ifeu -
Institute for Energy and
Environmental Research
Heidelberg GmbH

4F CROPS:

Future Crops for
Food, Feed, Fiber and Fuel

Set of environmentally friendly options

Final report on Task 4.4

Deliverable №:	**14**
Lead beneficiary:	**IFEU**
Delivery date:	**August 2010**
Dissemination level:	**Public**

Grant agreement №:	**212811 (FP7-KBBE-2007-1-3-01)**
Duration:	**01/06/2008 – 30/11/2010**

Heidelberg, October 2010

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement № 212811.

4F CROPS:
Future Crops for Food, Feed, Fiber and Fuel

Set of environmentally friendly options

Final report on Task 4.4

Authors:

Dipl.-Geoökol. Nils Rettenmaier

Dipl.-Landschaftsökol. Susanne Köppen

Dipl.-Phys. Ing. Sven Gärtner

Dr. Guido Reinhardt

ifeu – Institute for Energy and Environmental Research Heidelberg GmbH
Wilckensstraße 3
D-69120 Heidelberg
Phone: +49 (0)6221 47 67-0; Fax: -19
http://www.ifeu.de

Heidelberg, October 2010

Abbreviations

Abbreviation	Explanation
1,3-PDO	1,3-propanediol
BEV	Battery electric vehicle
BtL	Biomass-to-Liquid; thermochemical process yielding liquid biofuels from biomass
CHP	Combined heat and power (plant)
CNG	Compressed natural gas
CO_2	Carbon dioxide
EIA	Environmental Impact Assessment
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)
HVO	Hydrogenated Vegetable Oil; liquid biofuel made by hydrotreatment of vegetable oil
ICE	Internal combustion engine
IE	Inhabitant Equivalent, yearly environmental impact of an average European (EU27)
LCA	Life Cycle Analysis / Life Cycle Assessment
LUC	Land-use change
Mha	Megahectare (10^6 ha)
PJ	Petajoule (10^{15} Joule)
RED	Renewable Energy Directive; EU directive 2009/28/EC
t	(Metric) tonne (10^6 g)
WP	work package
yr	year

Table of Contents

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. Two assessment techniques are applied: environmental impact assessment (EIA) and life cycle assessment (LCA). LCA is used to determine the environmental aspects and potential environmental impacts of *products* such as a car, a packaging or a biofuel.

This deliverable (D 14) builds on the results of D 13 covering the screening life cycle analyses (LCAs) and the modelling of dependencies and sensitivities /Rettenmaier et al. 2010/.

Main results of the screening life cycle analyses (D 13)

The objective of D 13 is to analyse by means of LCA the environmental impacts associated with the production and use of bioenergy and bio-based materials from 15 selected future crops and to compare these impacts to those of their fossil or conventional equivalents.

The main outcome of D 13 is that the LCA results for all bioenergy and biomaterial paths under investigation show a distinct pattern: advantages in terms of energy and greenhouse gas savings and ambiguous results or even disadvantages regarding acidification, eutrophication, ozone depletion, summer smog, and human toxicity.

Thus, from a scientific point of view an objective conclusion regarding the overall environmental performance cannot be drawn. An overall conclusion rather has to be based on (subjective) value-choices, e.g. by prioritising certain environmental impact categories.

Quantitative results vary widely across environmental zones, depending on crop species, agricultural inputs and yield. Moreover, co-product accounting, co-product utilisation as well as the agricultural and fossil reference system play an important role.

Goal and scope

The overall goal of this report is to determine a set of environmentally friendly options for the production and use of selected future energy and industrial crops and resulting products. The report mainly builds on the results of the screening life cycle analyses (LCAs) and the modelling of dependencies and sensitivities, both of which are covered in D 13. In contrast to D 13 and for the sake of simplicity, the discussion regarding the most environmentally friendly options in this report only focuses on two out of the seven environmental impact categories. Using a multi-functional assessment tool, options with a high potential to save fossil energy and to mitigate greenhouse gas (GHG) emissions are identified[1].

The following key questions are answered in chapter 3.1 of this report:

1. Which crops or which crop group (e.g. oil, fiber, lignocellulosic or sugar crops) are to be preferred from an energy saving and greenhouse gas (GHG) mitigation point of view?
2. Which bioenergy and / or bio-based industrial product shall be produced from the crops if energy saving and mitigation of GHG emissions are given the highest priority?
3. If several conversion technologies are available for producing a certain bio-based product, which one should be chosen from an energy saving and GHG mitigation point of view?
4. Which advantages and disadvantages do future crops show compared to traditional crops in terms of saving energy and mitigating GHG emissions?
5. How do biofuels from future crops perform compared to other land-use options for renewable energy in the transport sector from an energy savings and climate protection point of view?

Furthermore, the report explores possibilities for scenario-based calculations of energy and GHG saving potentials (chapter 3.1.6), taking into account on the results of the land-use modelling (D 4, /Ganko & Kopczynski 2010/) and the development of non-food crop rotations (/Zegada-Lizarazu & Monti 2009/). Finally, chapter 3.2 compares the outcomes of the environmental analysis with those of the economic analysis (D 9, Soldatos et al. 2009b/ and D 10, /Soldatos et al. 2010/).

For the conclusions and recommendations in chapter 4, the focus is broadened again to all environmental impact categories and the trade-offs required between them. Moreover, the results of the environmental impact assessment (EIA) under task 4.1 (D 12, /Fernando et al. 2010/) as well as considerations regarding security of supply, land-use competition and technological / agronomic constraints are taken into account.

---

[1] Yet, it has to be kept in mind that the results show a distinct pattern which means that advantages in terms of energy saving and greenhouse effect are mostly associated with disadvantages regarding other environmental impact categories.

2 Approach

2.1 Multi-functional assessment tool

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 analyses (LCAs) under task 4.2 (see grey box below). It is able to simultaneously handle the large number (227) of different bioenergy and biomaterial paths which resulted from the multitude of processing and utilisation options. 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/.

Life cycle analyses (LCAs)

The life cycle analyses (LCAs) are carried out largely following the guidelines of the ISO standards 14040 and 14044 on product life cycle assessment /ISO 2006/. The analyses in this study are so-called screening LCAs which follow the 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. If necessary, they can be extended to a full LCA. 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).

For an in-depth documentation of the system boundaries, specifications and data sources that are used in the screening LCAs, refer to D 13 /Rettenmaier et al. 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.

Finally, the multi-functional assessment tool served the basis for the identification of best options under task 4.4, for which the reference scenarios were combined. In addition, the tool was linked to selected results of WP 1 (land-use modelling), WP 2 (non-food crop rotations) and WP 3 (economic analyses) which then allowed for scenario analyses and comparisons.

2.2 Life cycle analyses

In literature, hundreds of LCA studies on bioenergy and bio-based products can be found, covering a wide range of products. Rarely, a multitude of crops and products is investigated 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.

The aim was to perform the assessment for a representative selection of future crops which are covering different crop groups and different environmental zones throughout Europe combined with a representative selection of different energy and material uses of biomass.

Selection of crops and environmental zones

For the analysis of future non-food cropping systems, 15 crops were chosen in WP 2 covering five groups according to the main product to be used: oil, fiber, lignocellulose from woody and herbaceous biomass, and sugar. In order to cope with heterogeneous climatic and soil conditions throughout Europe, the division into environmental zones was adopted (following the approach of /Metzger et al. 2005/) and seven out of 13 were chosen for analysis: Atlantic Central (ATC), Atlantic North (ATN), Continental (CON), Lusitanian (LUS), Mediterranean North (MDN), Mediterranean South (MDS) and Nemoral (NEM). For each crop group and environmental zone, a representative future crop was selected. Table 2-1 gives an overview on the main products, the crops and the environmental zones which they are allocated to.

Table 2-1 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					●	●	●

Basic scenarios: Combination of selected crops and products (conversion paths)

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. The chosen conversion paths and main products are presented in Table 2-2. In total, 227 basic scenarios were analysed (number of environmental zones times number of main products).

Table 2-2 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 (thermochemical route)	FT diesel	
		Ethylene	Biomaterial
	Hydrolysis & fermentation (biochemical route)	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	

Reference scenarios: Variations and sensitivity analyses

In a second step, variations and sensitivity analyses were applied to the basic scenarios, transferring them into so-called ‘reference scenarios’. Each comparison of a bio-based product versus its conventional counterpart (basic scenario) was transferred to one ore more reference scenarios, which incorporate correlations using functional dependencies (for instance GHG savings along the entire life cycles as a function of yields, co-product uses or substituted power mixes).

Identification of a set of environmentally friendly options

For the identification of best options, all the reference scenarios were combined. Scenarios with a high potential to save fossil energy and to mitigate greenhouse gas (GHG) emissions are identified. This is in line with the European Renewable Energy Directive (RED, 2009/28/EC) which aims at a reduction of greenhouse gas emissions and promotes security of energy supply, among others by saving energy. An attempt was made to evaluate the overall potential environmental impact of the investigated crops by combining the LCA results with the results of the land-use modelling in WP 1 and the non-food crop rotations developed in WP 2 (see grey box below).

Excursus: Scenario-based energy and GHG savings potentials

In order to evaluate the overall potential environmental impact of the investigated crops, scenario analyses are performed. The aim is to quantify the overall environmental benefits and burdens of selected non-food cropping systems in Europe.

The approach chosen combines the results of the screening LCAs (D 13) with results obtained in other work packages. The basis for the scenario analyses is the amount of surplus land[2] which is quantified in WP 1 by means of land-use modelling (/Ganko & Kopczynski 2010/). Moreover, the non-food crop rotations as developed in WP 2 (/Zegada-Lizarazu & Monti 2009/) are taken into account. Together with the results of the screening LCAs (D 13), these data can be combined to calculate the overall energy savings and mitigation of GHG emissions, as depicted in Fig. 2-1.

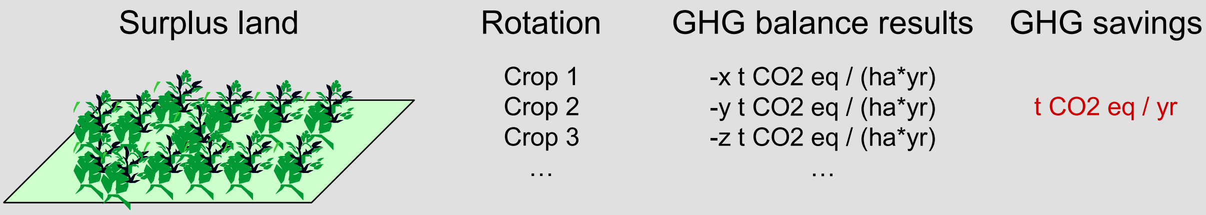

Fig. 2-1 Schematic approach used for the scenario analyses: Surplus land, crop rotations and the results of the GHG balances are combined to obtain the overall environmental benefits and burdens, e.g. GHG savings

Scenario analyses can be done for each of the environmental zones /Metzger et al. 2005/, which form the spatial resolution at which non-food crop rotations are developed and screening LCAs are performed within the 4F CROPS project. Only the amount of surplus land which is quantified at national level (different spatial resolution) needs to be converted to the environmental zone level.

This approach even allows for a comparison of different non-food crop rotations within the same environmental zone which helps to identify the most environmentally friendly options. Environmental performance is one of the key parameters determining the success of non-food cropping systems in the EU27.

---

[2] Agricultural land which is not needed to satisfy the demand for food and feed

2.3 Comparison of environmental and economic results

In addition to the identification of the most environmentally friendly options, the environmental results are also compared with economic results (chapter 3.2). For doing so, the results of the energy and greenhouse gas balances obtained from the screening life cycle assessments are combined with the results of the economic analyses, namely profits from crop production. These profits include all activities and operations required for agricultural production such as fixed and variable costs for land, labour and machinery as well as sale revenues. For further methodological details on the economic analysis, please refer to /Soldatos et al 2009a/.

For being able to compare environmental data with economic information, differences in the spatial reference need to be eliminated. Environmental analysis is based on spatial units which are homogenous in terms of climate and soil conditions (=environmental zones). In contrast to that, the economic analysis is focused on single countries, which are assumed to be homogenous in terms of production costs (e.g. land or labour costs). For making results comparable, for each environmental zone, one (or two) typical country is chosen as a case study.

The allocation of crops, environmental zone and country is shown in Table 2-3. Since it is outside the scope of this study to compare the economic and environmental results for all case studies, only selected results are presented in chapter 3.2. The selections are marked in grey in Table 2-3.

Table 2-3 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.			DE	DE	FR	■	■
Sunflower	*Helianthus annuus* L.	■	■	■	■	■	GR	■
Ethiopian mustard	*Brassica carinata* A. Braun	■	■	■	■	■	■	IT
Hemp	*Cannabis sativa* L.			■	■			■
Flax	*Linum usitatissimum* L.	■	■	FR	PL	■	■	IT
Poplar	*Populus spp.*		■		■	■		■
Willow	*Salix humilis* Marsh.	■		■			■	■
Eucalyptus	*Eucalyptus spp.*	■	■	■	■	■	■	
Reed canary grass	*Phalaris arundinacea* L.	SE	■	■	■	■	■	■
Miscanthus	*Miscanthus × giganteus*	■	UK NL	UK NL	RO		■	■
Switchgrass	*Panicum virgatum* L.	■	UK NL	UK NL	■	■	■	■
Giant reed	*Arundo donax* L.	■	■	■	■	■	PT	■
Cardoon	*Cynara cardunculus* L.	■	■	■	■	■	■	ES
Sugar beet	*Beta vulgaris* L.	■	■	UK		■	■	■
Sweet sorghum	*Sorghum bicolor* L. Moench	■	■	■	■	PT	GR IT	GR IT

As described in chapter 2.1, LCAs used for environmental analyses take into account the entire life cycle of a product, starting from crop cultivation until to the use and final disposal of the product (‘cradle-to-grave’ approach). In contrast, the scope of the economic assessment within 4F CROPS is to calculate profits at farm level, which means that production costs only cover the biomass cultivation stage (‘cradle-to-farm gate’ approach). Both system boundaries are shown in Fig. 2-2.

