Life cycle assessment of bioenergy and bio-based products from perennial grasses cultivated on marginal land

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SEVENTH FRAMEWORK
PROGRAMME

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1 Executive summary

The EC-funded **OPTIMA project** (Optimization of Perennial Grasses for Biomass Production, GA no. 289642) aims at identifying high-yielding perennial grasses for the Mediterranean region within an optimised production chain that will provide stable source for both biomass and new plant derived bio-products. Within this project, a so-called ‘integrated assessment of sustainability’ is performed, which consists of a series of individual assessments that separately assess the major aspects determining the sustainability of products derived from perennial grasses cultivated on marginal land in the Mediterranean region. A **screening life cycle assessment**, which is subject of this report, is part of the overall sustainability assessment within the OPTIMA project. It assesses global and regional environmental impacts throughout whole life cycles from the cultivation of perennial grasses on marginal land, through biomass conversion into bioenergy or biomaterials, to their use and, if applicable, to their disposal. To this end, the screening life cycle assessment analyses scenarios on potential future biomass production, conversion and use in 2020 in the Mediterranean region and compares them to impacts caused by equivalent products. In the following, key results, conclusions are summarised.

Compared to the provision of equivalent conventional products, the OPTIMA scenarios display **highly diverse results** in the screening life cycle assessment. Regarding climate change, for example, they can range from advantages (emission savings) to disadvantages (additional emissions). The reason for this is that the investigated scenarios are highly diverse including bio-based products, biofuels as well as liquid and solid bioenergy carriers. A considerable part of the range of results represents **freedom for future decision-making**. This freedom should be actively exploited to use the available marginal land in the Mediterranean region and other resources, such as the available water, as productively as possible, and to the benefit of the environment. In this study, **screening life cycle assessment is used to provide concrete recommendations** on how to achieve this goal.

OPTIMA – in contrast to other projects – focuses on the cultivation of perennial grasses **on marginal land** in the Mediterranean region, in particular in order to not present competition to food and animal feed production. Advantages can be identified by screening life cycle assessment for cultivation on **idle land** (not to be equated with the land quality descriptor 'marginal', but often affecting the same areas), because potentially highly detrimental indirect land use changes are avoided. In these terms, the achievement of the OPTIMA project is to bring low-quality land into production by adopting selected crops and agricultural practices. Possible support programmes for industrially used, perennial grasses should therefore take the previous use status into consideration as a condition, rather than site qualities (“marginality”).

In the majority of scenarios, clear **environmental advantages** can only be achieved in terms of energy savings and global warming and **at the cost of deleterious effects** for e.g. acidification and eutrophication – as often observed for bioenergy. Therefore, the approval of bioenergy and bio-based products in general assumes a preference for climate- and energy-related targets compared to other environmental targets. However, compared to the cultivation of annual crops, the expenditures and resulting environmental disadvantages of perennial crops are smaller. A **few scenarios, however, achieve advantages with minor or no disadvantages**. This is in particular achievable, if crops such as **Miscanthus**, that have a low nutrient demand and can be harvested with a low water content to reduce energy intensive drying, are used for **efficient stationary energy generation** such as combined heat and power generation. Where necessary (and if water is available), irrigation must be managed cautiously because it can cause high impacts and may not be justifiable at all depending on local water availability. These are **encouraging results** since they do not follow the pattern typically found for bioenergy or industrial biomass use. The large scale implementation of such options should thus be supported under consideration of certain boundary conditions detailed in this report. If Miscanthus cultivation is not possible, climate protection can also be achieved by the **alternative crops giant reed, cardoon and switchgrass.** At drought prone biomass production sites, for example, cardoon is a promising option due to its particular resistance to drought. However, larger environmental disadvantages in other impact categories must be accepted for those crops. Other use options such as the conversion into 1,3-propanediol, 2nd generation ethanol or biochar cannot compete with efficient stationary energy generation from an environmental perspective in the short to medium term but may represent very valuable options in the long term.

The boundary conditions necessary to achieve high environmental advantages at minor disadvantages include the **optimisation** of several key parameters in agriculture and pellet production, which have been studied in detail in this report. These are in particular **yield, irrigation, fertiliser demand and energy demand for drying**. Recommendations are given on how to optimise these parameters. Furthermore, less controllable **external factors** may also critically influence the results. The most important ones are **indirect land use changes** that may occur if previous land uses – also extensive ones – or previous uses of scarce water resources are displaced. Furthermore, it is important **which products are replaced** by new products derived from perennial biomass. For example, is has to be made sure that bioenergy does not compete with other renewable energy sources but is preferentially used to replace electricity derived from fossil fuels.

In summary, it can be stated that the cultivation of perennial grasses on marginal land and their use in stationary energy generation, such as combined heat and power generation, can achieve substantial greenhouse gas emission mitigation and non-renewable energy savings together with comparatively low additional other environmental impacts. From an environmental perspective cultivation and / or use should therefore be supported, if necessary, under the detailed boundary conditions, particularly including the efficient use and prevention of any competition for land and water.

2 Introduction

Background

In the last couple of years, a controversial discussion on the net benefit of biofuels, bioenergy and bio-based materials has been going on, showing that the use of biomass is not environmentally friendly *per se*, simply because biomass is a renewable resource. Turning into a mass market, the cultivation of non-food biomass crops is increasingly contributing to the pressure on global agricultural land. At the same time, world population growth (projected to reach 9.3 billion people by 2050 according to [United Nations 2015] and changing diets due to economic development lead to an additional demand for land for food and feed production. As a consequence, the already existing competition for land for the production of food, feed, fibre (bio-based products), fuel (biofuels and bioenergy) and ecosystem services might even aggravate over the next decades. Concerns have been raised both in terms of social and environmental impacts because land use competition might i) jeopardise food security and give rise to social conflicts, ii) result in an intensified use of existing agricultural land or iii) lead to an expansion of agricultural land, most likely at the cost of (semi-)natural ecosystems being converted into cropland [Rettenmaier & Hienz 2014].

At the same time, there is big concern for farming systems in warm and dry climates such as the Mediterranean region. Most of the global warming models show that the water supply will be much lower whereas air temperatures will be significantly higher in the short term, especially during the summertime [Black 2009; Metzger et al. 2005; Rosenzweig & Tubiello 1997]. This poses serious threats for several conventional crops, particularly in dry-summer areas such as the Mediterranean region where most precipitation is received during winter.

The cultivation of perennial grasses has the potential to tackle both challenges at the same time: perennial grasses are drought-resistant crops and considered not to compete for agricultural land because they can be grown on marginal or degraded lands where the economic returns to the farmer's labour and capital are not viable.

Against this background, the EC-funded OPTIMA project (Optimization of Perennial Grasses for Biomass Production, GA no. 289642) was launched which aims at identifying high-yielding perennial grasses for the Mediterranean region within an optimised production chain that will provide stable source for both biomass and new plant derived bio-products. The project was split in nine work packages (WPs). Within WP 7, a so-called ‘integrated assessment of sustainability’ is performed which consists of a series of individual assessments that separately assess the major aspects determining the sustainability of products derived from perennial grasses cultivated on marginal land in the Mediterranean region. One of these individual assessments is focussing on the environmental performance of the OPTIMA value chains. This report presents the results of the life cycle assessments performed under Task 7.2 which are based on the definitions and settings outlined in the ‘Final report on definitions, settings and system descriptions’ [Müller-Lindenlauf et al. 2012].

Goal and scope

The objective of WP 7 is to provide a multi-criteria evaluation of the sustainability of the entire OPTIMA value chains by taking into account technological, environmental, economic and socio-economic aspects. The most sustainable bioenergy and biomaterial pathways based on perennial grasses will be identified.

The integrated assessment of sustainability (WP 7) gives answers to a number of key questions. The main questions to be answered by WP 7 are:

- Which OPTIMA scenarios perform best from an environmental, economic and social point of view?
- How do the OPTIMA scenarios perform in comparison to the agricultural reference system and the conventional reference products?

These general questions cover the following more specific questions:

- What is the optimal processing and use option for biomass from perennial grasses?
- What are the advantages and disadvantages of the assessed crops from an environmental, economic and social point of view?
- What are the advantages and disadvantages of the assessed cultivation systems from an environmental, economic and social point of view?
- What is the best way to harvest and pre-treat the biomass?
- Which unit processes along the value chain determine the results significantly and what are optimisation potentials for these processes?

This report aims at answering the above mentioned questions from an environmental point of view. For clarity, these questions are not addressed one by one but the answers are part of the overall discussion of results.

General scientific approach

Comparative screening life cycle assessments are performed which i) quantify the potential environmental impacts of the OPTIMA value chains along the entire life cycle (i.e. from cradle to grave) and ii) compare these to environmental impacts associated with conventional products that are providing the same utility.

However, the impact assessment methodologies for several environmental impact categories, especially those capturing local and site-specific impacts (e.g. land use and water use), are still under development. Within OPTIMA, these local and site-specific aspects are dealt with in WP 6 [Fernando et al. 2015], however, not from a life cycle perspective but from an environmental impact assessment (EIA) perspective.

3 Methodology

3.1 Introduction: The LCA approach

Life cycle assessment (LCA) addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of emissions) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. The approach is therefore often called cradle-to-grave, well-to-wheel (fuels) or farm-to-fork (food).

Life cycle assessment (LCA) is structured, comprehensive and internationally standardised through ISO standards 14040:2006 and 14044:2006 [ISO 2006a; b] and can among others assist in:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle and
- informing decision-makers in industry, government or non-government organisations (e.g. for the purpose of strategic planning, priority setting, product or process design).

The life cycle analyses in this project are carried out following the above mentioned ISO standards on product life cycle assessment, which defines four phases in an LCA study (Fig. 3-1).

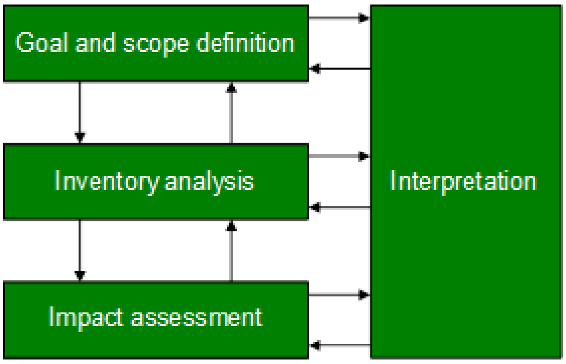

Fig. 3-1 Phases of an LCA [ISO 2006a; b]

The ISO 14040 and 14044 standards provide the indispensable framework for life cycle assessment (LCA). This framework, however, leaves the individual practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance. Hence, each standardisation approach necessarily restricts flexibility and it depends on the context if a particular standardisation approach helps to give better answer the questions asked or not.

One set of guidelines for a further standardisation of LCAs is the International Reference Life Cycle Data System (ILCD) [JRC-IES 2012]. The ILCD Handbook is a series of technical documents that provide detailed guidance on all the steps required to conduct a life cycle assessment (LCA). It also specifies in which decision context flexibility or strictness regarding these rules is more important (see also section 3.2.1). The LCA study carried out for OPTIMA takes into account the major requirements of the ILCD Handbook following these considerations of flexibility and strictness.

3.2 Definitions and settings for LCA in OPTIMA

3.2.1 Goal definition

The goal definition is the first phase of any life cycle assessment. Among others, intended applications, decision contexts and target audiences are specified during this phase.

Intended applications and goal and scope questions

The OPTIMA LCA study aims at several separate applications. The subject of the first group of applications is the project-internal support of ongoing production systems development:

- Comparisons of specific cultivation systems, which are potential results of ongoing production systems development, and biomass use options
- Identification of key factors for environmental friendly cultivation systems and product chains to support further optimisation

This makes this study an ex-ante assessment because the systems to be assessed are not yet implemented in this particular form on a relevant scale and for a sufficiently long time.

The second group of applications provides a basis to communicate findings of the OPTIMA project to external stakeholders, science and policy makers:

- Policy information: Which product chains have the potential to show a low environmental impact?
- Policy development: Which raw material production strategies and biomass use technologies may emerge, what are their potential environmental impacts, and how could policies guide this development?

In this context, a number of OPTIMA goal and scope questions have been agreed upon. They are documented in section 2.

Methodological limitations

The environmental impacts are analysed within OPTIMA via a screening LCA (this report), which is supplemented by an environmental impact assessment (EIA) prepared within work package 6 of the OPTIMA project [Fernando et al. 2015].

The focus of this screening LCA on a scenario-based ex-ante assessment with the purpose of providing decision support makes the results unsuitable for (ex-post) accounting purposes, in particular for entries in such databases.

The selection of impact categories within the LCA must be consistent with the goal of the study and the intended applications of the results, and it must be comprehensive in the sense that it covers all the main environmental issues related to the system.

Impact categories not tick-marked in Table 3-2 are excluded. These are:

- Ionising radiation (not relevant in the case of OPTIMA)
- Human toxicity and ecotoxicity (insufficient LCI data quality, see below)
- Resource depletion: water (covered by EIA in WP6)
- Land use (covered by EIA in WP6)

In the case of human toxicity and ecotoxicity, which cover an extensive list of substances, LCI data quality for 2020 is a limiting factor. The data available today is not suitable to derive results, which are balanced enough for decision support. Therefore, these categories are excluded from the LCA. Instead, important ecotoxicity impacts on biodiversity are covered within the EIA in WP6.

Reasons for carrying out the study and decision-context

Three relevant decision-contexts can be differentiated in LCA (see Table 3-1). Situation B applies for OPTIMA since its main application is policy information and development. It is assumed that the implementation of biomass production and use chains developed in OPTIMA could have consequences that are so extensive that they overcome thresholds and – via market mechanisms – result in additionally installed or additionally decommissioned equipment / capacity (e.g. production infrastructure) somewhere else. The ILCD handbook specifies situation B, particularly in a context of “policy options for different future raw materials strategies (e.g. biofuels vs. fossil fuels)”, as the extreme case in which flexibility should be given priority over strictness in standardisation (section 5.4 in [JRC-IES 2010a]). Furthermore, JRC sees limitations in the application of the ILCD handbook in its current form particularly in situation B in [JRC-IES 2012]. Therefore, major requirements of the ILCD handbook are taken into account in this study where suitable in this decision context.

Table 3-1 Combination of two main aspects of the decision-context: decision orientation and kind of consequences in background system or other systems [JRC-IES 2010a]

Decision support?		**Kind of process-changes in background system / other systems**	
		None or small-scale	Large-scale
	Yes	Situation A “Micro-level decision support”	Situation B “Meso/macro-level decision support”
	No	Situation C “Accounting”	

Target audience

The definition of the target audience helps identifying the appropriate form and technical level of reporting. In the case of OPTIMA, the target audience can be divided into internal stakeholders (project partners, most of which have a background in agricultural sciences or engineering) and external stakeholders (EC staff, political decision makers, interested layperson).

Comparisons between systems

This study includes comparisons of the overall environmental impact of two or more systems and is planned to be disclosed to the public. Usually, this aspect entails a number of additional mandatory requirements under ISO 14040 and 14044 on the execution, documentation, review and reporting of the LCA study due to the potential consequences the results may have for e.g. external companies, institutions, consumers, etc.

However, since these comparisons are made on a generic level and only for scenarios on potential future implementations, we think that statements regarding superiority, inferiority or equality of alternatives do not directly affect specific companies, institutions and stakeholders. Thus, these comparative assertions can be disclosed to the public even without entirely fulfilling the requirements for LCA studies to be disclosed to the public.

Commissioner of the study and other influential actors

The study is supported by the EU Commission, which signed a grant agreement with the OPTIMA consortium.

3.2.2 Scope definition

Function, functional unit and reference flow

The key elements of an LCA are the system's function and functional unit. The functional unit is a reference to which the environmental impacts of the studied system are related and the basis for the comparison of different systems.

The principal functional unit used in OPTIMA is:

- Use of 10 ha of land for the cultivation of perennial grasses for industrial purposes (area basis)

Independent of the functional unit, all life cycle comparisons, e.g. between biogenic and fossil products, are based on equal utility of both life cycles. This utility is measured and expressed in units specific for each product, e.g. 1 MJ of heat for domestic heating.

Depending on the question to be answered, results are also displayed related to the reference unit 1 tonne of dry biomass where appropriate.

System boundaries

System boundaries define, which unit processes are part of the product system and thus included into the assessment. The LCA for OPTIMA covers the entire value chain (life cycle) from feedstock production to distribution and usage of the final products including land use change effects and associated changes in carbon stocks (see Fig. 3-2).

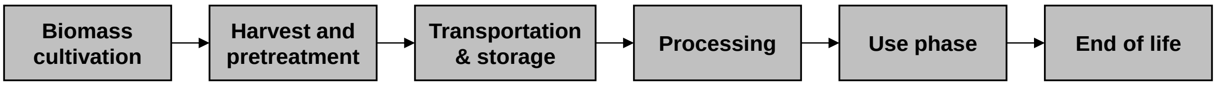

Fig. 3-2 System boundaries applied in the case of OPTIMA

Systematic exclusion of activity types

Infrastructure, i.e. the production and processing equipment, vehicles, buildings and streets connected with the crop's production and use, is not included in the inventory, except for background data (indeed generic LCI databases such as ecoinvent may include infrastructure with no possibility to exclude it). This applies to production and processing equipment, vehicles such as tractors, buildings and streets connected with the crop's production and use. In many LCAs assessing bioenergy systems it was shown that infrastructure accounts for less than 10 % of the overall results [Fritsche & 25 co-authors 2004; Gärtner 2008; Nitsch & 12 co-authors 2004]. However, this only applies for the environmental impact. In contrast, investment and capital costs for process equipment or buildings are an important part of the economic assessment.

Biogenic carbon

There are two possible sources for carbon dioxide (CO_2) emissions: (recent) biogenic or fossil carbon stocks. For biofuels, the amount of CO_2 released into the atmosphere from direct biofuel combustion equals the amount of CO_2 that has been taken up by the crops recently (short carbon cycle). This release of biogenic CO_2 is considered carbon neutral, i.e. it does not promote climate change. Therefore, the standard approach among LCA practitioners is to only report CO_2 emissions from fossil carbon. The ILCD Handbook stipulates to additionally inventory and evaluate both biogenic carbon emissions and uptake of atmospheric carbon by crops to avoid errors due to inconsistencies (provision 7.4.3.7 in [JRC-IES 2010a]). Within OPTIMA, the consistency of biogenic carbon accounting is verified but results are only reported if they are not zero, e.g. in the case of soil organic matter accumulation.

Direct land use change and carbon sequestration

Changes in land use patterns and related changes in organic carbon stocks of above- and below-ground biomass can have remarkable climate change impacts. The carbon stock changes and resulting release of greenhouse gases (mainly in the form of CO_2) are integrated into the GHG balances if alternative land use options lead to different carbon stocks. The methodologies described by the IPCC guidelines for national greenhouse gas inventories [IPCC 2006] are used.

As far as changes in soil organic carbon stocks are concerned, soil carbon sequestration is not taken into account in the main scenarios but only in a sensitivity analysis. This is because the potential to sequester carbon in soils is very site-specific and highly dependent on former, current and future agronomic practices (e.g. after clearing the perennial grass plantation), climate and soil properties [Larson 2006]. Therefore, it is uncertain for how long soil carbon is sequestered, i.e. taken out of the carbon cycle.

A critical point in terms of soil carbon is the clearing of the perennial grasses plantation: in case deep and/or repeated ploughing is necessary to clear the plantation (especially to destroy the root system), most of the carbon sequestered in the past 15 years is probably lost. In our calculations, we have made the assumption that a herbicide application will kill off the crops and that no mechanical removal of the roots is needed, i.e. no soil carbon is lost.

Since in LCA, usually a long-term perspective (e.g. 100 years) is taken, also the subsequent land use (after clearing the perennial grasses plantation in year 15) must be considered, i.e. the question what happens to the field in the following 85 years must be addressed: will a new perennial grasses plantation be established (plantation followed by plantation etc.) or will annual crops be cultivated again (including tillage)? In the second case (return to annual crops), we assume that the soil organic carbon stock in year 100 equals the soil organic carbon stock in year 1, i.e. no carbon would be sequestered – despite 15 (out of 100) years of cultivating perennial crops. In the first case (continuous cultivation of perennial grasses), we assume that the soil organic carbon stock will increase linearly over 20 years [IPCC 2006], reaching the same soil carbon stock as a permanent grassland in the Mediterranean region. The latter case is investigated in a sensitivity analysis.

Indirect effects

New systems using biomass can indirectly affect environmental indicators by withdrawing resources from other (former) uses. One of the most common indirect effects is indirect land use change: If land formerly used e.g. for food or feed production is now used for industrial crops, it is likely that feed and food production are shifted to other land elsewhere. This can cause clearing of (semi-)natural ecosystems (= indirect land use change) and hence changes in organic carbon stocks and damages to biodiversity. For OPTIMA, indirect land use changes are assessed in a sensitivity analysis because one main purpose of OPTIMA is to use marginal land to avoid indirect land use changes.

