel shows advantages regarding energy savings and greenhouse effect. However, the advantages come along with disadvantages regarding eutrophication and ozone depletion. Regarding acidification, fuel ethanol shows clear disadvantages whereas the use in a CHP and as FT diesel do not show clear results: here, credits and expenditures that occur along the life cycle almost completely outweigh each other. For human toxicity, fuel ethanol again shows clear disadvantages whereas for the other two use options, no clear results can be given. The same is true for the use in a CHP and for FT diesel in the impact category summer smog. Here, fuel ethanol shows clear advantages (see Fig. 4-11).
- The combustion of Miscanthus in a CHP is the bioenergy application that leads to the highest savings of energy and greenhouse gases as well as of photooxidants – followed by fuel ethanol and FT diesel. For all other environmental impact categories, fuel ethanol shows the most disadvantageous results. For acidification, eutrophication, ozone depletion and human toxicity, the use of Miscanthus in a CHP as well as for FT diesel show ambiguous results.

Results: biomaterials

- The environmental impact categories for which all bio-based materials assessed show advantages are energy savings and greenhouse effect. In contrast, all materials contribute to eutrophication and ozone depletion. Regarding acidification and human toxicity, the two ethylene pathways show disadvantageous results whereas 1,3-PDO shows advantageous results. Chemical ethanol performs neutrally regarding acidification and human toxicity. Regarding summer smog, chemical ethanol and 1,3-PDO help saving respective emissions. Here, both ethylene pathways show inconclusive results (see Fig. 4-11).
- Of all bio-based materials assessed, 1,3-PDO helps saving the most energy and greenhouse gases as well as photooxidants. Chemical ethanol, ethylene produced in a biorefinery as well as ethylene produced via biomass gasification show the next best results. 1,3-PDO performs also best regarding acidification, eutrophication, and human toxicity – closely followed by chemical ethanol. Both ethylene production pathways perform equally disadvantageous in these categories. Regarding ozone depletion, there is no significant difference between the four bio-based materials.

Reading the diagram – exemplification of 6th bar 'greenhouse effect' for biomaterials

Greenhouse gas savings equivalent to the yearly emissions of 118 Europeans can be achieved per 100 hectares of Miscanthus, if 1,3-PDO is produced from Miscanthus that replaces conventionally produced 1,3-PDO.

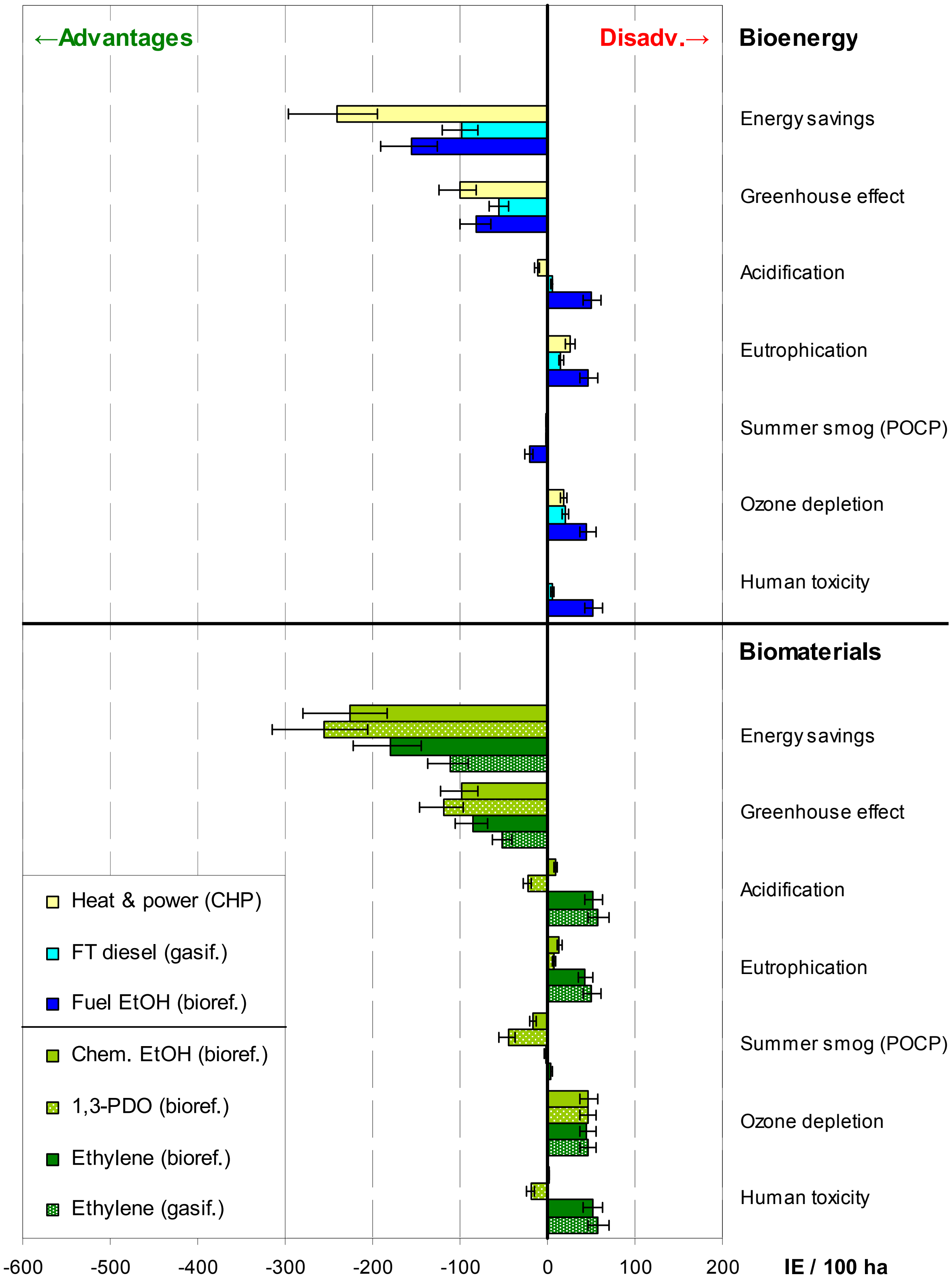

Fig. 4-11 Results of the life cycle comparison for bioenergy and biomaterials obtained from Miscanthus via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Atlantic North (ATN) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.4.3 Switchgrass (ATN)

Results: bioenergy

- All bioenergy pathways based on switchgrass help saving energy and greenhouse gas emissions compared to fossil energy carriers. On the contrary, most pathways are disadvantageous regarding eutrophication, ozone depletion, and human toxicity. Regarding the latter impact category, the use in a CHP and for FT diesel show ambiguous results. For acidification, fuel ethanol shows disadvantages and for the use as FT diesel or in a CHP, results are inconclusive. The same holds true for the use in a CHP and the production of FT diesel regarding summers smog. Here, fuel ethanol shows clear advantages (see Fig. 4-12).
- When comparing the bioenergy pathways among each other, the use of switchgrass in a CHP performs best in terms of saving energy and greenhouse gas emissions and also shows the best results regarding acidification. Regarding eutrophication and ozone depletion, the results of the use in a CHP and for FT diesel are very similar and both are less disadvantageous than fuel ethanol. For summer smog, fuel ethanol shows the highest savings.

Results: biomaterials

- By replacing conventionally produced materials by bio-based materials from switchgrass, energy demand and greenhouse gas emissions are reduced. In contrast, eutrophication and ozone depletion are increased. Regarding acidification and human toxicity, bio-based ethylene – regardless of the production pathway – increases the respective emissions. In these environmental categories, 1,3-PDO is advantageous whereas chemical ethanol shows inconclusive results. Chemical ethanol and 1,3-PDO help reducing summer smog whereas both ethylene pathways show ambiguous results (see Fig. 4-12).
- Among the four bio-based material use options assessed, 1,3-PDO helps saving most energy and greenhouse gases as well as most summer smog causing emissions. It is followed by chemical ethanol, ethylene produced in a biorefinery and ethylene produced via biomass gasification. The best performance of 1,3-PDO also occurs in all other environmental impact categories – except for ozone depletion, where all four products perform equally. In these categories, both ethylene pathways have almost similar results and highest disadvantages.

Reading the diagram – exemplification of 2nd bar 'energy savings' for biomaterials

If 1,3-PDO is produced from switchgrass replacing conventionally produced 1,3-PDO, the energy savings per 100 hectares equal the yearly energy demand of 258 Europeans.

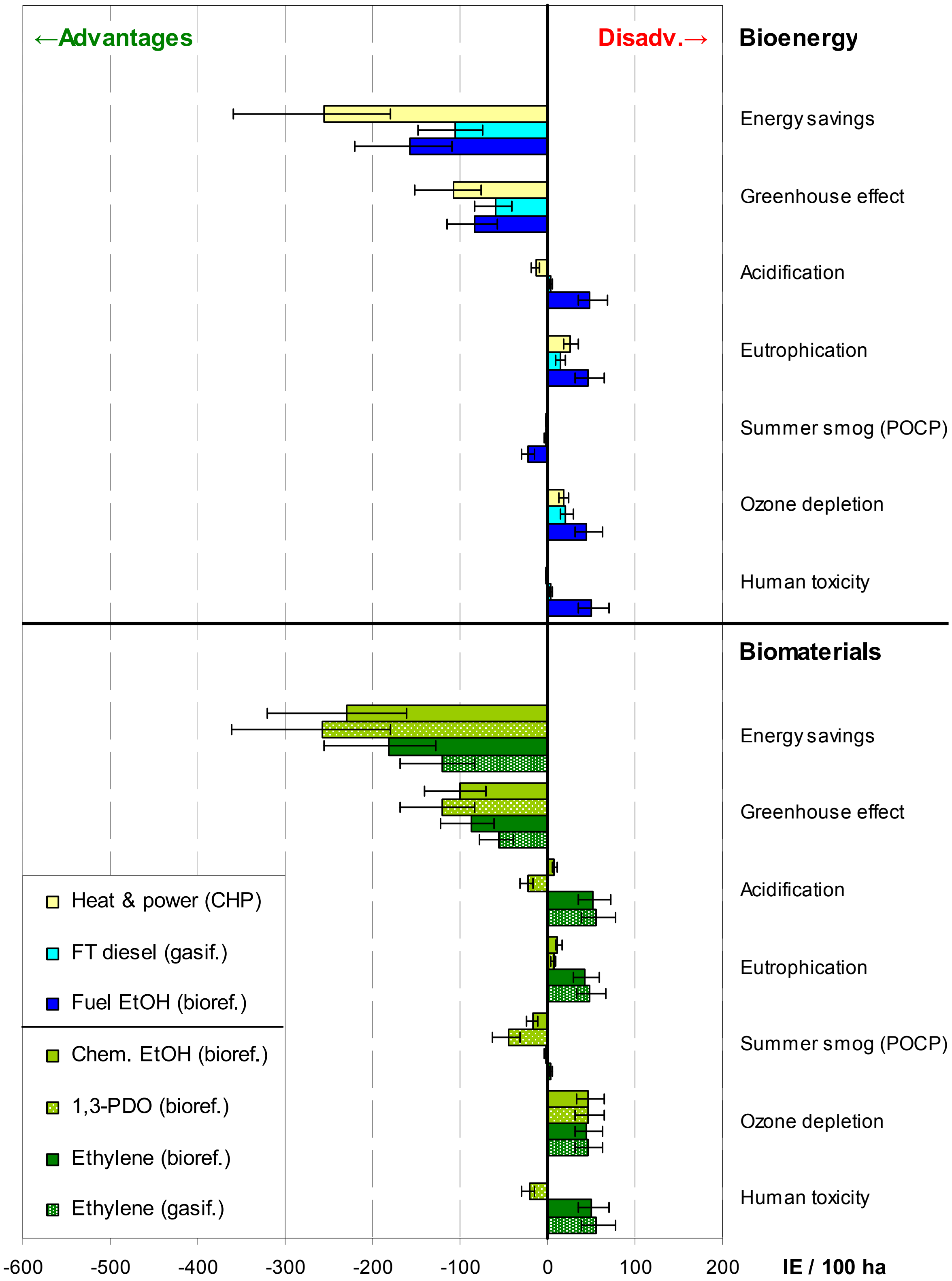

Fig. 4-12 Results of the life cycle comparison for bioenergy and biomaterials obtained from switch grass via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Atlantic north (ATN) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.4.4 Giant reed (MDN)

Results: bioenergy

- On the one hand, the use of giant reed for producing heat and power in a CHP or for the biofuels FT diesel or ethanol helps saving energy and greenhouse gas emissions. On the other hand, eutrophication, ozone depletion, and human toxicity are increased. Also regarding acidification, the production of biofuels show disadvantages. For the use in a CHP, results are inconclusive. Here, the credits gained from the co-products and for replacing fossil heat and power almost exactly compensate all expenditures that occur during the production process. Regarding summer smog, the use of giant reed for ethanol production shows clear advantages whereas for the other two bioenergy pathways, there are no clear results (see Fig. 4-13).
- Most energy and greenhouse gases can be saved if giant reed is used in a CHP, followed by its use for producing ethanol or FT diesel as transport fuels. Also regarding acidification, ozone depletion, and human toxicity, the use in a CHP shows best results, directly followed by FT diesel. For eutrophication, FT diesel shows slightly better results. Regarding summer smog, however, fuel ethanol is the best use option.

Results: biomaterials

- Most of the bio-based materials produced from giant reed show the following pattern: advantages regarding energy savings and greenhouse effect and disadvantages regarding acidification, eutrophication, ozone depletion, and human toxicity. As an exception, 1,3-PDO shows advantages regarding acidification and human toxicity. For summer smog, chemical ethanol and 1,3-PDO show advantages, whereas both ethylene pathways show ambiguous results (see Fig. 4-13).
- Of all bio-based materials assessed, 1,3-PDO shows the best results regarding energy savings and greenhouse effect, followed by chemical ethanol, ethylene produced in a biorefinery and ethylene produced via biomass gasification. Also regarding acidification and human toxicity, 1,3-PDO performs best. For summer smog, 1,3-PDO shows by far the best results, followed by chemical ethanol. Regarding ozone depletion, there are no significant differences between the bio-based materials assessed.

Reading the diagram – exemplification of 4th bar 'energy savings' for biomaterials

If ethylene is produced from giant reed via biomass gasification and replaces conventionally produced ethylene, the energy savings per 100 hectares equal the yearly energy demand of about 296 inhabitants.

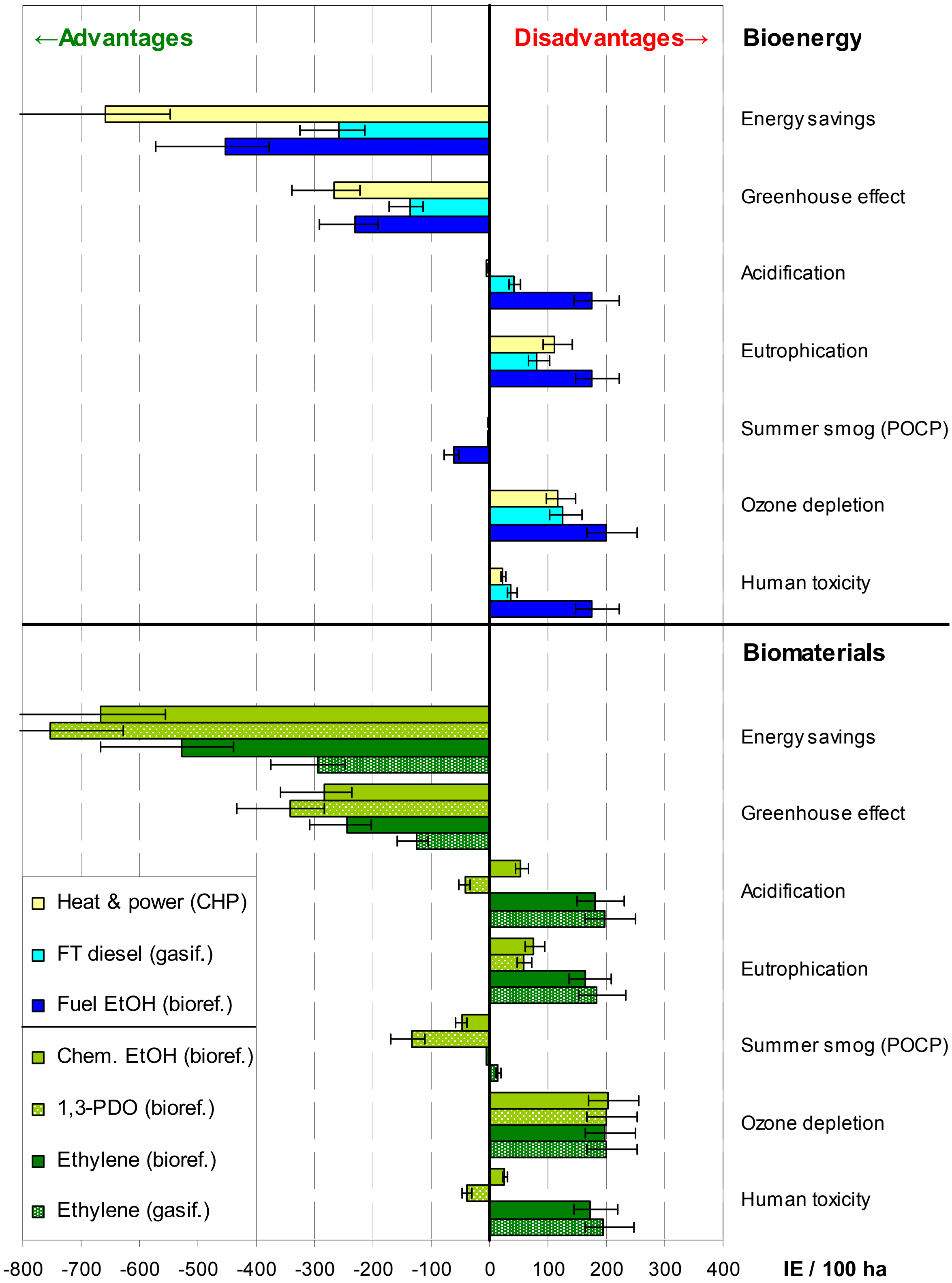

Fig. 4-13 Results of the life cycle comparison for bioenergy and biomaterials obtained from giant reed via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bio-ref.') for the Mediterranean North (MDN) zone (FT = Fischer-Tropsch, EtOH = E-thanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.4.5 Cardoon (MDS)

Results: bioenergy

- If cardoon is used for producing heat and power in a CHP or for producing the biofuels FT diesel and fuel ethanol, energy and greenhouse gas emissions can be saved compared to the fossil equivalent products. These advantages come along with disadvantages regarding eutrophication, ozone depletion, and human toxicity. However, the disadvantages regarding human toxicity for the use in a CHP are only very small. Regarding acidification, the use in a CHP is neutral whereas both biofuels show disadvantageous results. For summer smog, only fuel ethanol shows advantages whereas the use in a CHP or as FT diesel shows inconclusive results (see Fig. 4-14).
- If the three bioenergy use options are compared with each other, the combustion of cardoon in a CHP clearly performs best in terms of saving energy and greenhouse gases, followed by FT diesel and fuel ethanol. The use in a CHP also shows best results regarding acidification. For eutrophication, ozone depletion, and human toxicity the production and use of FT diesel performs equal with the use in a CHP and better than fuel ethanol. Only for summer smog, fuel ethanol is the best choice.