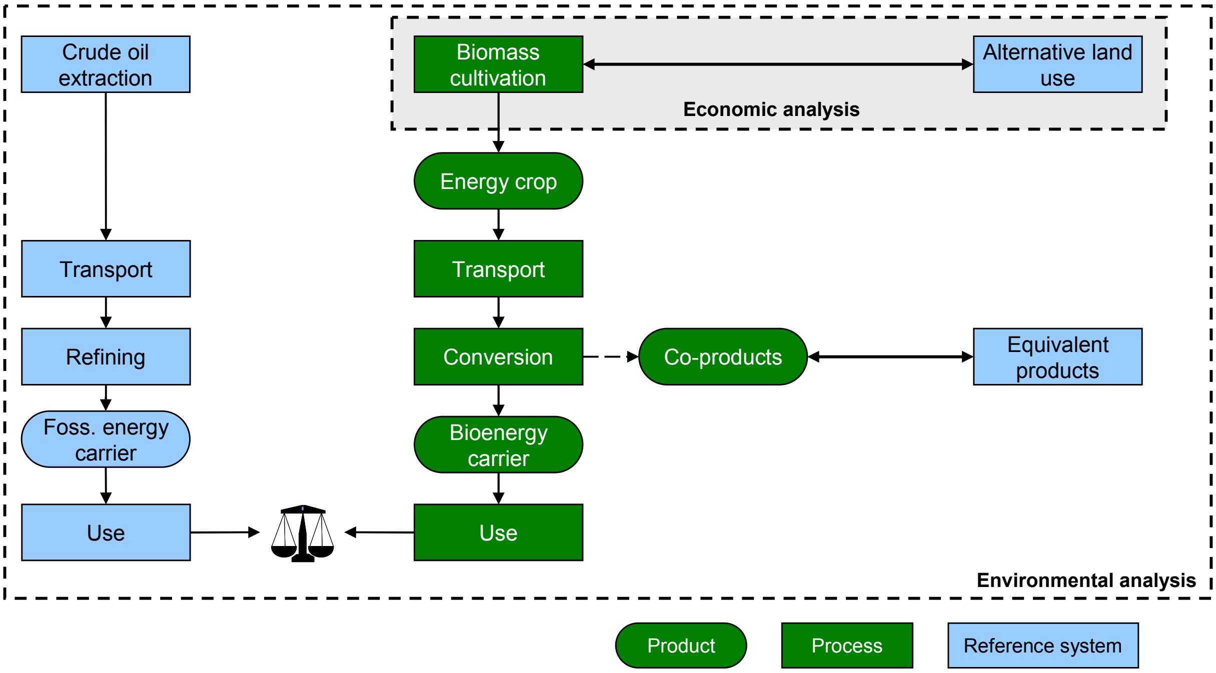

Fig. 2-2 System boundaries of the environmental and the economic analyses

The ‘cradle-to-farm gate’ approach used for the economic analyses is adequate within the 4F CROPS project, as the farmer’s profit certainly is one of the key parameters for the successful establishment of non-food cropping systems. Being the first actor within the value chain, the farmer has to make sure that his profit obtained from on a new crop at least equals or even exceeds the profit he would make growing a conventional crop – not to mention other obstacles which have to be overcome. If a new crop – which might or might not be politically prioritised – accounts for fewer profits than alternative choices, these losses of income would have to be compensated at farm level. Otherwise, there would be no incentive for the farmer to establish the new crop.

The environmental results in terms of life-cycle energy and greenhouse gas savings might be used as a basis for decision-making on which new cropping systems should be implemented. The combination of these savings with economic results clarifies whether and to what extent incentives are needed to stimulate the most environmentally friendly crop choices by farmers. Yet, it has to be kept in mind that the most profitable options from a farmer’s point of view does not necessarily coincide with the most economic option from a life cycle point of view: Further analyses using life cycle costing (LCC) methodology would be required to answer questions related to (final) product costs or CO_2 abatement costs.

3 Results: Set of environmentally friendly options

The following chapters aim at determining a set of environmentally friendly options for the production and use of selected future energy and industrial crops and resulting products. In chapter 3.1, the results of the screening life cycle analyses (D 13) are combined and compared. When identifying the best options, the focus is on energy savings and greenhouse effect. Chapter 3.1.6 explores possibilities for scenario-based calculations of energy and GHG saving potentials, taking into account on the outcomes of the land-use modelling in WP 1 (D 4, /Ganko & Kopczynski 2010/). Finally, chapter 3.2 compares the greenhouse gas balances of selected crops with the outcomes of their economic performance investigated in WP 3 (D 9, Soldatos et al. 2009b/ and D 10, /Soldatos et al. 2010/).

3.1 Results based on the screening life cycle analyses (LCA)

The first sub-chapter (3.1.1) compares biogenous paths and fossil or conventional paths, whereas the following sub-chapters compare different biogenous paths among each other.

3.1.1 Biogenous paths versus fossil or conventional paths (D 13)

Exemplification of results

Fig. 3-1 shall serve as an example to explain how the graphs in the following chapters are generated. It displays the results of the life cycle comparison between bioethanol produced from sugar beet and conventional gasoline. In the upper part, details are given for the credits and expenditures for sugar beet ethanol production as well as for the conventional gasoline being replaced. In the lower part, the resulting balances are shown, indicating whether bioethanol is disadvantageous or advantageous compared to conventional gasoline.

The first detailed bars in the upper right part of the figure show 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 credits related to the avoided 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. To obtain the balance bar, all expenditures and credits throughout the life cycle are summed up. 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.

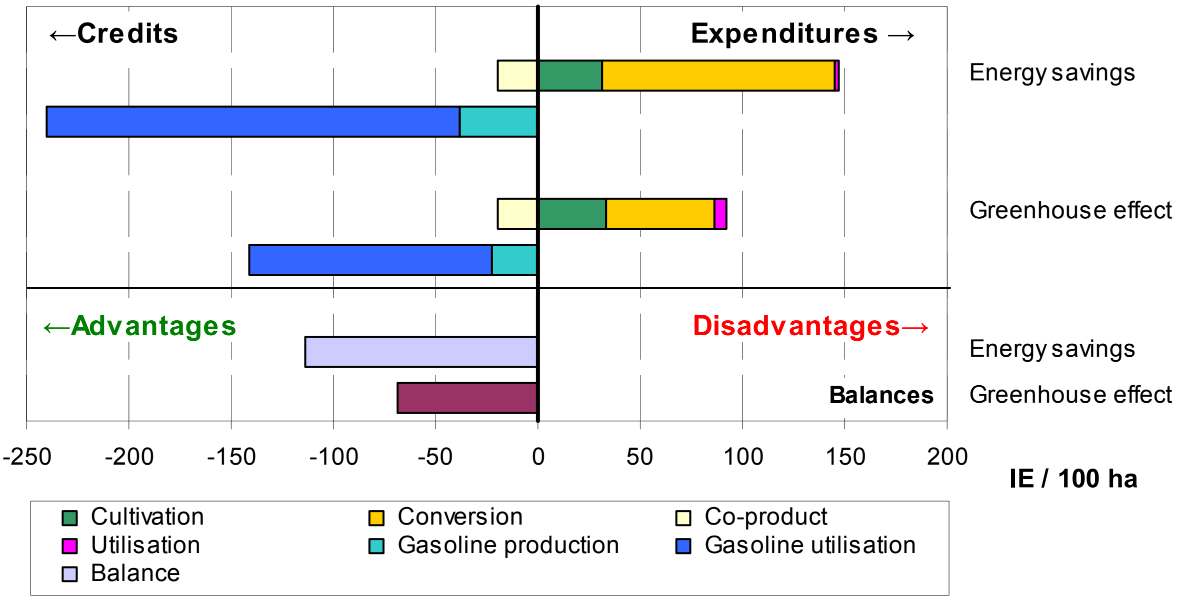

Fig. 3-1 Results of the life cycle comparison between bioethanol produced from sugar beet and conventional gasoline.

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 inhabitants. 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.

Balances are produced for each combination of crop, target product and conversion option. For putting focus on the research questions stated in chapter 1, several detailed results are aggregated into ranges. Depending on the question to be answered in the following chapters, different elements may be contained in the ranges. These elements are listed in the subtitle of each figure. The derivation of ranges is exemplified in Fig. 3-2: the energy and greenhouse gas ranges for fuel ethanol include two different sugar crops cultivated in five different environmental zones.

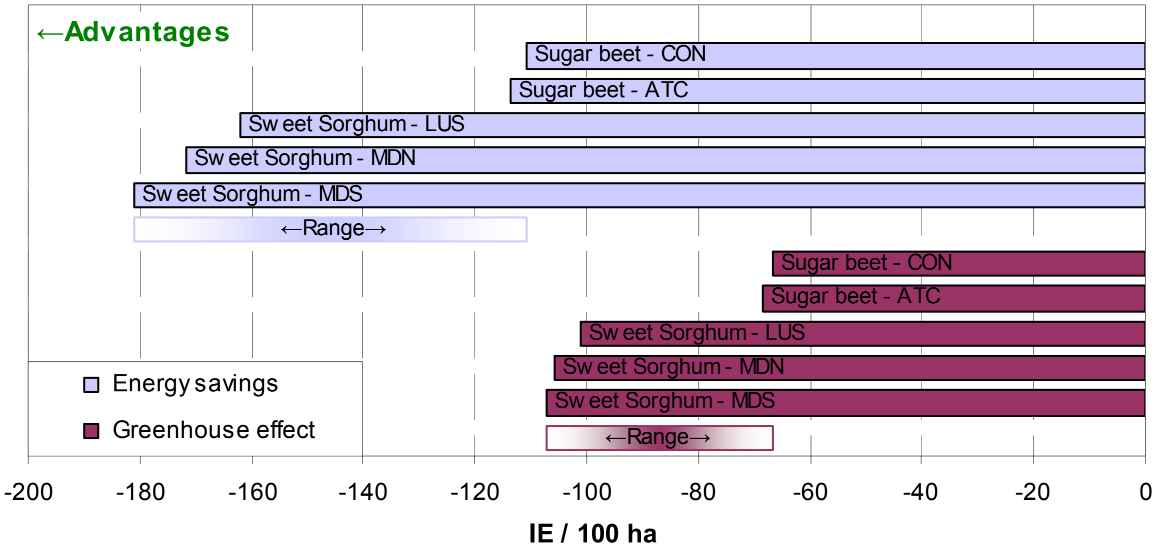

Fig. 3-2 Results of the life cycle comparison between fuel ethanol produced from two sugar crops and conventional gasoline in five different European environmental zones.

Results for the basic scenarios

The remaining future crops were assessed in analogy to sugar beet. The semi-quantitative results by crop group are compiled in Table 3-1. Looking at the results in Table 3-1, a distinct pattern becomes obvious: the energy and industrial crops show environmental advantages in terms of energy and greenhouse gas savings and ambiguous results or even disadvantages regarding acidification, eutrophication, ozone depletion, summer smog, and human toxicity. With that, from a scientific point of view, an objective conclusion regarding the overall environmental performance of biofuels, bioenergy and biomaterials produced from the investigated crops cannot be drawn. An overall conclusion has to be based on (subjective) value-choices, e.g. by ranking the impact categories in a given hierarchy.

The European Renewable Energy Directive (RED, 2009/28/EC) may serve as a guideline for ranking the results in a given hierarchy and thus come to an overall conclusion. The RED specifically 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 greenhouse gas emissions are subjectively given the highest priority, all bioenergy carriers and biomaterials assessed are superior to their fossil equivalent. However, it has to be noted that different individuals, organisations and societies may have different preferences; therefore different rankings may be derived based on the same objectively obtained results.

Table 3-1 Environmental performance of different crops used for non-food purposes; ‘++’: < –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

Modelling of dependencies and sensitivities

When performing a LCA, a number of choices regarding methods and data have to be made. A number of them are commonly known to be decisive (/Gnansounou et al 2009/, /Cherubini et al. 2009/), e.g. whether renewable or fossil fuels are used in the conversion process (/Farrel et al 2006/, /Börjesson 2009/), or which emission factors for nitrogen fertiliser-related emissions are applied (/Crutzen et al. 2007/, /Dallemand et al. 2009/, Erisman et al. 2010/). In the following, the most important parameters are summarised:

The choice of method used to account for co-products has a significant impact on the quantitative results of the life cycle assessments. Despite multiple options regarding the use of co-products and potentially larger variations in results, the substitution method (system expansion) reflects reality more adequately and should therefore be preferred over allocation for the purpose of policy analysis. Yet, regarding the choice of method there is no right or wrong.