Carbon storage in products and delayed emissions

Carbon storage time is expected to be much less than 100 years for all OPTIMA products – maybe except for biochar. Delayed emissions are not taken into account in this study.

3.2.3 Settings for Life Cycle Inventory Analysis (LCI)

Technical reference, time frame and geographical coverage

The technical reference describes the technology to be assessed in terms of plant capacity and development status / maturity. The time frame of the assessment determines e.g. the development status of biorefinery technology. Likewise, the environmental impact associated with conventional products changes over time (hopefully decreasing), e.g. greenhouse gas emissions associated with electricity generation. This study assesses scenarios depicting mature technology in the year 2020. This avoids biased comparisons of earlier immature implementations of OPTIMA processes to already mature conventional processes.

Geography plays a crucial role in many sustainability assessments, determining e.g. agricultural productivity, transport systems and electricity generation. The OPTIMA project focuses the Mediterranean region and thus all parameters and reference processes are chosen based on this region.

Data sources

The LCA of OPTIMA systems require a multitude of data. Data is obtained from the following sources:

Primary data:

- Data on biomass cultivation, irrigation, yields and nutrient content of biomass stem from OPTIMA partners and have been cross-checked by IFEU. All other data on cultivation, e.g. the amount of fertiliser input originate from IFEU's internal database [IFEU 2015].
- Data on the thermochemical conversion processes were partially provided by [van den Berg 2015]. Data on all other biomass conversion processes were taken from IFEU's internal database [IFEU 2015] and supplemented with literature data.

All processing steps analysed are based on estimates for commercial agricultural systems and industrial processing units.

Secondary data:

- Data on the upstream process of ancillary products (e.g. fertilisers, tractor fuel, pesticides etc.), data on transport processes as well as data on provision and use of fossil energy carriers and conventional products were mostly taken from IFEU's internal database [IFEU 2015]. Where necessary, these data are supplemented by data from external databases such as ecoinvent V2.2 [Ecoinvent 2010].

Energy consumption and production were assessed in the following way:

Net consumed electricity was assessed using an average European power mix equivalent to those, which are part of the background data on other processes like provision of input chemicals. Many scenarios do not show electricity consumption but substantial net electricity production. This output was assessed according to the marginal concept [Klobasa et al. 2009; Memmler et al. 2013]. A marginal power mix for 2025 was used based on 50 % natural gas and 50 % hard coal with a share of 25 % cogeneration and efficiency gains of 5 % from 2010 to 2025.

Attributional vs. consequential modelling

The identification of the most appropriate LCI modelling principles and method approaches is closely linked to the classification of the LCA work as belonging to one of three distinct decision-context situations [JRC-IES 2010a]. Since Situation B applies for OPTIMA, consequential modelling is applied.

Solving multifunctionality

Agricultural production systems and biomass processing often produce (co-)products with different functions. Every process that provides more than one product is termed “multifunctional”. Environmental impacts have to be assigned to the obtained co-products. The choice of how to solve multifunctionality of processes and products is closely related to the choice of the appropriate LCI modelling framework.

According to the ILCD Handbook, the approach to solve multifunctionality is influenced by the decision-context situations A, B, or C [JRC-IES 2010a]. Since OPTIMA is classified as belonging to Situation B (meso/macro-level decision support), the substitution approach is used wherever possible in this study. As no particular research questions to be answered required a deviation from this setting, allocation has not been applied.

3.2.4 Settings for Life Cycle Impact Assessment (LCIA)

Impact categories

Life cycle impact assessment (LCIA) methods exist for midpoint and for endpoint level. There are advantages and disadvantages associated with both levels. In general, on midpoint level a higher number of impact categories are differentiated and the results are more accurate and precise compared to the three Areas of Protection at endpoint level that are commonly used for endpoint assessments. Within the OPTIMA project, the impacts are assessed at midpoint level only.

This project assesses the midpoint indicators tick-marked in Table 3-2. The selected impact categories are mostly well-established categories in life cycle assessments [JRC-IES 2010a]. Some impact categories, which are not tick-marked in Table 3-2, are excluded because they are i) irrelevant for the OPTIMA systems (i.e. ionising radiation) or ii) still under methodological development (i.e. human toxicity and ecotoxicity).

Impacts on human toxicity and ecotoxicity (classified as level II / III in the ILCD Handbook) are only particularly relevant if bioenergy crop cultivation serves the purpose of “phytoremediation”. For these cases, toxicity-related impacts are discussed qualitatively and separated from the main LCA.

The categories “resource depletion: water” and “land use” are also under development and quite immature. They are classified as level III in the ILCD Handbook. Despite the particularly high relevance for the agricultural products assessed in OPTIMA, these categories are not included in the LCA for the main analyses because impacts are highly dependent on the regional conditions but the goal of this study is to assess generic scenarios for the Mediterranean region. Nevertheless, the impact variability for water scarcity is exemplarily discussed in a sensitivity analysis (section 5.4.1.3). Since the ReCiPe 2008 method does not include an assessment methodology for water scarcity, the Swiss ecoscarcity method is applied [Frischknecht et al. 2009]. Additionally, water and land use impacts are investigated as part of the environmental impact assessment (EIA) in WP 6 [Fernando et al. 2015].

LCIA methods

Regarding the LCIA methods, OPTIMA uses the ReCiPe 2008 methodology [Goedkoop et al. 2014] as a basis for assessment because it covers all impact categories in a consistent way. There are two deviations from ReCiPe:

- Ozone depletion is assessed according to [Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010], which in contrast to the ReCiPe method takes the impact of N_2O emissions on ozone depletion into account. In all assessed scenarios, the contribution of N_2O emissions to ozone depletion is at least about 10-fold higher than the contributions of all other substances together according to this impact assessment method. The reason is that biomass related systems are assessed, which lead to considerable N_2O emissions throughout their life cycles. The exact impact of N_2O on ozone depletion is still debated in the scientific community but if the order of magnitude suggested by [Ravishankara et al. 2009] is correct, then N_2O emissions are dominating this environmental impact for the assessed systems. Therefore, the ReCiPe impact assessment method, which does not take N_2O emissions into account, is considered to lead to distorted conclusions and the impact assessment method according to [Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010] is used instead.
- Furthermore, the ReCiPe indicator “Fossil fuel depletion” was substituted by the indicator cumulative non-renewable energy demand (“Non-renewable energy use, NREU”) [Borken et al. 1999; VDI (Association of German Engineers) 2012] because the latter takes nuclear energy into account, too. Depletion of ores used for the production of nuclear energy is accounted for by the ReCiPe indicator “Mineral resource depletion”, which is not used in this study. A joint LCIA category for depletion of non-renewable energy resources yields more robust results in the context of this study because the share of power from nuclear power plants varies considerably within the reference area. Therefore, this deviation from ReCiPe allows a more direct interpretation of results. To avoid confusion of cumulative non-renewable energy demand with the ReCiPe indicator, the former is expressed in MJ per functional unit instead of kg oil equivalent per functional unit.

For the impact categories “eutrophication” and “acidification”, the impacts are calculated by using the CML methodology [CML 2015] in addition to the ReCiPe methodology since ReCiPe has the following limitations in this regard:

- ReCiPe does not consider terrestrial eutrophication
- ReCiPe distinguishes between freshwater eutrophication and marine eutrophication. It is assumed that marine ecosystems are nitrogen limited and fresh water ecosystems are phosphorus limited. Therefore, the calculation of marine eutrophication considers only nitrogen and the calculation of fresh water eutrophication considers only phosphorus. But there are examples of European fresh water ecosystems that are nitrogen limited and at least seasons when marine ecosystems are phosphorus limited.

A sensitivity analysis in the annex (section 8.3.1) shows that there are no qualitative differences in the acidification results obtained via the two methodologies. Since ReCiPe does not consider terrestrial eutrophication, but two types of aquatic eutrophication, while CML considers terrestrial eutrophication and one type of aquatic eutrophication, the eutrophication results of ReCiPe and CML cannot be compared. Hence, results according to ReCiPe are displayed throughout the report to be consistent with the remaining impact assessment.

Table 3-2 Overview on midpoint impact categories covered: classification according to the ILCD Handbook [JRC-IES 2010b] and LCIA method chosen in OPTIMA

Midpoint impact category	Covered	ILCD classification	OPTIMA
Climate change	✓	I	ReCiPe (i.e. IPCC 2007)
Ozone depletion	✓	I	[Ravishankara et al. 2009; WMO 2010]
Human toxicity	–	II / III	–
Particulate matter formation	✓	I	ReCiPe
Ionising radiation	–	II - interim	–
Photochemical ozone formation	✓	II	ReCiPe
(Terrestrial) acidification	✓	II	ReCiPe + CML
Terrestrial eutrophication	✓	II	CML
Aquatic eutrophication (freshwater and marine, respectively)	✓	II	ReCiPe + CML
Ecotoxicity	–	II / III	–
Land use	(✓)	III	Part of the EIA in WP 6
Resource depletion: water	(✓)	III	Part of the EIA in WP 6
NREU: Non-renewable energy use	✓	II	[Borken et al. 1999; VDI 2012]

Normalisation

Normalisation helps to better understand the relative magnitude of the results for the different environmental impact categories. It is optional for LCAs. To this end, the category indicator results are set into relation with reference information. Normalisation transforms an indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected area.

In the OPTIMA LCA study, the environmental advantages and disadvantages are related to the environmental situation in the EU28. The reference information is the annual average resource demand and the average emissions of various substances per capita in Europe, the so-called inhabitant equivalent (IE). The reference values are presented in Table 8-1 in the annex (section 8.1) for all environmental impact categories except water and land use. For the categories water and land use, no IEs are available. These categories are reported separately and without normalisation. Due to the uncertainty related to future emissions of various substances, IE are calculated based on 2000 emissions although the time frame for OPTIMA is 2020.

Weighting

Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis. Weighting is not applied in this study.

4 OPTIMA scenarios and sensitivity analyses

For the OPTIMA project, several biomass production and use options were combined resulting in a set of scenarios for the sustainability assessment. They have been defined in a common process for all parts of the sustainability assessment [Müller-Lindenlauf et al. 2012]. This section describes the investigated scenarios. Please note that the scenarios depict potential future options of biomass provision and use. It is therefore possible that some of the analysed scenarios cannot be implemented at all or only with modifications. Their description follows the life cycles and thus deals with biomass production (section 4.1), logistics and biomass conditioning (section 4.2) and biomass conversion (section 4.3). Environmental impacts of the investigated systems particularly depend on certain crucial parameters. These parameters are varied in sensitivity analyses to assess their significance for the overall system performance. The investigated systems are illustrated in process flow diagrams with scenarios and sensitivity analyses highlighted in red. A summary of the investigated scenarios and sensitivity analyses is given in section 4.4.

4.1 Biomass production

Biomass production in OPTIMA consists of the cultivation of perennial grasses including removal of the plantation after the end of its economic life time, harvesting of the biomass including chopping or baling and transportation to a conditioning facility (Fig. 4-1). This study assesses several crops (4.1.1) and yield levels. Their production is compared to other use options for the same land (4.1.2). Critical settings and parameters are subject to further detailed sensitivity analyses (4.1.3). The generic life cycle comparison scheme with focus on biomass production (Fig. 4-1) displays the main investigated pathways and sensitivity analyses.

In the Mediterranean region, a great variety of biomass production sites can be found. While some of them offer favourable environmental conditions like high water availability and soil fertility, others suffer e.g. from water stress or even contaminations. One main purpose of the OPTIMA project is to optimise the use of marginal biomass production sites. For comparison, productive sites are included in the assessment, too. For this reason, a bandwidth of four biomass production settings was defined, termed “marginal 2”, “marginal 1”, “standard” and “high”. Main characteristic of these biomass production settings is the possible yield under the respective conditions, which is assumed to be targeted by cultivation practice. In order to reach the respective yields throughout the plantation’s life time, cultivation intensity must be adjusted accordingly. This determines e.g. the amount of fertilisers applied and the amount of diesel needed. The yield in turn determines the magnitude of a conversion plant’s radius for biomass acquisition. Table 4-1 gives an overview of the four yield levels defined for biomass production. In the following, due to the focus on marginal biomass production sites, the yield level “high” is not displayed.

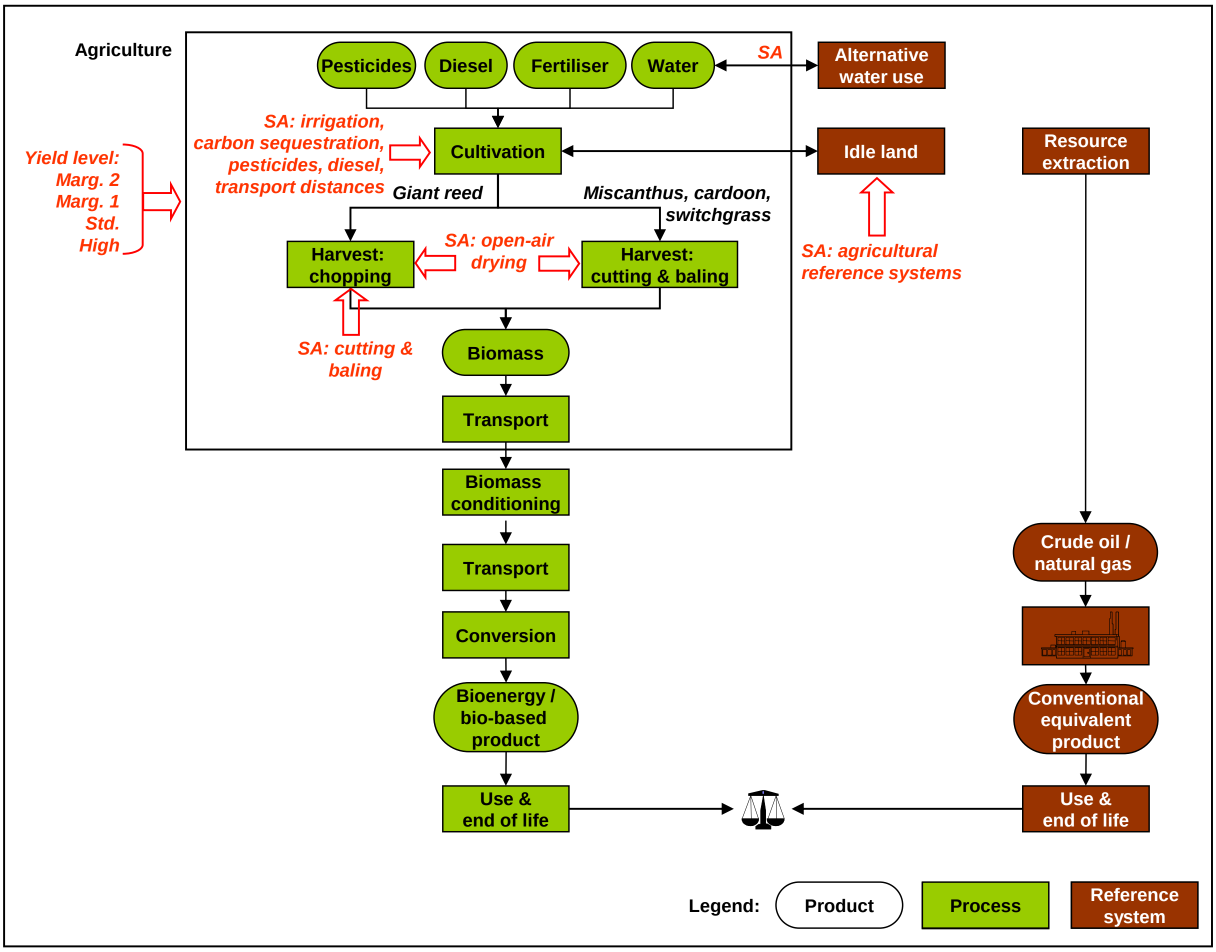

Fig. 4-1 Generic life cycle comparison scheme with focus on biomass production. Scenarios and sensitivity analyses are marked in red. Marg.: Marginal. SA: Sensitivity analysis. Std.: Standard.

Table 4-1 Yield levels for biomass production.

Name	Abbreviation	Explanation
Marginal 2	Marg. 2	Marginal conditions which lead to a considerable yield reduction, caused by different factors such as pronounced water stress, pronounced salt stress or high inclination; very low yield, very low nutrient demand, very low diesel demand per area for cultivation maintenance
Marginal 1	Marg. 1	Moderately marginal conditions can be caused by different factors such as moderate water stress, moderate salt stress or moderate inclination; low yield, low nutrient demand, low diesel demand per area for cultivation maintenance
Standard	Std.	Typical climate and soil conditions in the Mediterranean region; standard yield, standard nutrient demand, standard diesel demand per area for cultivation maintenance
High	High	High-input system on good soils and without any constraints; high yield, high nutrient demand, high diesel demand per area for cultivation maintenance

4.1.1 Investigated perennial crops for biomass production

The OPTIMA project focuses on the cultivation of perennial crops. Giant reed (*Arundo donax* L.), Miscanthus (*Miscanthus × giganteus*) and switchgrass (*Panicum virgatum* L.) are three perennial grasses that have been in the centre of scientific attention during the past ten years due to their favourable characteristics, including yield, nutrient demand, water use efficiency, adaptability to competitive environmental conditions, etc. A fourth crop investigated for the OPTIMA project is cardoon (*Cynara cardunculus* L.), which was chosen because it is particularly adapted to the Mediterranean region and may thus serve as a control species. The life cycle phase "cultivation" can be subdivided into the following processes: field preparation, seeding / planting, maintenance including weed control, the application of fertiliser and irrigation, harvest, and clearing after a plantation's life time. This is valid for each of the four crops under investigation. Several parameters are equal for each of the four crops, including the plantations' life time of 15 years. However, the four crops differ from each other with respect to the magnitude of inputs and outputs of one of the given processes listed above. The following subsections provide a brief description of the four crops and highlight the relevant differences between them. Table 4-2 lists several relevant properties of the investigated crops. Further LCA input data can be found in Table 8-2 in the annex.

4.1.1.1 Giant reed (*Arundo donax* L.)

Giant reed is a C_3 grass[1], which originates from Asia (probably the Indian subcontinent) and grows up to 6 m tall. Since it is incapable of producing fertile seeds, vegetative plant propagation material (rhizomes, cuttings, in-vitro propagated plantlets) is used for planting. Giant reed yields in terms of dry matter per hectare are highest among the investigated crops. However, the water content of harvested stalks is comparatively high – at least in the Warm temperate moist climate zone [IPCC 2006]. At a water content of 55 %, giant reed is harvested with a self-propelled forage harvester and chopped into small pieces.

4.1.1.2 Miscanthus (*Miscanthus × giganteus*)

Miscanthus is a C_4 grass, which originates from East Asia and grows up to 4 m tall. Similar to giant reed, *Miscanthus × giganteus* is incapable of producing fertile seeds, thus clones are used for planting. With respect to yield, Miscanthus ranks second among the investigated crops. The amount of nitrogen and phosphorus removed at harvest (which needs to be replenished via fertilisation) is very low compared to the other crops. After harvest, Miscanthus is baled, which is the preferred densification process for local biomass use.

4.1.1.3 Switchgrass (*Panicum virgatum* L.)

Switchgrass is a C_4 grass, which originates from North America and grows up to 3 m tall. Unlike giant reed and Miscanthus, switchgrass can be seeded. Switchgrass yields are lower than those of Miscanthus and giant reed. Its demand for potassium is very low compared to other crops. In contrast, its demand for nitrogen is high. Like Miscanthus, switchgrass is baled after harvest.

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[1] "C_3" / "C_4" are terms used to describe a plant's type of photosynthesis. C_3 plants are more common than C_4 plants. The water use efficiency of C_4 plants is superior to C_3 plants.

4.1.1.4 Cardoon (*Cynara cardunculus* L.)

Cardoon is a C_3 plant, which is native to the Mediterranean region. In contrast to the other investigated crops, cardoon is not a perennial grass but a thistle-like perennial herb. It produces significant amounts of oil containing seeds. Unlike the previous three grasses cardoon is a winter crop, developing its growth stage during winter months and maturing during summer, thus theoretically being able to grow without irrigation. Current research has shown that seeds can be separately harvested by means of conventional combine harvesters although this type of machines have not been optimised for this crop; ad-hoc harvesting technologies that separate seeds from other biomass may become available in the future. However, they still face technological drawbacks, e.g. on uneven terrain where the harvest is related to significant biomass losses [Pari et al. 2015]. For these reasons, whole-crop harvesting of cardoon biomass is set to be applied followed by baling, like for Miscanthus and switchgrass.

Table 4-2 Selected data on the cultivation of perennial crops on marginal land (yield level “marginal 1”). All data represent averages over the 15-year plantation period.