Results: biomaterials

- Similar to bioenergy, the bio-based materials obtained from cardoon all help saving energy and reducing greenhouse gas emissions. However, all biomaterials show disadvantages for eutrophication and ozone depletion. For acidification and human toxicity, both ethylene pathways are clearly disadvantageous. Also chemical ethanol is disadvantageous here, although the results are very small. 1,3-PDO, in contrast, shows slight advantages. Regarding summer smog, ethanol and 1,3-PDO show clear advantages, whereas the results for both types of ethylene are ambiguous (see Fig. 4-14).
- If the four bio-based materials assessed are compared with each other, the following results can be derived: 1,3-PDO performs best in saving energy and greenhouse gases and shows the highest advantages regarding acidification, summer smog, and human toxicity. Both ethylene pathways show similar results, however, they show highest disadvantages. Regarding ozone depletion, there is almost no difference between the four bio-based materials.

Reading the diagram – exemplification of 2nd bar 'energy savings' for bioenergy

If cardoon is used to produce FT diesel that replaces conventional diesel as a transport fuel, the energy savings per 100 hectares equal the yearly energy demand of 134 inhabitants.

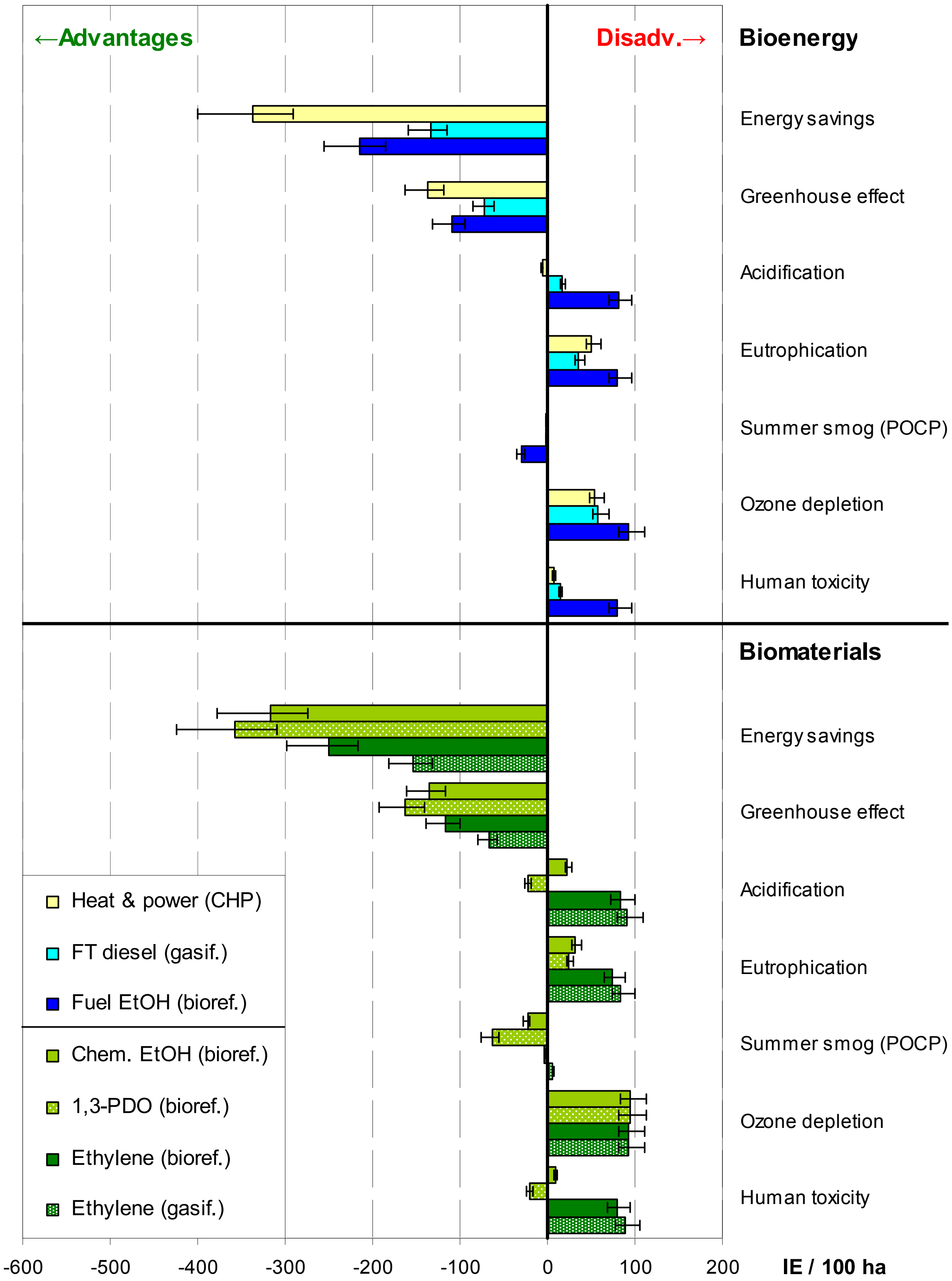

Fig. 4-14 Results of the life cycle comparison for bioenergy and biomaterials obtained from cardoon via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Mediterranean South (MDS) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.5 Sugar crops

The production and use of biofuel and bio-based materials from the sugar crops sweet sorghum and sugar beet differ substantially in their life cycles. For sugar beet, only the production of biofuel is assessed as bioenergy option. For sweet sorghum, energy and biomaterial options are assessed based on two different crop parts that are obtained at the same time: grains and a sugary juice. For every crop the environmental zone that the results refer to is indicated in the chapter title.

4.2.5.1 Sugar beet (ATC)

Results: bioenergy

- If fuel ethanol produced from sugar beet is used instead of conventional gasoline, fossil energy carriers can be saved and greenhouse gas as well as summer smog emissions can be reduced (see Fig. 4-15).
- However, sugar beet ethanol shows disadvantages regarding the environmental impact categories acidification, eutrophication, ozone depletion, and human toxicity.

Results: biomaterials

- All three bio-based materials produced from sugar beet show advantages regarding energy savings, greenhouse effect and summer smog. In contrast, clear disadvantages occur for eutrophication and ozone depletion. For acidification and human toxicity, chemical ethanol as well as 1,3-PDO show advantages whereas ethylene shows disadvantages. (see Fig. 4-15).
- Comparing the biomaterial use options shows that 1,3-PDO performs best regarding energy savings, greenhouse effect, acidification, summer smog, and human toxicity: in these impact categories, the highest savings can be obtained. However, regarding ozone depletion, it shows by far the highest disadvantages. Regarding energy savings and greenhouse effect, chemical ethanol has the second best results, followed by ethylene. Chemical ethanol also performs better than ethylene regarding acidification, eutrophication, summer smog, and human toxicity. Regarding ozone depletion, both products show the same results.

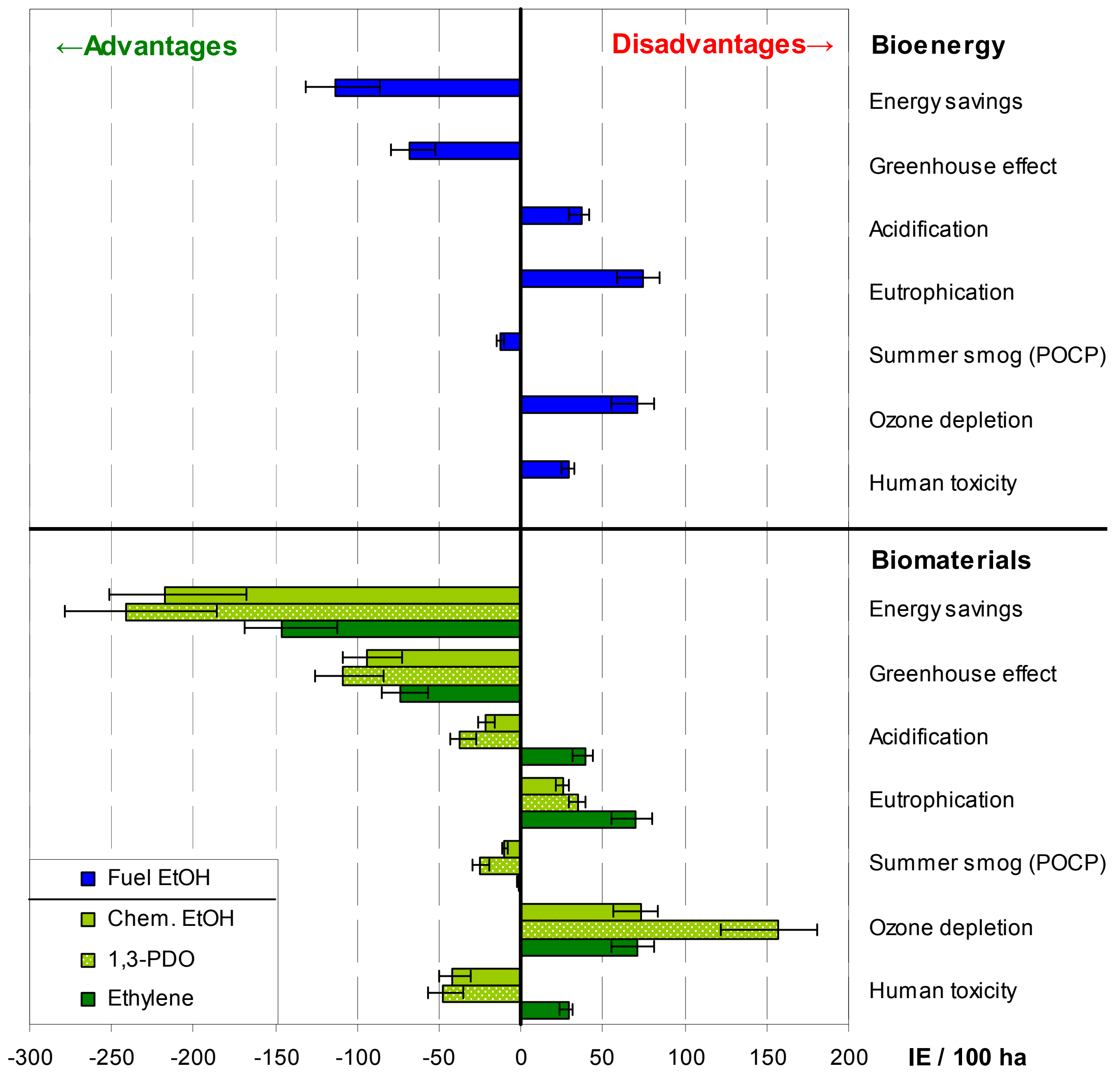

Fig. 4-15 Results of the life cycle comparison between bioenergy and biomaterials obtained from sugar beet and the conventional counterparts of the main products for the Atlantic Central (ATC) zone (EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Reading the diagram – exemplification of 1st bar 'energy savings' for bioenergy

If sugar beet is used to produce ethanol that replaces conventionally produced gasoline as a transport fuel, the energy savings per 100 hectares equal the yearly energy demand of 114 inhabitants.

4.2.5.2 Sweet sorghum (MDN)

For sweet sorghum, different crop parts (grains and juice) can be used in different ways. Both juice and grains can be used to produce biomaterials and bioenergy (for all combinations assessed, see Table 3-3). Theoretically, the production of bioenergy and biomaterials can be combined. This combination, however, is not assessed in this chapter in order not to mix both use paths. Only the combination of different biomaterial products is assessed. The respective combinations are indicated in the legend. The first product is produced from juice, the second one from the grains.

Results: bioenergy

- The production of ethanol from sweet sorghum juice and grains shows advantages regarding energy savings, greenhouse effect and summer smog (see Fig. 4-16).
- However, results regarding acidification, eutrophication and ozone depletion are slightly disadvantageous. Regarding human toxicity, no clear results can be derived.

Results: biomaterials

- All biomaterials assessed show advantages for energy savings and greenhouse effect as well as regarding summer smog and human toxicity. However, all materials perform disadvantageous regarding eutrophication and ozone depletion. For acidification, chemical ethanol and both combinations show advantages. Ethylene shows slight disadvantages.
- Chemical ethanol performs best in saving energy and greenhouse gases. Regarding acidification, summer smog and human toxicity, chemical ethanol (stand-alone or in combination with 1,3-PDO) show very similar results and perform better than ethylene (also both stand-alone and in combination with 1,3-PDO). Regarding eutrophication, both variations of ethylene also show very similar results and perform slightly better than 1,3-PDO. For ozone depletion, chemical ethanol and ethylene as well as both combinations of 1,3-PDO show similar results. The first group shows less disadvantages.

Results: bandwidths

- In contrast to all graphs in the previous chapters, in Fig. 4-16 the energy and greenhouse gas balances for average yields (depicted in the balances) do not lie between the results for minimum and maximum yields (depicted in the bandwidths). In contrast, results for maximum yields even perform less advantageous than results for minimum yields. The reason is that for maximum yields, the crop needs to be irrigated leading to great expenditures in energy and greenhouse gases (see also chapter 2.3). No such expenditures occur for average or minimum yields.

Reading the diagram – exemplification of 2nd bar ‘greenhouse effect’ for bioenergy

If the juice and the grains from sweet sorghum are used to produce ethanol that replaces conventional gasoline as a transport fuel, the greenhouse gas savings per 100 hectares equal the yearly greenhouse gas emissions of 106 inhabitants.

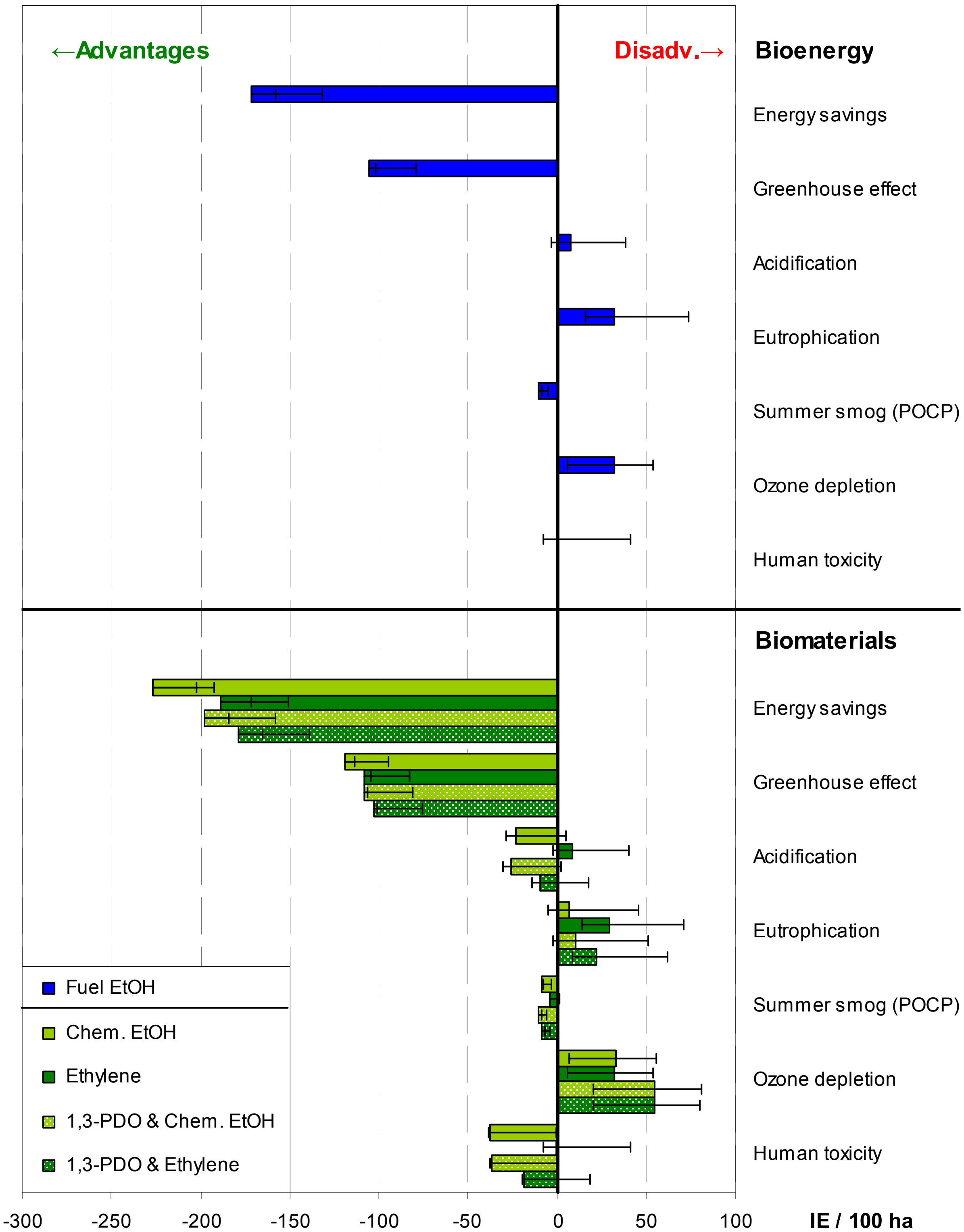

Fig. 4-16 Results of the life cycle comparison for bioenergy and biomaterials obtained from sweet sorghum and the conventional counterparts of the main products for the Mediterranean North (MDN) zone. Note that the production of 1,3-PDO from juice is combined with either chemical ethanol or ethylene from the grains (EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

4.2.6 Synopsis and conclusions

In the previous chapters, detailed results are presented for each of the 15 crops under investigation covering their uses for bioenergy production and as biomaterials. The most important conclusions are pointed out in the following paragraphs.