The most important single factor influencing the LCA results, however, is the choice of agricultural reference system including land-use changes. If energy crops are not cultivated on surplus land but on agricultural land currently used for food and feed production, these food and feed crops are displaced causing direct and indirect land-use changes. In some cases, more greenhouse gas emissions would be caused than by using fossil energy carriers (Fig. 3-3). However, research concerning indirect land-use changes (iLUC) is still in its infancy. Despite all efforts, to date there is no commonly accepted method on how to quantify iLUC effects, let alone integrate iLUC in LCA (/Kløverpris et al. 2008/, /Liska & Perrin 2009/).

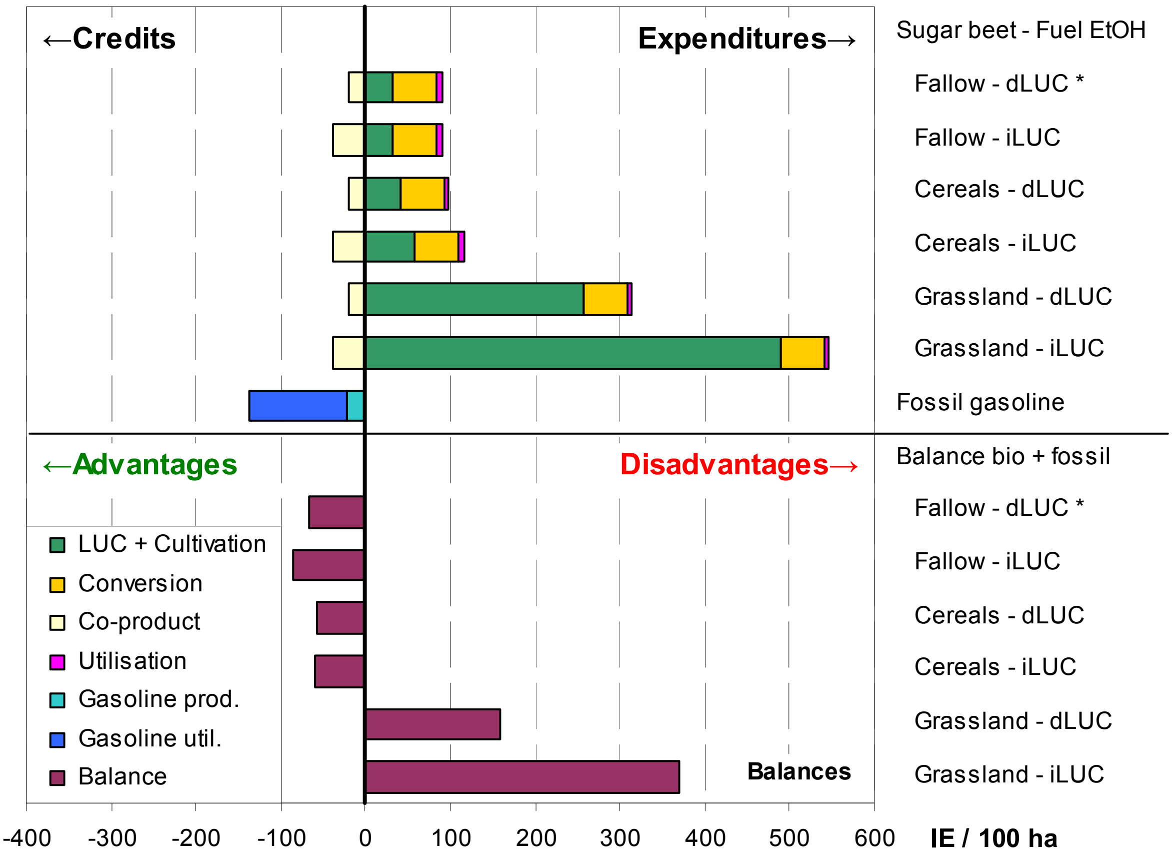

Fig. 3-3 Results of the life cycle comparison for ethanol from sugar beet with fossil gasoline taking into account direct and indirect land-use changes. * Default agricultural reference system in basic scenarios.

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.

3.1.2 Biogenous paths in comparison: best crop group and product

Despite the subjective trade-offs required between the environmental impacts, the non-food paths can still be compared among each other. For the sake of simplicity, the discussion regarding the most environmentally friendly options in this report only focuses on energy savings and greenhouse effect. For identifying best options in terms of crop groups and main products, the energy and greenhouse gas balances for all crop groups and products are presented in Fig. 3-4. The ranges cover all crops within one crop group as well as all environmental zones (for their derivation, see chapter 3.1.1). For the allocation of the crops to different environmental zones, refer to Table 2-1. Note that fiber crops are not used for bioenergy production but only their use as biomaterials is regarded.

Results – Best crop group

- Within and across all environmental zones, herbaceous lignocellulosic crops show the highest potentials in saving energy and greenhouse gases, followed by fiber and sugar crops. In contrast, oil crops achieve the lowest energy and greenhouse gas savings. The good performance of herbaceous crops is due to both high biomass yields (especially regarding the share of the crop which is actually used for non-food purposes) and efficient biomass conversion technologies.

Results – Best product

- Within each crop group, the results for the products show great ranges resulting from different crops and environmental zones, i.e. from yield differences. The ranges partly overlap which means that products that potentially show great potentials of energy and greenhouse gas savings might perform similar to less advantageous products in case a lower yielding crop is chosen and / or if a crop is produced in an environmental zone in which lower yields are achieved.
- The comparison of bioenergy and biomaterial use does not suggest a clear tendency towards one or the other, if the whole range of results is regarded. Both bioenergy and biomaterial paths can lead to similarly high savings of energy and greenhouse gases.
- Within the **bioenergy** paths, stationary heat and power production leads to higher energy and greenhouse gas savings than the use as transport fuel (‘mobile use’). One of the reasons is that the production of transport fuel requires much higher energy inputs than the production of heat and power, i.e. the conversion efficiency is much lower.
  - 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 upon replacement.
  - Within the transport biofuels, bioethanol as a gasoline substitute shows better results than all diesel substitutes (FAME, HVO and FT diesel) when compared within each crop category.

- Within the **biomaterial** paths, fiber crops show a remarkable potential to save energy and to mitigate GHG emissions which is comparable to the potential of herbaceous lignocellulosic crops. The latter lead to the highest savings if converted into biochemicals.
    - Regarding biochemicals, there are two fundamentally different approaches to convert biomass into products: the biochemical route (extraction of complex compounds synthesised by nature) and the thermochemical route (gasification, i.e. breakdown to C1 units, and subsequent chemical synthesis). The specific savings potentials differ considerably (relatively low for syngas-based chemicals; relatively high for complex compounds) as do the potential markets (large quantities of syngas-based chemicals needed; low quantities of for complex compounds) /Reinhardt et al. 2007/. Within the 4F CROPS project, however, no clear tendency can be found whether biochemical or thermochemical routes perform best due to the limited number of paths investigated.

Conclusions

From an energy saving and climate protection point of view, high yielding crops should be strived for in order to maximise land-use efficiency. However, it has to be kept in mind that there are agronomic restrictions regarding perennial crops (often, woody or herbaceous lignocellulosic crops are perennial) as they cannot be included into existing crop rotations.

However, the large and partly overlapping results ranges indicate that high yielding crops show less advantages if certain conversion paths and products are chosen. Therefore, in order to maximise environmental benefits it is not sufficient to choose the crop and environmental zone achieving highest crop yields but also to make sure that the biomass is converted and used in a very efficient way. In other words: for a meaningful comparison of future crops, it is essential to assess their entire life cycle, as the overall environmental impact largely depends on what the biomass is used for, how efficiently it is converted and which fossil fuel or energy carrier it substitutes. Besides crop yields, the target product produced from crops significantly influences a crop's environmental performance. However, for specific questions related to agriculture, e.g. to point out opportunities for improvement, a cradle-to-farm gate approach as applied by /Monti et al. 2009/ might be sufficient.

Generally, both bioenergy and biomaterial paths can lead to similarly high savings of energy and greenhouse gases, i.e. the results not suggest a clear tendency towards material or energy use. Within the bioenergy paths, the direct use for heat and power production should be preferred over a use as transport fuels. However, the exact quantitative results depend on the case-specific conditions, e.g. on the composition of the substituted conventional power mix (see D 13). Within the biomaterial paths, both fiber crops and herbaceous lignocellulosic crops show a remarkable potential. Regarding biochemicals, however, no clear tendency could be found whether biochemical or thermochemical routes perform best.

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

If oil crops are used to produce FAME (biodiesel), the energy savings per 100 hectares are equivalent to the yearly energy demand of about 20 to 63 inhabitants.

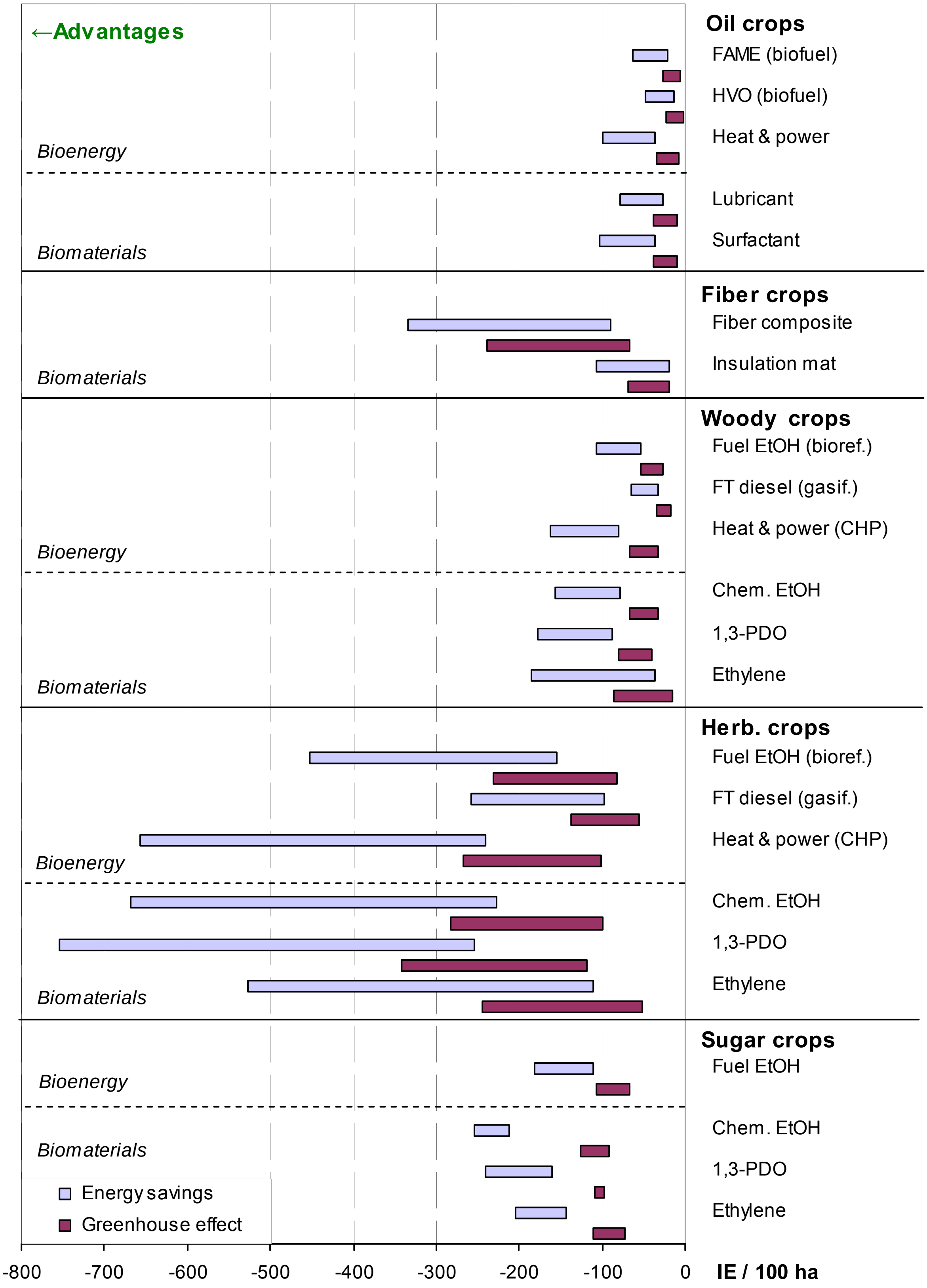

Fig. 3-4 Energy and greenhouse gas balances for all crop groups and types of bioenergy and biomaterials; ranges cover different energy crops and environmental zones within each crop group; FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil, EtOH = ethanol, FT = Fischer-Tropsch, 1,3-PDO = 1,3-propanediol.

3.1.3 Biogenous paths in comparison: best conversion path

Some of the biofuels and biochemicals assessed in this study can be produced with different conversion technologies. For instance, ethanol can be produced via fermentation of sugar crops (1st generation) or via enzymatic hydrolysis and fermentation of lignocellulosic feedstocks (2nd generation). In most cases, the comparison of different conversion technologies implies the comparison of different crop groups since both elements are linked. For identifying the most efficient conversion path, the respective energy and greenhouse gas balances are shown in Fig. 3-5. The ranges cover different crops and different environmental zones.