Parameter	Unit	Giant reed	Miscanthus	Switchgrass	Cardoon
Biomass removal from field	t fm / (ha × year)	39	17.5	10.3	11.5
Moisture at removal from field	% fm	55	20	15	15
Water supply to crops (e.g. via irrigation)	m^3 / (ha × year)	6,000	6,000	4,000	2,000*

fm: fresh matter; dm: dry matter

* Irrigation assumed for the purpose of environmental assessment even though this crop is intended for dry farming (see sections 4.1.1.4 and 5.2.1).

4.1.2 Agricultural reference system

For life cycle assessment of biomass production systems, the agricultural reference is a crucial parameter for the outcome of the investigation. It describes the alternative land use, i.e. what the cultivation area would be used for if the crop under investigation was not cultivated [Jungk et al. 2002]. Since the OPTIMA project aims at avoiding a relocation of existing forms of land use, “idle land” was defined as the main agricultural reference system.

By definition, the agricultural reference system comprises any change in land use or land cover induced by the cultivation of the investigated crop. Land-use changes involve both direct and indirect effects [Fehrenbach et al. 2008]. Direct land-use changes (dLUC) comprise any change in land use or land cover, which is directly induced by the cultivation of the industrial crop under investigation. This can either be a change in land use of existing agricultural land (replacing idle / set-aside land) or a conversion of (semi-)natural ecosystems such as grassland, forest land or wetland into new cropland. Indirect land-use changes (iLUC) occur if agricultural land so far used for food and feed production is now used for industrial crop cultivation.

Assuming that the demand for food and feed remains constant, then food and feed production is displaced to another area, which once again provokes unfavourable land-use changes, i.e. the conversion of (semi-)natural ecosystems might occur. Both direct and indirect land-use changes ultimately lead to changes in the carbon stock of above- and below-ground biomass, soil organic carbon, litter and dead wood [Brandão et al. 2011]. Depending on the previous vegetation and on the crop to be established, these changes can be neutral, positive or negative. In many cases, land use changes also have remarkable effects on other environmental issues as well as social and economic concerns.

If land use changes are considered, they often are the most influential contribution to the greenhouse gas balance of the investigated agricultural system. In order to guarantee undistorted conclusions from the drawn comparisons between the investigated scenarios, land use changes are not part of the main scenarios, but assessed in sensitivity analyses.

4.1.3 Sensitivity analyses

As indicated in Fig. 4-1, several important settings and parameters of the life cycle stage biomass production are analysed for their influence on the results. This includes the agricultural reference system, irrigation and limited water availability, consideration of carbon sequestration, pesticides and diesel demand for cultivation and the transport distances.

Agricultural reference systems

A variety of different agricultural land uses exists in the Mediterranean region. It is possible that the cultivation of the investigated crops will be located on areas that were formerly used e.g. as pasture or for cereal production although it is the explicit aim of the OPTIMA project to avoid this kind of land use change. Therefore, a sensitivity analysis is conducted assuming “pasture” and “cereal production” as exemplary agricultural reference systems as summarised in Table 4-3 and Fig. 4-2.

Pastures provide feed for livestock. The ploughing of pastures for the cultivation of the investigated perennial crops means that the livestock feed has to be provided by other means. This scenario is based on the provision of lacking feed by conventional soy feed imported from South America. In the Mediterranean region different climate conditions are found, amongst others affecting the carbon stock of pastures. Thus a distinction is made between warm temperate moist climate (above and below ground carbon stock of pasture 70 t C / ha) and warm temperate dry climate 27 t C / ha). Depending on the climate zone, soy cultivation in South America is set to require 0.3 and 0.9 hectares, respectively. The soy cultivation is set to take place either on former grassland or rainforest areas.

Assuming that the global demand for cereals remains constant, the cultivation of the investigated perennial crops on land formerly used for cereal production means that cereals need to be produced somewhere else. This scenario is based on wheat production in North America as substitute for the lacking cereals. As cereal yields in North America and the Mediterranean region differ from each other, the cultivation of the investigated perennial grasses on 1 hectare of land formerly used for cereals production corresponds to the occupation of 1.7 hectares in North America, which are set to be converted grassland.

Table 4-3 Main agricultural reference system and alternative agricultural reference systems for sensitivity analyses. Source: [Schmidt et al. 2015].

Agricultural reference system		Description
Main	Idle land	Cultivation on former idle land.
SA I	Pasture (moist climate) vs. soy on GL	Mediterranean region: cultivation on land formerly used as pasture. Moist climate (affecting carbon stock of pasture and feed production). South America: cultivation of soy on former grassland.
SA II	Pasture (dry climate) vs. soy on GL	Mediterranean region: cultivation on land formerly used as pasture. Dry climate (affecting carbon stock of pasture and feed production). South America: cultivation of soy on former grassland.
SA III	Pasture (moist climate) vs. soy on RF	Mediterranean region: cultivation on land formerly used as pasture. Moist climate (affecting carbon stock of pasture and feed production). South America: cultivation of soy on former rainforest area.
SA IV	Cereals vs. cereals on GL	Mediterranean region: cultivation on land formerly used for cereals. North America: cultivation of cereals on former grassland.

GL: grassland; RF: rainforest; SA: sensitivity analysis

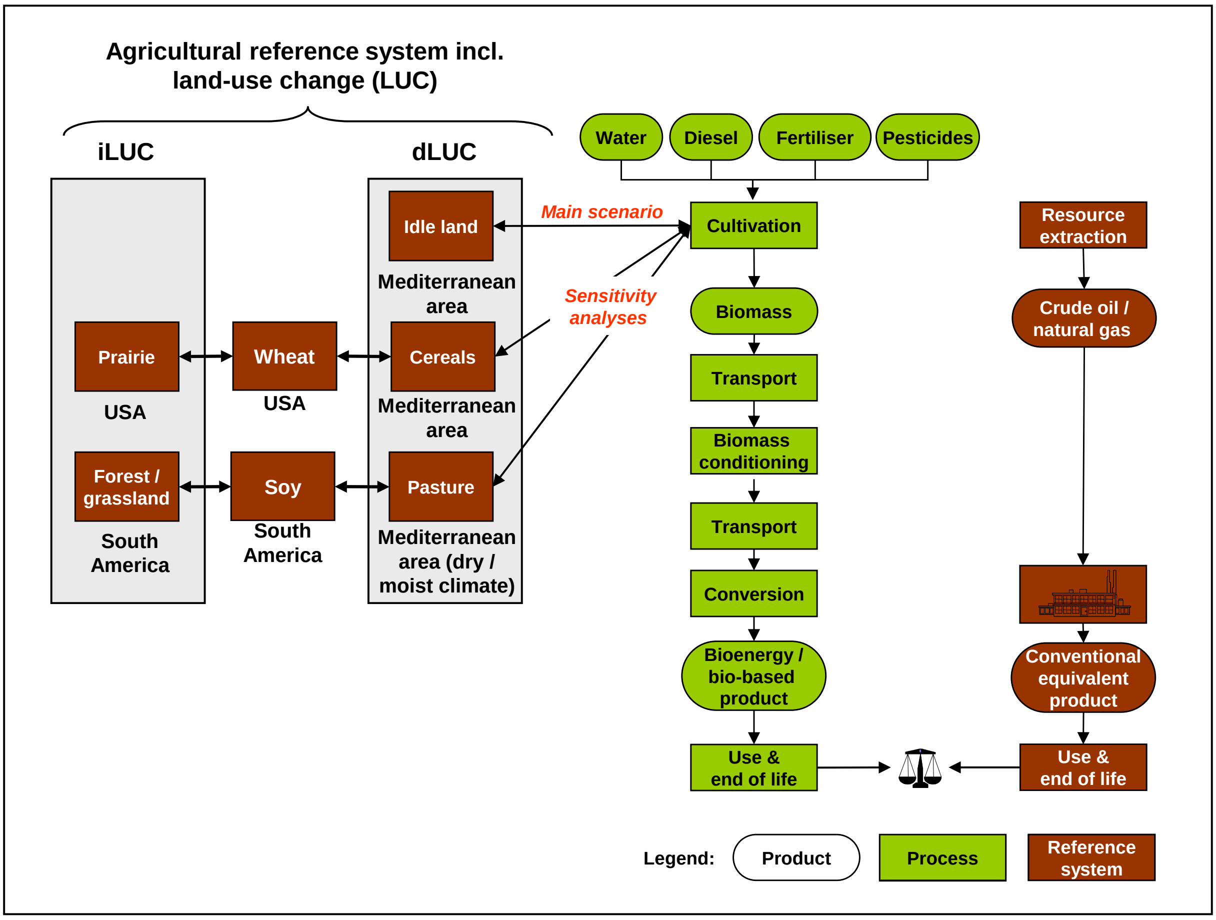

Fig. 4-2 Generic life cycle comparison scheme illustrating the considered alternative agricultural reference systems. Source: [Schmidt et al. 2015].

Irrigation and water availability

For the main scenarios, it is assumed that crops are cultivated on marginal land which is currently not used for agricultural purposes (i.e. lying idle). On this kind of land, irrigation is considered physically possible, though currently too costly for any kind of biomass cultivation. Nevertheless, for the main scenarios, it is assumed that perennial crops are irrigated, leading to considerable environmental impacts related to provision and application of water. However, in some parts of the Mediterranean region, irrigation may not be necessary due to sufficient rainfall. For this reason, impacts related to technical irrigation are subject to a sensitivity analysis for biomass production.

In the Mediterranean region, water availability may be strongly limited, depending on local or regional circumstances. Non-food crops should only be irrigated if sufficient water is available in the respective drainage basin. If this is not the case, it might be possible that water which is still used for irrigation of the investigated crops reduces available water for irrigation of other crops, which consequently reduces yields of other crops. This is reflected in a sensitivity analysis, assuming that less irrigation is applied to cereals cultivations, lowering the cereals yield by 60 %. Lacking cereals are set to be produced in North America and transported to the Mediterranean region. A yield loss of 1 tonne is set to correspond to the occupation of 0.3 ha / year in North America, which is set to be converted grassland.

Carbon sequestration

Carbon sequestration is investigated in WP 6 and according to [Monti 2015], perennial crops may be able to accumulate carbon in the soil. This effect improves soil fertility and may add to climate change mitigation by delaying and / or mitigating carbon dioxide emissions. However, clearing the planation after its life time significantly reduces long-term effects. For that reason, the relevance of such carbon accumulation for climate change mitigation is still subject to debate. Hence, climate-relevant carbon sequestration was not considered in the main scenarios. Still, in order to assess the parameter’s influence on the environmental performance of the investigated perennial crops, carbon sequestration is subject of a sensitivity analysis. Due to the high scientific uncertainty as to the magnitude of the effect, carbon sequestered by cultivation of investigated crops is set to range from 1 t C / ha to 10 t C / ha.

Diesel demand, pesticides and transportation distances

In order to estimate the effect of diesel demand for maintenance and harvest, application of pesticides and transportation distances from biomass production sites to conditioning facility, these parameters are varied by a factor of 2 in a sensitivity analysis.

Moisture content of biomass removed from field

In the Warm temperate dry climate zone [IPCC 2006], it might be possible to harvest crops at a water content of only 15 % by cutting, windrowing and intermediately storing them on the field for several days to dry. Afterwards, the biomass is baled. Thus, expenditures for technical drying are reduced. In this case, harvest of giant reed is conducted by a cutter and baler. See the following section 4.2 for a detailed description.

4.2 Logistics and biomass conditioning

Prior to conversion and use, the baled or chopped fresh biomass is set to undergo conditioning and several logistic steps. For all use options in the default scenario, this involves transportation to a separate conditioning facility where chopped giant reed is ground, dried and pelletised and where baled Miscanthus, switchgrass and cardoon are crushed/ground, dried and pelletised. Since the harvested biomass has a water content ranging from 15 – 55 % (see Table 4-2), technical drying is applied to avoid moulding. Additionally, conventional pelleting requires dry processed biomass with a moisture content of around 10 %. Since pellets have become an established form of biomass intermediates suitable for most downstream processing and use options, pelleting is applied in all default scenarios. Hence, biomass pellets are the feedstock of all use options depicted in the following section. Conventional pelleting relying on dried input material with a moisture content of around 10 % is defined for the main scenarios.

Depending on the case-specific production chain, climatic condition and downstream use option, conditioning processes may partially or even completely be unnecessary. For instance, biomass with a moisture content of 15 % or even higher (chopped at harvest or crushed/ground bales) may be suitable feedstock for production of 2nd generation ethanol or 1,3-PDO. Nevertheless, dry pellets are set as feedstock for all use options because it facilitates comparison among scenarios and use options. Moreover, the concrete design of future plants for production of 2nd generation ethanol or 1,3-PDO is still subject to uncertainties.

Since technical drying is very energy intensive, the following set of sensitivity analyses is conducted:

- First, energy carrier used for drying is varied: Instead of natural gas, either light fuel oil (LFO) or the harvested and dried biomass are used as energy carrier. As to the latter, less biomass can be pelletised and used in a given use option.
- Second, drying efficiency is varied by a factor of 20 %.
- Third, given that biomass is produced in the Warm temperate dry climate zone [IPCC 2006], cut biomass is left on the field for a couple of days to dry. By this means, water content of the cut biomass is reduced to 15 %. Afterwards, biomass is baled for transportation to the conditioning facility. Intermediate storage at the field margin is related to 5 % biomass losses. Since water content of feedstock for conventional pelleting must not exceed 10 %, some technical drying is still necessary though energy expenditures are lower.

As to pelleting, investigations in the OPTIMA project suggest that wet pelleting may become an applicable option, accepting feedstock with a moisture content of up to 30 %. Practical experiences, however, have shown that pelleting of Miscanthus and switchgrass biomass at moisture contents greater than 10 % may be problematic [Sternowsky 2015]. Against this background, the following sensitivity analyses were conducted:

- First, pelleting efficiency is varied by a factor of 20 %.
- Second, wet pelleting as proposed by 2ZK is assessed, lowering power demand for pelleting by 50 % due to acceptance of wet biomass.
- Third, pelleting is completely left out. This option is possible only when biomass is used for the production of 2nd generation ethanol or 1,3-PDO because technical processing may accept baled biomass.

Pellets are subsequently transported to a conversion facility by truck. Transport distances are set to range from 15 km to 30 km. Fig. 4-3 summarises the process steps in the life cycle phase logistics and biomass conditioning and highlights conducted sensitivity analyses.

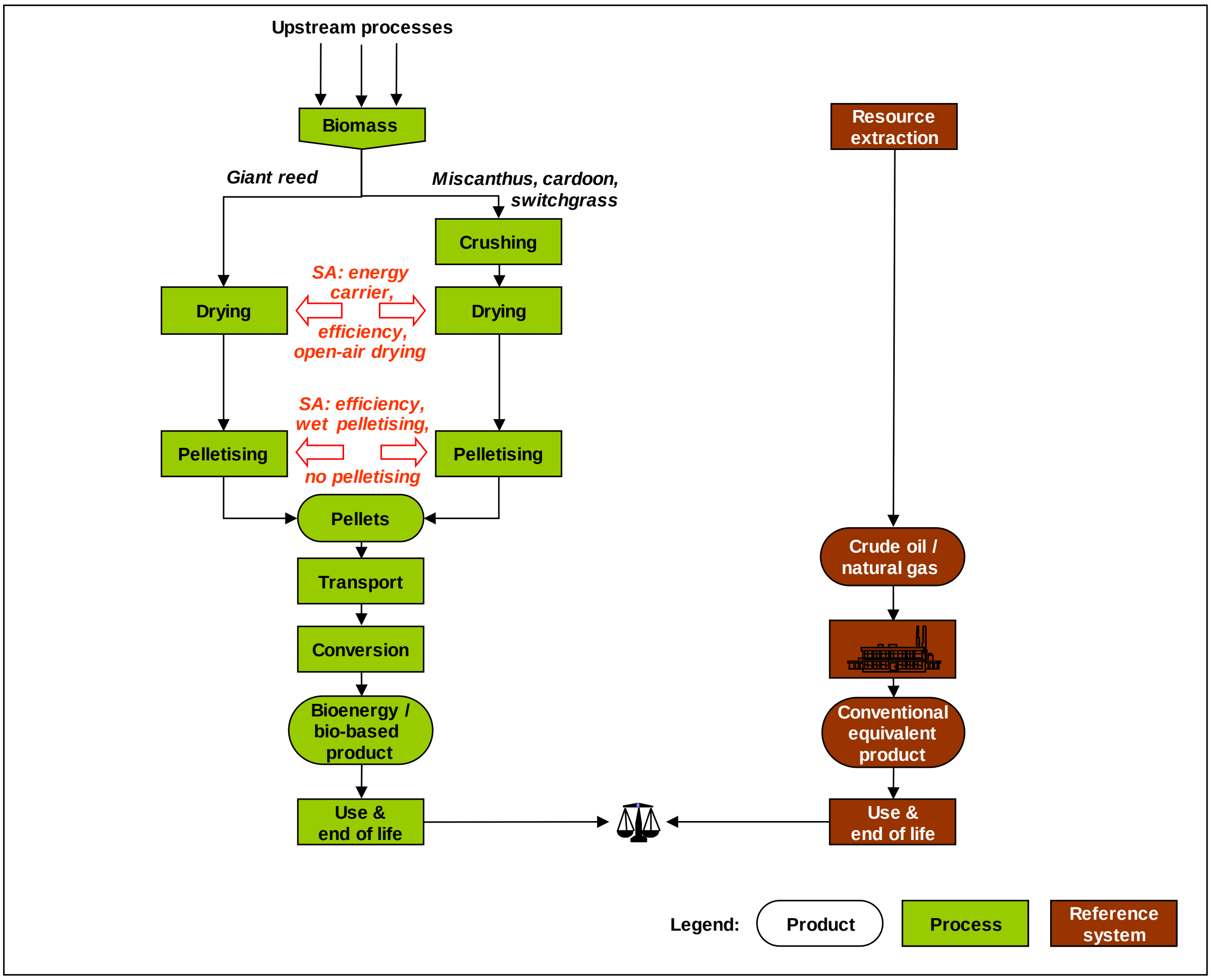

Fig. 4-3 Generic life cycle comparison scheme with focus on logistics and biomass conditioning. SA: Sensitivity analysis.

4.3 Biomass conversion, use and end of life

Nowadays, a wide variety of use options exists for lignocellulosic biomass. This variety is reflected by the set of processing and use options defined for the OPTIMA project. Recently developed conversion technologies like production of 2nd generation ethanol as well as established and simple technologies like combustion in a pellet boiler to produce heat for domestic use are included. No use options for oil processing are included in the analysis, since cardoon’s oil-containing seeds are not considered to be harvested separately (see section 4.1.1.4).

For most use options, biomass from perennial grasses will very likely have to be mixed with other biomass such as wood (e.g. combustion) or straw (e.g. ethanol) to fulfil technical specifications. The assessed scenarios depict only the share of biomass from perennial grasses in the value chains. Since major synergies beyond fulfilment of specifications are not expected, total sustainability effects of mixed fuel pathways can be assigned to the individual feedstock shares. Under these preconditions, this is identical to assessing *additional* effects of the introduction of biomass into mixed pathways while increasing the total production volume. The approach entails that additional measures necessary for using grass pellets only are not assessed. This includes the addition of limestone to pellets for neutralisation or the installation of additional flue gas treatment equipment that may become necessary if technical specifications are not met by the grass pellets.

In order to show the bandwidth of possible sustainability assessment results, three conversion efficiencies for all use options were defined, similar to the yield levels for biomass production. While the OPTIMA project focusses on studying a wide spectrum of agricultural production sites, only generic configurations of industrial conversion pathways are analysed. For this reason, a common bandwidth for industrial conversion processes is defined ranging from “low” to “high” efficiency. A summary and a definition of the conversion efficiencies are given in Table 4-4. The scenarios reflect potential implementations of conversion technology in 2020. Innovative industrial conversion technologies such as 2nd generation ethanol are modelled as mature technology implementations on industrial scale. Sensitivity analyses are conducted to assess the significance of several selected parameters as well as the provision of conventional reference products.

Transport distances from the pelleting facility to the conversion plant are set to the same generic values independent of the use option. Plausible deviations from these generic transport distances due to different scales of pelleting facility and conversion plant, geographic distributions, purchasing and logistics concepts and other influences are examined in a sensitivity analysis.

Table 4-4 Conversion efficiencies for biomass use options.

Name	Definition
Low	Low conversion efficiency, high transport distance (30 km), low output of co-products, high resource demand, low product quality
Standard	Standard conversion efficiency, standard transport distance (20 km), standard output of co-products, standard resource demand, standard product quality
High	High conversion efficiency, low transport distance (15 km), high output of co-products, low resource demand, high product quality

4.3.1 Domestic heat

In the Mediterranean region, households have a certain (usually low) heating demand during winter. The installation of a pellet boiler fuelled by regionally produced biomass might be an attractive option. Therefore, combustion of pellets for domestic heat is investigated.