As exemplified in chapter 4.1 for bioethanol from sugar beet, the single life cycle stages contribute to the overall results to different extents. For example, the conversion phase, i.e. the use of fossil energy carriers as process energy has the largest influence on energy and greenhouse gas balances. In contrast, this stage only is of minor importance for acidification and eutrophication. Here, cultivation and use phases are most relevant due to fertilizer application and use emissions. In total, it is not possible to determine one single life cycle stage with the largest contribution to the overall results across all environmental impact categories but the influences differ between the environmental impact categories.

All credits and expenditures along the life cycles sum up to advantages or disadvantages of the products from non-food crops compared to their fossil equivalents. For an easy overview on the environmental performance of all crops assessed here, the detailed results of the previous chapters are simplified and aggregated in Table 4-1. All in all, the crops show both environmental advantages and disadvantages. The following overall pattern can be identified: advantages in terms of energy and greenhouse gas savings and ambiguous or even disadvantageous results regarding acidification, eutrophication, ozone depletion, summer smog, and human toxicity. With that, an objective conclusion regarding the overall environmental performance of bioenergy and biomaterials produced from the 15 crops is impossible from a scientific point of view. The overall rating rather has to be based on subjective criteria. For that purpose, LCAs offer optional elements such as grouping and weighting. Grouping for example involves a ranking of the impact categories in a given hierarchy (e.g. high, medium, and low priority). However, it has to be noted that any ranking is based on (subjective) value-choices. Different individuals, organisations and societies may have different preferences; therefore different rankings may be derived based on the same objectively obtained results.

The RE Directive (2009/28/EC) may serve as a guideline for ranking the results. As an overall goal, it aims at a reduction of greenhouse gas emissions and promotes security of energy supply, among others by saving energy. If – based on this directive – energy saving and mitigation of GHG emissions are subjectively given the highest priority, all bioenergy carriers and biomaterials assessed in this study are superior to their fossil or conventional equivalents. Summing up, a conclusion regarding the overall environmental performance of bioenergy and biomaterials is possible based on subjective value-choices, but it is not scientifically defendable.

Despite the impossibility to come to an objective conclusion on whether the biogenous or the fossil / conventional pathways are to be preferred, the biogenous pathways can still be compared among each others. Generally, herbaceous and sugar crops show the highest advantages in terms of energy and greenhouse gas savings. Woody crops perform best regarding acidification, eutrophication, summer smog, ozone depletion, and human toxicity. Oil crops show least advantages.

A thorough and more in-depth comparison of the crops and the respective use pathways will be provided in a separate report on the identification of best options (D 14).

Table 4-1 Environmental performance of different crops for non-food purpose; '++': < –100; '+': < –25; 'o': –25 to +25; '-': > 25; '--': > 100; all values in IE / 100 ha

		Energy savings	Green-house effect	Acidi-fication	Eutro-phica-tion	Sum-mer smog	Ozone deple-tion	Human toxicity
Oil crops	Biodiesel (FAME)	+	o	o	-	o	--	o
	HVO	+	o	o	-	o	--	-
	Power	+	o	-	-	o	--	-
	Heat & power	+	o	-	-	o	--	-
	Heat	+	o	-	-	o	--	-
	Lubricant	+	o	o	-	o	--	o
	Surfactant	+	o	o	-	o	--	o
Fiber crops	Composite	++	++	o	-	o	-	o
	Insulation material	+	+	-	-	o	-	-
Woody crops	Fuel ethanol	+	+	o	o	o	o	o
	FT diesel	+	o	o	o	o	o	o
	Power	+	o	o	o	o	o	o
	Heat & power	+	+	o	o	o	o	o
	Heat	+	+	o	o	o	o	o
	1,3-PDO	++	+	o	o	o	o	o
	Chemical ethanol	+	+	o	o	o	o	o
	Ethylene (biochem.)	+	+	o	o	o	o	o
	Ethylene (thermoc.)	+	o	o	o	o	o	-
Herbaceous crops	Fuel ethanol	++	++	-	-	+	-	-
	FT diesel	++	+	o	-	o	-	o
	Power	++	+	o	-	o	-	-
	Heat & power	++	++	o	-	o	-	o
	Heat	++	++	-	-	o	-	-
	1,3-PDO	++	++	+	o	+	-	+
	Chemical ethanol	++	++	o	o	o	-	o
	Ethylene (biochem.)	++	++	-	-	o	-	-
	Ethylene (thermoc.)	++	+	-	-	o	-	-
Sugar crops	Fuel ethanol	++	+	-	-	o	-	-
	1,3-PDO	++	++	+	-	+	--	+
	Chemical ethanol	++	++	o	-	o	-	+
	1,3-PDO & Ethanol	++	++	o	o	o	-	+
	1,3-PDO & Ethylene	++	++	o	-	o	-	o

4.3 Reference scenarios: Variations and sensitivity analyses

In the following chapters, the outcomes of the modelling of multi-functional dependencies described in chapter 3.4 are presented. For the variations and sensitivity analyses, numerous parameters are varied, followed by a quantification of the respective influence on the results.

4.3.1 Agricultural reference system

The choice of agricultural reference system (including direct and indirect land-use changes) affects the greenhouse gas balances, as presented in Fig. 4-17. The results are exemplified for first and second generation bioethanol from sugar beet and Miscanthus, respectively. Both crops are cultivated in the Continental (CON) zone. The basic scenario (fallow) is marked with an asterisk. For details on the scenarios, refer to chapter 3.4.1, for background information on direct and indirect land-use changes, see chapter 2.2.2.

Results

- Land-use changes and associated changes in carbon stocks can have significant influences on the greenhouse gas balances of energy crops. In certain cases, previously advantageous results even become disadvantageous.
- For **sugar beet**, there is almost no difference between fallow or cereal replacement if only direct land-use changes are regarded (Fallow – dLUC / Cereals – dLUC). Carbon stocks do not change and there are just small expenditures for the production of additional cereals. In contrast, grassland conversion on organic soils (Grassland – dLUC) causes great CO_2 emissions and disadvantageous results.
  The integration of indirect effects has a strong impact on all scenarios. These effects may be advantageous due to land release related to the feed use of pulp and vinasse which supersede soy production in Brazil. If grassland is re-established on this released land, the credits for carbon sequestration equal the carbon loss related to US prairie conversion for additional food production (Fallow – iLUC / Cereals – iLUC). In contrast, indirect effects related to the displacement of feed production (Grassland – iLUC) lead to disadvantageous results: carbon emissions from forest conversion in Brazil for soy production are added to carbon losses from grassland conversion. These losses cannot be compensated by the land release due to co-products.
- For **Miscanthus**, the same results are derived if only direct effects are included: there is no difference between the cultivation on fallow and the displacement of food production (both showing advantages) whereas great disadvantages occur for grassland conversion. If indirect effects are included, however, results differ from sugar beet. Since in Miscanthus processing, no co-product occurs that could be used as feed, no carbon credits can be given that would compensate for part of the carbon losses associated with the displaced food or feed production. Whereas these losses are only small for US prairie conversion compensating the displaced wheat production, they are large for the displacement of feed production. Here, carbon emissions from grassland conversion and emissions from forest conversion for soy production sum up to very disadvantageous results.

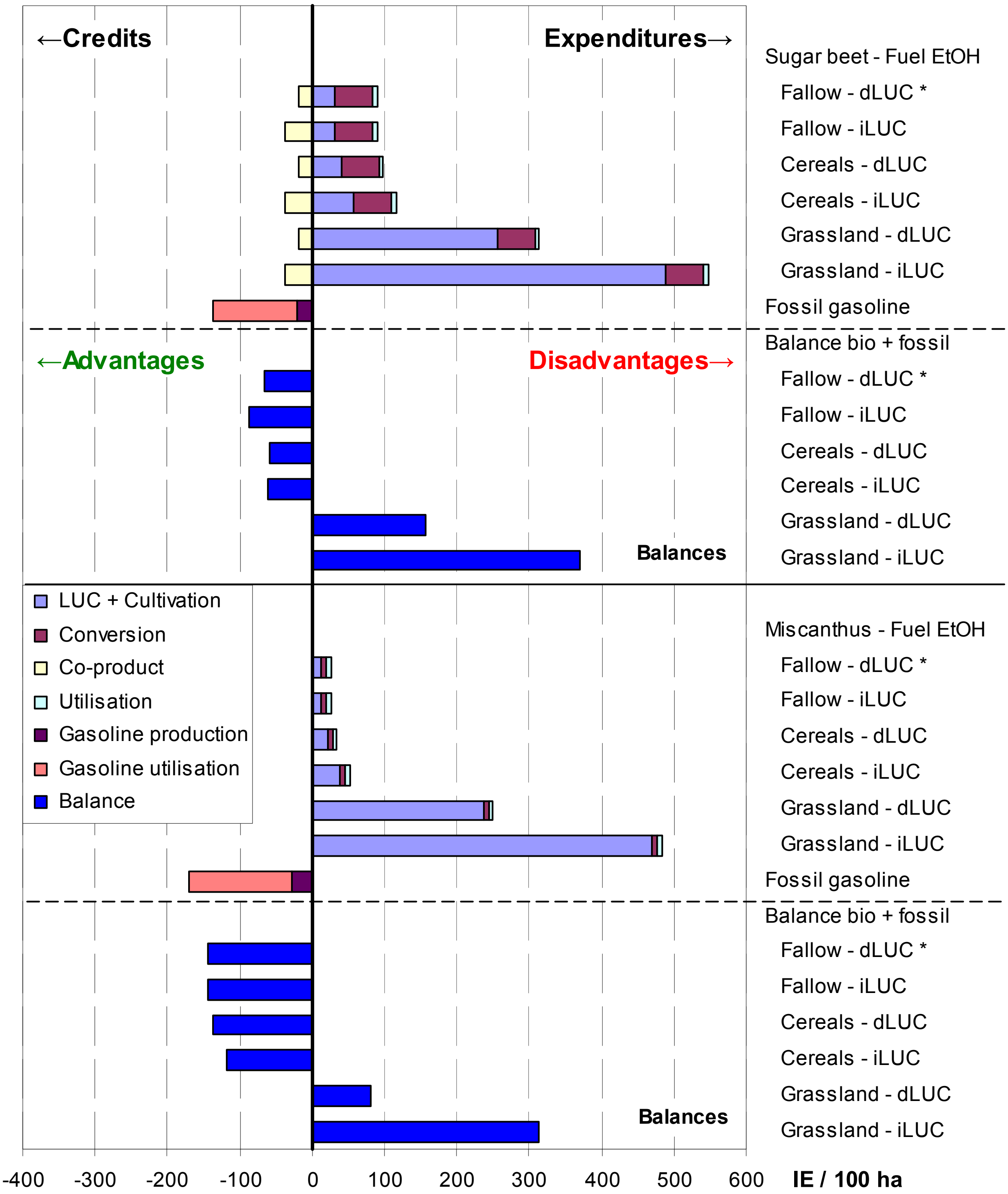

Fig. 4-17 Results of the life cycle comparison for ethanol from sugar beet and Miscanthus with fossil gasoline taking into account direct and indirect land-use changes. * default agricultural reference system in basic scenarios.

Note:

The scenarios regarding direct and indirect land-use change are subjectively chosen and not based on an analysis of land-use dynamics using e.g. general or partial equilibrium models. Therefore, the results are only exemplary, indicating the order of magnitude of these effects.

Conclusions

Land-use changes caused by the production of energy crops can significantly influence the outcome of the greenhouse gas balances. Depending on the carbon stock of the reference system, even disadvantageous results are obtained.

Since to date, no coherent and commonly accepted method is available to quantify indirect effects of land-use changes, they only can be exemplified in life cycle analyses. However, the sensitivity analysis has shown that indirect land-use changes – either associated with the conversion of natural ecosystems as a compensation for displaced feed or food production or with co-product use – can have great impacts on the results. These impacts can be positive or negative.

To avoid negative effects associated with energy or biomaterial crop cultivation, the conversion of carbon-rich vegetation for this purpose has to be avoided. Although in Europe the conversion of forests is not allowed, carbon-rich grassland may be converted to a certain extent leading to the above mentioned impacts on climate change. Especially grasslands on organic soils should totally be excluded from conversion. The preservation of grasslands would not only be advantageous from a climate protection point of view but is also important for biodiversity conservation and water retention.

However, even if all direct land-use changes could be avoided still there are indirect effects which are difficult to track and to avoid. One option would be the establishment of global certification systems covering all aspects of biomass use (i.e. food, feed, fiber and fuel) instead of focussing on bioenergy as is the case with systems currently put into practice. The results have also shown the necessity to develop models and methodologies for including indirect effects in life cycle analyses. This would facilitate a more exact analysis of the impact of bioenergy production on climate.

4.3.2 Yields

Since yields may influence the outcomes of life cycle analyses, the results based on different yields are presented in the following. First, yield changes in different environmental zones are assessed (chapter 4.3.2.1). Second, results based on future yield changes are presented (chapter 4.3.2.2).

4.3.2.1 Variation of yields between environmental zones

Presentation of results: derivation of ranges

In Fig. 4-18, the environmental impacts of rapeseed biodiesel are presented for the impact categories energy savings, greenhouse effect, acidification and eutrophication and for five different environmental zones: Nemoral, Continental, Atlantic Central, Atlantic North, and Lusitanian. The yields that are achieved in the zones are presented in Table 2-5 (chapter 2.3). Based on the different results for the environmental zones, ranges are generated that represent the whole variation of results. They are displayed below the balances. In the following chapter, such ranges are displayed for all crops that are cultivated in more than one environmental zone.

Results

- The yields that are achieved in the different environmental zones significantly influence the outcomes of the balances. The higher the yields, the more energy and greenhouse gases can be saved. Regarding energy savings, in the zone with the highest yield (Atlantic Central) almost twice as much energy can be saved as in the zone with the lowest yield (Nemoral).
- However, the higher the yields and thus the savings of energy and greenhouse gases, the more acidification and eutrophication are caused due to higher fertiliser input.

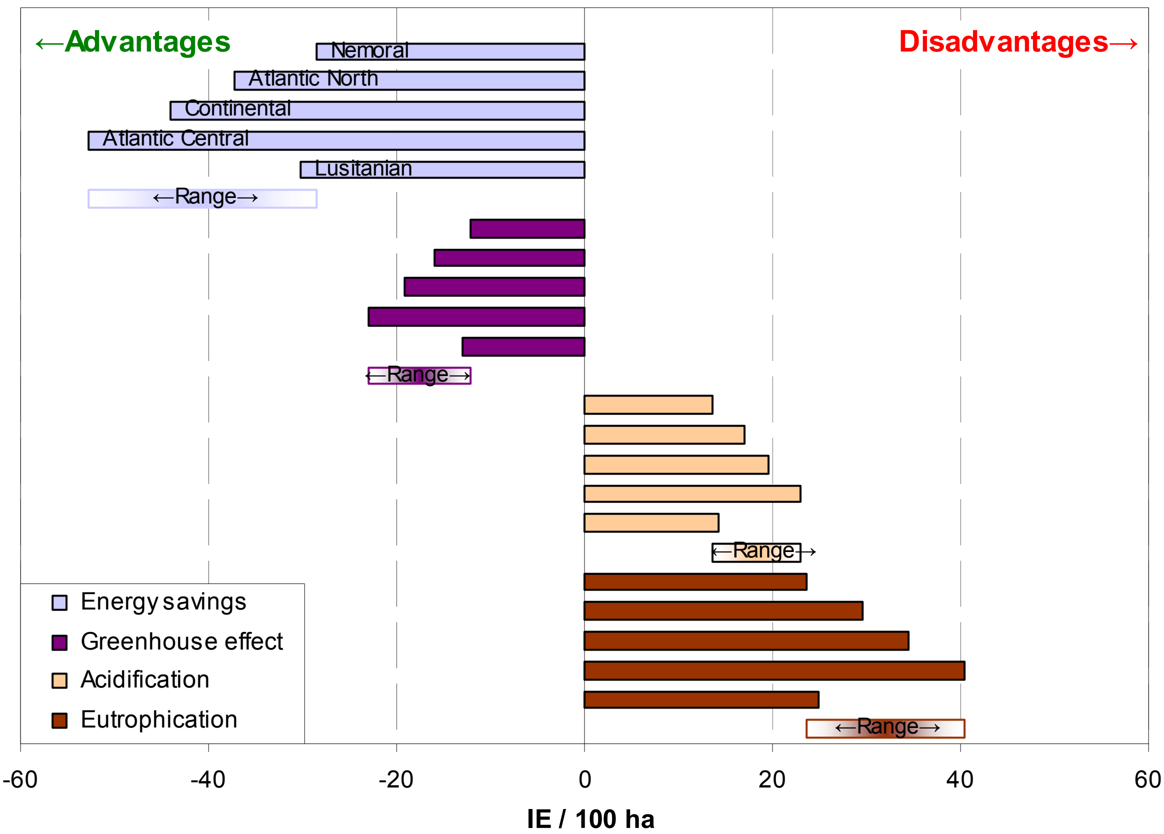

Fig. 4-18 Results of the life cycle comparison for rapeseed biodiesel (FAME) and fossil diesel in five different European environmental zones.