Results – Biofuels

- Regarding **diesel substitutes**, the production of Fischer-Tropsch diesel via biomass gasification and subsequent FT synthesis (2nd generation) shows by far the best results in terms of energy and greenhouse gas savings. Although chemically different, FAME and HVO show about the same results, but lead to much less savings of energy and greenhouse gases than FT diesel.
- As far as **gasoline substitutes** are concerned, only ethanol from sugar crops (1st generation) and lignocellulosic crops (2nd generation) is investigated. 2nd generation ethanol tends to better results, but is not superior *per se*: 1st generation ethanol from sugar beet, for example, is only surpassed by lignocellulosic ethanol from herbaceous crops.

Results – Biochemicals

- Concerning the investigated biochemicals, no clear tendency can be found towards one or the other. Ethanol, 1,3-PDO and ethylene lead to rather similar results in terms of energy and greenhouse gas savings.
- Products obtained via enzymatic hydrolysis and fermentation of lignocellulosic feedstock (2nd generation technology, e.g. applied in future biorefineries) show better results than products obtained via fermentation of sugar crops using 1st generation technology.
- Regarding the production of ethylene, the advanced biochemical route (biorefinery) shows advantages over the thermochemical route (gasification) in terms of energy and greenhouse gas savings. The classical biochemical route via ethanol produced from sugar crops leads to intermediate results.

Conclusions

The choice of the conversion technology significantly influences the results. However, it is not possible to derive a general recommendation regarding conversion technologies, as they are most often implicitly linked to certain crops or crop groups. Therefore, it is essential to assess the environmental impacts along the entire life cycle. Except for specific questions, it is not sufficient to focus on single life cycle stages only (e.g. crop cultivation), as the extent to which each stage contributes to the overall environmental impact differs between paths.

The comparison of 1st and 2nd generation technologies suggests that the latter might achieve better results from an energy saving and GHG mitigation point of view, especially if biochemicals are produced in future biorefineries using 2nd generation technology.

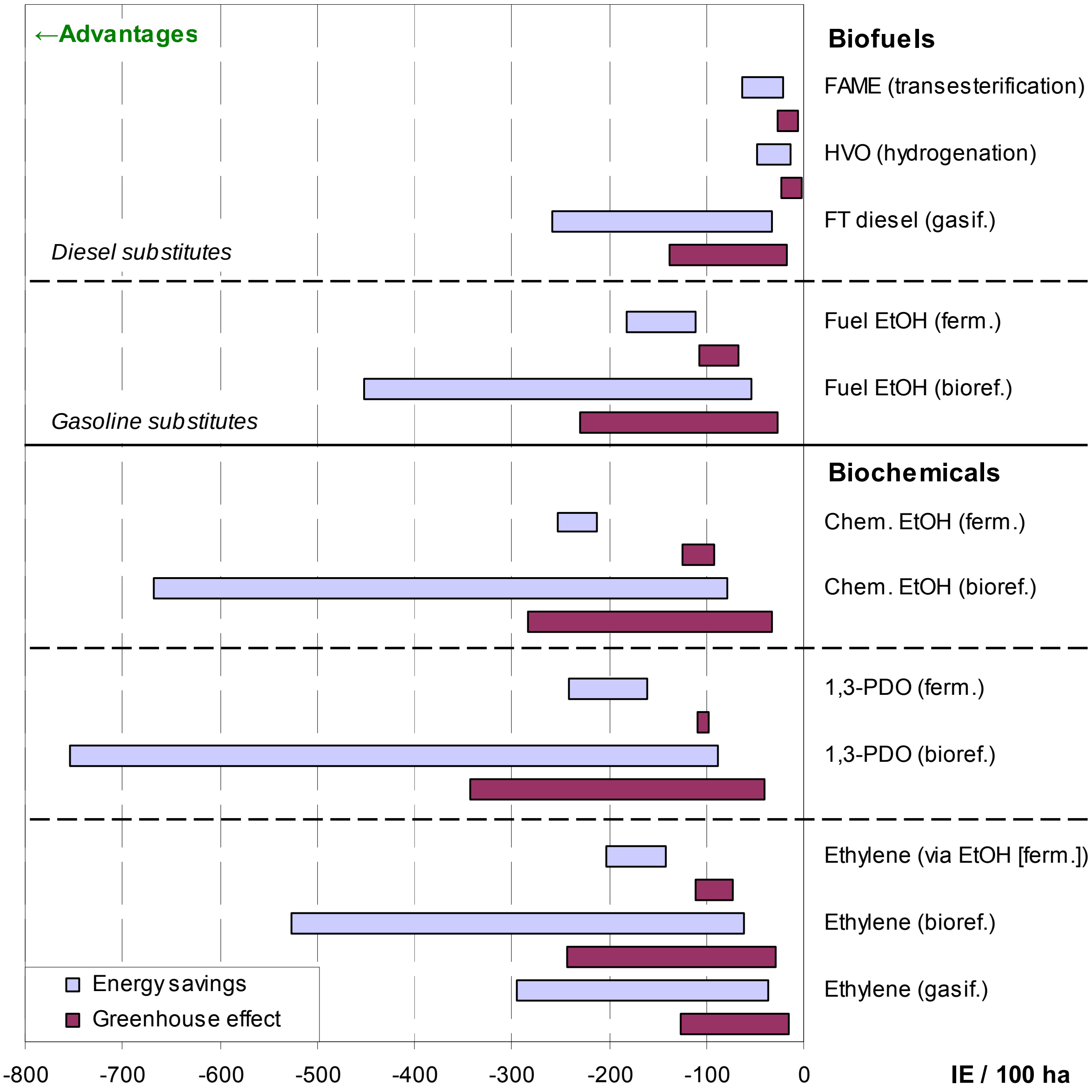

Fig. 3-5 Results of the life cycle comparison for all main products that can be produced with different conversion paths; ranges cover all crops and environmental zones; FAME = fatty acid methyl ester, HVO = hydrogenated vegetable oil, FT = Fischer-Tropsch, EtOH = ethanol, 1,3-PDO = 1,3-propanediol.

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

If oil crops are used to produce FAME (biodiesel), per 100 hectares about the same amount of greenhouse gases can be saved that is yearly emitted by 5 to 28 inhabitants.

3.1.4 Bioenergy paths in comparison: traditional versus future crops

The main objective of the 4F CROPS project is to analyse future non-food cropping systems for the production of either bioenergy or biomaterials. However, already today there are well established cropping systems providing bioenergy and biomaterials.

Taking bioenergy (both transport fuels and stationary use) as an example, Fig. 3-6 compares traditional crops and future crops in terms of energy and greenhouse gas savings. The ranges of the traditional crops (wheat and corn; in addition to the crops listed in Table 2-1) cover different cultivation and conversion conditions, whereas those for the crops assessed in this study cover different environmental zones. Sunflower, rapeseed and sugar beet have an intermediate status since they are considered future crops within this study – at least for some environmental zones – although they have traditionally been cultivated in other zones.

Results

- Both within biofuels and stationary bioenergy, future herbaceous lignocellulosic crops lead to higher energy and greenhouse gas savings than traditional crops. In contrast to heat and power generation, for which lignocellulosic crops can be used already today, these crops can only be used in the transport sector if future 2nd generation technologies are in place. Therefore, both promising traditional (sugar beet) and future sugar crops (sweet sorghum) using 1st generation technology should not be neglected.
- All other future crops are similar to traditional crops with Ethiopian mustard being at the lower end and sweet sorghum at the higher end of the ranges. If used for bioenergy, woody lignocellulosic crops lead to energy and greenhouse gas savings which are comparable to today's biogas paths.

Conclusions

When comparing traditional and future crops, some future crops show clear advantages from an energy and greenhouse gas saving point of view: high savings can be achieved with the implementation of herbaceous lignocellulosic crops – provided they are used in the most efficient way. However, their use in the transport sector as liquid biofuels is restricted since respective technologies are still under development. In the stationary bioenergy production there is no such bottleneck.

Apart from herbaceous lignocellulosic crops, the other future crops show a tendency towards better results, but they are not *per se* superior to traditional crops, taking Ethiopian mustard as an example. Therefore, promising traditional crops should not be neglected, as the crops can be easily integrated into existing crop rotations and as mature industrial-scale conversion technology is used.

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

If wheat is used to produce ethanol, the energy savings per 100 hectares are equivalent to the yearly energy demand of about 9 to 48 inhabitants.

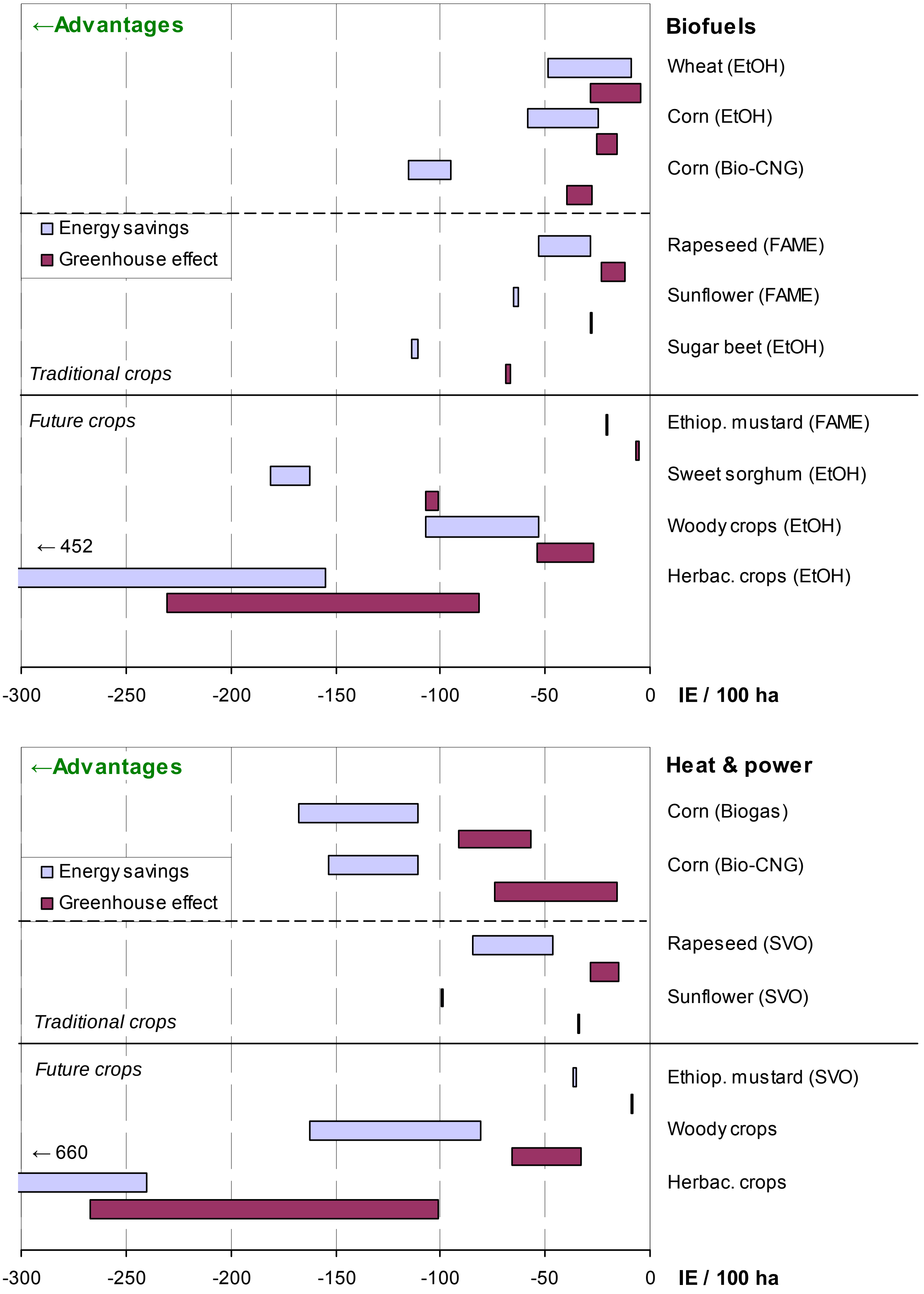

Fig. 3-6 Results of the life cycle comparison for traditional and future crops in biofuel and bioenergy application; for ranges see introduction of this chapter; EtOH = ethanol, FAME = fatty acid methyl ester, CNG = compressed natural gas.

3.1.5 Biofuel paths versus other renewable energies in the transport sector

One of the main drivers behind dedicated energy crop cultivation in Europe is the Renewable Energy Directive (2009/28/EC) which fosters the use of biomass for energy in order to reduce greenhouse gas emissions. The directive sets a sectoral target of at least 10 % of energy from renewable sources to be used in the transport sector by 2020 /CEC 2009/. This target can be met either by (liquid or gaseous) biofuels or by electric vehicles powered by renewable energy. The latter can be generated from various renewable sources, among others from biomass, wind power or solar energy (photovoltaics).

Electric vehicles such as battery electric vehicles (BEV) might replace conventional cars with internal combustion engines (ICE) which can be fuelled with either fossil or bio-based fuels. Fig. 3-7 shows the greenhouse gas and energy balances for wind power, solar energy and biomass used in the transport sector – the latter both as green power in electric vehicles and as liquid biofuels.