The life cycle comparison is displayed in Fig. 4-4. Dried and pelletised biomass is directly (i.e. without any further processing) transported from the pelleting facility or the regional vendor to the households by truck. Afterwards, the pellets are combusted in a pellet boiler to produce domestic heat. The pellet boiler is defined to apply modern technology, i.e. it complies with current emission limits regarding particulate matter emissions[2]. The combustion of biomass pellets in a stove or small furnace is not part of the assessment.

The produced heat replaces heat provided by conventional energy carriers such as natural gas or light fuel oil. The conventional energy carrier is extracted from the ground, processed, transported, stored and also combusted in a boiler.

The conversion efficiencies for this biomass use option (low, standard, high) reflect that the installed pellet boilers differ with respect to their thermal efficiency. Thus, this parameter is varied between 85 and 95 %. Furthermore the delivery distance between vendor and household is varied between 15 and 30 km (see Table 4-4). This variation in transport distance is also applied to all subsequent use options.

Additionally, a sensitivity analysis is conducted that displays a variation of substituted conventional energy carrier because both light fuel oil and natural gas are typically used for domestic heating in the Mediterranean region. The thermal efficiencies of the boiler for light fuel oil and natural gas are defined as 88 % and 95 %, respectively.

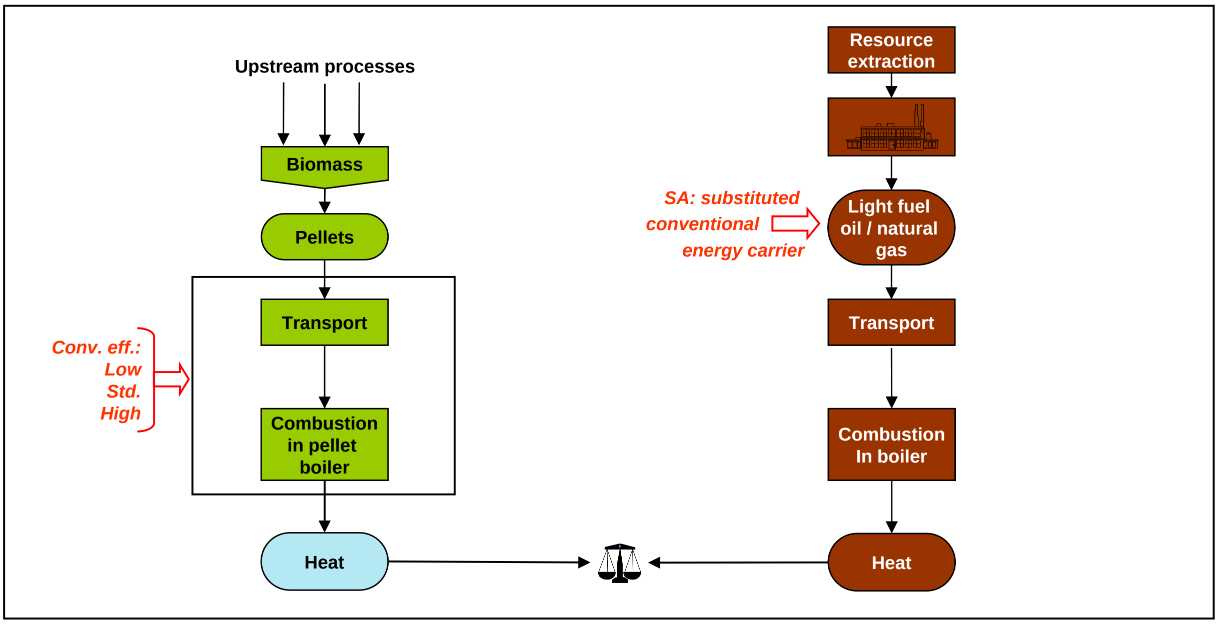

Fig. 4-4 Life cycle comparison scheme for the conversion and use option domestic heat. SA: Sensitivity analysis; Conv. eff.: Conversion efficiency; Std.: Standard.

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[2] Limits in 2020 may be stricter. However, scenarios on potential new legislation are not part of this analysis.

4.3.2 CHP (small & large scale)

Another use option for biomass pellets is the combustion in a combined heat and power plant (CHP). The life cycle comparison scheme is depicted in Fig. 4-5. This use option may be attractive to companies for small and large scale use of biomass pellets. The main reason for the installation and / or operation of the CHP is the provision of the company's process heat demand. Thus, the operation of the CHP is defined as heat-controlled with a power to heat ratio ranging from 0.18 (small scale) to 0.46 (large scale).

The conventional reference product for heat is heat produced via the combustion of a fossil energy carrier in a boiler (natural gas or light fuel oil). The conventional reference product for power is power from grid. As this study follows a consequential approach and thus its influence on the energy sector has to be taken into account, power consumption is assessed following a marginal concept [Klobasa et al. 2009; Memmler et al. 2013]. According to this, additionally produced power of new plants such as CHPs prevents either new power plants to be built or causes old power plants to be shut down earlier. Based on the assumption that renewable energies mainly compete with fossil energy sources rather than with each other due to political boundary conditions, the bandwidth of marginal energy sources ranges from natural gas to hard coal (see section 3.2.3 for details on LCA input data).

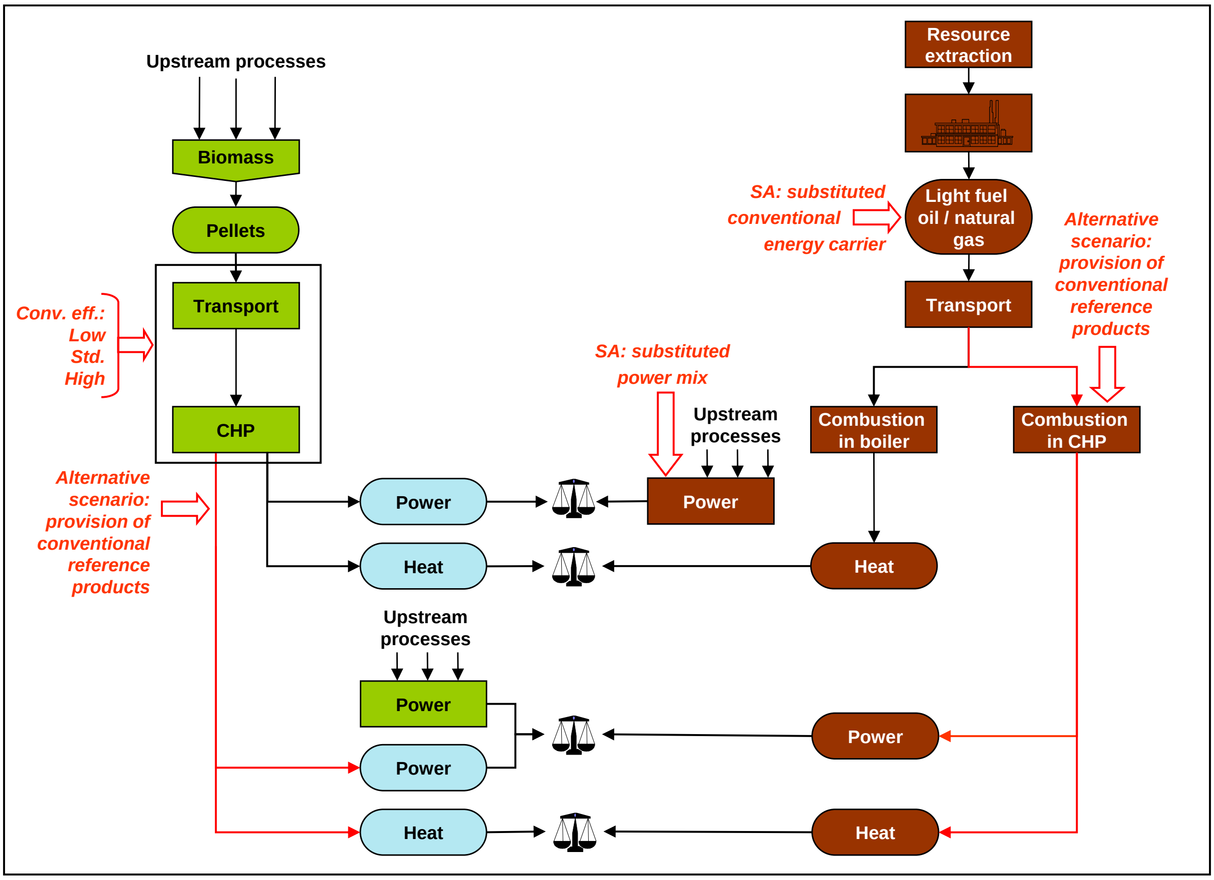

Fig. 4-5 Life cycle comparison scheme for the use options 'small CHP' and 'large CHP'. SA: Sensitivity analysis; Conv. eff.: Conversion efficiency; Std.: Standard.

Similar to the use option described in section 0, for the conversion efficiencies (low, standard, high), the total efficiency of the CHP is varied, ranging from 65 % in the lowest case (small scale) to 88 % in the highest case (large scale).

Furthermore, an alternative scenario is assessed in which both conventional reference products are co-produced by the combustion of a conventional energy carrier (light fuel oil / natural gas) in a CHP. This sensitivity analysis is conducted because the definition of the provision of conventional reference products can have a significant influence on the LCA results. The power to heat ratio of a CHP that utilises light fuel oil or natural gas is greater than the power to heat ratio of a CHP that utilises bioenergy carriers. In this use option, the provision of industrial process heat is the main incentive for the installation of the CHP. For this reason, the amount of heat produced via both the biomass and fossil CHP are defined to be equal. As a consequence, the operation of the biomass CHP provides less power than the fossil CHP. The difference has to be provided from grid. In this case grid mix is applied.

Finally, two sensitivity analyses are conducted. First, the substituted conventional energy carrier for heat production is varied for similar reasons as explained in section 0. Second, the substituted power mix is varied. This variation is conducted because the substituted power mix evidentially has a strong influence on the LCA results. Also, the power mixes of the countries located in the Mediterranean region differ from each other and they may be subject to shifts within the next few years. Substituted conventional power is set to be produced from hard coal plants / natural gas plants within this sensitivity analysis.

4.3.3 Upgraded pyrolysis oil

Major advantages of pyrolysis oil include its storability, high energy density compared to raw biomass and flexibility with respect to downstream processing and use options. Furthermore, lignocellulosic biomass may serve as feedstock resulting in advantageously little interlinkages to the food and feed markets.

As displayed in Fig. 4-6, the production of upgraded pyrolysis oil mainly consists of the two processes fast pyrolysis and upgrading, which both occur in one integrated plant. The biomass pellets first undergo a fast pyrolysis. Apart from crude pyrolysis oil, surplus heat and surplus electricity are co-products of the fast pyrolysis. From these, the whole demand of the integrated plant for low temperature heat and power can be satisfied. Surplus power is fed into the grid, while low temperature heat is used in a small district heating system. By upgrading, crude pyrolysis oil becomes suitable for several applications. These applications include heating, fuels for transportation and bio-based materials. In any of these cases, the upgraded pyrolysis oil substitutes light fuel oil. Since the latter two options may have certain technical restrictions or may require certain process modifications, the assessment in OPTIMA is based on the combustion of upgraded pyrolysis oil instead of light fuel oil in a boiler. Varied parameters include the efficiency of the conversion process, the necessary heat input as well as the electricity and heat output.

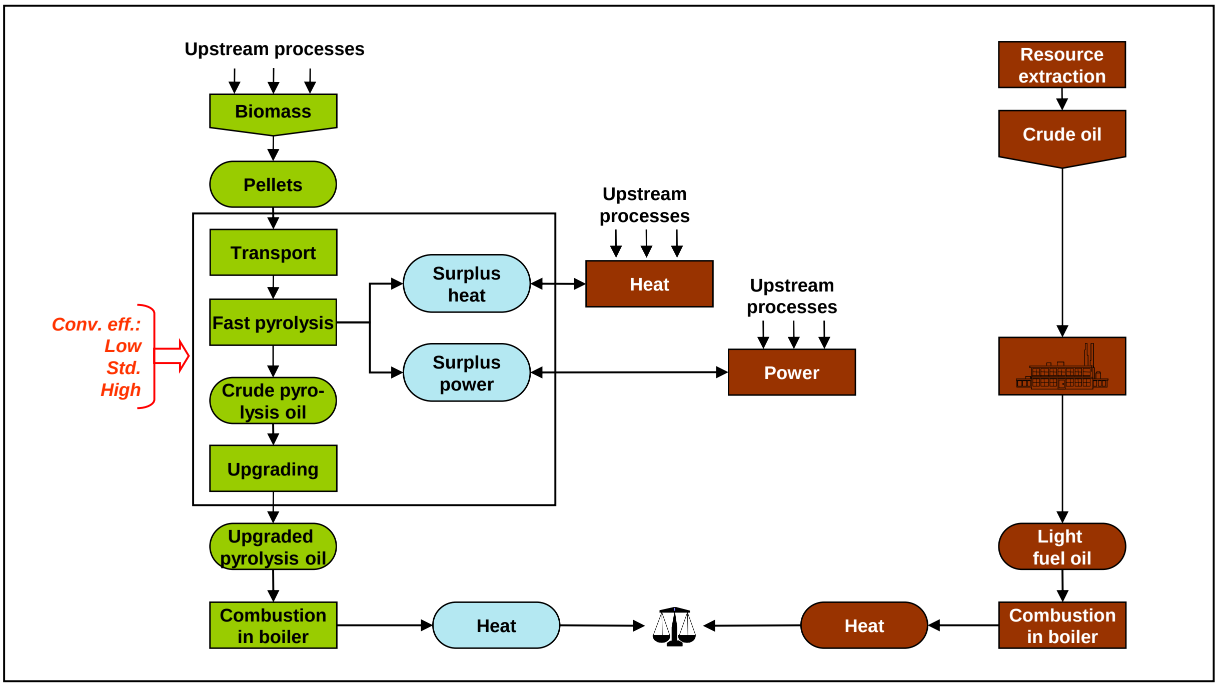

Fig. 4-6 Life cycle comparison scheme for the conversion and use option 'upgraded pyrolysis oil'; Conv. eff.: Conversion efficiency; Std.: Standard.

4.3.4 Biochar

Biochar is applied to fields. This provides two benefits: first, soil fertility is improved. Second, carbon fixed by the perennial crops and contained in the biochar is intended to be sequestered in soils. Hence, carbon dioxide emissions may be delayed or even partly permanently avoided.

As shown in Fig. 4-7, for this use option, biomass pellets are transported to a conversion plant. The main process for the production of biochar is termed torrefaction. It is a pyrolysis at low temperatures, increasing the product's energy density. After torrefaction, the obtained biochar contains 75 % carbon [Hammond 2009]. It is then applied to fields. The percentage of carbon contained in biochar that remains in the ground for more than 100 years is still subject to debate. For the OPTIMA project, a value of 40 % is defined, representing an average of current scientific statements [Lehmann et al. 2006].

The function of biochar as a soil improver is similarly debated. Probably, it depends very much on very site-specific conditions such as soil, temperature and water availability. Until studies become available under which conditions which effects can be reliably achieved for how long, an assessment of this function is not possible.

There is no appropriate conventional product reference system for the function of biochar as carbon sink because there are no comparable conventional carbon sequestration services that could be replaced. Nevertheless, the benefit of the service "carbon sequestration" is directly reflected in the life cycle impact assessment. Thus, a product reference system is not necessary for comparing this product use option to others because no product or service leaves the system boundaries without being taken into account.

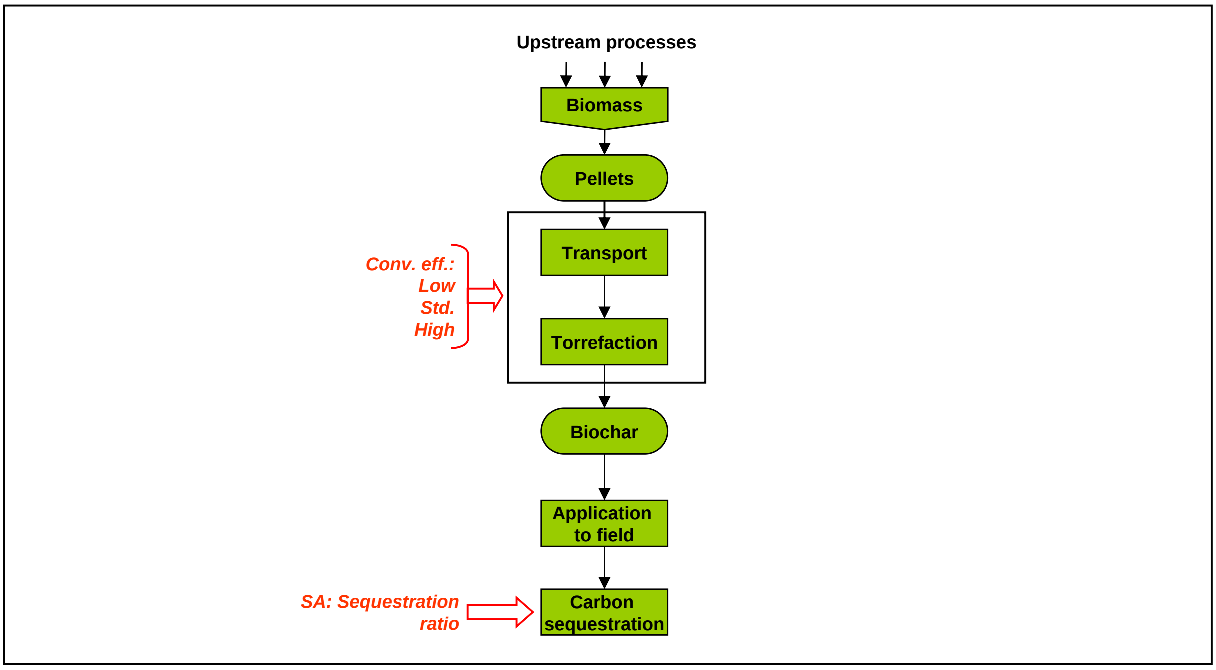

Fig. 4-7 Life cycle comparison scheme for the conversion and use option biochar. Conv. eff.: Conversion efficiency; SA: Sensitivity analysis; Std.: Standard.

Among others, the bandwidth of the use option's conversion efficiencies reflects the varying ratio of biochar produced per mass unit of biomass pellets as well as the energy input and the energy carrier for torrefaction. Reflecting the scientific uncertainty as to the fraction of the carbon contained in biochar, which is sequestered for more than 100 years, this parameter is varied in a sensitivity analysis ranging from 20 % – 80 %.

4.3.5 2nd generation ethanol

Lignocellulosic biomass can be converted into ethanol via 2nd generation ethanol processes. Such processes are very innovative but first industrial plants already exist such as the Biochemtex plant in Tortona, Italy or are close to realisation. Therefore, 2nd generation bioethanol production is a realistic option for the OPTIMA project. The processes assessed here are generic scenarios for 2nd generation ethanol processes in the year 2020 using mature technology and full industrial scale plants. In this case, “high conversion efficiency” represents a high intensity conversion variant with particularly high inputs and outputs, “standard” a conversion variant with moderate inputs and outputs, and “low” is a conversion variant with comparatively low efficiency and thus outputs but still moderate to high inputs.

The individual process steps from biomass to ethanol are shown in Fig. 4-8. The main process chain consists of a pre-treatment step to physically break up lignocellulose, hydrolysis to convert cellulose and hemicellulose into C6 and C5 sugars, respectively, fermentation to convert C5 and C6 sugars into ethanol and finally a distillation to purify ethanol.