Reading the diagram – exemplification of 1st bar 'energy savings'

If rapeseed is cultivated in the Nemoral zone and if its oil is used to produce biodiesel that replaces conventional diesel, the amount of primary energy saved per 100 hectares equals the energy demand of 28 inhabitants.

Ranges for multiregional crops

In Fig. 4-19, the greenhouse gas balances are shown for all crops that are cultivated in more than one environmental zone and for the respective main products. The ranges are derived in analogy to the method presented in the previous paragraph: they cover all environmental zones the crops are cultivated in and thus the related yields. These yields are presented in Table 2-5 (chapter 2.3).

The results are depicted taking greenhouse gas savings as an example. They can be transferred to the other environmental impact categories according to the findings from the previous chapter: energy and greenhouse gases as well as acidification and eutrophication, respectively, run parallel. However, the results of these two groups are directly opposed: the more energy and greenhouse gases are saved, the higher are acidification and eutrophication.

Results

- Yield differences related to different environmental zones considerably influence the outcome of the GHG balances of each pathway. A higher yield per hectare leads to higher GHG savings.
- When comparing different pathways among each other in terms of absolute GHG savings, it becomes obvious that differences are not just determined by the sheer biomass yield, but also by the specific GHG savings potential (CO_2 eq. / $t_{biomass}$) of each pathway: the higher the specific GHG savings potential is, the more the absolute GHG savings increase with yield. For example, the result range for Miscanthus is quite large both because the yields range from 13.0 t / ha (ATN) to 34.0 t / ha (LUS) and because high specific savings can be achieved with most of the Miscanthus pathways.

Conclusions

For each pathway, there is a linear relationship between biomass yield per hectare and the greenhouse gas savings achieved. The absolute GHG savings, however, are also determined by the specific GHG savings potential of each pathway.

Therefore, in order to maximise GHG savings, it is not sufficient to choose the environmental zone with the highest yield, but also to make sure that the biomass is converted and used in the most efficient way. In other words: the entire life cycle has to be taken into account.

Moreover, it has to be kept in mind that higher yields also require a higher fertiliser input. Therefore, higher energy and greenhouse gas savings are in many cases connected with increases of acidification and eutrophication.

Reading the diagram – exemplification of 2nd bar 'rapeseed HVO'

If rapeseed oil from 100 hectares is used to produce HVO that replaces conventional diesel as transport fuel, the greenhouse gas savings equal the annual greenhouse gas emissions of 12 to 23 inhabitants – depending on the environmental zone rapeseed is cultivated in.

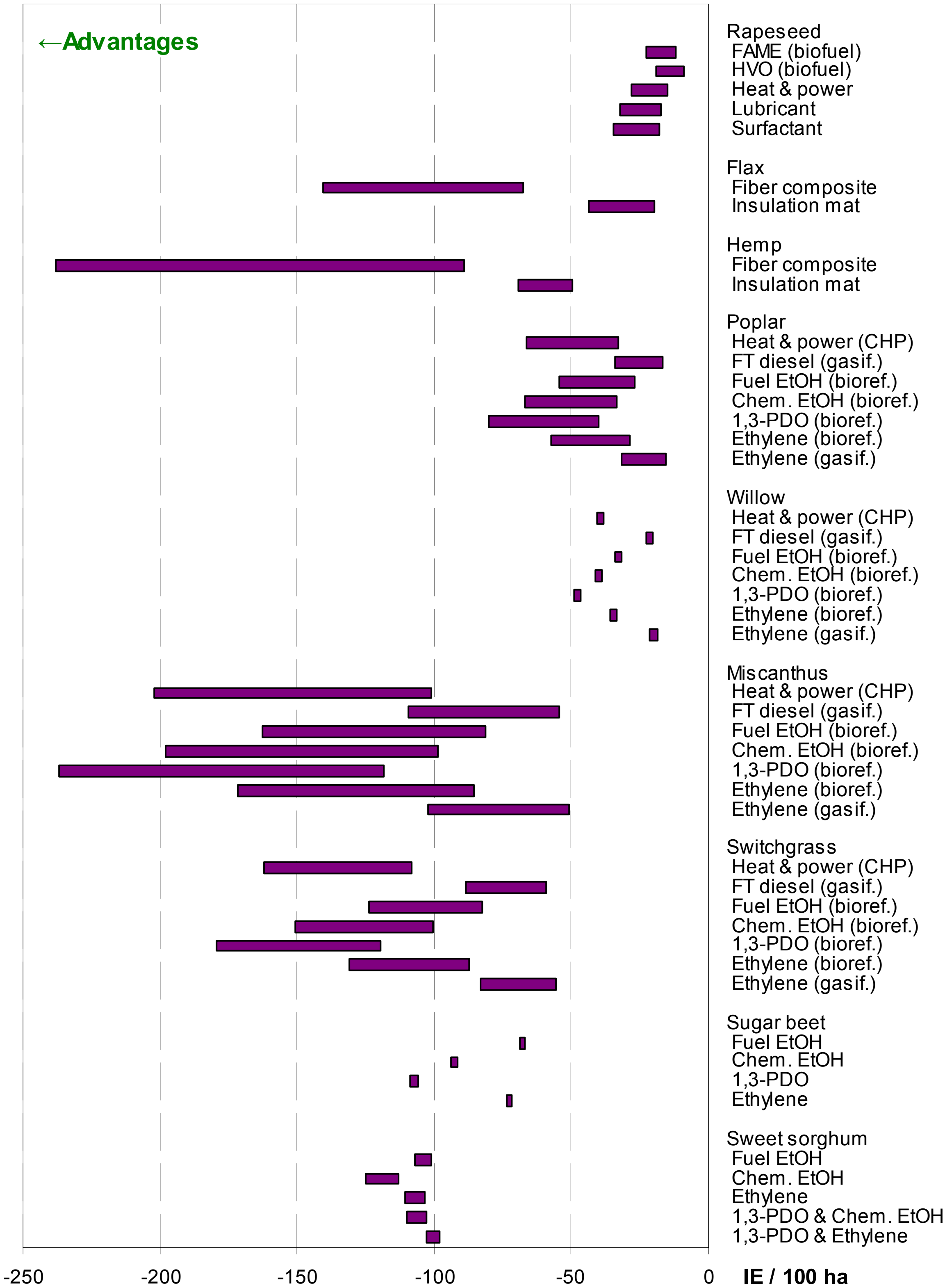

Fig. 4-19 Greenhouse gas savings for crops that are cultivated in more than one environmental zone and all their main products; ranges cover the different environmental zones.

4.3.2.2 Variation of yields in time: future yields

Yields do not only vary in different environmental zones due to climatic and biophysical conditions but they will also change in future due to progress in crop breeding. In Fig. 4-20 the results related to the yield increases extrapolated into the future (2020 & 2030) are presented. For this analysis, all crops that are grown in the Atlantic Central (ATC) zone are assessed in order to exclude differences related to different biophysical conditions. The ranges cover the main products that are obtained. The results are presented for energy savings and greenhouse effect. They can be transferred to acidification and eutrophication (though in the opposite direction) as explained in chapter 4.3.2.1.

Results

- The results show again that yields have a considerable influence on the outcomes of the balances: the higher the yields will be in future, the more energy and greenhouse gases can be saved. However, it has to be kept in mind that higher savings of energy and greenhouse gases are related to increased acidification and eutrophication.
- The absolute energy and greenhouse gas savings increase in a linear way, i.e. the higher the specific savings (GJ / $t_{biomass}$ and CO_2 eq. / $t_{biomass}$) are for a certain pathway, the more they increase with yield ($t_{biomass}$ / (ha*yr)). The absolute savings (GJ / (ha*yr) and CO_2 eq. / (ha*yr)) are thus dependent on two factors.

Conclusions

Yields are among the main factors to influence the outcomes of the energy and greenhouse gas balances – at least if results are displayed on a hectare-basis.

Therefore, from an energy savings and climate protection point of view, all efforts should be put into striving for yield increases. However, since higher yields require a higher fertiliser input, acidification, eutrophication and stratospheric ozone depletion (the latter is not displayed) will increase at the same time.

However, in order to maximise energy and GHG savings, it is not sufficient to breed for high yields, but also to ensure that the biomass is converted and used in an optimal way, i.e. the entire life cycle has to be taken into account.

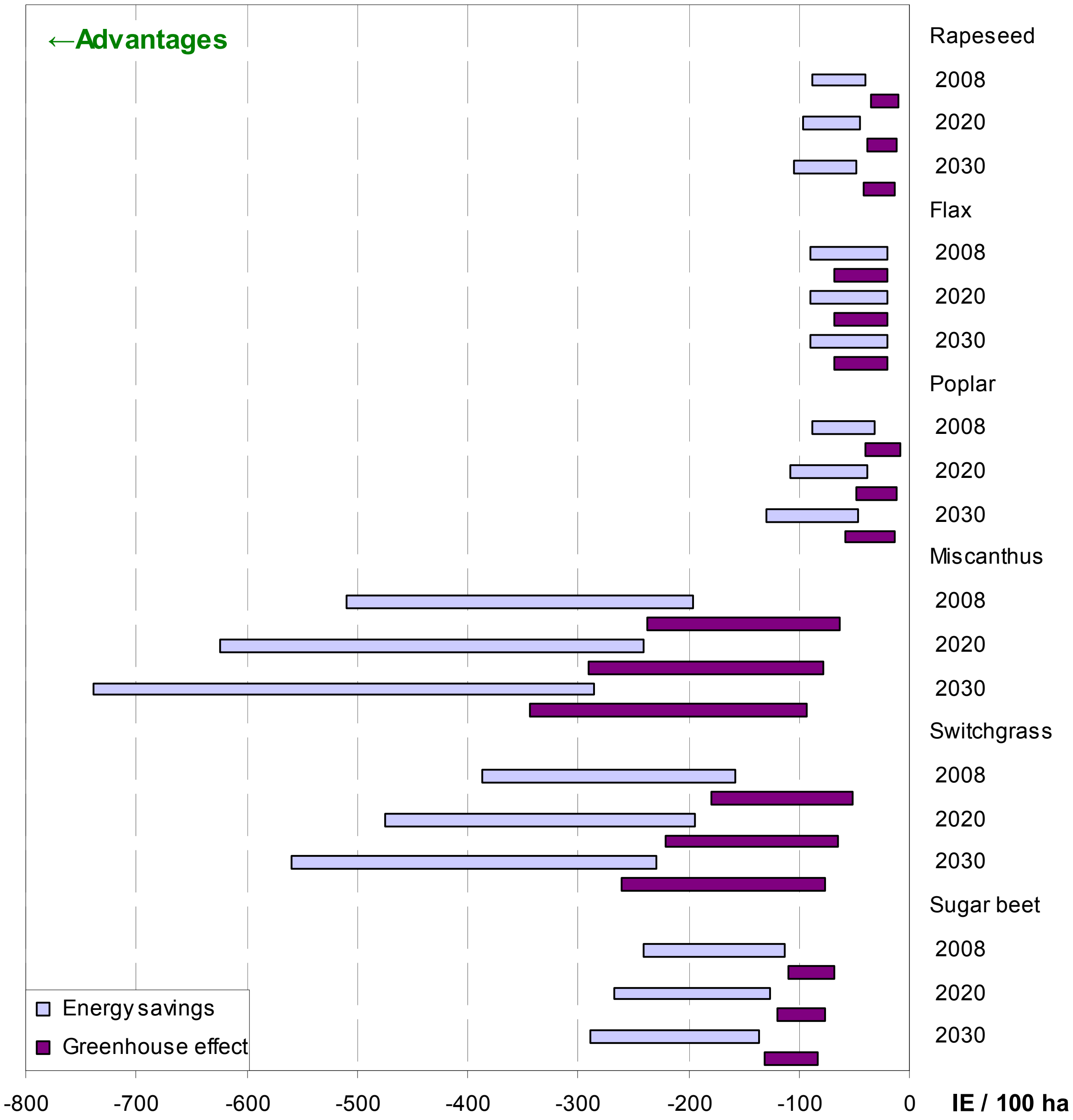

Fig. 4-20 Results of the life cycle comparison for future yield increases; ranges cover different environmental zones as well as all main products that can be obtained from the crops; all crops are cultivated in the Atlantic Central (ATC) zone.

Reading the diagram – exemplification of 2nd bar 'greenhouse effect' for rapeseed 2008

If rapeseed oil is used to produce bioenergy or bio-based materials and if the yields of 2008 are assumed, per 100 hectares about the same amount of greenhouse gases can be saved that is yearly emitted by 10 to 35 inhabitants.

4.3.3 Co-product use and allocation

4.3.3.1 Variation of co-product use

Along the life cycles of the crops, various co-products are obtained that can be used in different ways (see chapter 3.4.2). Fig. 4-21 shows the environmental impacts of different co-product use options. One crop is taken as an example for each crop group (oil, fiber, ligno-cellulosic, sugar). All results are related to the Lusitanian (LUS) zone. The standard use options are marked with an asterisk.

Results

- The purposes which the co-products are used for in most cases have a significant impact on the results. Exceptions are the sweet sorghum combinations EtOH / feed and energy / DDGS that do not show any significant difference.
- Regarding the relation between energy savings / greenhouse effect as well as acidification / eutrophication, the results do not follow the same pattern. For rapeseed, acidification and eutrophication increase if more energy and greenhouse gases are saved. For hemp, willow and sweet sorghum, in contrast, the more energy and greenhouse gases can be saved, the better are the performances regarding acidification and eutrophication.
- For rapeseed, most energy and greenhouse gases can be saved if the meal is used for bioenergy production in a CHP instead of as feed. However, this use option increases acidification. For willow, results are opposite: the biomaterial use leads to better results than the use for bioenergy production. For sweet sorghum, results for all energy and greenhouse gas savings are best if the bagasse is used for process energy production and stillage is used as feed. Best results regarding acidification and eutrophication can be achieved if the stillage is further processed into Distillers' Dried Grains with Solubles (DDGS). However, in this case there is only a small difference to the use of bagasse for second generation ethanol production and the direct use of the stillage as feed.

Conclusions

The choice of the co-product use has a clear influence on the outcomes of the life cycle analyses. Therefore, optimising co-product use is very essential. However, this choice is subjective, a fact which is often used as an argument against system expansion (substitution method). On the other hand, it shows that an optimised co-product use clearly has a positive impact on LCA results (which is not the case when using the allocation method).

A general statement is not possible on whether the co-products should rather be used as biomaterials or for bioenergy production – this depends on the crop. Also regarding the relation between acidification / eutrophication and energy savings / greenhouse effect, no general result can be derived – sometimes, they run parallel, however, in some cases acidification and eutrophication increase if more energy and greenhouse gases are saved.

Therefore, no general advice can be given on the 'best' use of the co-products. Decisions have to be taken considering case-specific conditions. Moreover, there might be other reasons than the environmental performance of a certain co-product use. For example, the combustion of rapeseed meal might be better from an environmental point of view, however, from a food security point of view it should be used as a protein-rich feed.