The ranges of wind and solar energy cover different plant / panel configurations and efficiencies. Ranges of biomass use in electric vehicles cover different conversion paths as well as different co-product uses. The ranges of the liquid biofuels cover the 4F crops in the respective crop groups (e.g. all oil crops for biodiesel production) as well as all environmental zones.

Results

- The use of power generated by wind turbines or solar panels in the transport sector shows by far the highest land-use efficiency in terms of energy and greenhouse gas savings. Also in the worst cases, results are still better than the best results from other biomass applications.
- Also among biomass applications in the transport sector, power generation and its use for electric propulsion shows more savings than traditional liquid biofuels like bioethanol or biodiesel and even second generation biofuels such as lignocellulosic ethanol. However, this is only the case if electricity is produced in a CHP and if the waste heat is used.
- Among the liquid biofuels, second generation ethanol production from herbaceous biomass shows the best results in terms of energy and greenhouse gas savings. This is due to the high biomass efficiency both due to high yields per hectare and due to the fact that the whole crop can be converted into a biofuel.

Conclusions

From a land use point of view, there are more efficient options to implement renewable energy carriers in the transport sector than liquid biofuels: by far the highest energy and greenhouse gas savings can be achieved with solar energy or wind power which are used in electric vehicles. Also the use of biomass for power in electric propulsion performs much better than liquid biofuels. Therefore, and in view of the increasing shortage of the resource land the implementation of electric propulsion in transportation should be strived for with all efforts. Even though electric propulsion is not a feasible solution for the transport sector as a whole, at least passenger traffic could be electrified.

The land-use efficiency of wind power even can be increased since it allows for the use of the subjacent area for crop cultivation. In wind farms, only a small part of the area is actually needed for the foundation of the wind turbine. The remaining area could be used for non-food crops production or for feed and food production. The latter option would contribute to the mitigation of the competition between food and fuel production.

In contrast to wind turbines, open-field solar panels cannot be combined with crop cultivation on the same area – they are mutually exclusive. With respect to the increasing pressure on agricultural land, large-scale open-field photovoltaic systems should only use areas which cannot be used for food or feed production (e.g. contaminated soils). Preferably, roofs and façades should used for the establishment of solar panels.

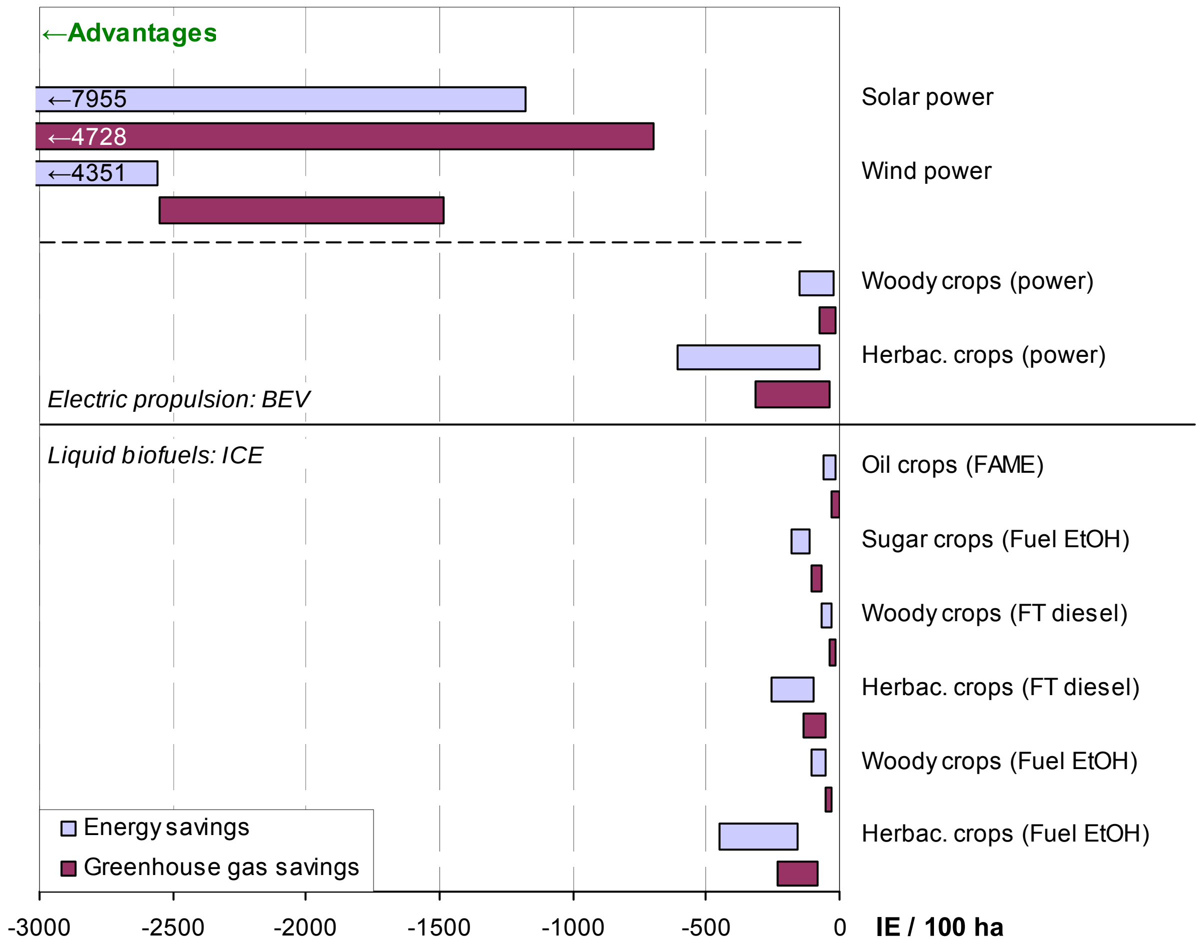

Fig. 3-7 Results of the life cycle comparison of wind power, photovoltaic as well as biomass applications in the transport sector; for ranges see introduction of this chapter; BEV = battery electric vehicle, ICE = internal combustion engine, FAME = fatty acid methyl ester, FT = Fischer-Tropsch, EtOH = ethanol.

Reading the diagram – exemplification of 9th bar 'energy savings' for biodiesel

If oil crops are used to produce biodiesel (HVO or FAME), the energy savings per 100 hectares are equivalent to the yearly energy demand of about 14 to 63 inhabitants.

3.1.6 Excursus: Scenario-based energy and GHG savings potentials

The scenario analyses presented in this chapter are performed in order to quantify the overall environmental benefits and burdens of selected non-food cropping systems in Europe.

3.1.6.1 Surplus land

The basis for the scenario analyses is the amount of surplus land which is quantified in WP 1 by means of land-use modelling /Ganko & Kopczynski 2010/. As it is quantified at national level, it needed to be converted to the environmental zone level at which non-food crop rotations are developed and screening LCAs are performed. This was kindly done by EC BREC /EC BREC 2010/ using GIS software by intersecting their results at national level with Metzger's map of the environmental zones /Metzger et al. 2005/. The latter was kindly provided by A&F. The results are displayed in Table 3-2.

Table 3-2 Surplus land [ha] available for non-food crops in 2008, 2020 and 2030 in different environmental zones. Based on /Ganko & Kopczynski 2010/

		Base case 2008	Scenario 2020	Scenario 2030
NEM	Nemoral	470,228	1,006,528	1,328,802
ATN	Atlantic North	866,989	1,298,516	1,610,392
ATC	Atlantic Central	1,444,336	2,106,845	2,549,045
CON	Continental	3,242,824	6,386,087	8,578,507
LUS	Lusitanian	562,404	718,766	838,096
MDN	Mediterranean North	2,063,309	2,164,425	2,306,439
MDS	Mediterranean South	2,454,887	2,476,579	2,512,830
	TOTAL	**11,104,976**	**16,157,747**	**19,724,112**

Results

- In 2008, approximately 11.1 Mha of surplus land were available for the production of non-food crops in the environmental zones covered within the 4F CROPS project. Almost one third of the surplus land is located in the Continental zone. It roughly equals the current total arable land in Germany.
- The amount of surplus land increases to 16.2 Mha in 2020 and 19.7 Mha in 2030, respectively.

It has to be kept in mind that the model applied in WP 1 is based on land allocation and balancing procedures. Surplus land, which is potentially available for non-food crops, is calculated after the allocation of available land resources for the production of different food and feed crops. The major drivers in the scenarios established are the expected growth in crop production intensity and changes in food demand. As land quality is not analysed in the model, the amount of surplus land has to be considered as a theoretical potential which does not take into account the suitability (e.g. in terms of climate and soil) for specific crops. As a consequence, the amount of surplus land suitable for a specific crop cannot be calculated.

3.1.6.2 Annual crops

The second step towards scenario-based energy and greenhouse gas savings potentials involves the combination of surplus land (irrespective of its quality) with the non-food cropping systems as developed in WP 2 /Zegada-Lizarazu & Monti 2009/. Table 3-3 shows rotation possibilities for seven environmental zones.

Table 3-3 Environmental zones and rotation possibilities in an hypothetical scenario where all crops are exclusively dedicated to bioenergy production /Zegada-Lizarazu & Monti 2009/

Environmental zone		Hypothetical suggested crop rotations	Product
NEM	Nemoral	Rapeseed – Flax – Safflower	Vegetable oil
ATN	Atlantic North	Rapeseed – Flax – Safflower	Vegetable oil
ATC	Atlantic Central	Rapeseed – Flax – Safflower	Vegetable oil
CON	Continental	Maize – Sugar beet – Sorghum	Ethanol
		Rapeseed – Flax – Safflower	Vegetable oil
LUS	Lusitanian	Maize – Sugar beet – Sorghum	Ethanol
		Soybean – Ethiopian mustard – Sunflower	Vegetable oil
		Rapeseed – Flax – Safflower	Vegetable oil
MDN	Mediterranean North	Maize – Sugar beet – Sorghum	Ethanol
		Soybean – Ethiopian mustard – Sunflower	Vegetable oil
		Rapeseed – Flax – Safflower	Vegetable oil
MDS	Mediterranean South*	Maize – Sugar beet – Sorghum	Ethanol
		Soybean – Ethiopian mustard – Sunflower	Vegetable oil

* Some crops such as maize and sugar beet may require supplemental irrigation

Results

- The non-food crop rotations displayed in Table 3-3 only cover oil crops and sugar / starch crops leading to vegetable oil and ethanol. Fiber crops and annual (herbaceous) lignocellulosic crops are not included.
- Moreover, the suggested crop rotations in Table 3-3 contain additional crops such as flax (for energy), safflower, maize and soybean which are not included in the list of selected crops in Table 2-1. According to the latter table, sugar beet and sweet sorghum are mutually exclusive in the same environmental zone (within the 4F CROPS project).

In the third step, the non-food crop rotations are combined with the results of the screening LCAs (D 13) in order to calculate for example the overall energy and GHG savings potential. This step could not be performed due to incompatible non-food crop rotations (see above).

Conclusions

The approach chosen to calculate the overall energy and GHG savings potential did not lead to the desired results for annual crops, as the suggested non-food crop rotations contained additional crops as well as crop combinations which were incompatible with the list of selected crops on which the environmental assessment is based.

3.1.6.3 Perennial crops

In contrast to annual crops, perennial crops by definition are not a constituent part of crop rotations. Therefore, the scenario-based energy and greenhouse gas savings potentials can be calculated by combining – for each environmental zone – the amount surplus land (disregarding its quality) with the LCA results for the respective perennial crops listed in Table 2-1 (poplar, willow, eucalyptus, reed canary grass, Miscanthus, switchgrass and giant reed).

Results

- Depending on the combination of perennial crop and product, the energy saving potentials range from 300 – 3,910 PJ/yr which roughly equals 0.8 – 9.7% of EU's yearly energy demand. The higher end of the range is achieved with herbaceous perennial crops.
- The greenhouse gas savings potentials amount to 20 – 230 Mt CO_{2eq}/yr (0.2 – 4.4%).

Conclusions

A considerable amount of energy and greenhouse gases could be saved if 11.1 Mha of surplus land were used to grow perennial crops. However, these potentials are theoretical, as the quality of surplus land has not been taken into account.