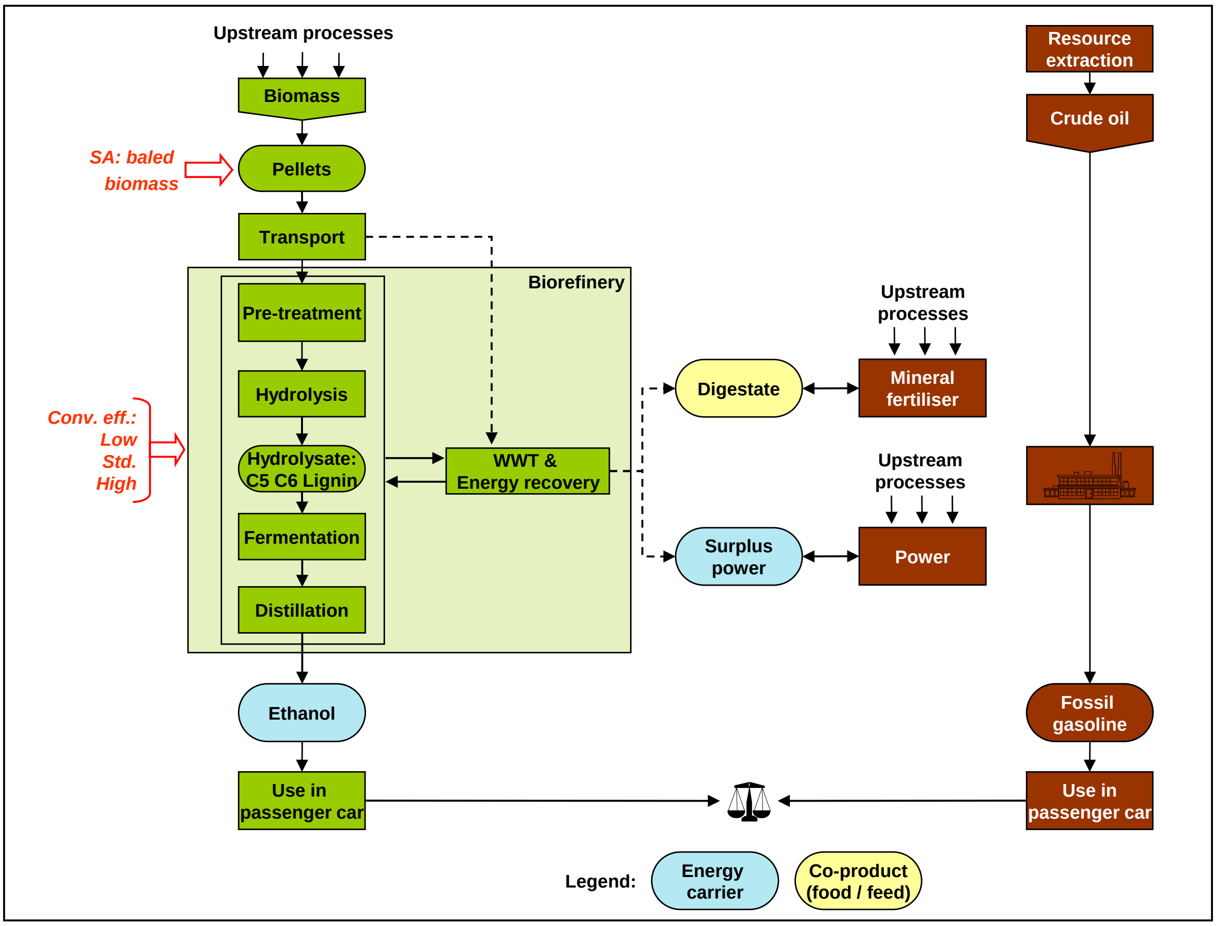

Fig. 4-8 Life cycle comparison scheme for the conversion and use option 2nd generation ethanol. Dotted lines indicate material flows that do not occur in all scenarios. C5: Pentose sugars; C6: Hexose sugars; Conv. eff.: Conversion efficiency; Std.: Standard; WWT: Wastewater treatment.

All analysed scenarios have in common that biomass fractions such as lignin, which are not converted into ethanol, are used for process energy generation in a combined heat and power plant. Depending on the scenario, this energy can be sufficient for providing all heat and power for the main process and surplus electricity can be exported to the grid. Otherwise, part of the input biomass is used directly for energy generation instead of for ethanol production. This way, none of the 2nd generation ethanol scenarios uses imported energy such as fossil energy carriers or electricity from the grid. Depending on the concrete process of biomass residue conversion into energy, digestate may occur as a co-product, which can be used as fertiliser. The co-product digestate substitutes mineral fertiliser and the co-product surplus power substitutes power from a mix of marginal sources (see also section 3.2.3).

As stated in section 4.2, in contrast to other use options, feedstock with a moisture content of 15 % or even higher may be processed in a 2nd generation ethanol plant. Also, feedstock does not necessarily have to be shaped as pellets. Instead, baled biomass is suitable as well. In this case, a bale opener/breaker and a crusher/grinder would be required.

4.3.6 1,3-propanediol

1,3-propanediol (1,3-PDO) or trimethylene glycol is a chemical mostly used for the production of the polymer polytrimethylene terephthalate (PTT). PTT is a relatively new polymer, which is mainly used to produce textile fibres. In certain fields of applications, these have superior characteristics compared to fibres from chemically related PET or nylon. A strong growth is predicted for the PTT market – and thus for 1,3-PDO. So far, the production of 1,3-PDO stems mostly from petrochemical sources although some biological production has been implemented. The latter is applied since 2006 by DuPont that produces 1,3-PDO from corn starch fermentation (capacity: 45 000 tonnes/yr).

The following uses of 1,3-PDO are covered:

- Usage in chemical industries as substitute for 1,3-PDO from fossil sources (crude oil → naphtha → ethylene oxide → 1,3-PDO)
- Usage in chemical industries to produce additional PTT and replace PET

It is possible that an increasing availability of bio-based 1,3-PDO leads to an expansion of the PTT production, which then replaces other polymers like PET. In that case, not fossil 1,3-PDO would be replaced but PET (or other polymers) from fossil resources, which can be produced very efficiently. This would generally result in smaller avoidances of environmental burdens. This scenario is very hard to predict because PTT cannot be compared directly to PET due to possible superior properties of PTT in processing and use [Kurian 2005].

We included the substitution of PET by PTT from biomass-derived 1,3-PDO in the main scenario and the substitution of 1,3-PDO from fossil resources in an alternative scenario (see Fig. 4-9). This is based on the assumption that PTT has no advantages from superior properties. Thus, this conversion variant represents an estimate of the lowest possible avoidance of environmental burdens.

Carbon dioxide as main gaseous by-product is emitted to the atmosphere while organic compounds and microbial biomass remain in the fermentation broth, which is used for energy generation via combustion.

As already stated for the production of 2nd generation ethanol (previous section), in contrast to other use options, feed material for the production of 1,3-PDO does not necessarily have to be shaped as pellets. Instead, cut and baled biomass is suitable as well. Also, feedstock that has a moisture content of 15 % or even higher may be processed.

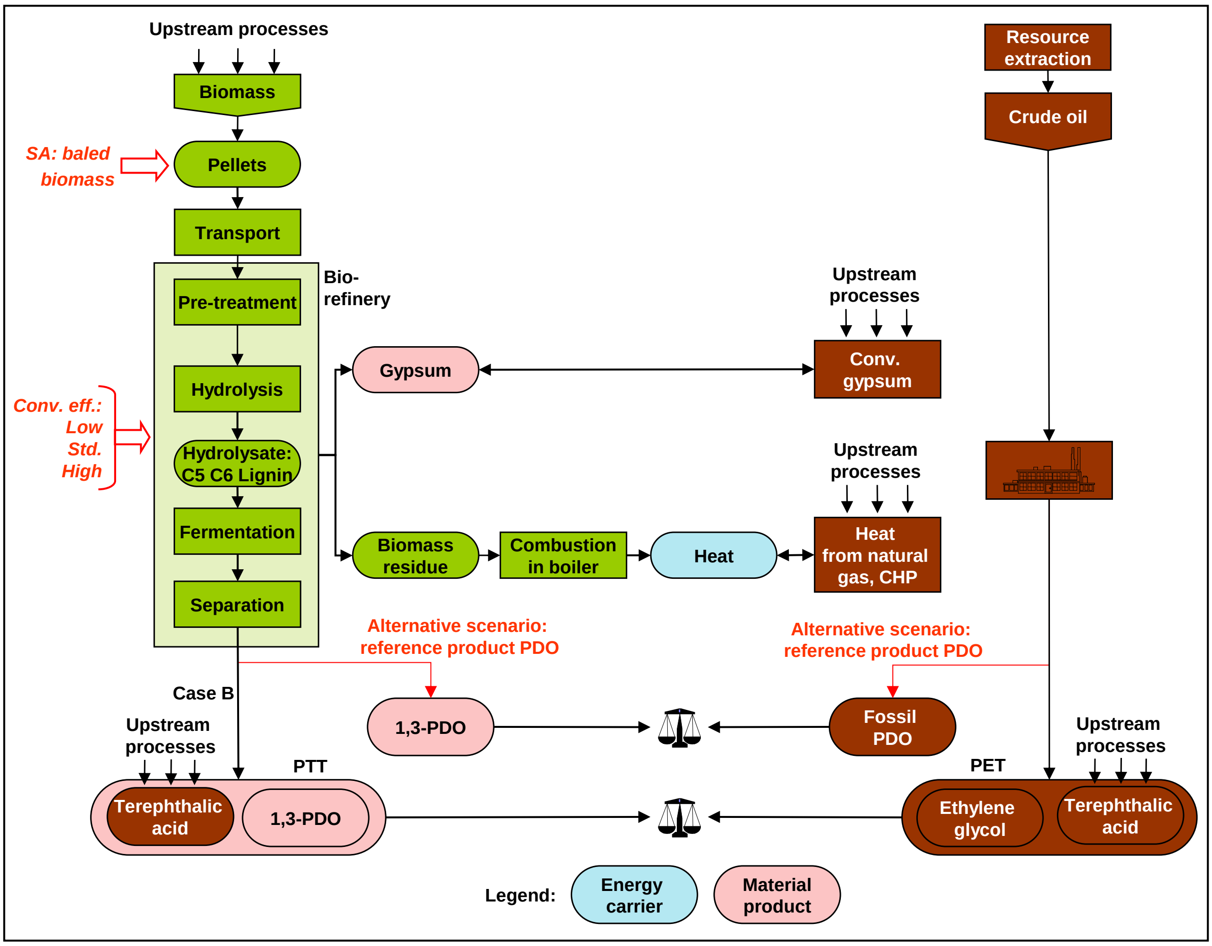

Fig. 4-9 Life cycle comparison scheme for the use option 1,3-propanediol. C5: Pentose sugars; C6: Hexose sugars; Conv. eff.: Conversion efficiency; PDO: 1,3-propanediol; Std.: Standard; WWT: Wastewater treatment.

4.3.7 Insulation material

Assessment of biomass usage for insulation material was targeted by the OPTIMA project partners in order to benefit from a better understanding as to the advantages and disadvantages related to material use of biomass compared to biomass use for energy provision. However, assessment was not possible because no data was made accessible as to material requirements and processing.

4.4 Summary

All assessed scenarios and sensitivity analyses are summarised in Table 4-5 and Table 4-6.

Table 4-5 Overview of main and alternative scenarios with the most often depicted scenario marked in bold.

Biomass cultivation	**Biomass conversion and use**	**Conventional (fossil) reference system**
Giant reed **Miscanthus** Switchgrass Cardoon	Direct combustion (boiler) → Domestic heat from biomass	Domestic heat from fossil fuel (natural gas or light fuel oil)
	Direct combustion (small CHP) **→ Heat & power from biomass**	**Heat from boiler** (natural gas or light fuel oil) & **power (grid) mix** Alternative scenario: Heat & power from convent. CHP plant (natural gas or light fuel oil)
	Direct combustion (large CHP) → Heat & power from biomass	Heat from boiler (natural gas or light fuel oil) & power (grid) mix Alternative scenario: Heat & power from convent. CHP unit (natural gas or light fuel oil)
	1. Pyrolysis & upgrading → Upgraded pyrolysis oil (biofuel) 2. Direct combustion (boiler) → Industrial heat from biomass	Industrial heat from boiler (light fuel oil)
	Torrefaction → Biochar (carbon sequestration)	–
	1. Hydrolysis & fermentation → 2G Ethanol (biofuel) 2. Use in passenger car	Conventional gasoline
	1. Hydrolysis & fermentation → 1,3-propanediol (biochemical) 2a. Use for biopolymer production 2b. Use as such (1,3-PDO)	a. Ethylene glycol (in PET) b. 1,3-PDO (from ethylene oxide)

Potential technical limitations

All scenarios are based on the assumption that it is technically feasible to implement them with the assumed efficiencies and adhering to all regulations, such as emissions limits. This implies that state of the art equipment is used, e.g. no old boilers. Even then, it is very likely that only mixed pellets can be used (see section 4.3). When adopting innovative use options, such as conversion to bioplastics, special challenges are anticipated. However, also in mature domestic heating systems emissions limits could for example be exceeded by grass pellet combustion. Moreover, it may not be possible to use cardoon in existing thermochemical plants, for example in the production of pyrolysis oil. However, this can only be determined through additional research and development in the fields involved.

Table 4-6 Overview of all sensitivity analyses and excursuses

	Varied parameters	**Possible settings (default in bold)**
Biomass cultivation	Yield and yield-depending parameters	Very low (marg. 2) | **low (marg. 1)** | standard (std.)
	Agricultural reference system	**Idle land** | pasture (moist climate / dry climate) | cereals
	Irrigation	**Technical irrigation** | no irrigation | irrigation & indirect effects
	Carbon sequestration in soil	**No C sequestration** | 1 t C | 5.5 t C | 10 t C (excursus)
	Harvesting of giant reed	**Forage harvester** | cutter (→ open air-drying) & baler
	Moisture content of biomass removed from field → determines energy demand for drying	Giant reed: **55 %** | 15 % Miscanthus: **20 %** | 15 % Switchgrass: **15 %** | 15 % Cardoon: **15 %** | 15 %
	Pesticides, diesel demand	Low | **standard (std.)** | high
Logistics and biomass conditioning	Storage at field margin	**Not applicable** | applicable only in case biomass is baled at 15 % moisture content
	Transport in form of...	**Chopped biomass (giant reed) or bales (all other crops)**
	Transport distance	Inverse to yield: high | **standard (std.)** | low
	Crushing/grinding	**Applicable for baled biomass only**
	Drying: Necessity	**Technical drying to 10 % water content** (before conventional or after wet pelleting)
	Drying: Energy carrier	**Natural gas** | light fuel oil | biomass
	Drying: Energy demand	Depending on moisture content of incoming biomass
	Drying: Energy efficiency	Low | **standard (std.)** | high
	Pelleting	**Applicable** | not applicable
Conversion	Conversion efficiency	Low | **standard (std.)** | high
	Direct combustion	**Heat or heat & power** | power via co-firing in coal power plant (excursus)
Use	Replaced energy carrier for direct combustion	**Natural gas** | light fuel oil
	Replaced power (grid) mix	**Marginal mix** | coal | natural gas
	Carbon sequestration ratio for biochar	Low | **standard (std.)** | high

5 Results of the screening life cycle assessment

This section describes the magnitude of the environmental impacts associated with various potential implementations of the OPTIMA bioenergy concept in comparison to conventional ways of providing equivalent products. Section 5.1 exemplarily shows how the results of a comprehensive life cycle comparison arise. In the following sections, the environmental performance of various ways of implementing the OPTIMA bioenergy concept is compared to each other. First, the influence of the bioenergy crop (section 5.2) and of the products made from them (section 5.3) is analysed. In section 5.4, sensitivity analyses are carried out varying biomass production, the agricultural reference system, storage / drying / pelleting / logistics options, biomass conversion options and the substituted reference products. This section concludes with a synopsis of the results (section 5.5).

5.1 Principal results for main scenarios

This section explains the results in individual environmental impact categories for a life cycle comparison (section 5.1.1) and the normalisation of results (section 5.1.2).

5.1.1 Results for individual environmental impact categories

Comparing bioenergy paths to conventional ways of providing equivalent products requires analysing many individual life cycle steps. This section details for one specific scenario (Miscanthus used for small combined heat/power production, see Fig. 4-5 in section 4) and one environmental impact category (climate change) how these life cycle steps contribute to the overall result (Fig. 5-1). Furthermore, it is shown how variations of possible implementations for each life cycle step contribute to a bandwidth of the overall result.

Fig. 4-5 depicts the entire life cycle of the OPTIMA bioenergy scenario “Miscanthus → small CHP”. All processes in green boxes take place if this bioenergy scenario is implemented and replace all conventional processes (brown boxes).

The environmental impacts from this scenario are exemplarily shown for the impact category climate change in Fig. 5-1. It depicts the impacts of individual life cycle stages (bars with coloured sections) and how they contribute to the overall results (orange bars below). There are expenditures associated with each bioenergy life cycle, which are depicted as positive (additional) emissions. They arise from the green processes in Fig. 4-5, which are established if this bioenergy scenario is implemented. The avoided emissions from the replaced processes brown processes in Fig. 4-5) are credited to the bioenergy scenario and are thus depicted as negative emissions in Fig. 5-1.

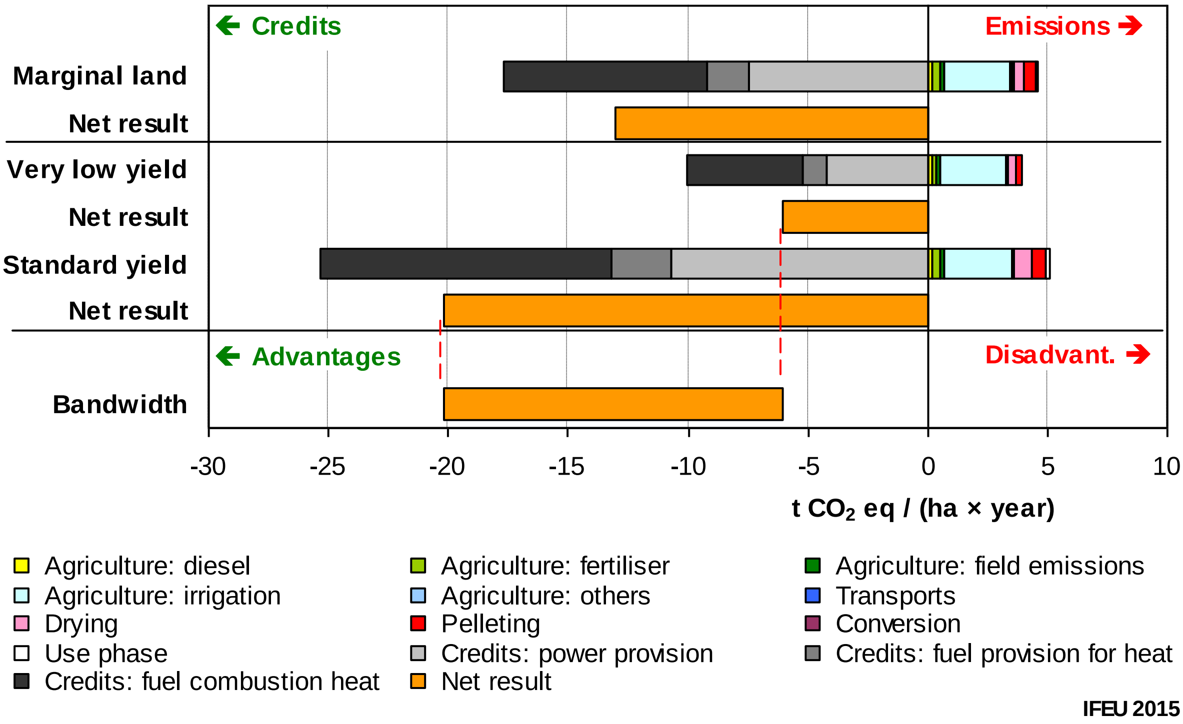

Fig. 5-1 Contributions of individual life cycle steps (coloured bars) to the overall net result (orange bars) of the scenario “Miscanthus → Small CHP” compared to the fossil equivalent in the environmental impact category climate change. Results are shown for low yields (on marginal land) as well as very low and standard yields. The bar below displays the bandwidth of net results.

How to read the first bar in Fig. 5-1:

The annual production of Miscanthus on one ha marginal land and its use for heat and power production in a small CHP causes greenhouse gas emissions of nearly 5 t CO_2 equivalents (positive value, “Emissions”). This avoids emissions of nearly 18 t CO_2 equivalents because less conventional heat and power have to be produced (negative value, “Credits”).

The results vary significantly depending on the conditions under which the bioenergy scenario is implemented and operating. Examples for the variations between the three subscenarios displayed here are the energy and conversion efficiencies of the biomass conversion plant. Some of these parameters are up to the choice of the designer / operator of the biomass conversion plant (e.g. should one invest in an efficient combined heat and power unit or a cheaper, less efficient one?), some can be influenced to a certain degree (e.g. how much is invested in research and development to try to improve the conversion efficiencies?) and some cannot be influenced by the operator (e.g. how large is the share of coal in the electricity mix?).

As can be seen in the exemplary scenario and one impact category, many life cycle steps contribute significantly to the overall environmental impact of the bioenergy life cycle. On the one hand, there are emissions from agriculture such as fertiliser / field emissions and irrigation, but also emissions for biomass conditioning such as drying and pelleting. On the other hand, the replaced heat and power are credited to the system. Other processes are of less importance for the analysed environmental impacts such as transports or diesel for agriculture. For climate change caused by combined heat and power production from Miscanthus, the conversion and use phase are also less important since there is no conversion prior to combustion and since use phase CO_2 emissions are mostly of biogenic origin and thus not displayed[3]. Several input parameters of the scenarios are analysed in dedicated sensitivity analyses: For the processes of less impact, see the sensitivity analysis in section 8.3.2.1 in the annex. For the impacts of different conversion technologies, see section 5.3. Further to the processes, there are parameters influencing the volume of each process, such as the yield (see sensitivity analysis section 5.4.1.1) or conversion efficiencies (see section 5.4.3.1).