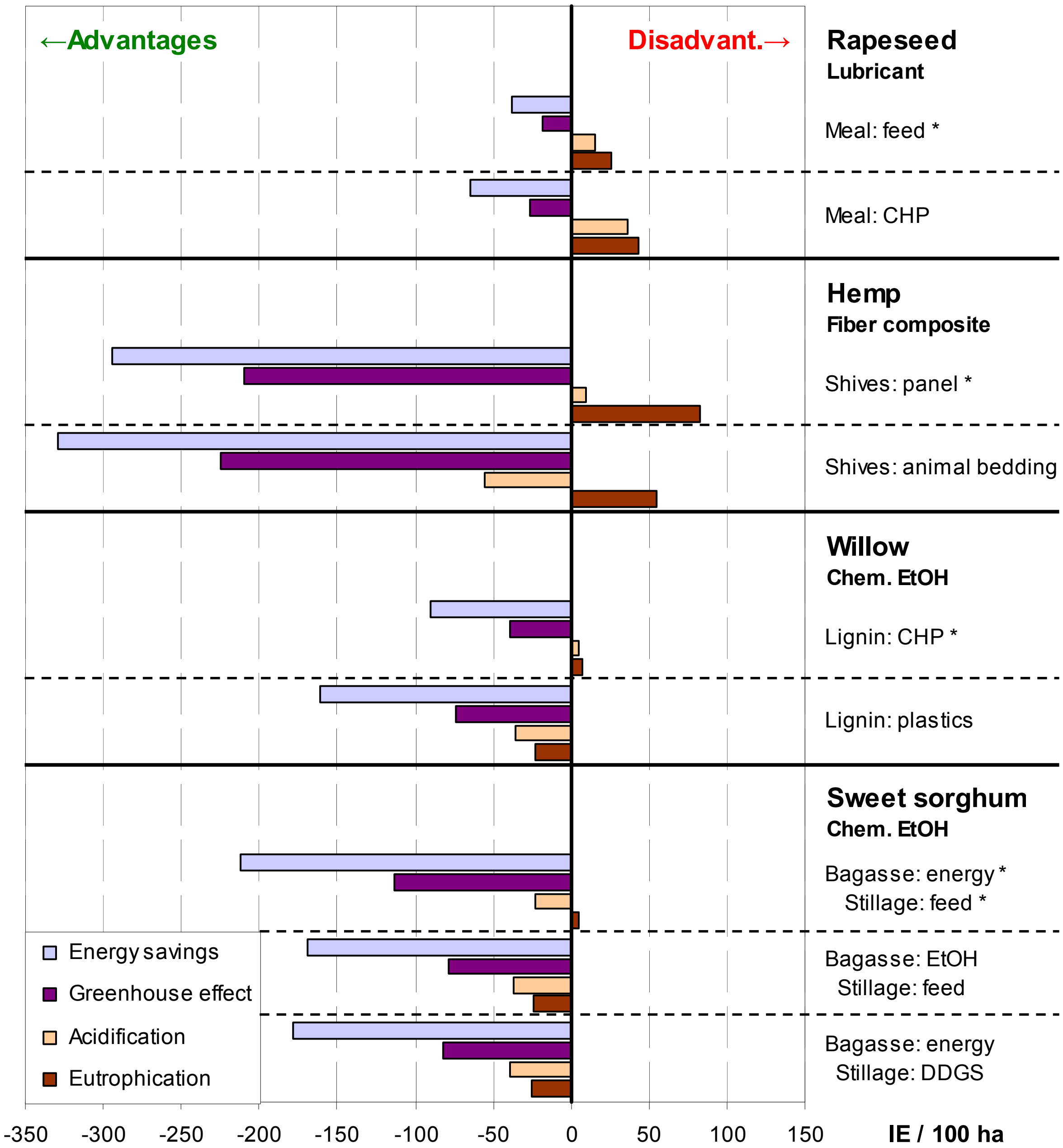

Fig. 4-21 Results of the life cycle comparison for different crops and different co-product use options; the zone for all crops is the Lusitanian (LUS) zone; * default use option in basic scenarios.

Reading the diagram – exemplification of 2nd bar 'greenhouse effect' for rapeseed

If rapeseed oil is used to produce lubricant that replaces conventionally produced lubricants and if the meal is used as feed, per 100 hectares about the same amount of greenhouse gases can be saved that are emitted by 18 inhabitants per year.

4.3.3.2 Variation of co-product allocation

As described in chapter 3.4.2, different possibilities exist to account for the co-products that occur along the life cycles of products. In this study, the substitution method is taken as a standard. In addition, the allocation method is calculated as a sensitivity analysis in this chapter. The allocation is based on the following references: the economic value of the products (€), their energy content (lower heating value; MJ), and their mass (kg). For the substitution method, two different co-product use options are assessed since these are major influencing factors in this method.

The results are presented in Fig. 4-22 taking rapeseed biodiesel (FAME) cultivated in the Continental (CON) zone as example.

Results

- Irrespective of the method applied, the results for rapeseed biodiesel show the same pattern: advantages regarding energy savings and greenhouse effect as well as disadvantages regarding acidification and eutrophication. The order of results runs parallel in both methods.
- The choice of method when dealing with co-products influences the outcomes of the life cycle analysis. When applying the substitution method, higher advantages regarding energy savings and greenhouse effect are derived as well as higher disadvantages regarding acidification and eutrophication. The dimension of the difference between both methodologies, however, depends on the exact specifications within each methodology. For instance, if the substitution method is applied and if the meal is used for heat and power production, the difference to the allocation method is much higher than if the meal was used as animal feed. In the latter case, results are very similar to all results derived when applying the allocation method.
- The methods also show differences regarding the susceptibility of results to variations within the systems. In the substitution method, results respond much stronger to different system boundaries, i.e. different uses of the co-products. In contrast, with the allocation method a much narrower range of results is derived.

Conclusions

The choice of method used to account for co-products influences the outcomes of the life cycle analyses. These influences can be considerable – depending on the exact specifications within each methodology.

Both methodologies also differ regarding the range of results: they can vary substantially in the substitution method depending on the use of the co-products, whereas for the allocation method, a much smaller range of results is derived. The multitude of choices regarding the use of co-products is an argument often used against the substitution method. However, this method reflects reality more adequately than the allocation method.

Therefore, the choice of method when dealing with co-products should be based on the purpose for which the assessment is done. For policy analysis, the product system is to be modelled as realistically as possible; therefore the substitution method should be taken.

However, if results need to be clear and transparent for the purpose of regulation, e.g. for the verification of compliance with the sustainability criteria, allocation would be the more adequate choice since it is easier to define in standards and directives.

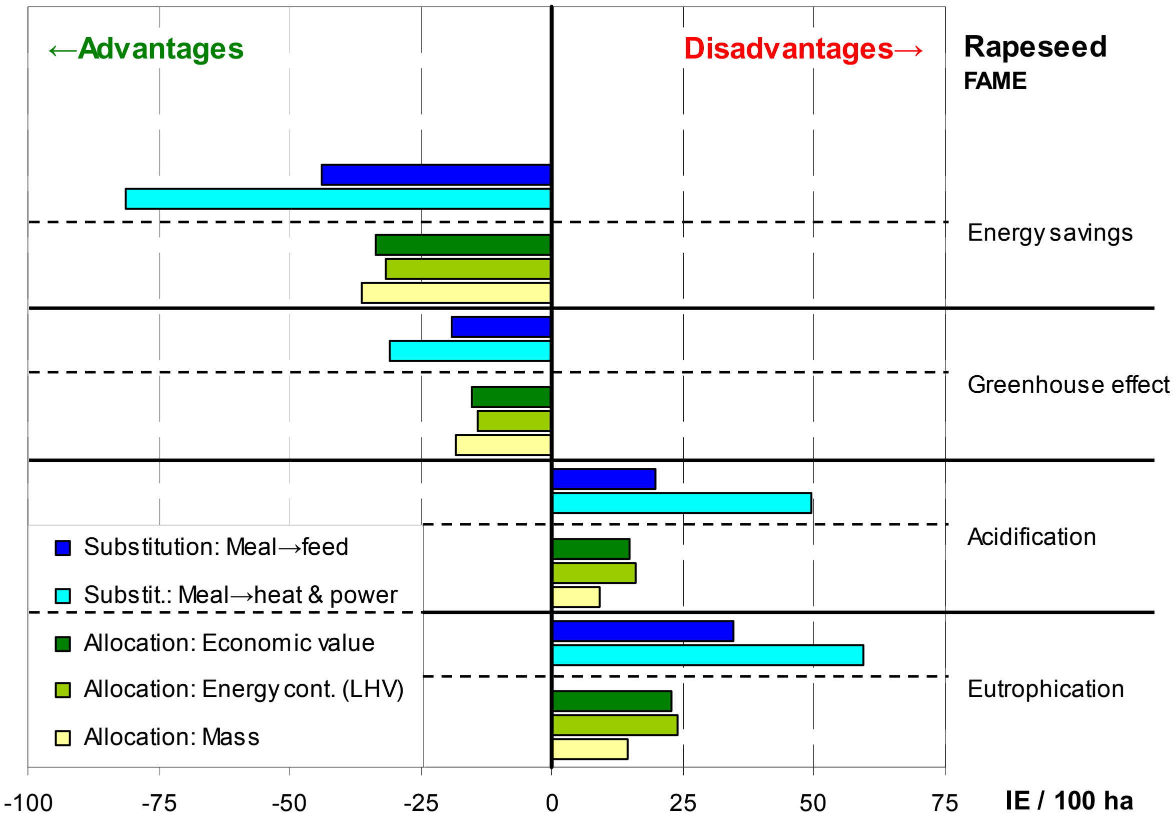

Fig. 4-22 Results of the life cycle comparisons for rapeseed biodiesel if the substitution and the allocation method are taken as a basis; rapeseed is cultivated in the Continental (CON) zone.

Reading the diagram – exemplification of 1st bar 'energy savings'

If rapeseed oil is used to produce biodiesel that replaces conventional diesel as transport fuel, and if the meal is used as feed, the energy savings per 100 hectares equal the yearly energy demand of 44 inhabitants if the substitution method is applied.

4.3.4 Fossil reference system

4.3.4.1 Variation of stationary energy use

All oil and lignocellulosic crops assessed in this study can be used for the production of heat and / or power either via the combustion in a combined heat and power plant (CHP) or via the use in separate heat or power plants (see chapter 3.3). Accordingly, either fossil-fired combined heat and power plants or separate fossil-fired heat plants or power from the grid are substituted. For this sensitivity analysis, one crop of each of the crop groups is chosen: straight vegetable oil from rapeseed and biomass from poplar as well as from Miscanthus. The environmental zone for each crop is the Atlantic Central zone (ATC). Fig. 4-23 shows the results of the life cycle comparisons for the environmental impact categories energy savings, greenhouse effect, acidification, and eutrophication.

Results

- Almost all use options and crops show the following pattern: advantages regarding energy savings and greenhouse effect and disadvantages regarding acidification and eutrophication. One exception is the use of poplar for a combined heat and power production: regarding acidification, results are ambiguous. For Miscanthus, the use in a CHP performs slightly advantageous regarding acidification.
- For all crops assessed, best results regarding energy savings and greenhouse effect can be achieved if power and heat are produced in combined heat and power plants (CHP) due to the high conversion efficiency. The second best option is the production of heat. However, for rapeseed there is almost no difference between heat and power production regarding energy savings.
- Also regarding acidification and eutrophication, CHP is the best use option. Power production performs slightly better than does heat production regarding acidification whereas regarding eutrophication, there is no significant difference between both options. In the latter impact category there is not much difference between all three use options if rapeseed or poplar are used.

Conclusions

If vegetable oil or crop biomass is used to produce heat and / or power, environmental advantages and disadvantages occur. From an environmental point of view, the use in a CHP in order to produce heat and power is the best choice in most cases: it helps saving most energy and greenhouse gases and shows the least disadvantageous results regarding eutrophication and acidification. Regarding energy and greenhouse gas savings, heat production is the second best option.

Therefore, from an energy saving and climate protection point of view, the biomass should best be used for a combined heat and power production in order to achieve a maximum use efficiency.

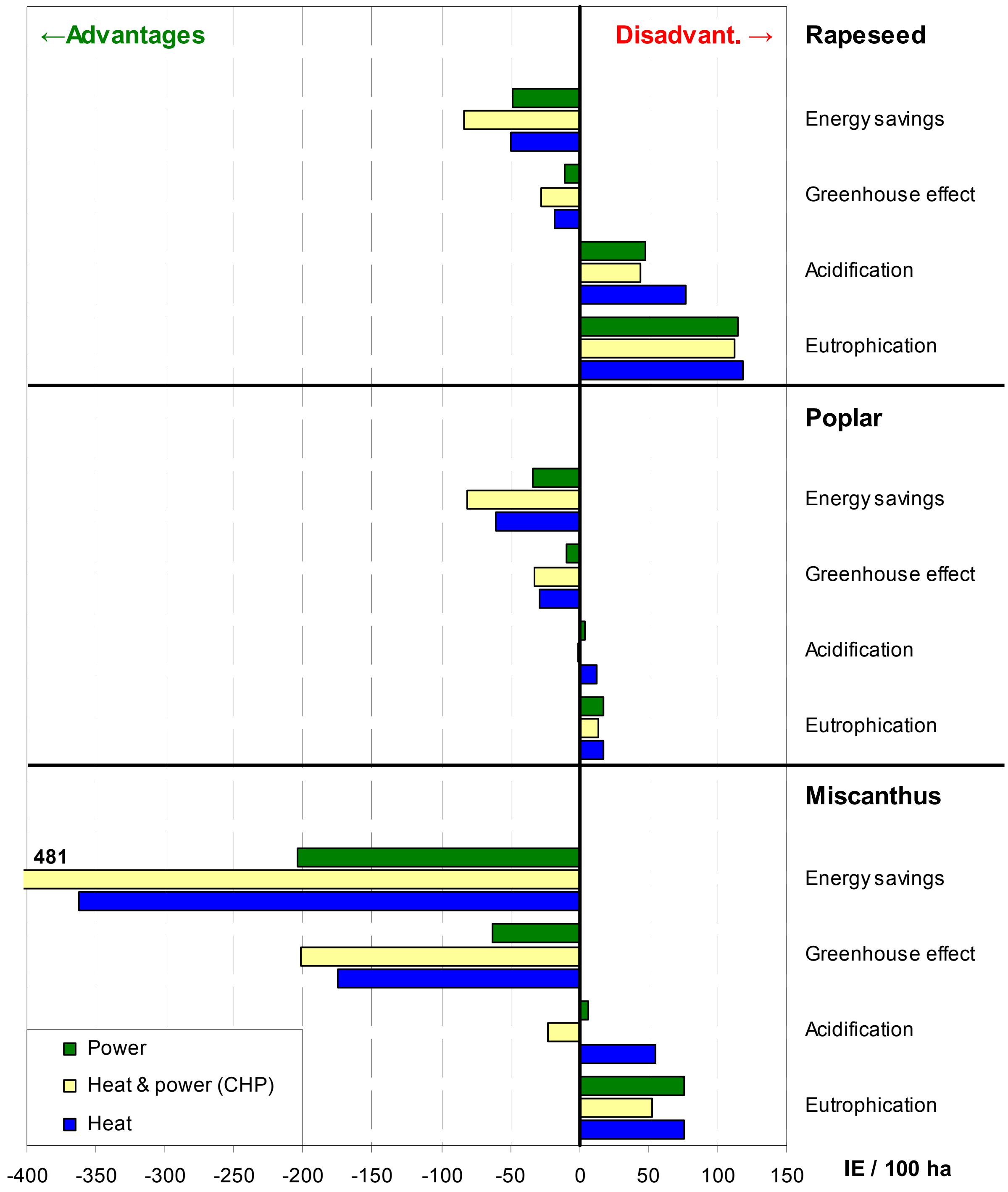

Fig. 4-23 Results of the life cycle comparison for three different stationary energy uses of different crops; the environmental zone for all crops is the Atlantic Central zone (ATC).

Reading the diagram – exemplification of 1st bar 'energy savings' for power from rapeseed oil

If rapeseed oil is used to produce power that replaces conventional power from the grid, the energy savings per 100 hectares equal the yearly energy demand of about 49 inhabitants.

4.3.4.2 Variation of substituted power mix

In almost all pathways assessed in this study green electricity is produced either as main or as co-product that replaces conventional power from the grid. Since the composition of the substituted power mix can be of great importance for the outcome of the life cycle analyses, five different power mixes are compared: in addition to the UCTE mix (which is the default power mix in the basic scenarios) results based on the country-specific Swedish, French, German, and Polish mix are shown in Fig. 4-24. The reasons for this choice are described in chapter 3.4.3. Results are exemplified for willow cultivated in the Continental (CON) zone.

Results

- The composition of the power mix that is replaced by the electricity produced from willow has a significant impact on the results of the life cycle analyses. Highest **energy savings** are achieved if the Polish mix is replaced and lowest if the Swedish mix is replaced. Replacing French mix would be the second best option. The Polish power shows the highest specific need of non-renewable energy with more than 90 % coal which is used in inefficient power plants. Its replacement by green power thus leads to high savings in fossil energy carriers. Sweden, in contrast, uses large amounts of hydro power being a renewable energy carrier. The French mix contains only small amounts of fossil energy sources, but has a high share of nuclear power requiring uranium. This is a non-renewable energy carrier the extraction of which is very energy intensive.
- Also regarding the **greenhouse effect**, highest savings are achieved if the Polish power mix is replaced. It shows high specific emissions of CO_2 in power production due to the big share of coal. In contrast, by replacing the Swedish mix no greenhouse gases can be saved since a lot of "clean" hydro power and nuclear power are used. The latter also emits only small amounts of CO_2. France obtains more than 80 % of its electricity from nuclear power, therefore replacing its electricity mix also does not show any advantages in terms of greenhouse gas savings. However, the specific CO_2 emissions in France are still twice the emissions in Sweden as double the amount of nuclear power is used.
- For **acidification**, results are again best if Polish power from the grid is replaced by the power gained from willow wood – here results are even advantageous. In Poland, the specific SO_2 emissions in electricity production are immense – again due to the large shares of coal as well as due to the insufficient flue gas desulphurisation in power plants. The credits for power substitution even overcompensate the emission of acidifying substances which in the standard scenario leads to disadvantageous results. Of all other power mixes, replacing the Swedish mix leads to the highest disadvantages. Here, nuclear and hydro power are replaced that emit only small amounts of SO_2 equivalents. As a result, the balances stay disadvantageous since the acidifying emissions occurring along the life cycles cannot be overcompensated. In Germany, quite a lot of coal power is used, however, plants are efficient and flue gas desulphurisation is in place.
- Regarding **eutrophication**, the results all stay disadvantageous, however, to different extents. As for acidification, the amount of coal plays a crucial role since its use causes high NO_x emissions. This is why again for the Polish mix the best results are obtained whereas for Sweden, the most disadvantageous results are obtained.