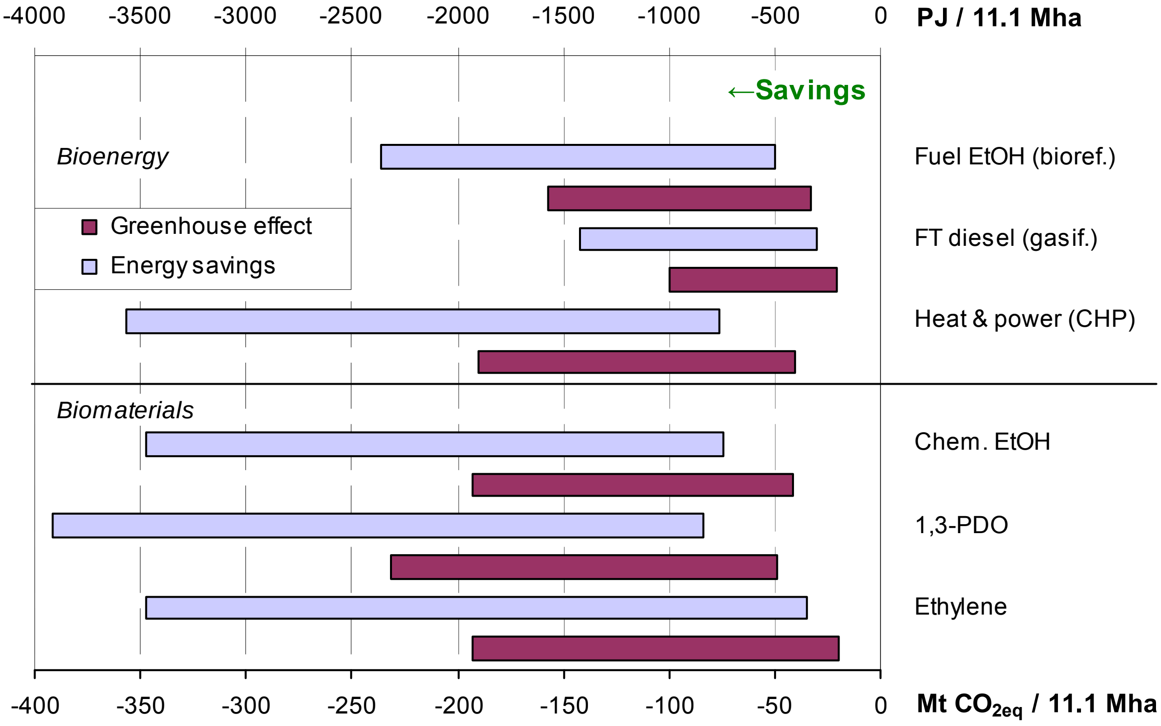

Fig. 3-8 Energy and greenhouse gas savings potentials for different bioenergy carriers and biomaterials produced from perennial crops grown on 11.1 Mha of surplus land.

Reading the diagram – exemplification of 9th bar 'energy savings' for 1,3-PDO

If 11.1 Mha of surplus land were used to grow perennial crops for the production of 1,3-PDO, the energy savings amount to 840 – 3,910 PJ/yr.

3.2 Comparison of environmental and economic results

When implementing new cropping systems, besides environmental aspects also their economic viability plays an important role. This chapter highlights the relation between the two aspects by combining the outcomes of the environmental analysis (i.e. energy and greenhouse gas balances) with those of the economic analysis (i.e. profits). The latter has been part of WP 3 within the 4F CROPS project. Results are presented in D 9 /Soldatos et al. 2009b/ and D 10 /Soldatos et al. 2010/, respectively. For details regarding differences in system boundaries, see chapter 2.3.

Fig. 3-9 and Fig. 3-10 show the combination of profits with energy and greenhouse gas savings for selected crops, environmental zones and countries. For each crop, one environmental zone and one representative country have been selected as an example. The combinations are listed in Table 2-3. The upper part of the figures shows an overview on all crops selected, the lower part zooms into the results for a selection of crops.

The ranges of energy and greenhouse gas balances include all use options (bioenergy and biomaterial) of the selected crops (see Table 2-2). Also economic results show a great variability in different countries. For reasons of clarity, only Miscanthus (dark blue square) is taken as an example to show these ranges in the lower part of the figures: the light blue circle indicates the results for different countries.

3.2.1 Results for the comparison of energy savings and profits

Results

- The environmental and economic results do not run parallel, i.e. higher energy savings not always come along with high profits and – vice versa – crops accounting for high profits do not always result in high energy savings. For example, giant reed leads to average energy savings of about 403 GJ primary energy per hectare and does not account for any profit. In contrast, with rapeseed oil 27 € can be gained per hectare, however, only 38 GJ primary energy can be saved on average (see Fig. 3-9).
- The large ranges of energy savings result from different conversion and use paths. This means that if crops with high potentials of saving energy are not used in an optimal way, savings can drop considerably and reach the same range as less promising crops. Also the economic results show great ranges depending on the country the crops are cultivated in.

Reading the diagram – exemplification of sunflower (pink square)

With the production of sunflower oil, 0.3 € can be gained per hectare. At the same time, its use can lead to energy savings of 42 to 89 GJ primary energy per hectare – depending on whether the oil is used for bioenergy production (stationary or transport fuel use) or as biomaterial.

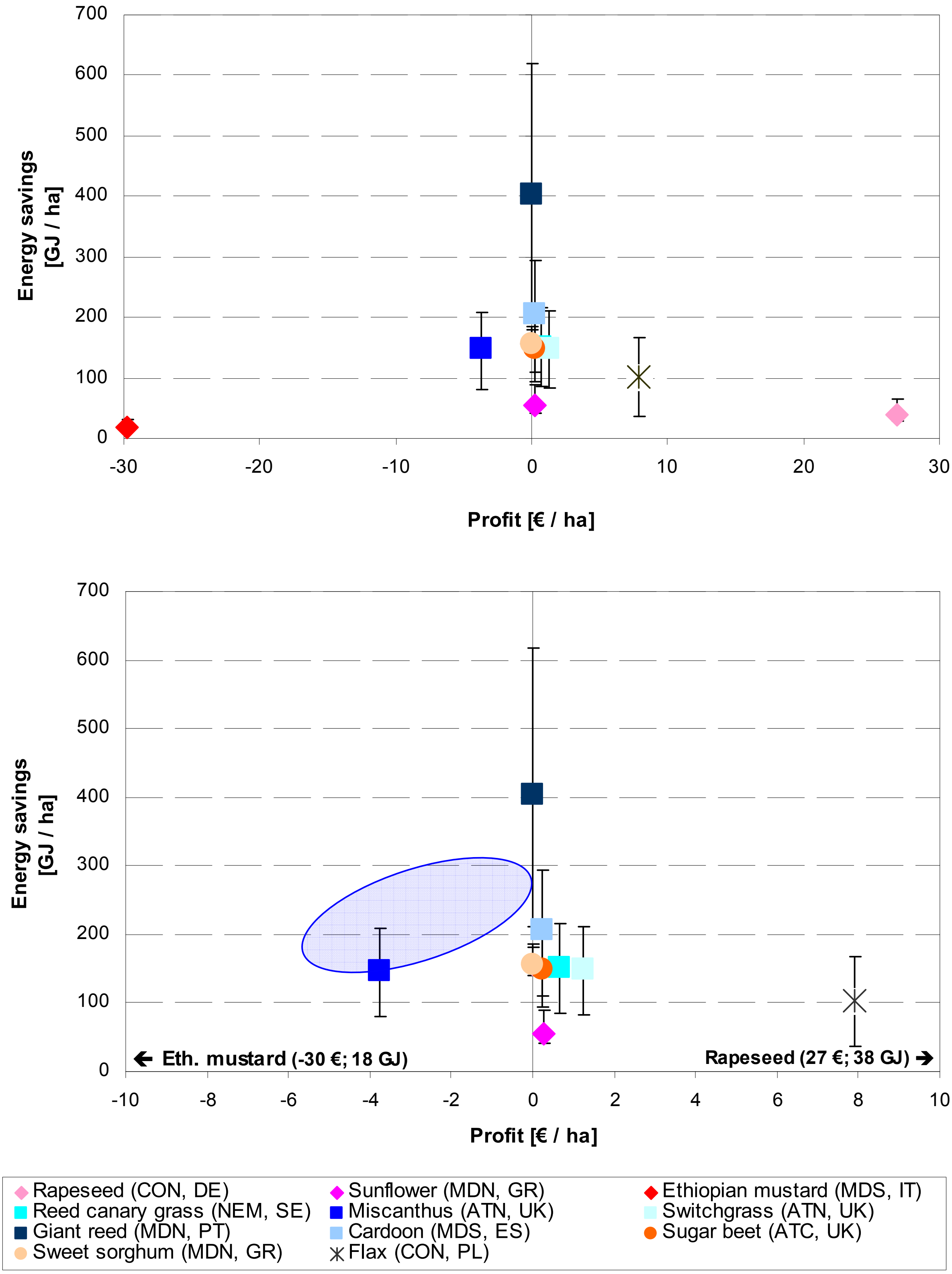

Fig. 3-9 Comparison of energy savings and profits for selected crops, environmental zones and countries; upper figure: complete overview, lower figure: partial view for economic results; ranges for energy savings cover different conversion and use pathways (bioenergy and biomaterials); blue circle in lower figure indicates country-specific economic variability for Miscanthus (dark blue square).

3.2.2 Results for the comparison of GHG savings and profits

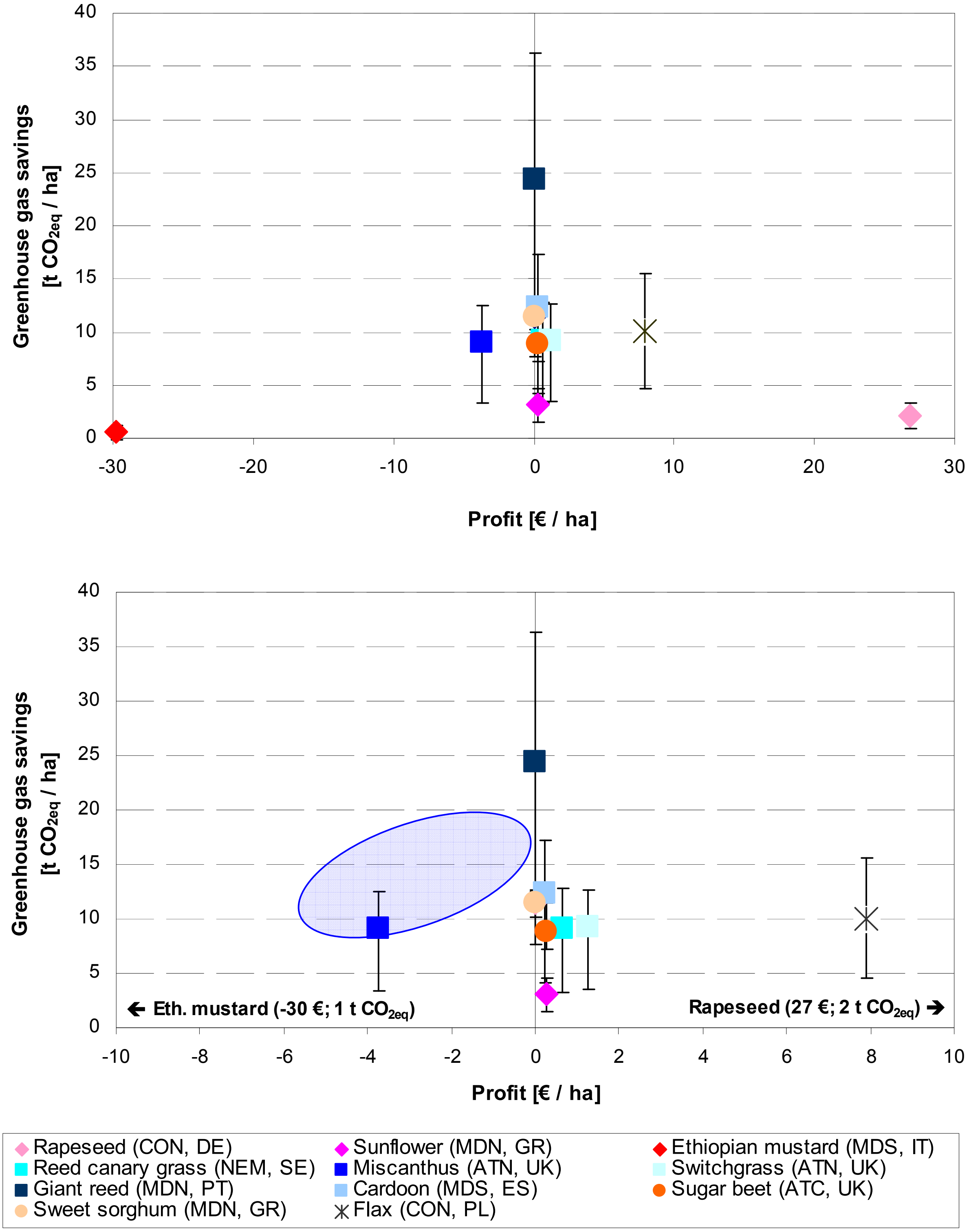

Fig. 3-10 Comparison of greenhouse gas savings and profits for selected crops, environmental zones and countries; upper figure: complete overview, lower figure: partial view for economic results; ranges for greenhouse gas savings cover different conversion and use pathways (bioenergy and biomaterials); blue circle in lower figure indicates country-specific economic variability for Miscanthus (dark blue square).

Reading the diagram – exemplification of Miscanthus (dark blue square)

Miscanthus cultivation causes losses of 4 € / hectare. At the same time, its use can lead to greenhouse gas savings of 3 to 13 CO_2 equivalents per hectare – depending on whether it is used for bioenergy production (stationary or transport fuel use) or as biomaterial.

Results

- As for energy savings, also the outcomes of the greenhouse gas balances strongly differ from the economic results: high greenhouse gas savings might come along with small or no profits and – vice versa – crops accounting for high profits might result in low greenhouse gas savings. Giant reed again shows the highest average greenhouse gas savings of about 24 t CO_2 equivalents per hectare but at the same time does not account for any profit. Highest profits can be made with rapeseed oil (27 € / hectare), however, only 2 t CO_2 equivalent can be saved (see Fig. 3-10).
- Again, greenhouse gas savings and the economic results show large ranges. The environmental performance depends on the conversion and use paths the crops are allocated to. This means that if crops with high potentials of saving greenhouse gases are not used in an optimal way, savings can drop considerably and reach the same range as less promising crops. The economic results differ depending on the countries the crops are produced in.