Obviously, there are many options how to implement each life cycle step in 2020. Accordingly, the overall environmental performance varies depending on choices that are not yet made and depending on uncertain developments in the industrial and energy sector. As can be seen in the analysis of other biomass conversions later on, these variations can lead to an overall reduction of environmental burdens, but also to an increase compared to conventional, non-biogenic ways of providing the equivalent amount of energy or product. Therefore, comprehensive life cycle assessment is an invaluable tool to identify crucial choices and their most promising options during the conceptual design and implementation of a bioenergy production and usage path.

Conclusion:

Depending on the scenario, life cycle stages contribute to the results to a different extent. Agricultural yields are a central influence factor for e.g. climate change mitigation that can be achieved per hectare. For this reason, a sensitivity analysis on this parameter is shown in section 5.4.1.1.

In the following, if not stated otherwise, only low yield conditions are displayed as they are to be expected on marginal land.

Fig. 5-2 shows the environmental performance of the OPTIMA bioenergy scenario “Miscanthus → Small CHP” in two different environmental impacts, climate change and acidification, again in individual life cycle stages (bars with coloured sections) and how they contribute to the overall results (orange bars below).

From Fig. 5-2**,** one can see that bioenergy schemes do not only have important impacts on climate change but also on other environmental aspects, which have to be taken into account in the same way. Furthermore, it becomes clear that the use of Miscanthus for heat and power production can cause both advantages and disadvantages at the same time in different environmental impact categories. In such cases, the question arises how to compare the different environmental impacts. Weighting the impacts on the basis of personal value choices, beyond scientific arguments, is not done in this study (see section 3.2.4). In order to compare the magnitude – not the severity – of different impacts in a scientifically

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[3] Uptake of identical amounts of CO_2 in the agricultural system, i.e. negative emissions, are not displayed either.

sound way, it is possible to normalise the results using inhabitant equivalents. In this case, the impacts caused by a certain process, e.g. per hectare per year, are compared (normalised) to the average annual impact that is caused by an inhabitant of the reference region. For normalisation factors please see section 3.2.4.

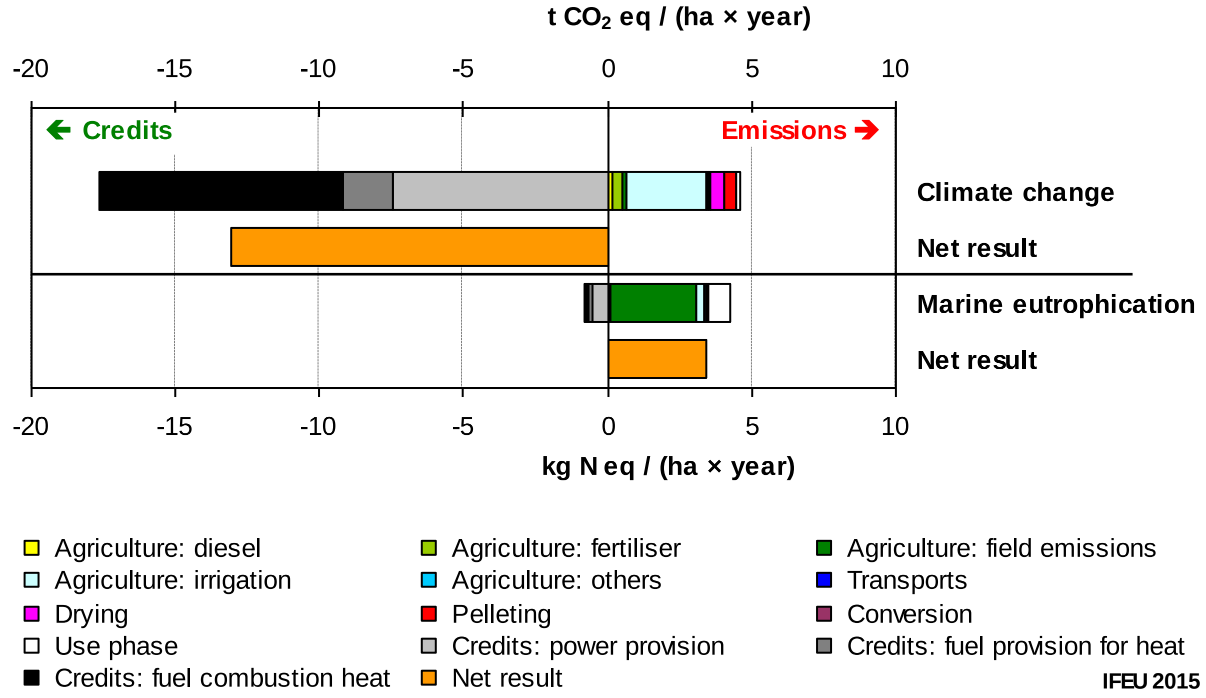

Fig. 5-2 Contributions of individual life cycle steps to the overall net result of the scenario “Miscanthus → Small CHP” compared to the fossil equivalent in the environmental impact categories climate change and marine eutrophication (nutrient input).

How to read the third and last bar in Fig. 5-2:

The annual production of Miscanthus on 1 ha marginal land and its use for heat and power production in a small CHP causes nutrient emissions into the sea (marine eutrophication) of about 5 kg N equivalents (3rd bar, emissions). This avoids emissions of about 1 kg N eq. because less conventional heat and power have to be produced (3rd bar, credits). In total, this leads to additional emissions of about 4 kg N eq. and thus disadvantages for the bioenergy system (last bar).

Conclusion:

In many cases, bioenergy production systems show at the same time advantages and disadvantages in different environmental impacts. Normalisation of these different environmental impacts helps to compare the results by magnitude. In the following, this will be done by comparing the results to the average annual impacts that are caused by an inhabitant of the EU28 (see section 3.2.4). Furthermore, different life cycle steps contribute to the results to a different extent.

5.1.2 Normalisation of results

The previous section shows that in order to display life cycle assessment results in a whole range of environmental impact categories, it is advisable to use normalisation. This has been done in Fig. 5-3, where the overall net results of the scenario “Miscanthus → Small CHP” are shown. As mentioned above, the individual impacts are compared, i.e. normalised, to a reference.

In the OPTIMA LCA study, the environmental advantages and disadvantages are related to the environmental situation in the EU28. The reference information is the annual average resource demand and the average emissions of various substances per capita in Europe, the so-called inhabitant equivalent (IE, see also section 3.2.4). The environmental impacts per unit (e.g. x t CO_2 equiv. / 10 ha / yr) of the life cycle are divided by the annual average impact per inhabitant thus yielding a dimensionless value per unit (e.g. y IE / 10 ha / yr). The reference values are presented in Table 8-1 in the annex (section 8.1) for all environmental impact categories.

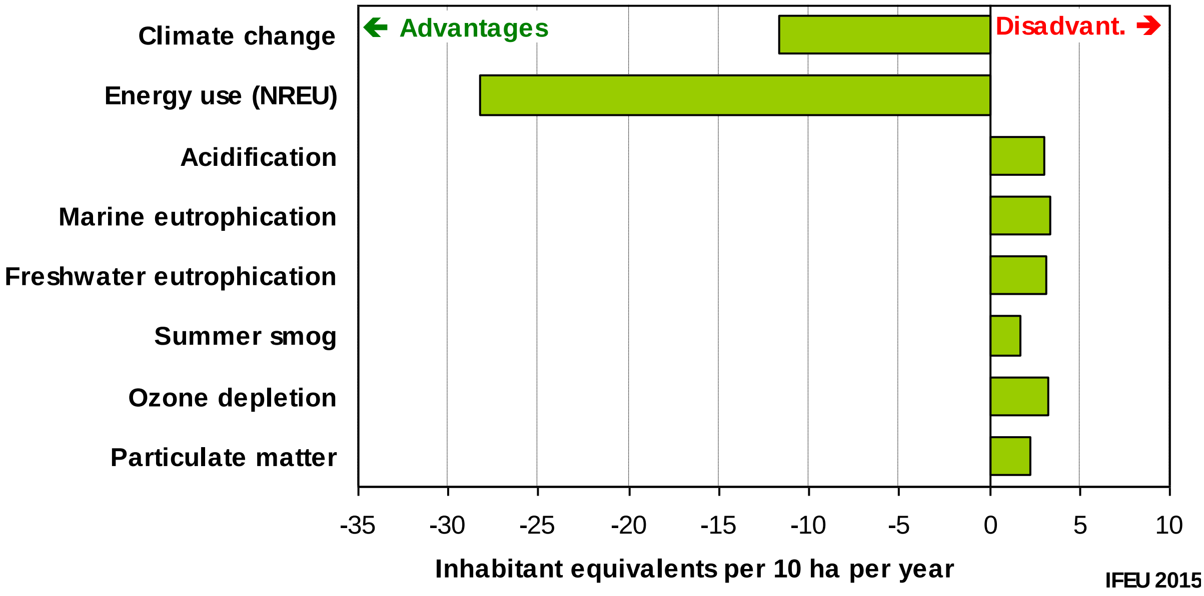

Fig. 5-3 Overall net result of the scenario “Miscanthus → Small CHP” compared to fossil equivalent products in all environmental impact categories regarded in this project. NREU: non-renewable energy use.

How to read the third bar in Fig. 5-3:

The annual production of Miscanthus on 10 ha and its use for heat and power production in a small CHP causes more acidification than the conventional provision of the same amount of power and heat. The amount of these additional emissions is comparable to the average annual acidifying emissions caused by 3 EU inhabitants.

Regarding the environmental impact on water resources, according to the current status of scientific discussion of methodologies, detailed statements are impossible on the basis of the generic, not site-specific information available for the agricultural conditions in the Mediterranean region. However, since this topic is of major importance, the water consumption is varied in a sensitivity analysis (section 5.4.1.3).

Fig. 5-3 reveals that there are advantages and disadvantages in the different environmental impact categories. Miscanthus combustion in small CHPs instead of conventional power and heat production decreases climate change and resource depletion, but increases acidification, eutrophication and ozone depletion. In other impact categories, no clear statement for or against the bioenergy scenario is possible. Therefore, no scientifically justified, objective decision for the biogenic or fossil option is possible. Instead, value based choices are required. If, for instance, one’s highest priority is to reduce climate change, then Miscanthus combustion in small CHP plants should be preferred over heat production from natural gas and power from the grid.

In the impact category summer smog, low net advantages or disadvantages result from relatively high emissions and credits (not displayed here). This is valid also for other scenarios. Due to this uncertainty, the biomass path cannot be considered advantageous or disadvantageous compared to the fossil path regarding summer smog. In the following, this impact category will not be displayed anymore.

Conclusion:

We find advantages in some environmental impacts and disadvantages in others. Thus, an objective, scientific decision for or against the bioenergy carrier or bio-based product cannot be drawn. However, a valuation is possible setting subjective criteria. If, for instance, one’s highest priority is to reduce climate change, then the bioenergy scenarios investigated here should be preferred over the assessed fossil energy options.

Unless mentioned otherwise, the unit of following figures is inhabitant equivalents.

In the category summer smog, emissions and credits are about as high and net results are thus not robust. Since this is valid also for the other scenarios, this impact category will not be displayed anymore.

5.2 Perennial grasses in comparison

As shown in work packages 1 to 4 in the OPTIMA project, the characteristics of the investigated perennial grasses differ significantly. In this section, the life cycles of biomass production and its combustion in CHPs using different kinds of feedstock are assessed and compared to each other. The perennial grasses are giant reed, Miscanthus and switchgrass; furthermore, the perennial non-grass crop cardoon is investigated for comparison.

Two main questions are answered in this section:

- The cultivation of which perennial grass is the most environmentally friendly way of using a defined area of marginal land? (see section 5.2.1)
- Given identical amounts (dry matter) of perennial grasses, which one has the lowest environmental impacts in its life cycle? (see section 5.2.2)

5.2.1 Environmental impacts per agricultural area

Fig. 5-4 gives an answer to the question of environmental performance of perennial grasses grown on a hectare of marginal land.

As can be found in Fig. 5-4, the results in the environmental impact categories non-renewable energy use and climate change show the same patterns. This is valid also for other usage paths. When irrigated, Miscanthus performs better than giant reed, which in turn performs better than cardoon. Cardoon saves more energy and greenhouse gas emissions than switchgrass. The performance is mainly influenced by yield. However, even though giant reed has the highest yield (and thus the highest energy credits per hectare), the high need for drying makes it rank second. Similarly, cardoon’s lower (or even no[4]) need for irrigation improves its performance despite the low yield. This also reveals the significance of the scenario settings, especially the inclusion of technical drying in all default scenarios.

Like energy use and climate change, also marine and freshwater eutrophication and ozone depletion show the same pattern of results. The more nitrogen and phosphorous fertiliser is used, the higher are the additional net emissions in all the environmental impacts. In general, this holds true also for acidification and particulate matter emission, with the exception that cardoon performs better than switchgrass or even Miscanthus. This is caused by the lower irrigation needs of cardoon. In many places, cardoon is able to grow even without irrigation.

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[4] In fact, a dry farming field experiment was successfully conducted within the OPTIMA project in an environment with <400 mm/yr rainfall.

Conclusion:

All investigated perennial crops show advantages regarding climate change and non-renewable energy use and disadvantages for the other environmental impacts. The amount of advantages depends on the yield, but also on the required intensity of drying. The disadvantages are crucially influenced by the amount of nitrogen and phosphorous fertiliser and partially by the intensity of irrigation.

In total, using Miscanthus in a small CHP produces the highest advantages and the lowest disadvantages per hectare. This holds true also for most other products.

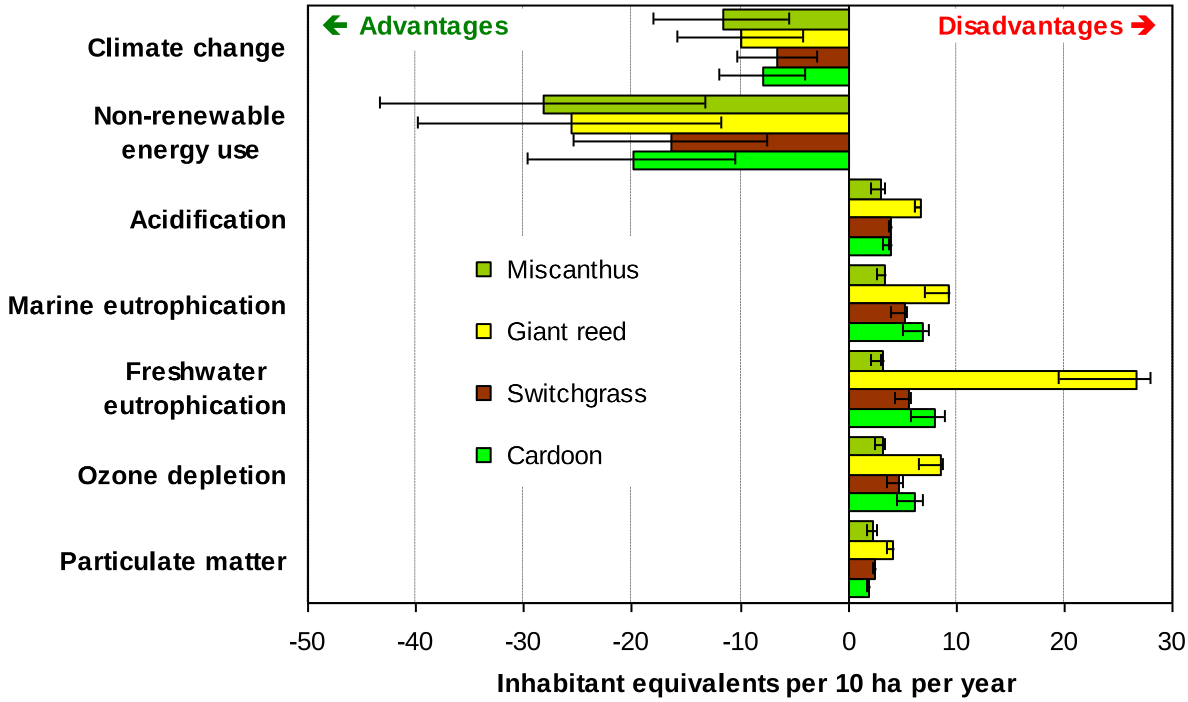

Fig. 5-4 Overall net results of the scenario “Biomass → Small CHP” compared to the fossil equivalent with different feedstock types per agricultural area. Error bars indicate variation of results due to yield levels (see section 5.4.1.1 for more details). Source: [Schmidt et al. 2015].

How to read the last bar in Fig. 5-4:

The annual production of cardoon on 10 ha and the use of the whole plants – i.e. including seeds – for heat and power production in a small CHP causes more particulate matter emissions than the conventional provision of the same amount of power and heat. The amount of these additional emissions is comparable to the average annual particulate matter emissions caused by 3 EU inhabitants.

5.2.2 Environmental impacts per dry mass of crop

Fig. 5-5 responds to the question of how to rank the environmental impacts of the investigated crops on a product mass basis, i.e. per tonne (dry matter) of biomass.

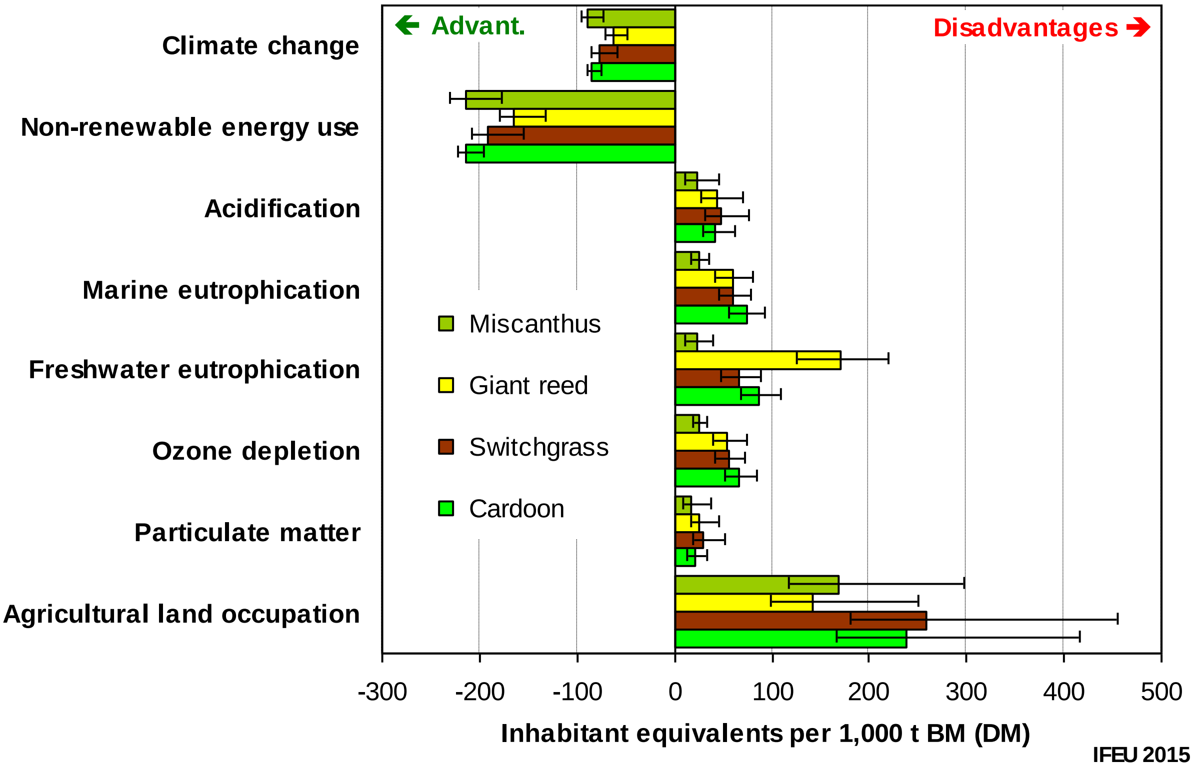

Fig. 5-5 Overall net results of the scenario “Biomass → Small CHP” compared to the fossil equivalent with different feedstock types per dry matter of crop. Error bars indicate variation of results due to yield levels (see section 5.4.1.1 for more details).

How to read the last bar in Fig. 5-5:

The annual production of 1,000 tonnes of cardoon (dry matter) and the use of the whole plants for heat and power production in a small CHP causes more particulate matter emissions than the conventional provision of the same amount of power and heat. The amount of these additional emissions is comparable to the average annual particulate matter emissions caused by 25 EU inhabitants.