Conclusions

The composition of the power mix that is replaced by the green power has a significant influence on the results. The specific non-renewable energy demand for producing a kWh of electricity depends on both the share and the type of non-renewable energy carriers in a power mix. The higher the specific non-renewable energy demand is in the existing power mix, the more energy savings can be achieved by replacing it. The same applies for the other environmental impact categories: the more specific emissions of greenhouse gases as well as acidifying or eutrophying substances are caused in existing electricity production, the better results can be obtained by replacing it. In contrast, if a lot of renewable energy is used, its replacement has less advantages from an environmental point of view. Thus, best results regarding all impact categories can be obtained if the Polish power mix is replaced. In contrast, replacing power from the grid in Sweden makes much less sense from an environmental point of view. Here, it should be assessed more closely whether an alternative use of the biomass would result in higher environmental advantages.

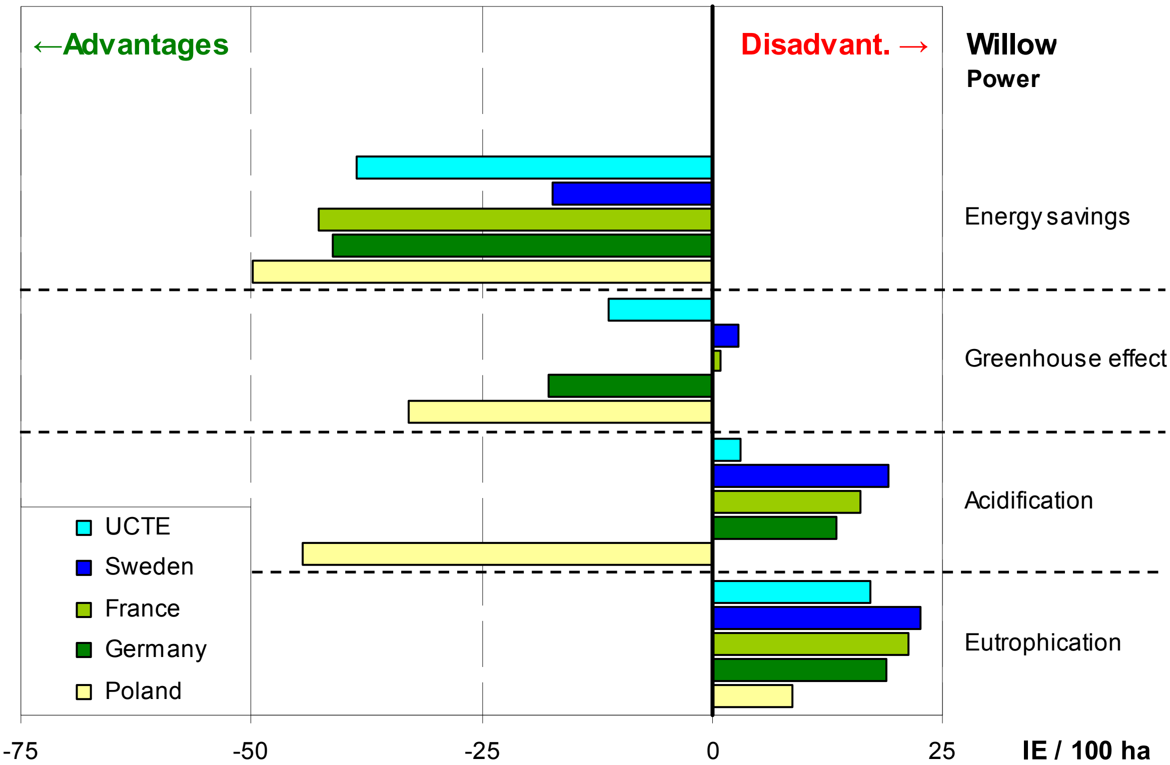

Fig. 4-24 Results of the life cycle comparison for power production from willow in the Continental (CON) zone taking into account different substituted power mixes: UCTE (European), Swedish, French, German, and Polish mix.

Reading the diagram – exemplification of 2nd bar 'energy savings' in Sweden

If willow is combusted for producing green electricity that replaces power from the grid in Sweden, per 100 hectares the same amount of energy can be saved that is demanded by 17 inhabitants per year.

5 Summary and conclusions

Environmental advantages and disadvantages

The main goal of this study was to identify environmental advantages and disadvantages of bioenergy and bio-based materials made from 15 future crops in comparison to their fossil or conventional counterparts. The crops under investigation cover different crops groups (oil, fiber, woody and herbaceous lignocellulosic, sugar) and are cultivated in seven environmental zones within Europe.

All crops show a certain potential for saving energy and greenhouse gases – regardless of the environmental zone they are cultivated in and the purpose they are used for. However, in most cases these benefits are associated with ambiguous or even disadvantageous impacts regarding acidification, eutrophication, summer smog, ozone depletion as well as human toxicity. Therefore, from a scientific point of view an objective conclusion regarding the overall environmental performance of bioenergy and biomaterials cannot be drawn. An overall conclusion rather has to be based on (subjective) value-choices, e g. by ranking the impact categories in a given hierarchy (e.g. high, medium, and low priority). For instance, if – in line with the goals of the RE Directive (2009/28/EC) – energy saving and mitigation of GHG emissions are subjectively given the highest priority, all bioenergy carriers and biomaterials assessed in this study are superior to their fossil or conventional equivalents.

Contribution of life cycle stages

Subgoal 1 was to identify the life cycle stages which make the largest contribution to the overall results. In general, the cultivation, conversion and utilisation stage are most important, whereas transports and the provision of specific ancillary products only have a minor influence. However, the extent to which each stage contributes to the overall balance differs both *between pathways* and *between environmental impact categories* within one pathway:

- Regarding transport biofuel and biomaterial pathways, for example, the conversion stage makes a large contribution. On the contrary, it is less important for bioenergy pathways (e.g. direct combustion).
- The cultivation stage is most important in terms of acidification, eutrophication and ozone depletion, which are dominated by nitrogen fertiliser-related field emissions (NH_3 & N_2O).
- The conversion stage has the largest influence on energy and greenhouse gas balances due to the use of fossil energy carriers causing CO_2 emissions.
- The utilisation stage has a considerable impact on acidification and eutrophication, mainly through NO_X emissions.

As a consequence, it is essential to assess the entire life cycle of bioenergy and bio-based materials. It is not sufficient to focus on single life cycle stages (e.g. crop cultivation) as the overall impact largely depends on what the biomass is used for, how efficiently it is converted and which fossil or conventional product it substitutes. Regarding transport biofuels and bioenergy for example, the stationary use of biomass, e.g. in a combined heat and power plant (CHP), usually outperforms the biofuel use of the biomass. However, the quantitative results of the stationary use of biomass for energy depend on the case-specific conditions, e.g. on the composition of the substituted conventional power mix. The higher its specific non-renewable energy demand and specific emissions are, the better the results if it is substituted. With respect to the most efficient biomass use, biomaterials should not be neglected since in certain cases they match up to or even surpass the stationary energy use!

Optimisation potentials

Regardless of the pathway chosen, there are a number of opportunities to improve the environmental performance of bioenergy or bio-based materials. Subgoal 2 aimed at the identification of such optimisation potentials. The following ones could be identified:

- **Yields:** Higher yields clearly lead to higher energy and greenhouse gas savings. Therefore, from an energy saving and climate protection point of view, high yields should be strived for. However, at the same time more acidification and eutrophication are caused. In this respect it also has to be noted that the irrigation of the crops (in order to increase yield) may even show less advantage per unit area than non-irrigated crops.
- **Use of co-products:** The use of the co-products that occur during crop processing can have a great impact on the results and considerably increase environmental advantages. However, no general advice can be given on the 'best' use of the co-products. Decisions have to be taken considering case-specific conditions.

Dependencies and sensitivities

Subgoal 3 of this study was to identify multi-functional dependencies and to quantify the impacts of methodological and data choices on the results. The key parameters are:

- **Agricultural reference system:** In this study, fallow / set-aside land has been chosen as the default alternative land use, in line with the WP 1 assumption that only surplus land is used for the cultivation of energy or industrial crops. However, if food or feed crops were displaced causing direct and indirect land-use changes, the greenhouse gas balances could become disadvantageous, i.e. more greenhouse gas emissions would be caused than by using fossil or conventional products. It has to be noted that research concerning indirect land-use changes is still in its infancy and that a harmonised approach to account for indirect effects in life cycle assessments urgently needs to be developed.
- **Accounting for co-products:** The choice of method used to account for co-products influences the outcomes of the life cycle analyses. In this study, system expansion – also called substitution method – has been applied. Despite multiple options regarding the use of co-products and potentially larger variations in results, this method reflects reality more adequately and should therefore be preferred for the purpose of policy analysis.

In this study, no overall and objective conclusion could be drawn on whether bioenergy or biomaterials are to be preferred over their fossil / conventional equivalents. Nevertheless, the results still allow for a comparison of the crops as well as conversion and use pathways among each other. Thereby, they serve the basis for the identification of options with a high energy and greenhouse gas savings potential. This is done in a separate report (D 14).

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7 Appendix

Results: Basic scenarios

In the following, the results of the life cycle comparisons are presented for additional environmental zones. Together with the results in chapter 4.2, a total number of 27 cases are investigated, the same that are analogously analysed in terms of economy (WP 3).

Rapeseed (LUS)

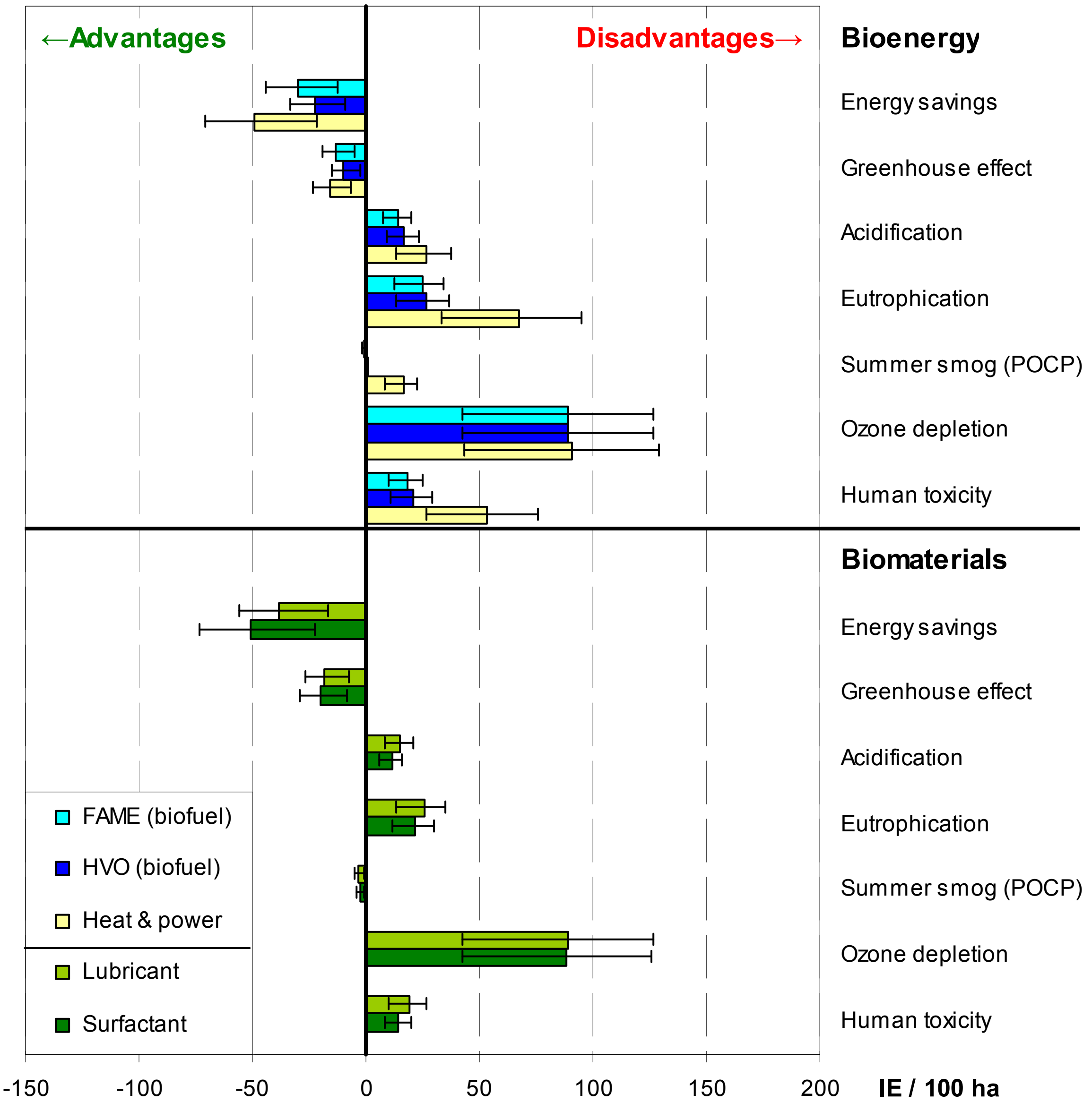

Fig. 7-1 Results of the life cycle comparison of bioenergy and biomaterials produced from rapeseed oil with their conventional equivalent products for the Lusitanian (LUS) zone (FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Rapeseed (ATC)

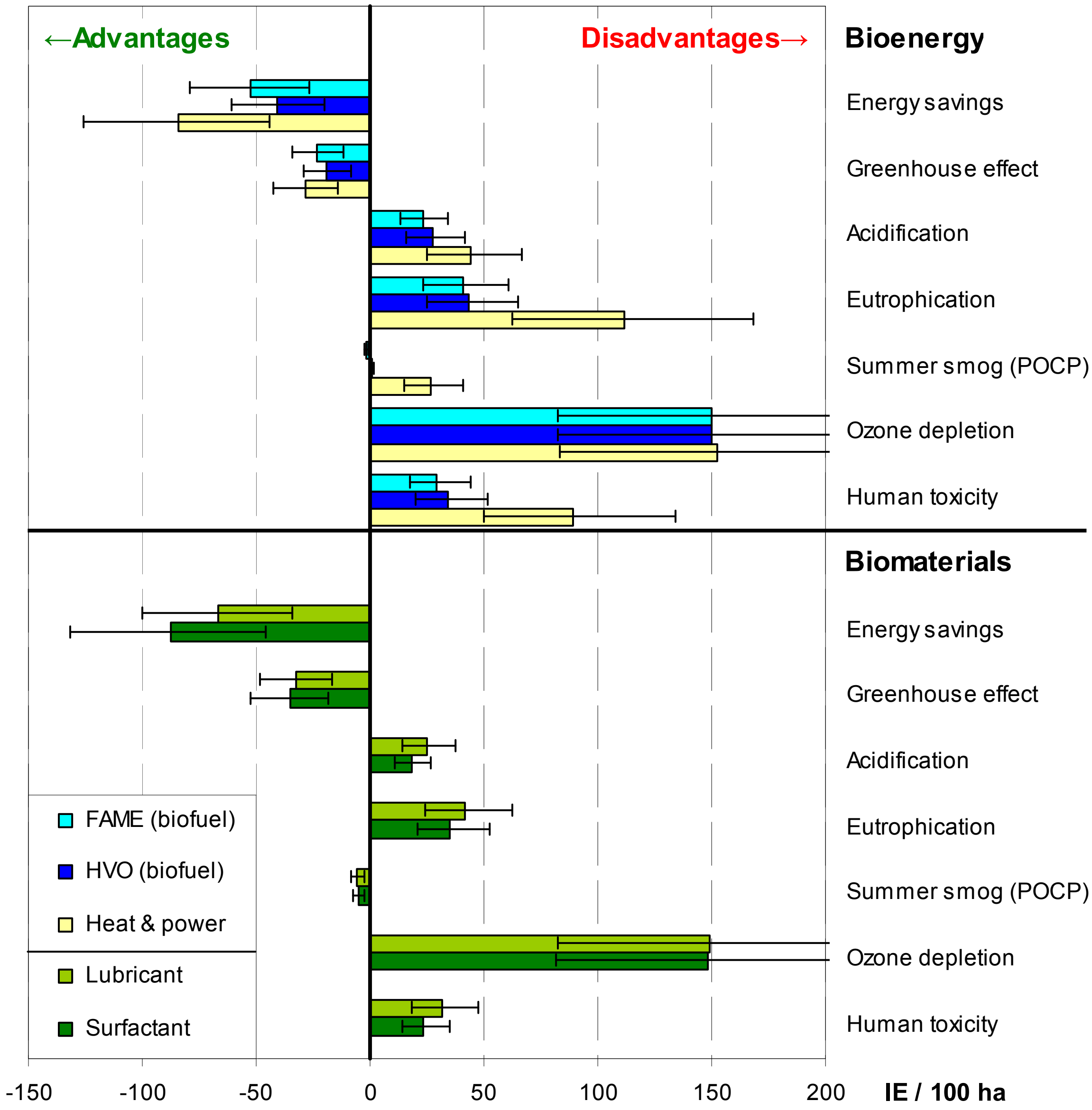

Fig. 7-2 Results of the life cycle comparison of bioenergy and biomaterials produced from rapeseed oil with their conventional equivalent products for the Atlantic Central (ATC) zone (FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Flax (ATC)