3.2.3 Conclusions

The comparison of energy and greenhouse balances with economic data both show that the environmental and economic point of views might lead to different conclusions. The best crop choice from an environmental point of view is not always the best choice from an economic point of view and vice versa. This means that if from a political point of view new cropping systems are to be implemented that lead to high energy and / or greenhouse gas savings, it might become necessary to compensate farmers for the loss of income compared to more profitable choices.

However, the great ranges in the environmental results indicate that just cultivating certain promising crops is not sufficient. Rather, the whole life cycle needs to be taken into account, i.e. it has to be guaranteed that the crop is used in an optimal way. If this is not the case, in the worst case, energy and greenhouse gas savings could drop to the same range as savings of crops which could be implemented using much less (or even no) subsidies.

Since both environmental and economic performances strongly differ between countries and with different framework conditions, no general decision can be drawn here on which crop should be implemented at what costs. This needs to be decided for each single case taking into account the whole life cycle as well as the specific circumstances.

4 Summary, conclusions and recommendations

4.1 Summary

The overall goal of this report is to determine a set of environmentally friendly options for the production and use of selected future energy and industrial crops and resulting products. The report mainly builds on a preceding study on life cycle analyses (D 13, /Rettenmaier et al. 2009/) which investigated the environmental impacts associated with the production and use of bioenergy and bio-based materials from 15 selected future crops and compared these impacts to those of their fossil or conventional equivalents. The crops under investigation cover different crop groups (oil, fiber, woody and herbaceous lignocellulosic, sugar) and are cultivated in seven environmental zones within Europe. The analysis is based on the assumption that only surplus land – as identified in WP 1 – is used for future non-food crop cultivation. Thus, no competition with food and feed production occurs, which might result in direct and indirect land-use changes. This is a key assumption, as several studies have pointed out the negative impact of such direct and indirect land-use changes, among others in terms of biodiversity loss and greenhouse gas emissions /Searchinger et al. 2008/, /Fargione et al. 2008/, Gibbs et al 2008/, /Gallagher et al. 2008/.

The main result of the present study (D 14) is that it is not possible to identify a single crop, product or conversion technology which is to be preferred from an energy savings and climate protection point of view. For a meaningful comparison of future non-food crops, it is essential to assess their entire life cycle (i.e. cradle-to-grave), as the overall environmental impact largely depends on what the biomass is used for, how efficiently it is converted and which fossil or conventional product it substitutes. Keeping this in mind, the following answers can be given to the key questions in chapter 1:

- Within and across all environmental zones, herbaceous lignocellulosic crops show the highest potentials in saving energy and greenhouse gases, followed by fiber and sugar crops. In contrast, oil crops achieve the lowest energy and greenhouse gas savings. The good performance of herbaceous crops is due to both high biomass yields (especially regarding the share of the crop which is actually used for non-food purposes) and efficient biomass conversion technologies. The good environmental performance of lignocellulosic crops is also described by /Delucchi 2010/ and /Larson 2006/. The first points out advantages due to a lower fertilizer need and high carbon storage whereas the latter stresses the fact that the whole crop and not only part of it can be used for energy purposes.
- In terms of energy and greenhouse gas savings, the results cover a wide range and do not suggest a clear tendency towards material or energy use. Generally, only few studies are available which compare material and energy use of biomass in terms of energy and greenhouse gas savings. /Dornburg et al. 2003/ compare different bio-based polymers with bioenergy production and concluded that the biomaterials mostly score comparably or even better than bioenergy production. Within the bioenergy paths, the stationary use of biomass for heat and power generation usually outperforms the mobile use as a trans-

port biofuel. This result is supported by /Cherubini et al. 2009/ who give an overview on LCA results of different biofuel and bioenergy systems from 1st and 2nd generation crops. 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 (see D 13). The higher its specific non-renewable energy demand and specific emissions are, the better the results upon replacement. /Cherubini et al. 2009/ arrive at the same result comparing energy and GHG savings per hectare and year for fuels, electricity and heat generation from biomass depending on whether inefficient coal or efficient natural gas is replaced.

- Regarding conversion technology for biofuels, 2nd generation biofuels tend to better results, but are not superior *per se*: 1st generation ethanol from sugar beet, for example, is only surpassed by lignocellulosic ethanol from herbaceous crops. Slightly better results for 2nd generation biofuels are also described in literature reviews by /Menichetti & Otto 2009/ and /von Blottnitz & Curran 2007/. /Jungbluth et al. 2008/, however, who compare biomass-to-liquid (BtL) fuels from woody feedstocks with other biofuels, did not find a general advantage of BtL fuels. Biochemicals obtained via enzymatic hydrolysis and fermentation of lignocellulosic feedstock (2nd generation technology, e.g. applied in future biorefineries) may lead to higher energy and greenhouse gas savings, but given the large range of results only optimised conversion paths outperform existing ones.
- The investigated future crops might lead to higher energy and greenhouse gas savings than traditional ones, but their potential can only be tapped if appropriate technologies are in place. Future lignocellulosic bioethanol from herbaceous crops might outperform conventional bioethanol from sugar beet, but the technology required is still in its infancy.
- As far as the transport sector is concerned, the use of biomass power in an electric vehicle leads to higher energy and greenhouse gas savings than liquid biofuels in a conventional vehicle. Wind or solar power would even be more land-use efficient. Examples for a comparison of solar power and biomass energy in terms of net energy yields can be found in /Reijnders 2008/. /Helms et al. 2010/ compare the environmental impacts of electric vehicles with liquid transport fuels and conclude that battery electric vehicles charged with renewable electricity show by far the best environmental performance.

Besides assessing the best options from an environmental point of view, this study also compares the outcomes of the environmental assessment with economic results, more exactly with the profits at farm gate for each crop. The comparison shows that energy and greenhouse gas balances do not correlate with the economic profits. This means that crops showing e.g. high greenhouse gas savings along their entire life cycle do not necessarily account for high profits at farm gate and vice versa. Therefore, if certain cropping systems are to be preferred from a greenhouse gas mitigation or energy saving point of view, it might become necessary to incentivise those cropping systems at farm level to compensate for lower profits compared to crops which are less favourable from an environmental point of view.

4.2 Conclusions and recommendations

Biomass for fiber or fuel?

The two main drivers for the European wide expansion of renewable energy use are climate protection and an increased supply security. Objectives have already been set throughout Europe. By 2020 the use of renewable energy sources should be 20% in energy consumption and 10% in the transport sector. Greenhouse gas emissions should be decreased by 20% as well as a 20% savings of primary energy should be realised through enhanced energy efficiency /CEC 2009/. Biomass, especially energy and industry crops, plays an important role in achieving these objectives. Despite being renewable biomass is a scarce good itself due to the fact that agricultural area is limited. This scarcity requires biomass to be used as efficiently as possible.

In this study two of the „4F“ uses are analysed, ‘fiber’ (i.e. bio-based materials) and ‘fuel’ (i.e. bioenergy). The results indicate that the material and energy use of biomass may lead to similarly advantageous results in climate protection (i.e. mitigation of greenhouse gas emissions). The large range of results, however, do not allow for a general statement. Instead each single pathway has to be assessed within the context of all use options and while taking into account specific (national) framework conditions. Only a specific assessment allows for the development of optimal strategies for a biomass allocation between all consuming sectors (industry and energy). In this context, possibilities for a cascade use, i.e. the sequential / successive use of biomass for bio-based products and bioenergy, should be explored, as a cascade use of biomass might considerably improve the environmental performance compared to a singular energy use.

When it comes to enhancing the supply security, material and energy biomass uses have different prerequisites: for energy production there are alternative renewable sources to biomass namely wind, solar and hydropower, despite the fact that today the largest share of biomass is used for this purpose. In contrast, the chemical industry depends on biomass as renewable carbon-containing feedstock as it is the only renewable alternative to fossil sources. Sun, wind and water produce energy but no biomaterials or renewable raw materials for industrial uses. However, there are neither quantitative political goals nor financial support schemes for the material use of biomass. Though there are strategic commitments, action plans and initiatives, the material use is not actively promoted or supported. The establishment of adequate funding instruments is necessary to counter this imbalance.

- In terms of energy and greenhouse gas savings, the results cover a wide range and do not suggest a clear tendency towards material or energy use. In many cases, biomaterial paths match up to or even surpass biofuels / bioenergy paths.
- From a supply security point of view, the material use of biomass should be encouraged or even preferred over energy use. Biomass is the only renewable resource for sectors depending on carbon-containing feedstocks such as the chemical industry. In this context, possibilities for a cascade use, i.e. the sequential / successive use of biomass for bio-based products and bioenergy, should be explored.

Biofuels – a land-use efficient option?

Besides an efficient use of biomass itself, the efficient use of agricultural land is particularly important. In this study the assumption is made that all crops under investigation are produced on surplus land. This helps avoid competition with feed and food production, although even surplus land is not always readily available.

It has already been shown that material and energy biomass uses may lead to similar results in terms of climate protection (i.e. mitigation of greenhouse gas emissions) as other renewable energy sources. Thus biomass (and therefore agricultural land) will most likely continue to be used for energy production rather than as biomaterials, despite the higher advantages in energy security of biomaterials. This is mainly due to the fact that biomass can usually be stored quite easily and can be provided year-round. The availability of other renewable energy sources such as wind or solar power shows a large spatial and temporal variation.

Biomass can be used for power and heat production (stationary use) as well as a liquid or gaseous biofuel in the transport sector. This study shows that the combined heat and power production in stationary use leads to far higher energy and greenhouse gas savings than use for transportation. This is because in stationary use biomass can be converted with far higher efficiency and that the replaced power and heat mixes have higher CO_2 loads than replaced conventional fossil fuels in the transport sector.

In the short and medium term (until 2020) the use of liquid and gaseous biofuels is the only way to implement renewable energy in the transport sector. In the long run, electric propulsion could open up new perspectives both for the use of biomass electricity (which is more advantageous than liquid or gaseous biofuels) and other renewable electricity sources. It would allow the use of solar, wind and hydropower in the transport sector. However, only motorized private transport can be electrified, not air, or ship traffic and freight transport by road for which the only renewable option will be liquid and gaseous biofuels. From a land use efficiency point of view, biofuels made from herbaceous lignocellulosic crops show the greatest potential of saving energy and greenhouse gases and should therefore be implemented as soon as second generation technologies become available.

In terms of land use efficiency electricity produced from biomass is clearly inferior to wind and solar power. Wind power especially shows great advantages since it occupies only small areas while the remaining area can be used for agriculture. Solar power also shows better results than bioenergy. With solar power, mainly roof areas and facades should be used in order to save the limited agricultural area. Bioenergy can only be compared with wind and solar power to a limited extent due to differences regarding the spatial and temporal availability of these systems. These differences do not allow for an unlimited substitution of systems.

- Renewable energy can be generated from a number of sources, among others biomass. The results indicate that biomass is not *per se* the most land-use efficient option.
- Nevertheless, biomass for energy will play an important role due to its advantages in terms of storability and year-round availability. The most efficient option is the stationary use of biomass for heat and/or power generation which outperforms the mobile use as a biofuel for transportation.

There is more than carbon footprint: other environmental impacts

If no clear decision can be drawn from the energy and greenhouse gas balances of different systems then other environmental impact categories should be drawn on as the basis for a decision. However, even if energy and greenhouse gas balances show clear advantages for a certain option, it should be kept in mind that other environmental impact categories might be disadvantageous. Often advantages regarding energy and greenhouse gases come along with considerable disadvantages regarding other environmental impact categories, e.g. an increase in emissions of acidifying and eutrophying pollutants.

Being generic, an LCA can be applied to any system, but it also has some limitations, as it was developed to compare products. Still, an LCA cannot address site-specific environmental impacts only occurring at some of the life cycles stages, which cannot be averaged without losing their significance. Examples are impacts on biodiversity and soil as well as impacts from pesticide use. These impacts should be taken into account at all costs especially prior to political strategy decisions and the planning of large scale biomass production projects. For the time being the environmental impact assessment (EIA) is the only instrument available for this. For example, the EIA conducted within the 4F CROPS project showed that perennial crops show less harming environmental impacts than annual crops (D 12, /Fernando et al. 2010/).

- For a comprehensive environmental assessment, the results of the other environmental impact categories should be considered as well, especially if no decision can be made based on the results of the energy and greenhouse gas balances.
- Site-specific environmental impacts such as impacts on biodiversity and soil still cannot be addressed by an LCA. For those impacts, it is necessary to undertake an environmental impact assessment (EIA) prior to a project, e.g. a large-scale non-food cropping system.

Risks of increased pressure on land: land-use competition and land-use changes

This study is based on the assumption that the crops under investigation are produced only on surplus land. This is agricultural land which is not needed for food or feed production and thus, in theory, is available for the cultivation of renewable raw materials.