Generally, qualitative advantages or disadvantages of any bioenergy scenario compared to the respective conventional reference are independent of the reference unit (area basis or product basis). Likewise, similarities in result patterns among impact categories such as climate change and non-renewable energy use do not depend on the reference unit. However, the ranking of the crops differs. When expressed per t of biomass, Miscanthus and cardoon perform better than switchgrass and giant reed. The reasons are that switchgrass requires more specific irrigation and giant reed more drying than the other crops. For marine eutrophication and ozone depletion, Miscanthus shows lower disadvantages than giant reed, switchgrass and cardoon because of the specific nitrogen demands. The same picture can be found for freshwater eutrophication: here, the ranking is directly linked to the phosphorous demand of the crops. Acidification and particulate matter emissions show the following common pattern: switchgrass performs worst (highest irrigation demand), giant reed second worst (relatively high irrigation and high drying demand), cardoon is the second best (despite the highest specific nitrogen demand, but fertilisation-related impacts play a minor role), Miscanthus performs best (very low specific nitrogen demand). When referring environmental impacts to biomass produced, the amount of agricultural land occupied is a parameter that should be indicated. In this case, agricultural land occupation is the inverse of the dry matter yield per hectare. Thus, ranking of crops is directly linked to dry matter yield, i.e. giant reed is associated with smallest agricultural land occupation while switchgrass is related to the largest agricultural land occupation.

Conclusion:

Yield is not the dominating parameter any more if results are given per tonne of biomass. Here, other characteristics play a major role.

However, also per tonne of biomass, Miscanthus used in small combined heat and power production shows the highest advantages and the lowest disadvantages. Advantages for Miscanthus over the other investigated crops can be found for most other products, too.

5.3 Products from perennial grasses in comparison

The OPTIMA project consortium chose to assess a very broad range of usage options of the perennial grasses – from direct combustion for heat and power to production of solid fuels or chemicals. In order to analyse which use performs better from an environmental point of view, the life cycles of all different use options of one biomass type are evaluated and compared. While Miscanthus is selected as example for the biomass, the use options are domestic heat production, small and large combined heat and power production, pyrolysis, torrefaction (biochar production), and production of 2nd generation ethanol and 1,3-propanediol.

In Fig. 5-6, the environmental impacts of the life cycles of the different Miscanthus uses are displayed. All other environmental impact categories except for marine eutrophication show substantial result differences between the investigated use options. There are advantages and disadvantages to be found. Climate change and non-renewable energy use (NREU) show similar patterns except for the use option biochar. This is because biochar is the only product that does not replace any fossil product thus does not provide benefits for NREU. However, it does cause carbon sequestration thus creating benefits in terms of climate change. For the bioenergy scenarios, high-value energy products (electricity instead of heat) and higher efficiencies create higher energy and greenhouse gas savings. Likewise, the disadvantageous impacts (acidification, freshwater eutrophication, particulate matter) are reduced or even reversed to advantages. For the non-energy products investigated here, higher advantages regarding climate change are connected to less disadvantages regarding the other environmental impacts. Exceptions are found in marine eutrophication and ozone depletion (both mostly with only small variations). Especially for the evaluation of the use options 2nd generation ethanol and 1,3-PDO, it should be considered that biomass conditioning including energy-intensive drying as well as pelleting is included in the default scenarios, though possibly avoidable depending on the facility’s design.

The bandwidth bars in Fig. 5-6 result from the best and worst conversion settings (efficiencies, inputs, outputs) to be expected for the specific process.

Conclusion:

The higher the conversion efficiency, the higher are the greenhouse gas and energy savings and the lower the other environmental impacts. Only marine eutrophication and ozone depletion being influenced by only few parameters (phosphorus fertiliser and nitrous oxide emissions, respectively) show similar results for most usage options.

One can see that large, highly efficient CHPs have the highest advantages, followed by small CHPs.

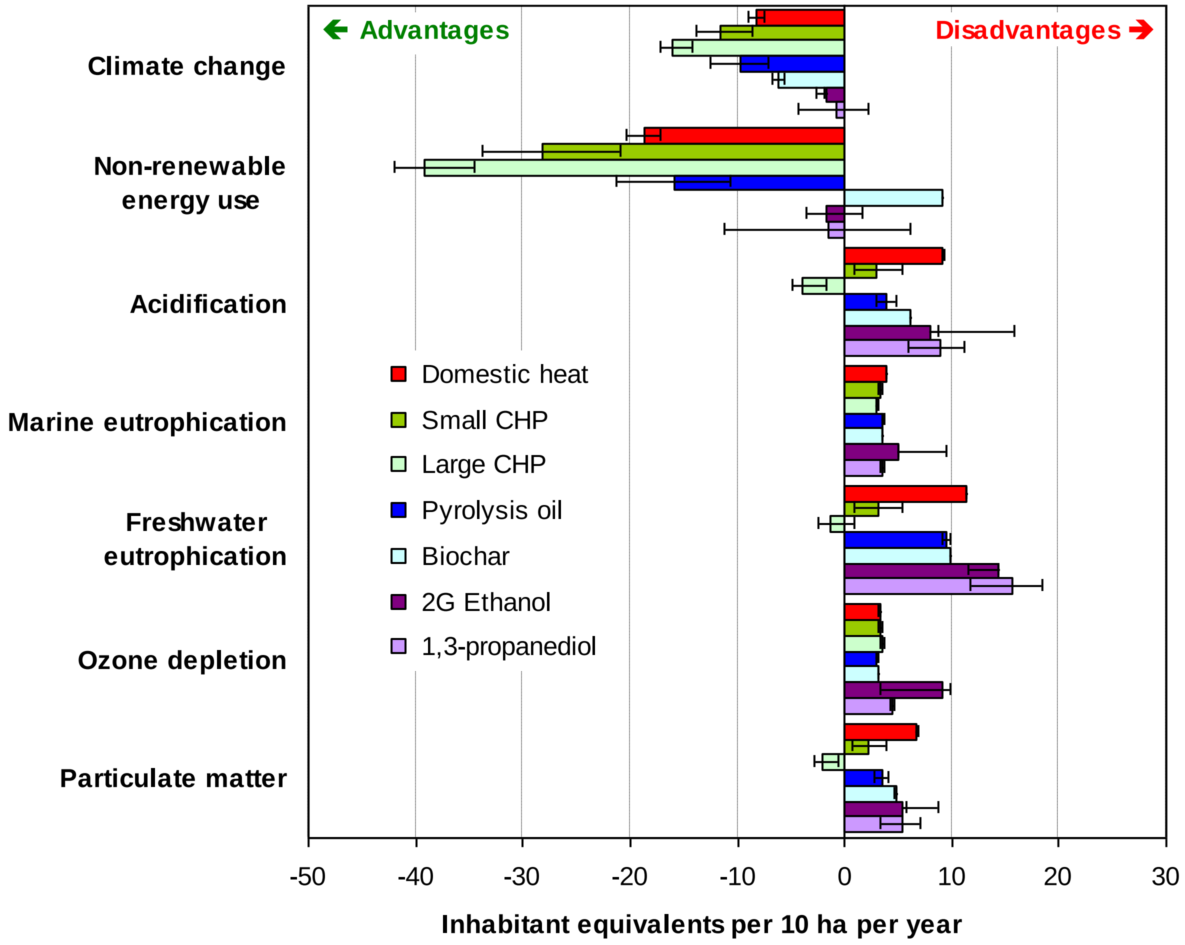

Fig. 5-6 Overall net results for Miscanthus used for different use options compared to the fossil equivalent. Error bars indicate variation of results due to conversion efficiency (see section 5.4.3.1 for more details). Adapted from [Schmidt et al. 2015].

How to read the last bar in Fig. 5-6:

The annual production of Miscanthus on 10 ha and its use for production of 1,3-propanediol (PDO) as an intermediate product for the production of polytrimethylene terephthalate (PTT), which substitutes for PET, causes more particulate matter emissions than the conventional provision of the corresponding amount of PET. The amount of these additional emissions is comparable to the average annual particulate matter emissions caused by 5 EU inhabitants.

In order to discuss the contributions of the single life cycle stages, Fig. 5-7 shows result details of the processes in selected environmental impacts.

Life cycle stages contribute to the results to a different extent. Regarding **climate change**, any of the credits from the fossil reference systems is generally larger than most of the emissions from the biomass system – the larger the conversion and / or usage efficiency, the larger the credits. This holds true for heat and power production, fuel use and provision of chemicals such as 1,3-PDO. The use phase of biochar results in significant CO_2 sequestration instead of a credit for avoided emissions. The major emissions of greenhouse gases stem from irrigation, material inputs used for biomass conversion, and – in the case of 1,3-PDO production – also energy use in biomass conversion. The largest contributions to **acidification** and **particulate matter** formation are often caused in the use phase, but also by material inputs used in biomass conversion and (for 1,3-PDO) energy provision. Like for climate change, irrigation plays an important role in all life cycles. For other crops, also field emissions can have a weight. Significant credits result from power production, provision of fuels or 1,3-PDO and combustion of fossil fuels.

Conclusion:

The life cycle stages contribute to the results to a different extent, depending on the environmental impact category and usage option. In the following, the most important life cycle stages regarding conversion and use options are investigated in sensitivity analyses (section 5.4.3).

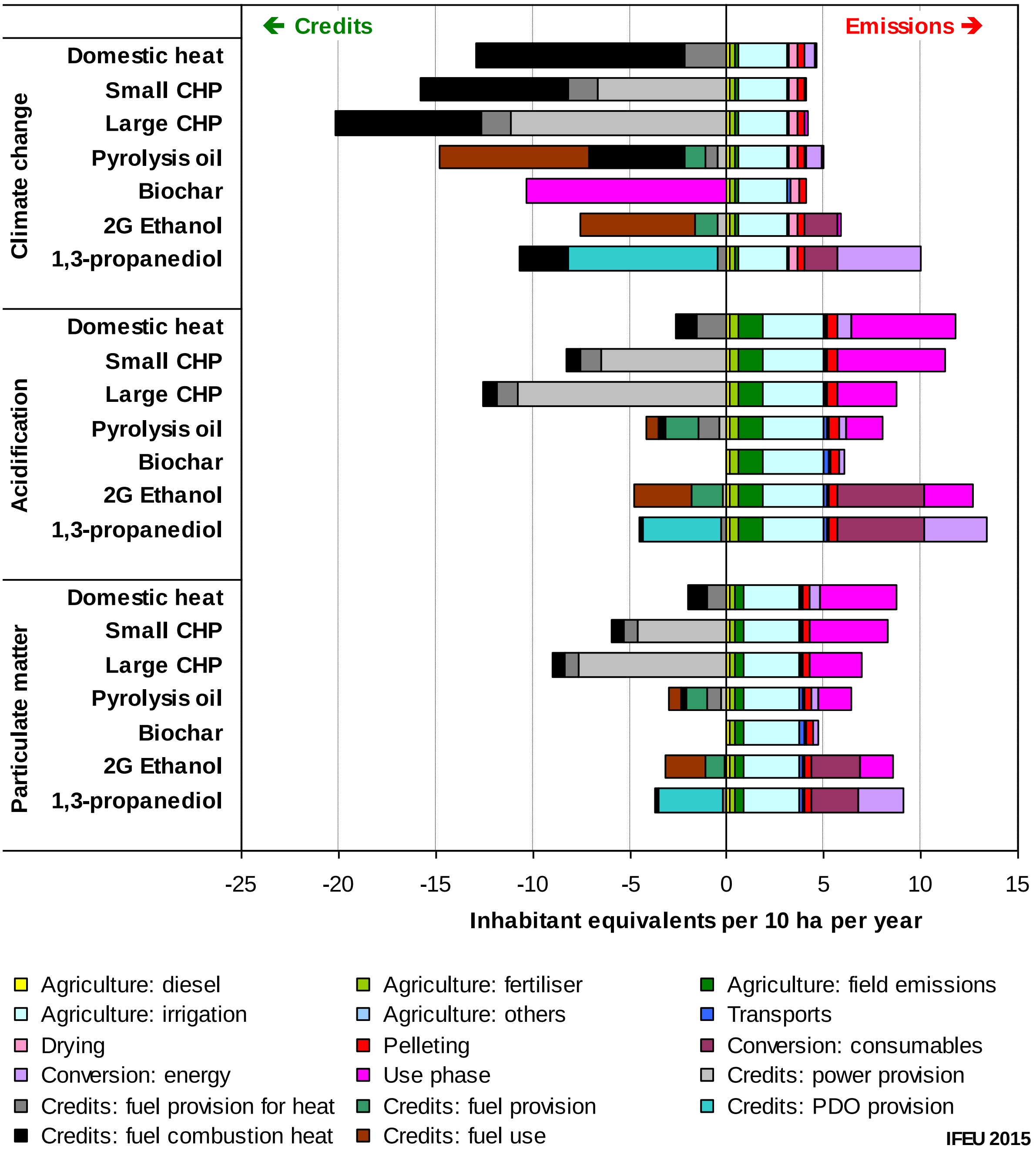

Fig. 5-7 Details of different use options for Miscanthus in certain environmental impact categories compared to the fossil equivalents.

How to read the last bar in Fig. 5-7:

The annual production of Miscanthus on 10 ha and its use for production of 1,3-propanediol (PDO) as an intermediate product for the production of polytrimethylene terephthalate (PTT), which substitutes for PET, causes an amount of particulate matter emissions equal to the average annual emissions caused by 9 EU inhabitants. The conventional provision of the corresponding amount of PET leads to annual particulate matter emissions that equal the average annual emissions caused by about 4 EU inhabitants.

5.4 Sensitivity analyses and alternative scenarios

The following sensitivity analyses show the influence of important input parameters on the LCA results. The identification and analysis of critical parameters highlights options for optimisation and potential sources of uncertainty. The sensitivity analyses are grouped by life cycle stages.

5.4.1 Biomass production

The most important inputs regarding biomass production are related to the agricultural yield (section 5.4.1.1), the agricultural reference system (section 5.4.1.2), irrigation and water availability (section 5.4.1.3) and carbon sequestration (section 5.4.1.4). Further agricultural input parameters (pesticide inputs, diesel consumption and transport distances) have been analysed for their influence on the results in section 8.3.2.1 in the annex.

5.4.1.1 Variation of biomass yield

In section 5.1.1, agricultural yield is identified as the central influencing factor for the LCA results. For this reason, the analysis conducted in section 5.1.1 is extended to all other investigated impact categories and relevant aspects are discussed. The yields defined for each crop and yield level are summarised in Table 8-2 in the annex (section 8.2). The following results can be obtained (see Fig. 5-8):

- Yield increase significantly improves the energy and greenhouse gas balance of the displayed scenario. This is also valid for all other investigated crops and most use options (not shown). This is because benefits related to the increased provision of bio-based products or bioenergy exceed the additional burdens related to fertiliser provision, field emissions, drying and pelleting.
- As to acidification, marine eutrophication, ozone depletion and human toxicity, yield increase may deteriorate the results because additional fertiliser is required. For some other use options, the deterioration is even more pronounced than depicted in Fig. 5-8.
- For the depicted scenario, energy and greenhouse gas savings are achieved even with very low yields. However, if Miscanthus biomass is used for another option that is less favourable as to energy and greenhouse gas savings such as 2nd generation ethanol (see Fig. 5-6), very low yields lead to additional energy demand and greenhouse gas emissions (not shown).
- As documented in Table 8-2, yield is varied by a factor of 2.5 for the yield levels “very low” (“marginal 2”) and “standard”. The normalised results for climate change and energy savings depicted in Fig. 5-8 show a variation factor greater than 3, which underlines the importance of yield.

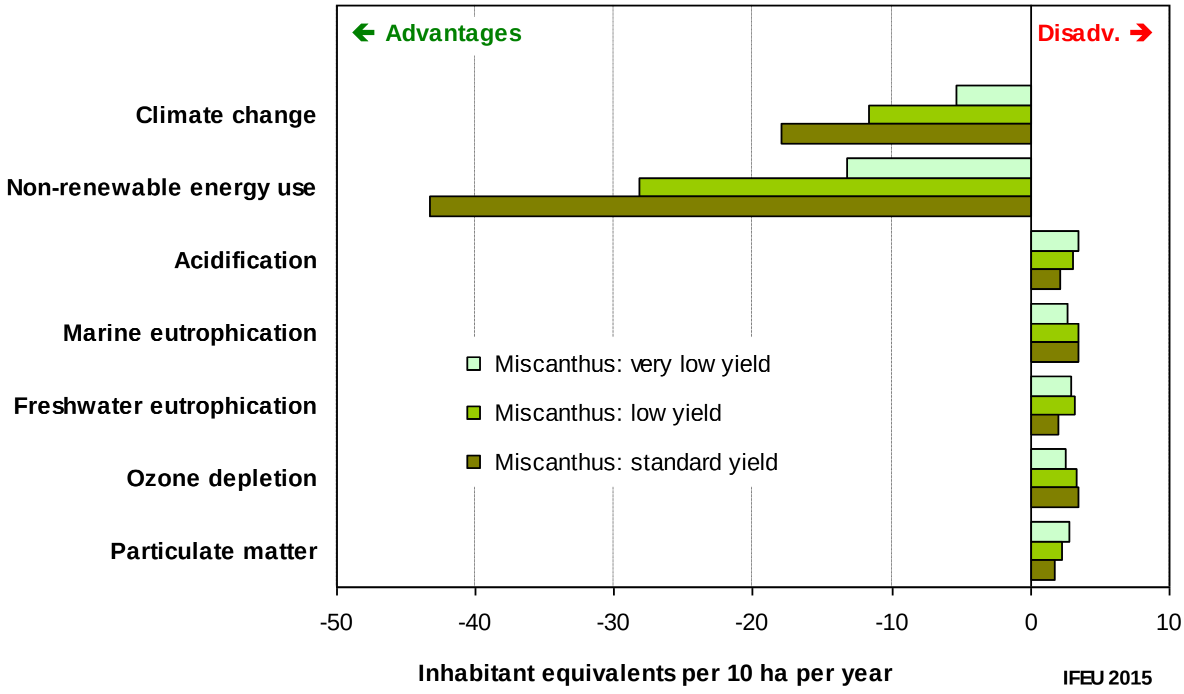

Fig. 5-8 Impact of yield variation on the overall net results of the scenario “Miscanthus → Small CHP”. “Low yield” corresponds to the yield level set for the main scenario “marginal land”.

Conclusion:

Yield increases lead to greater energy and greenhouse gas savings. As to other impact categories, the qualitative impact of yield increase can be positive or negative. If greenhouse gas savings per used area are considered the most important aim, yield is the most important parameter to optimise.

No general conclusion can be drawn as to minimum yields necessary for energy and greenhouse gas savings. OPTIMA investigations revealed that very low yields (yield level “very low” / “marginal 2”) may be related to advantages or disadvantages, depending on the use option and further parameters (e.g. conversion efficiency), i.e. the scenario’s complete life cycle. Nevertheless, very low yields still lead to advantages if the biomass is used for stationary energy generation.

5.4.1.2 Variation of agricultural reference system

In the following, the influence of the chosen agricultural reference system on the greenhouse gas balance is discussed. As described in section 4.1.3, the assessed scenarios include that the cultivation of investigated crops may either take place (1) on idle land or (2) on land formerly used as pasture or (3) on land formerly used for cereals production. If crops are cultivated on land formerly used as pasture, substitute feed has to be produced somewhere else. It is defined that soy produced in South America is used as substitute feed. In South America, either grassland or rainforest areas are converted into agricultural land for soy production. Furthermore, grass yields of pastures in the Mediterranean region vary and are greater in moist regions than in dry regions, determining the amount of necessary substitute feed. If investigated crops are cultivated on land formerly used for cereals production, cereals have to be produced somewhere else. It is defined that substitute cereals production takes place in North America. For further information regarding the underlying scenario settings, see section 4.1.3. In Fig. 5-9 the investigated variation is displayed for Miscanthus cultivation on marginal land used for heat and power production in a CHP (small scale). The following results can be obtained:

- Land use change and associated changes in carbon stocks can significantly deteriorate the greenhouse gas balance.
- With respect to the agricultural reference system “pasture”, both main varied parameters have a strong influence on the greenhouse gas balance: first, the climatic condition in the Mediterranean region (dry or moist); second, the type of land that is converted into agricultural land to produce soy that substitutes for feed formerly produced on pastures (grassland or rainforest).
- The ploughing of pastures in a region with moist climate causes more greenhouse gas emissions than in a region with dry climate. This is because first, carbon stocks of pastures in a moist climate are larger than in a dry climate. Second, in a moist climate, pastures allow for the provision of more feed than in a dry climate so that more soy has to be cultivated as substitute for the lacking feed.
- If feed formerly produced on pastures in the Mediterranean region is substituted by soy cultivated on former rainforest areas, emissions related to the agricultural reference system are the largest contribution to the greenhouse gas balance. In a dry Mediterranean region (low provision of feed on pasture) these emission are so high that hardly any greenhouse gas savings are achieved any more. In a moist Mediterranean region (high provision of feed on pasture) the greenhouse gas emissions related to land use changes by far exceed the savings related to biomass use.
- If the feed formerly produced on pastures in the Mediterranean region is substituted by soy cultivated on former grassland or if the crops are cultivated on land formerly used for cereal production, the greenhouse gas balance is also significantly deteriorated. However, net greenhouse gas savings can still be achieved if the Miscanthus biomass is efficiently used in a CHP. For several other crops and use options, this is not valid.