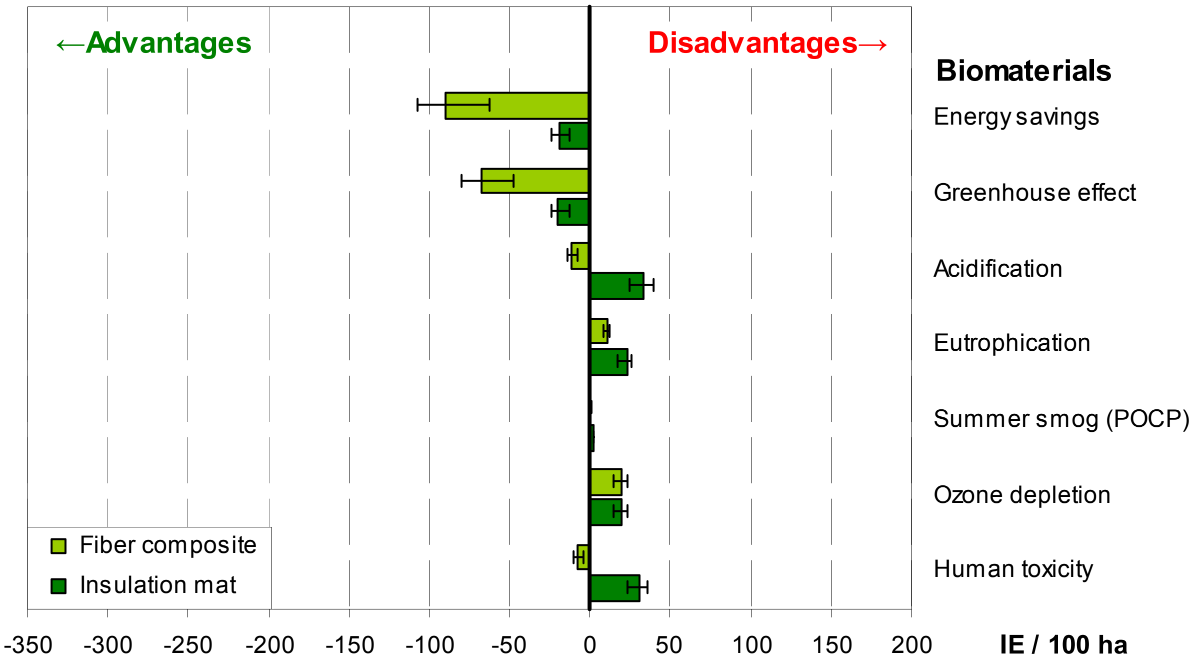

Fig. 7-3 Results of the life cycle comparison of biomaterials produced from flax fibers grown in the Atlantic Central (ATC) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Flax (MDS)

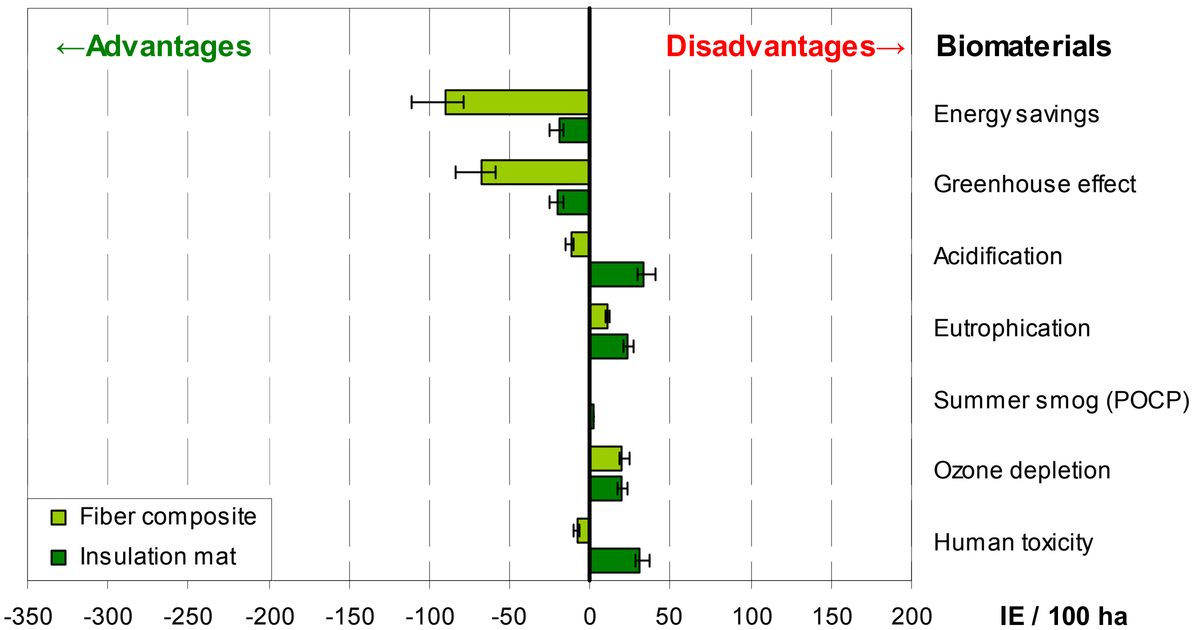

Fig. 7-4 Results of the life cycle comparison of biomaterials produced from flax fibers grown in the Mediterranean South (MDS) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Hemp (MDN)

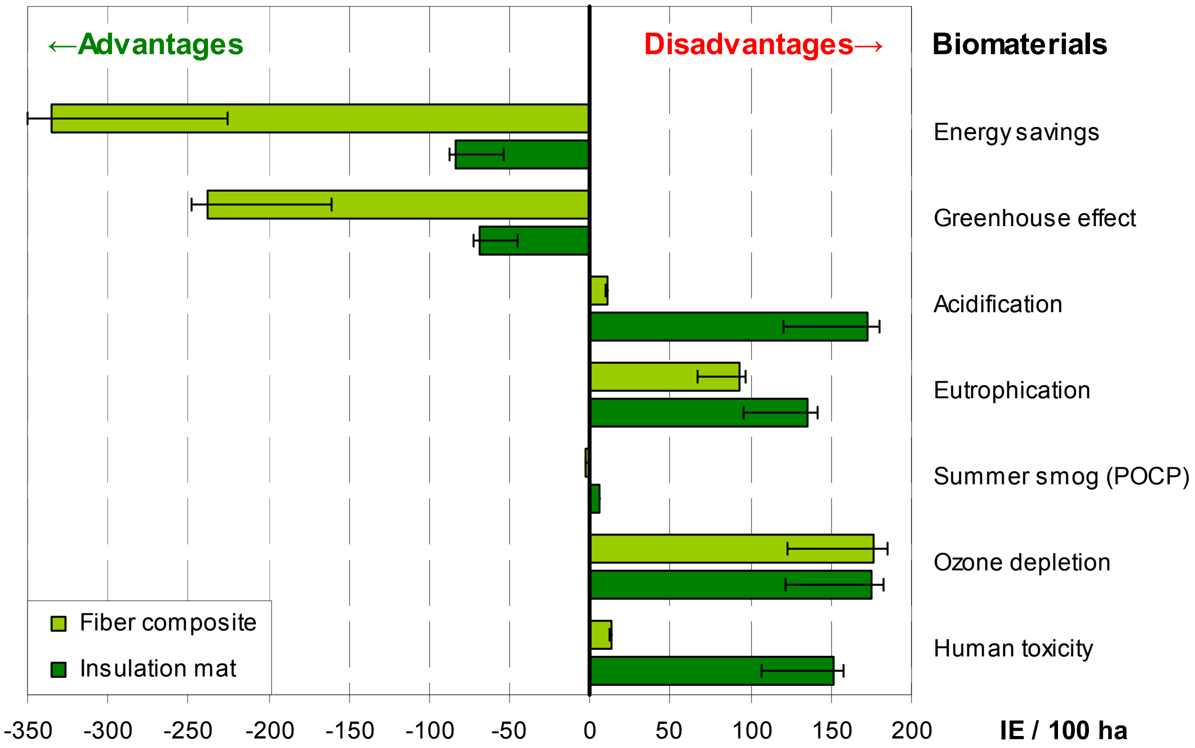

Fig. 7-5 Results of the life cycle comparison of biomaterials produced from hemp fibers grown in the Mediterranean North (MDN) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Poplar (MDN)

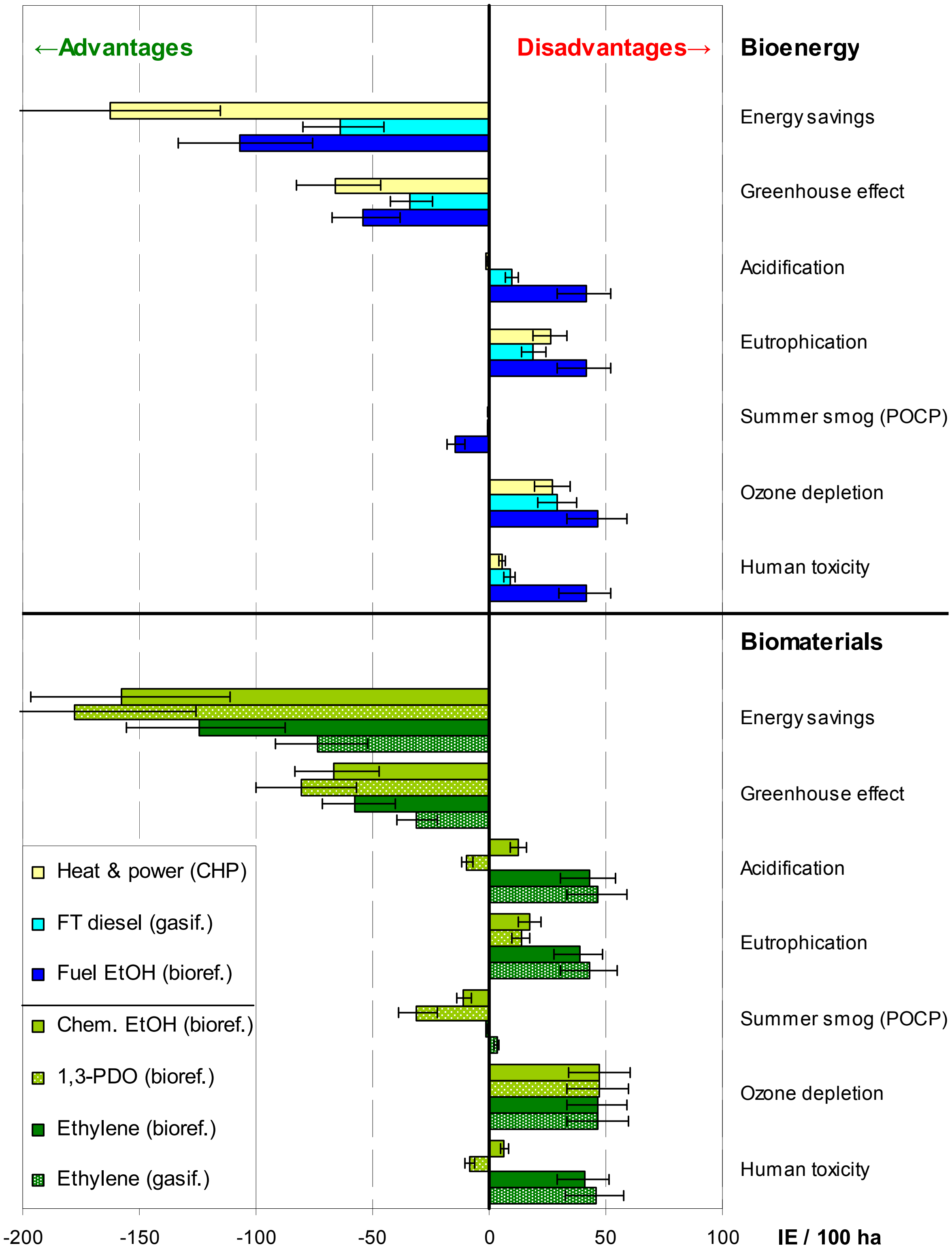

Fig. 7-6 Results of the life cycle comparisons for bioenergy and biomaterials obtained from poplar via direct combustion ('CHP'), gasification ('gasif.'), and in a biorefinery ('bioref.') for the Mediterranean North (MDN) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Willow (ATN)

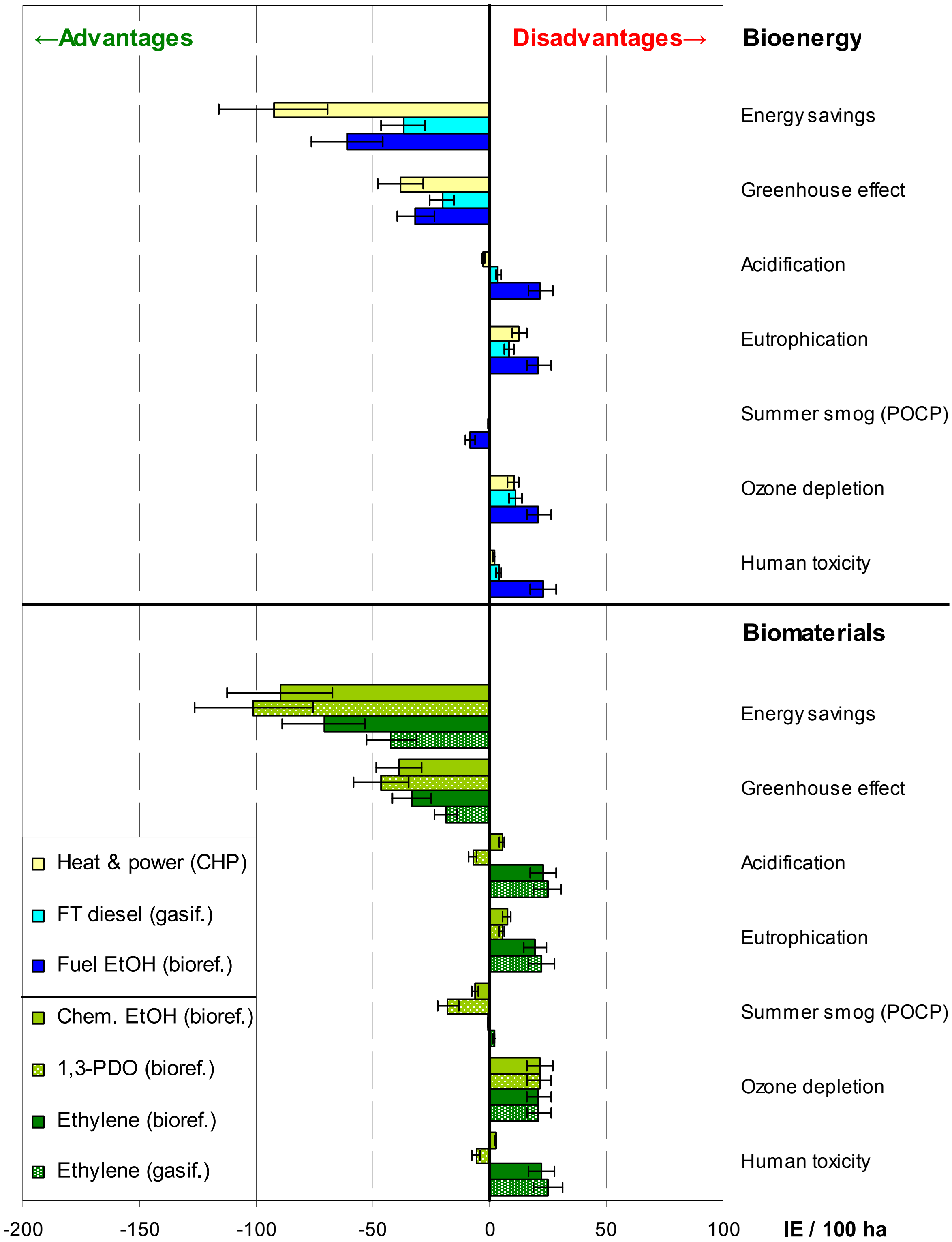

Fig. 7-7 Results of the life cycle comparison for bioenergy and biomaterials obtained from poplar via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Atlantic North (ATN) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Miscanthus (ATC)

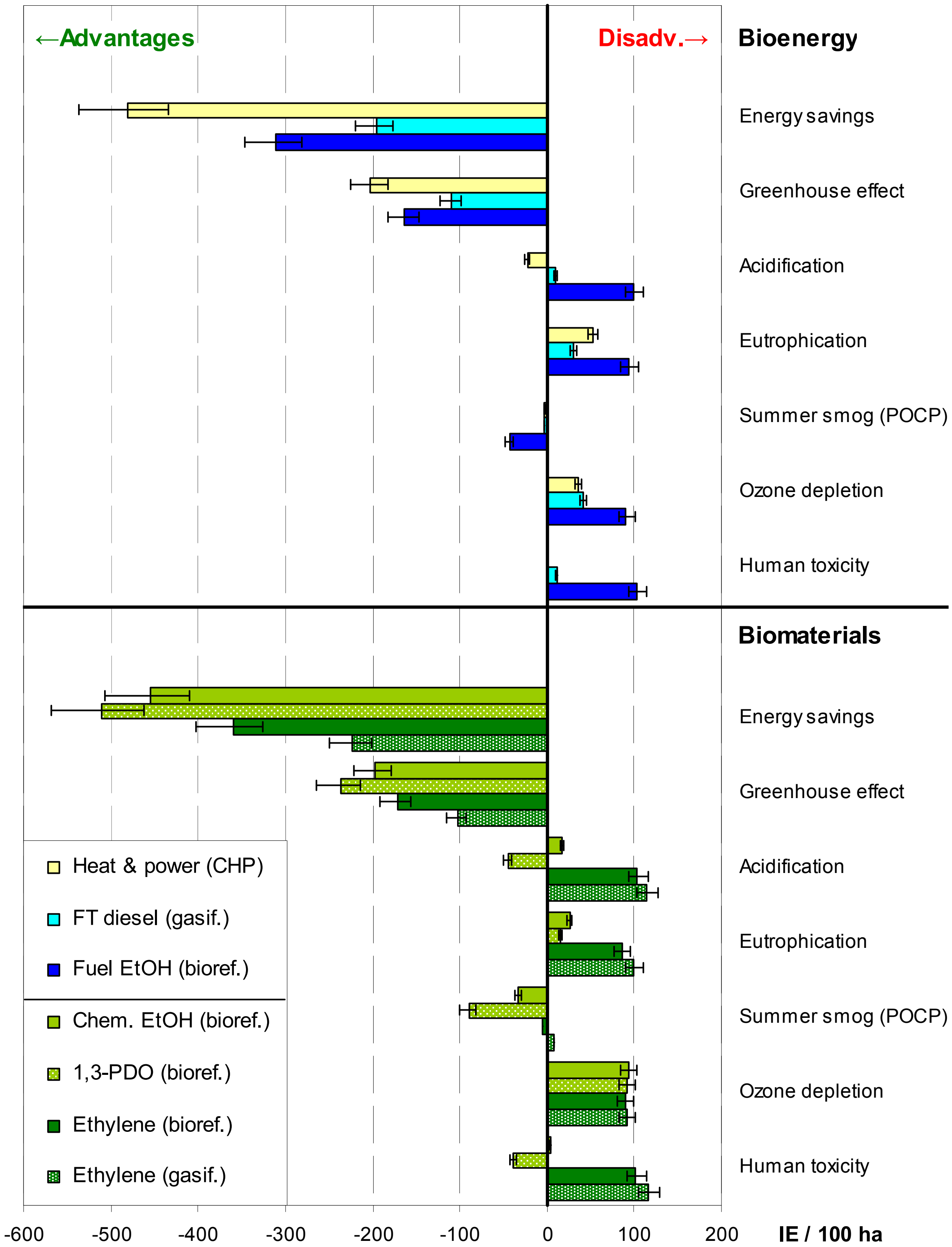

Fig. 7-8 Results of the life cycle comparison for bioenergy and biomaterials obtained from Miscanthus via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Atlantic Central (ATC) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Miscanthus (CON)