While working towards a bio-based economy it has to be kept in mind that modern society has multiple claims to land area which have to be weighed against each other. There are several sustainability goals not only in terms of climate protection but also regarding the protection of nature, soil and water. All these goals can only be implemented if enough area is available. Examples are the protection of biological diversity, the creation of connected biotope areas or the expansion of organic farming. For biological diversity, areas that are set-aside play an important role. However, recently there has been clear evidence that such areas are again taken into production and that agricultural environmental programs become less attractive due to the ambitious renewable energy expansion objectives. There is a risk that the implementation of the above mentioned sustainability goals might fall behind which in certain cases might lead to a irreversible loss of an ecosystems goods and services. To avoid such losses, obligatory and effective safety measures should be established for agricultural land use as a whole (not only for energy and industrial crop cultivation) and based on a society wide consensus.

Whether and to what extent surplus land will be available in the future for the production of renewable raw materials depends on many factors: food and feed demand (which in turn depends on population development and consumption patterns), how efficiently it can be produced (depending on cultivation and livestock farming systems as well as on technical and breeding progress), and on climate change. Such complex interrelations can best be assessed by a combination of econometric and biophysical models. However, if biomass is not produced on surplus land but instead competes with food and feed production indirect land use changes would occur. The inclusion of the change in carbon stocks into the greenhouse gas balances has a clear disadvantageous impact on the results. In the worst case biomass use could even show more greenhouse gas emissions than fossil or conventional equivalent products (see Fig. 3-3).

- There are a number of area-demanding sustainability goals in place concerning nature, soil and water conservation. In order to safeguard their implementation, effective safety measures are urgently needed to confine agricultural land use to a sustainable level. Therefore, only a certain share of the surplus land should be used for non-food crops.
- If non-food crops are not cultivated on surplus land but displace food and feed crops, indirect land use changes are caused. The latter might lead to unfavourable greenhouse gas balances, i.e. the bio-based product leads to higher emissions than its fossil or conventional equivalent.

Back to the future? Traditional versus future crops

The analysis shows that future crops are not necessarily superior to existing traditional crops. Traditional crops, for which there are already mature and efficient technologies, should be preferred over new crops and biofuels for which technologies might still be immature. In particular for the conversion of herbaceous lignocellulosic crops, which are especially climate friendly, there are still considerable technological difficulties. Difficulties concern the gasification as well as the enzymatic decomposition and fermentation of lignocellulosic biomass for ethanol production. Such crops should be produced at a large scale only after these technological difficulties have been solved. Until then existing and mature traditional biomass use systems can be drawn on.

Besides the technological difficulties, the perennial lignocellulosic crops cannot be integrated into existing annual crop rotation systems. Therefore, the area available for such crops is further limited.

The most advantageous crops from an environmental point of view do not necessarily show the best economic results. Economic incentives could become necessary at a farm level if the cultivation of the most environmentally efficient crops is expanded. However, since the combination of environmental and economic results in this study is based on different system boundaries, no statements can be made on the macroeconomic costs of additional CO2 savings via the support of especially climate friendly renewable raw materials.

- As far as future crops are concerned, there are still considerable challenges in terms of production, harvesting and conversion technology as well as in terms of integration into crop rotations. For traditional crops mature industrial-scale technology is applied. Some of them are competitive to future crops regarding their environmental performance.
- Environmental and economic analysis of future non-food crops often lead to contradictory results, i.e. the most environmentally friendly crop is not necessarily the most profitable one from a farmer’s point of view. However, the economic analysis should cover the entire life cycle (as for the environmental analysis) in order to evaluate the societal costs and benefits, too.

5 References

/BMELV 2009/ Federal Ministry of Food, Agriculture and Consumer Protection: Aktionsplan der Bundesregierung zur stofflichen Nutzung nachwachsender Rohstoffe (Action plan of the Federal Government for a material use of biomass). Berlin, 2009.

/Börjesson 2009/ Börjesson, P.: Good or bad bioethanol from a greenhouse gas perspective – What determines this? Applied Energy 86: 589–594.

/Bozell et al. 2007/ Bozell, J. J., Holladay, J. E., Johnson, D., White, J. F.: Top value added chemicals from biomass – Volume II: Results of Screening for Potential Candidates from Biorefinery Lignin. Prepared for the U.S. Department of Energy, 2007.

/Carus et al. 2010/ Carus, M., Raschka, A., Piotrowski, S.: The development of instruments to support the material use of renewable raw materials in Germany (Summary). Nova-Institut, Hürth, 2010.

/CEC 2009/ Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union L 140/16, Brussels, 07.06.2009.

/Cherubini et al. 2009/ Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S.: Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resources, Conservation and Recycling 53(8): 434–447.

/Crutzen et al. 2007/ Crutzen, P.J., Mosier, A.R., Smith, K.A., Winiwarter, W.: N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmospheric Chemistry and Physics Discussions 7: 11191–11205.

/Dallemand et al. 2009/ Dallemand, J.F., Leip, A., Rettenmaier, N.: Biofuels for transport: The challenge of properly assessing their environmental impact. Pollution Atmosphérique Special Issue April 2009: 89–104.

/Delucchi 2010/ Delucchi, M.A.: Impacts of biofuels on climate change, water use, and land use. Annals of the New York Academy of Sciences 1195:28–45.

/Dornburg et al. 2003/ Dornburg, V., Lewandowski, I., Patel, M.: Comparing the land requirements, energy savings, and greenhouse gas emissions reduction of biobased polymers and bioenergy – An analysis and system extension of life cycle assessment studies. Journal of Industrial Ecology 7 (3-4): 93–116.

/EC BREC/ Ganko, E.: Personal communication, 11/06/2010.

/ecoinvent 2010/ Frischknecht, R. et al.: ecoinvent data v2.2 – Ökoinventare für Energiesysteme. ESU-services, Uster (Switzerland), 2010

/Erisman et al. 2010/ Erisman, J.W., Grinsven, v.H., Leip, A., Mosiery, A., Bleeker, A.: Nitrogen and biofuels; an overview of the current state of knowledge. Nutrient Cycling in Agroecosystems 86: 211–223.

/Fargione et al. 2008/ Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P.: Land clearing and the biofuel carbon debt. Science 319: 1235–1238.

/Farrell et al. 2006/ Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M.: Ethanol can contribute to energy and environmental goals. Science 311: 506–508.

/Fernando et al. 2010/ Fernando, A. L., Duarte, M. P., Almeida, J., Boleo, S., Mendes, B.: Final Report on Task 4.1: Environmental impact assessment (EIA) of Energy Crops production in Europe. Prepared for the 4F CROPS project ("Future Crops for Food, Feed, Fiber and Fuel"), supported by EC's FP7 programme. Universidade Nova de Lisboa, Lisbon, 2010.

/Gallagher 2008/ Gallagher, E.: The Gallagher Review of the Indirect Effects of Biofuel Production. Renewable Fuels Agency, London.

/Ganko & Kopczynski 2010/ Ganko, E., Kopczynski, P.: Land use in EU27 now, in 2020 and 2030. Prepared for the 4F CROPS project ("Future Crops for Food, Feed, Fiber and Fuel"), supported by EC's FP7 programme. EC BREC, Warsaw, 2010.

/GEMIS 2010/ Fritsche, U. et al.: Global Emission Model for Integrated Systems (GEMIS), Version 4.6. Öko-Institut e.V., Darmstadt, 2010

/Gibbs et al. 2008/ Gibbs, H.K., Johnston, M., Foley, J.A., Holloway, T., Monfreda, C., Ramankutty, N., Zaks, D.: Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. Environmental Research Letters 3, 034001.

/Gnansounou et al. 2009/ Gnansounou, E., Dauriat, A., Villegas, J., Panichelli, L.: Life cycle assessment of biofuels: Energy and greenhouse gas balances. Bioresource Technology 100(21): 4919–4930.

/Helms et al. 2010/ Helms, H., Lambrecht, U., Rettenmaier, N.: The 'renewables' challenge – biofuels versus electric mobility. Proceedings of the 8th International Colloquium Fuels, 19–20 January 2011, Technische Akademie Esslingen.

/IFEU 2010/ Continuously updated internal IFEU database. Heidelberg, 2010.

/ISO 2006/ International Organization for Standardization: ISO 14040:2006 / 14044:2006. Environmental management – Life cycle assessment – Principles and framework / Requirements and guidelines. Beuth Verlag, Berlin, 2006.

/Jungbluth et al. 2008/ Jungbluth, N., Büsser, S., Frischknecht, R., Tuchschmid, M.: Life cycle assessment of biomass-to-liquid fuels. Prepared for the Federal Office for Energy (BFE), the Federal Office for the Environment (BAFU) and the Federal Office for Agriculture (BLW), Berne, 2008.

/Kløverpris et al. 2008/ Kløverpris, J., Wenzel, H., Banse, M., Milà i Canals, L. Reenberg, A.: Conference and workshop on modeling global land use implications in the environmental assessment of biofuels. Int. Journal of Life Cycle Assessment 13: 178–183.

/Larson 2006/ Larson, E.D.: A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy for Sustainable Development X(2): 109–126.

/Liska & Perrin 2009/ Liska, A.J., Perrin, R.K.: Indirect land use emissions in the life cycle of biofuels: regulations vs science. Biofuels, Bioprod. Bioref. 3: 318–328.

/Menichetti & Otto 2009/ Menichetti, A., Otto, M.: Energy balances & greenhouse gas emissions of biofuels from a life cycle perspective. In: Howarth, R.W., Bringezu, S. (eds.): Biofuels: environmental consequences & implications of changing land use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International biofuels project rapid assessment, 22–25 September 2008, Gummersbach, 81–109.

/Metzger et al. 2005/ Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A., Watkins, J. W.: A climatic stratification of the environment of Europe. Global Ecology and Biogeography 14 (6): 549–563

/Monti et al. 2009/ Monti, A., Fazio, S., Venturi, G.: Cradle-to-farm gate life cycle assessment in perennial energy crops. European Journal of Agronomy 31: 77–84.

/Oertel 2007/ Oertel, D.: Industrielle stoffliche Nutzung nachwachsender Rohstoffe (Industrial conversion of biomass). Prepared by the Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (Office of Technology Assessment at the German Bundestag), Berlin, 2007.

/Patel et al. 2006/ Patel, M., Crank, M., Dornburg, V., Hermann, B., Roes, L. Hüsing, B., Overbeek, L., Terragni, F., Recchia, E.: Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources – The potential of white biotechnology (The BREW Project). Funded by the European Commission's GROWTH programme (DG Research), Utrecht, 2006.

/Reijnders 2008/ Reijnders, L.: Transport biofuels – a life-cycle assessment approach. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 3(071): 1–8.

/Reinhardt et al. 2007/ Reinhardt, G. A., Detzel, A., Gärtner, S. O., Rettenmaier, N., Krüger, M.: Nachwachsende Rohstoffe für die chemische Industrie: Optionen und Potenziale für die Zukunft (Renewable Resources for the Chemical Industry: Options and Potentials for the Future). Supported by the German Chemical Industry Association (VCI), Frankfurt am Main, 2007.

/Rettenmaier et al. 2010/ Rettenmaier, N., Köppen, S., Gärtner, S. O., Reinhardt, G. A.: Life cycle analyses (LCA) – Final report on Tasks 4.2 & 4.3. Prepared for the 4F CROPS project ("Future Crops for Food, Feed, Fiber and Fuel"), supported by EC's FP7 programme. IFEU, Heidelberg, 2010.

/Scheurlen et al. 2005/ Scheurlen, K, Reinhardt, G. A., Gärtner, S. O.: Environmental assessment. Prepared for the project "Bio-energy chains from perennial crops in south Europe" (BIO-ENERGY CHAINS), funded by the European Commission's FP 5 programme. Institut für Umweltstudien Weisser & Ness & IFEU, Heidelberg, 2005.

/Searchinger et al. 2008/ Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.H.: Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science 319: 1238–1240.

/Soldatos et al. 2009a/ Soldatos, P., Lychnaras, V., Asimakis, D.: Cost analysis and economic evaluation. Prepared for the 4F CROPS project (“Future Crops for Food, Feed, Fiber and Fuel”), supported by EC’s FP7 programme. Agricultural University of Athens (AUA.eco), 2009.

/Soldatos et al. 2009b/ Soldatos, P., Lychnaras, V., Asimakis, D.: Cost breakdown of conventional crops in Europe. Prepared for the 4F CROPS project (“Future Crops for Food, Feed, Fiber and Fuel”), supported by EC’s FP7 programme. Agricultural University of Athens (AUA.eco), 2009.

/Soldatos et al. 2010/ Soldatos, P., Lychnaras, V., Asimakis, D.: Cost breakdown of future crops in Europe. Prepared for the 4F CROPS project (“Future Crops for Food, Feed, Fiber and Fuel”), supported by EC’s FP7 programme. Agricultural University of Athens (AUA.eco), 2010.

/von Blottniz & Curran 2007/ von Blottniz, H., Curran, M.A.: A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. Journal of Cleaner Production 15: 607–619.

/Werpy et al. 2004/ Werpy, T., Petersen, G., Aden, A., Bozell, J., Holladay, J., White, J., Manheim, A.: Top value added chemicals from biomass – Volume I: Results of screening for potential candidates from sugars and synthesis gas. Prepared for the U.S. Department of Energy, 2007.

/Zegada-Lizarazu & Monti 2009/ Zegada-Lizarazu, W., Monti, A.: Non-food energy crops rotation possibilities. Prepared for the 4F CROPS project (“Future Crops for Food, Feed, Fiber and Fuel”), supported by EC’s FP7 programme. University of Bologna, 2009.