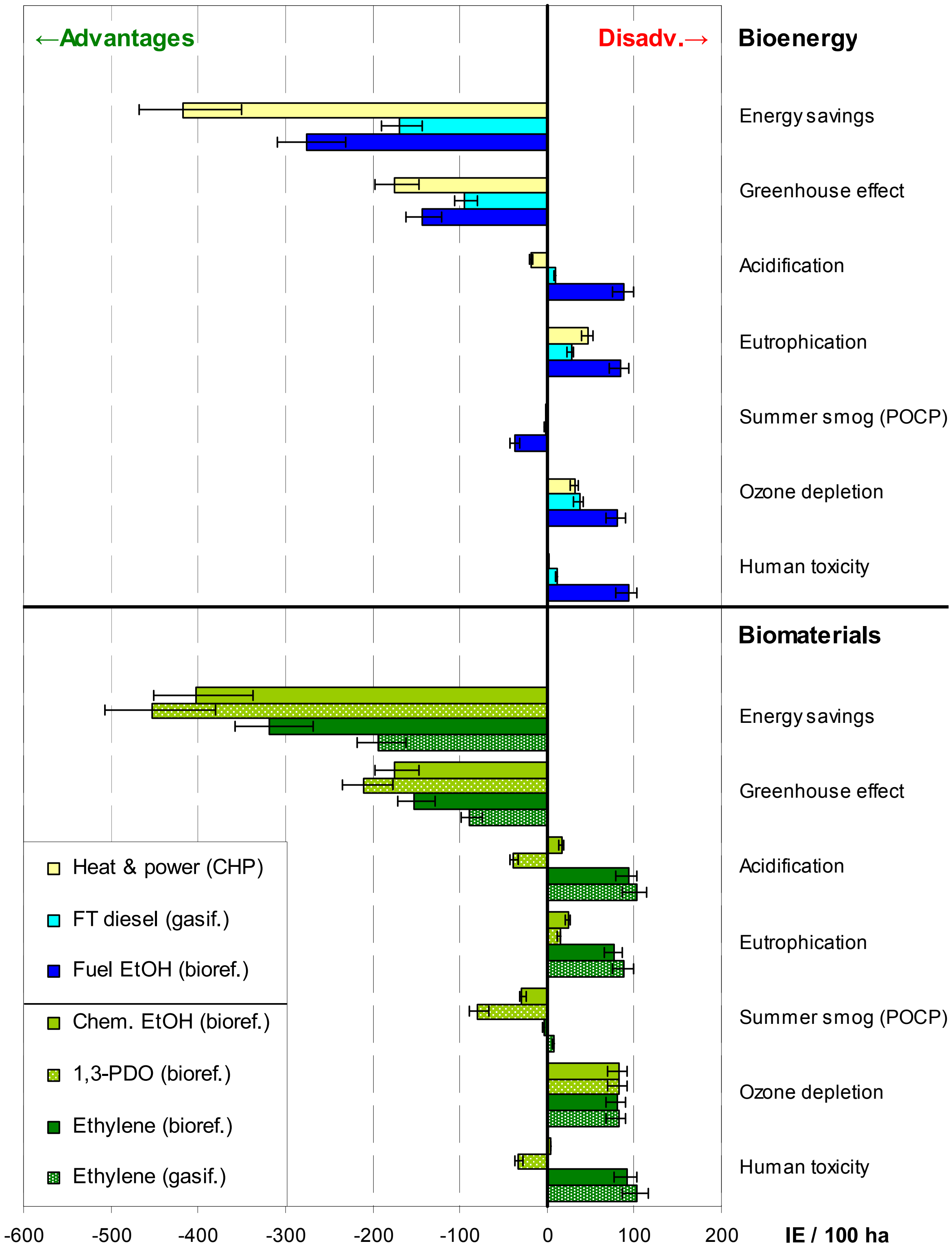

Fig. 7-9 Results of the life cycle comparison for bioenergy and biomaterials obtained from Miscanthus via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Continental (CON) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Switchgrass (ATC)

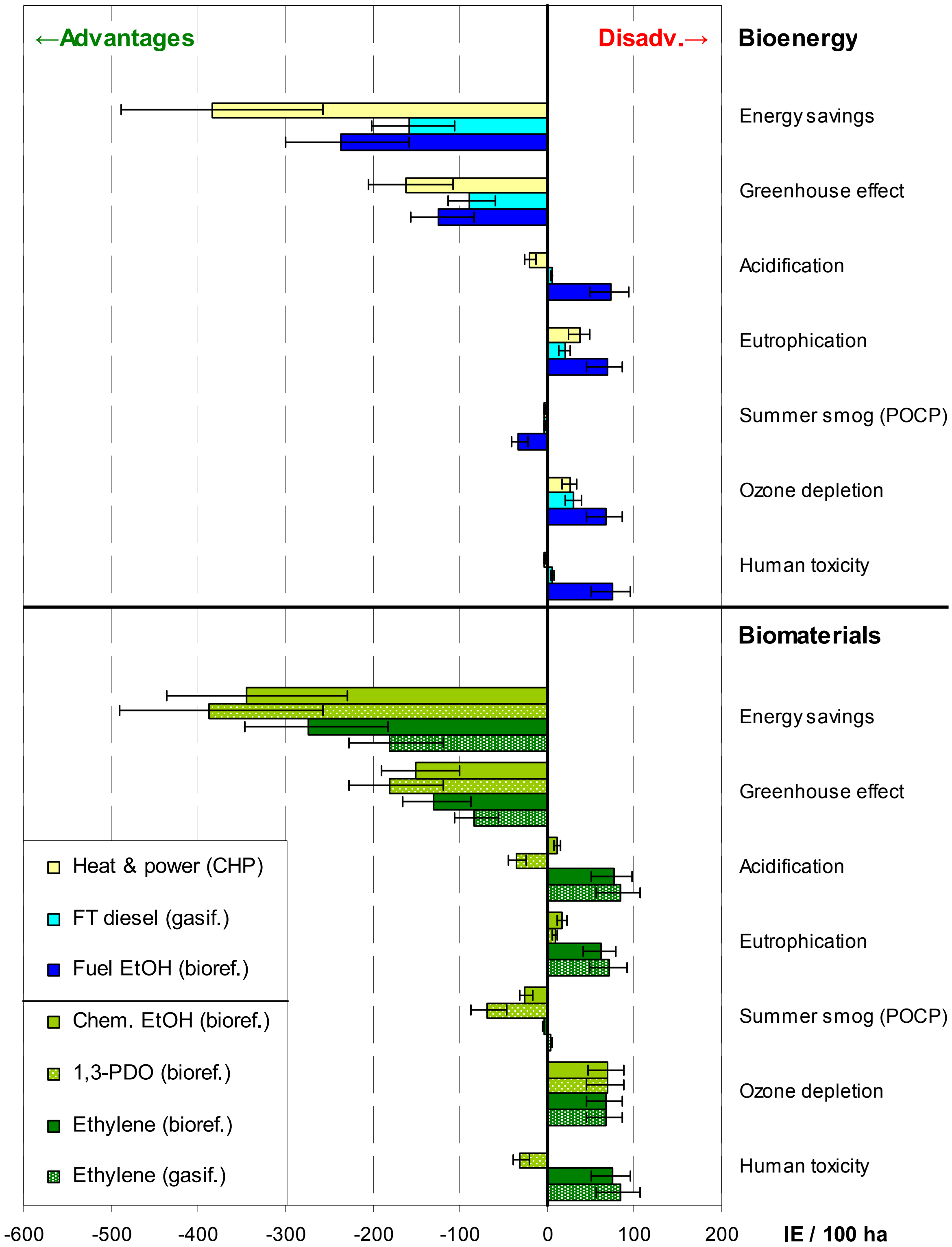

Fig. 7-10 Results of the life cycle comparison for bioenergy and biomaterials obtained from switch grass via direct combustion ('CHP'), gasification ('gasif.'), and biorefinery ('bioref.') for the Atlantic Central (ATC) zone (FT = Fischer-Tropsch, EtOH = Ethanol, 1,3-PDO = 1,3-propanediol); bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Sweet sorghum (LUS)

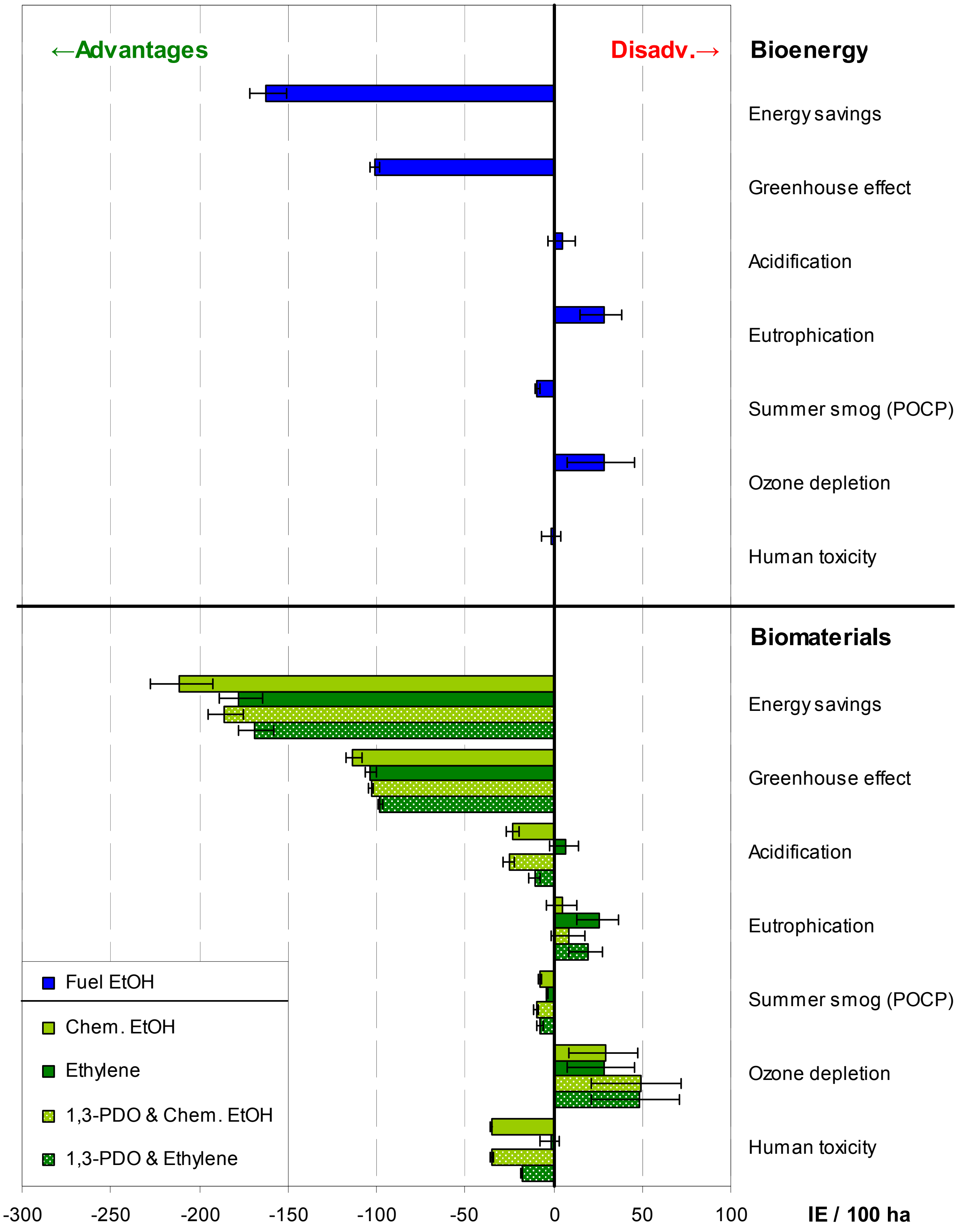

Fig. 7-11 Results of the life cycle comparison for bioenergy and biomaterials obtained from sweet sorghum and the conventional counterparts for the Lusitanian (LUS) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).

Sweet sorghum (MDS)

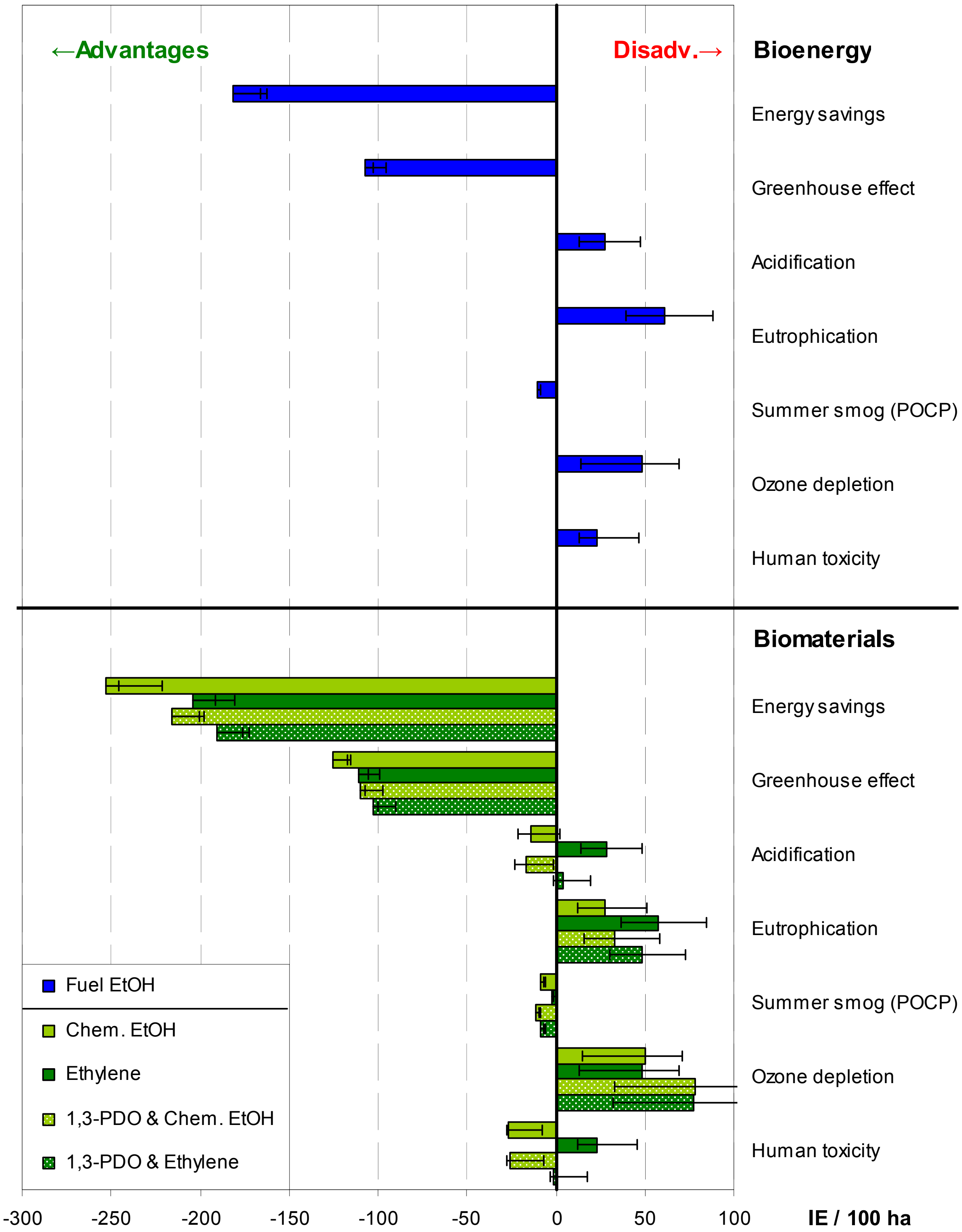

Fig. 7-12 Results of the life cycle comparison for bioenergy and biomaterials obtained from sweet sorghum and the conventional counterparts for the Mediterranean South (MDS) zone; bandwidths refer to minimum and maximum yields, respectively (see chapter 2.3).