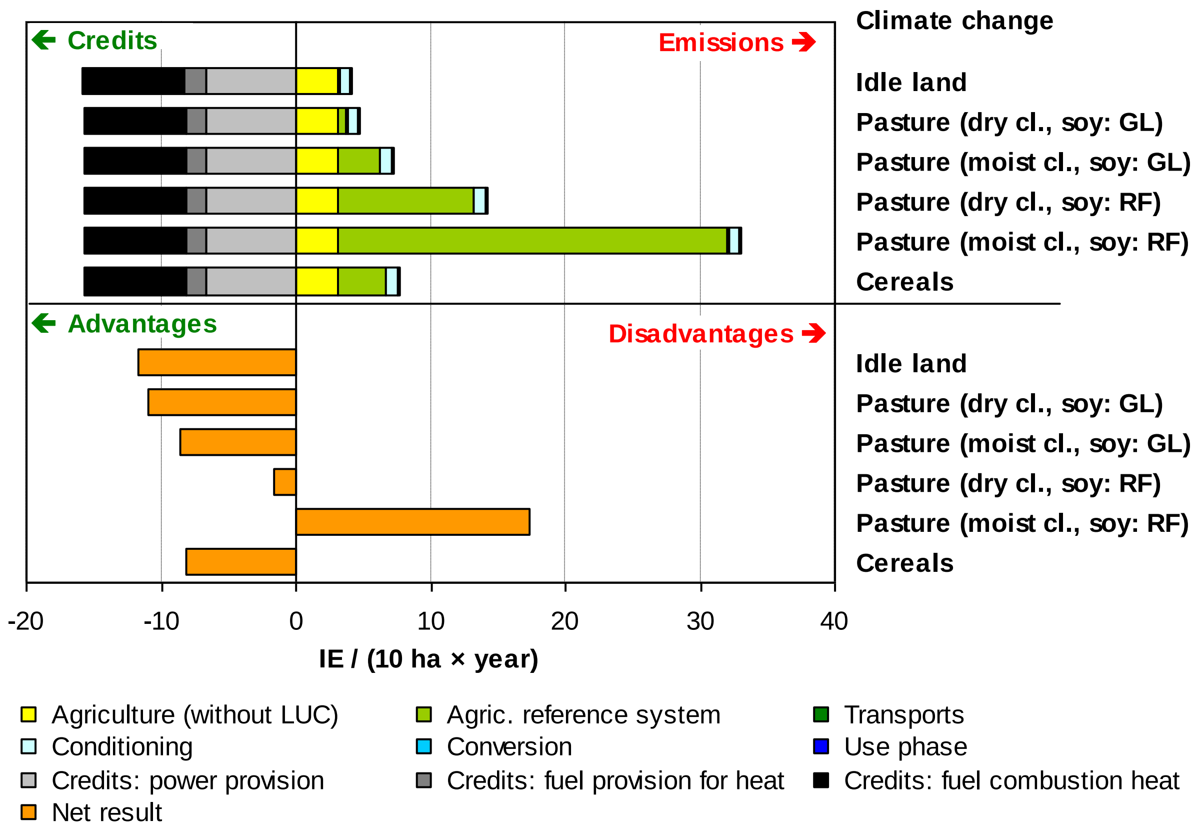

Fig. 5-9 Impact of varied agricultural reference systems on results for the impact category climate change of the scenario "Miscanthus → Small CHP". cl: climate. GL: grassland. RF: rainforest. Source: [Schmidt et al. 2015].

Conclusion:

If investigated crops are not cultivated on idle land but on land formerly used as pasture or for the production of cereals the greenhouse gas balance can be significantly deteriorated. Especially if rainforest areas are converted into agricultural land for the production of substitute feed, greenhouse gas emission savings cannot be achieved any more for many crops and use options. Hence, only idle land should be used for cultivation.

5.4.1.3 Irrigation and water availability

In this sensitivity analysis, we discuss the significance of irrigation and water availability for the environmental impacts related to the cultivation and use of the investigated crops.

As described in section 4.1.3, in the first part it is analysed how results change if rainfall provides all necessary water to achieve full yield levels (“no irrigation”). Fig. 5-10 allows for the following results to be obtained (compare red and blue bars):

- The environmental performance improves with respect to all displayed impact categories.
- The effect is distinctly visible and, as to the impact categories acidification and particulate matter, the effect can even change a net disadvantage into a net advantage. Thus, impacts related to technical irrigation can significantly contribute to the LCA results.
- The effect’s impact depends on the water demand of the investigated crop, which is set to be equal for Miscanthus, giant reed and switchgrass scenarios. Only cardoon has a lower water demand so that the improvement of results is less distinct (not shown).

Another issue related to irrigation is that the impacts of using the resource water as such are not reflected in the applied standard impact assessment methods. Water use within the assessed systems can have two consequences:

1. **Additional water is used.**
   Water use in the Mediterranean context with local or regional water stress can be a significant environmental impact as such. The impact assessment of water use, however, has to be as location or region-specific as the water stress levels are. Within the geographical scope of this study, the same amount of water used can have an impact varying by a factor of 9 according to [Frischknecht et al. 2009] based on country-specific average values. A variation by a factor of 5 based on country-specific average values or more than 10 based on region-specific values can be found from [Pfister et al. 2009]. Thus, it depends on regional water availability if irrigation can be acceptable to achieve an improvement e.g. regarding life cycle greenhouse gas emissions.
2. **Water is diverted from other uses.**
   If local water availability is very limited or water use is capped by preventive policies, water used for irrigation of the assessed crops cannot be used any more for other purposes (given that additional efficiency measures are not or cannot be applied). If irrigation of other crops in the region is reduced, this will lead to yield reductions and potentially to a shift of agricultural production to other regions in the world (water-induced iLUC).

Exemplarily, water diversion from cereal production in the Mediterranean region and a subsequent shift of cereal production to North America are assessed as part of this sensitivity analysis (see section 4.1.3 for further information). Fig. 5-10 allows for the following results to be obtained (compare red and green bar):

- Consideration of water-induced land use changes leads to worse results in all displayed impact categories. If other vegetation than prairie grassland is cleared for agricultural production elsewhere in the world, these additional disadvantages can be much higher.

- Except for marine eutrophication, the impact is visible for all displayed impact categories. This is because in addition to the conversion of grassland in North America and the related CO_2 emissions, the cereals produced in North America need to be transported to the Mediterranean region, which leads to burdens with respect to the impact categories non-renewable energy use, acidification and particulate matter.
- Since irrigation scenarios for Miscanthus, giant reed and switchgrass are based on the same amount of applied water, the impact of water-induced iLUC is equal for these crops.

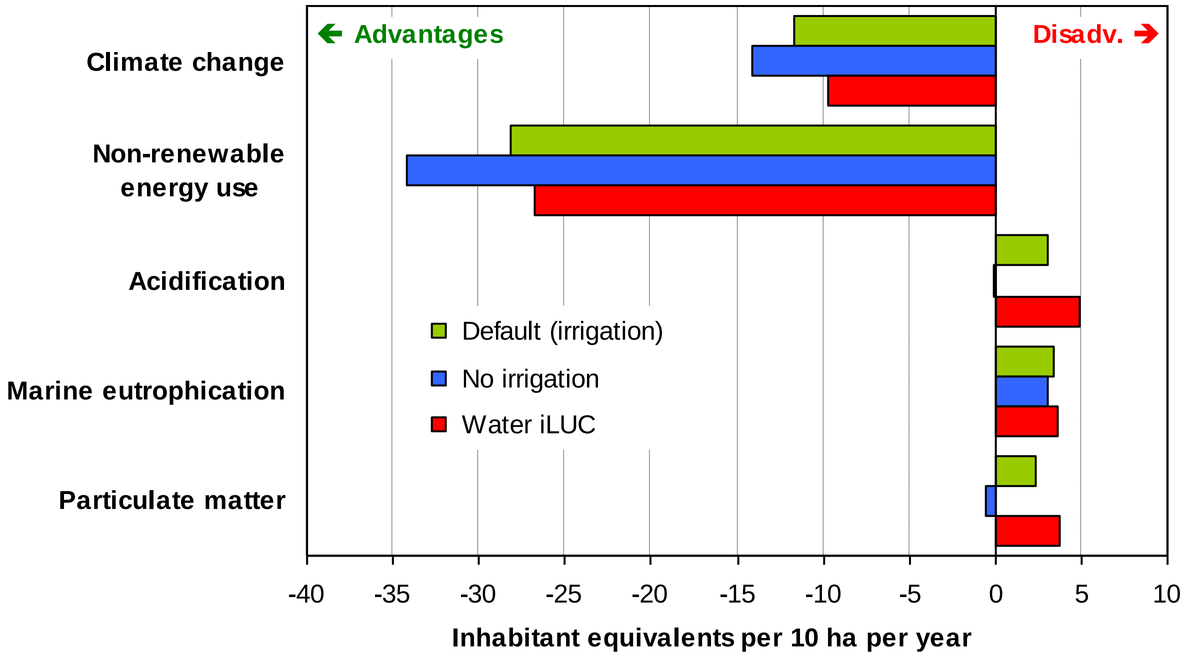

Fig. 5-10 Impact of irrigation and consideration of water-induced indirect land use changes on the results for selected impact categories of the scenario "Miscanthus → Small CHP". Source: [Schmidt et al. 2015].

Conclusion:

Technical irrigation can lead to yield increases but also to substantial environmental burdens, especially if water supply is limited. Thus, irrigation should be avoided where possible. First, suitable options for cultivating perennial grasses in parts of the Mediterranean region with sufficient rainfall should be used. Second, a careful site-specific analysis of water stress is necessary before cultivating perennial grasses in parts with limited rainfall and need for irrigation. Furthermore, efficiency measures should be applied. Also, only as much water should be applied as the crops reasonably need.

If more water is used for perennial crop cultivation than available in a certain region, irrigation of investigated crops may cause yield reductions for other cultivations and water induced indirect land use changes.

Advantages and disadvantages of irrigation have to be considered based on a site-specific assessment.

5.4.1.4 Excursus on carbon sequestration in soil

As stated in section 4.1.3, perennial grasses may accumulate carbon in soil. This effect's influence on the greenhouse gas balance is displayed in Fig. 5-11, which allows for the following results to be obtained:

- Consideration of carbon sequestration improves the greenhouse gas balance. However, the contribution is rather small, even if a high sequestration ratio is assumed.
- Consideration of carbon sequestration does not impact the results of other impact categories (not shown).
- Depending on the sequestration ratio, the impact varies between 2 and 15 IE / ha / year. This factor of approx. 10 demonstrates the uncertainty with respect to basic parameters.

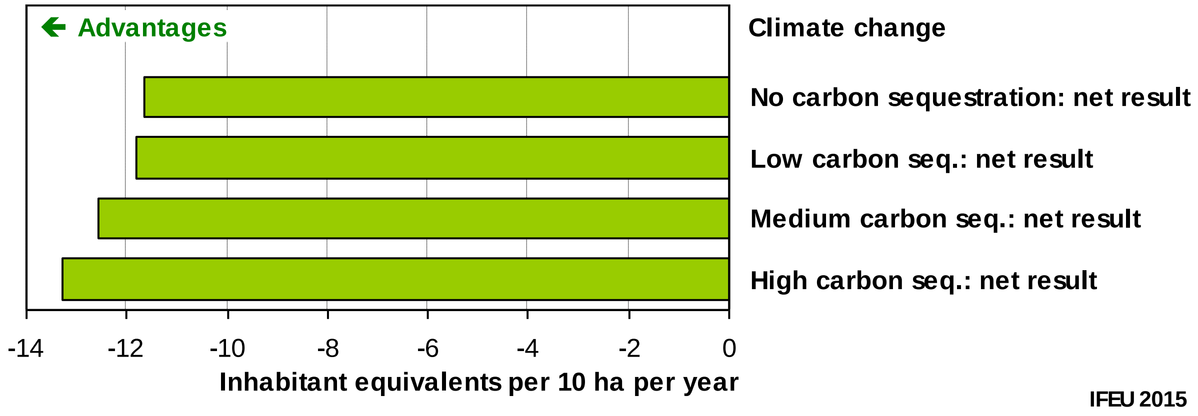

Fig. 5-11 Impact of carbon sequestration on the results for the impact category climate change of the scenario "Miscanthus → Small CHP". Seq.: sequestration.

Conclusion:

The consideration of carbon sequestration improves the greenhouse gas balance but its extent is very uncertain. However, the contribution to the life cycle greenhouse gas balance is small even if it would be possible to achieve a high sequestration ratio under realistic conditions. Carbon sequestration thus cannot serve as a decisive argument for the cultivation of perennial grasses.

5.4.2 Logistics and conditioning

The most important parameters in the life cycle stage logistics and conditioning are related to biomass drying and pelleting. Their influence is analysed in this section. Transport distances are analysed in the annex (section 8.3.2.1).

5.4.2.1 Drying

Environmental impacts related to drying depend on the energy carrier used for drying, drying efficiency and the moisture content of biomass prior to drying, which may be significantly lower when harvested crops are open air-dried. See section 4.2 regarding the underlying definitions made for this scenario, e.g. the moisture content of crops achieved by drying on the field and the necessary moisture content for conventional pelleting. Fig. 5-12 illustrates the influence of the varied parameters on the greenhouse gas balance for the cultivation and use of giant reed. Giant reed is chosen because of its high moisture content and thus the particularly high relevance of drying for this crop.

As to the impact of the energy carrier used for drying, the following results can be obtained from Fig. 5-12:

- Using light fuel oil instead of natural gas for drying deteriorates the greenhouse gas balance significantly due to the higher carbon dioxide emissions during combustion. Except for primary energy demand, all other investigated impact categories show less significant or no decreases in environmental performance (not shown).
- The use of biomass instead of natural gas for drying results in markedly decreased net greenhouse gas emissions related to drying. However, less biomass can be used for the production of heat and power so that less greenhouse gas savings are achieved by this means. In case of the use in a CHP plant, the disadvantages slightly exceed the advantages. This is valid for the other investigated environmental impact categories as well (not shown). In contrast, concerning the greenhouse gas and energy balance all other use options benefit from biomass-fired drying because achievable greenhouse gas and energy savings are lower. On the other hand, with respect to the impact categories acidification and particulate matter, drying with biomass deteriorates the environmental performance for most use options (not shown).
- The effects seen for giant reed also apply to Miscanthus, switchgrass and cardoon though to a much lower extent. This is because giant reed has the highest moisture content and thus savings potential related to drying.

As to the impact of drying efficiency, the following results can be obtained from Fig. 5-12:

- Installation of a very efficient drying facility moderately reduces the greenhouse gas emissions related to cultivation and use of giant reed by approx. 10 %. For other impact categories and crops, the relative significance of an increased drying efficiency is lower (not shown). Similarly, an inefficient drying facility deteriorates the greenhouse gas balance.

As to the impact of open air-drying, the following results can be obtained from Fig. 5-12:

- If moisture content of input biomass is already 15 % prior to drying, technically drying the biomass until the target moisture content of 10 % is related to low environmental burdens.
- For giant reed, open air-drying can significantly improve the greenhouse gas balance and energy demand. All other investigated impact categories show a less significant or no improvement of the environmental performance (not shown).
- On the other hand, as intermediate storage of giant reed biomass and collection of stalks afterwards is linked to biomass losses, lower credits are achieved by production of bioenergy or bio-based products. As to giant reed, advantages related to lower drying emissions exceed disadvantages related to biomass losses. This is valid for all use options and all impact categories.

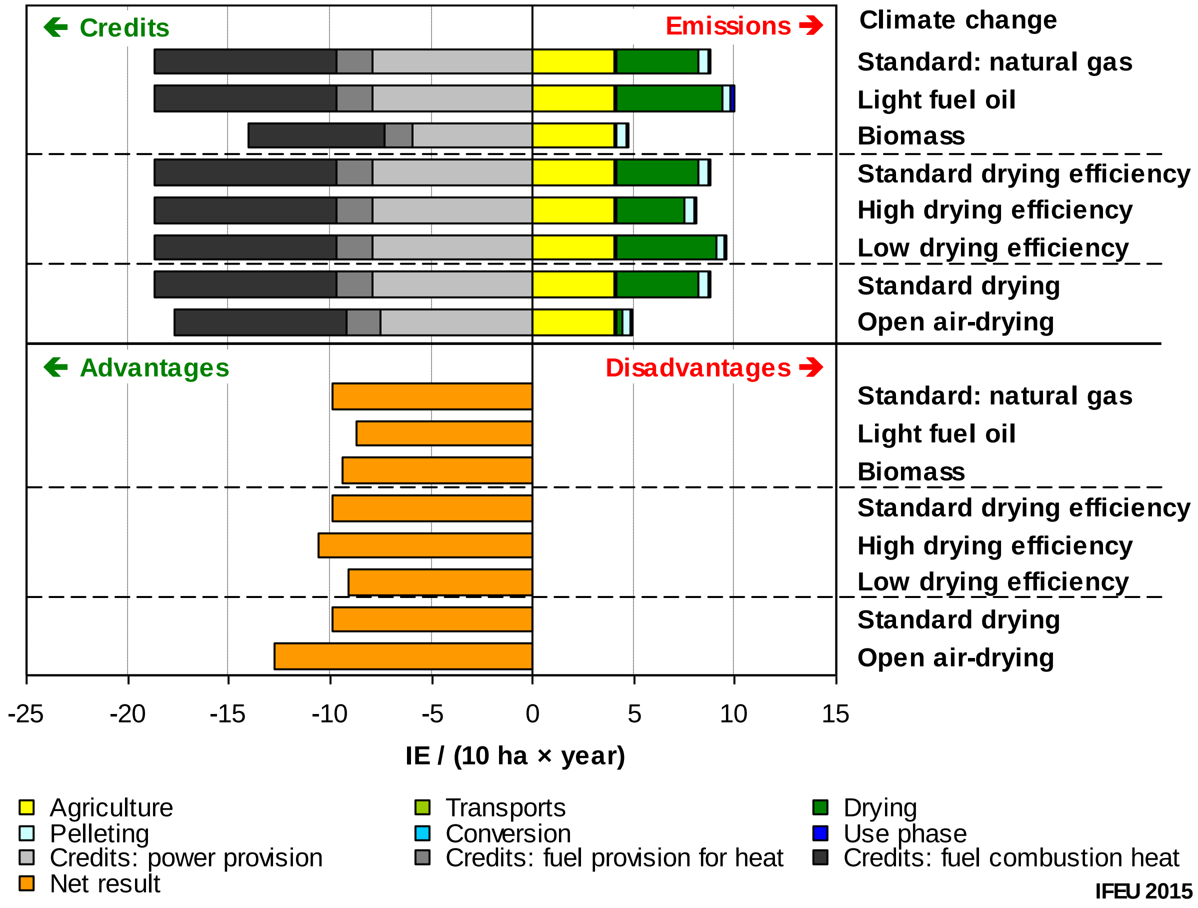

Fig. 5-12 Impact of varying energy carriers for drying, drying efficiency and moisture content prior to drying on the results for the impact category climate change of the scenario “Giant reed → Small CHP”

- As to Miscanthus, switchgrass and cardoon, the impact of the moisture content prior to technical drying on the greenhouse gas balance is less significant than for giant reed (see Fig. 8-3Fehler! Verweisquelle konnte nicht gefunden werden. in the annex). Since the moisture content of switchgrass and cardoon set in the assessed scenarios is already rather small (15 %, see Table 4-2), the decreased emissions related to drying are hardly recognisable for these crops. However, the biomass losses significantly lower the credits achieved by production of bioenergy or bio-based products. If used for the production of heat and power in a CHP plant, disadvantages related to biomass losses exceed the benefits related to the reduced drying emissions (see Fig. 8-3Fehler! Verweisquelle onnte nicht gefunden werden. in the annex). For other use options it depends on the impact category whether advantages exceed disadvantages or vice versa (not shown).
- For some use options, technical drying may even determine whether the complete scenario is advantageous or disadvantageous with respect to a given impact category. For instance, when the moisture content of biomass is reduced prior to technical drying by means of open air-drying, using giant reed for the production of 2nd generation ethanol leads to greenhouse gases savings instead of emissions (see Fig. 8-4 in the annex).

Conclusion:

Drying with natural gas is superior to using light fuel oil. Drying with biomass may improve or deteriorate the environmental performance depending on the use option and the impact category. Unless used for heat and power generation in a CHP plant, drying with biomass leads to greenhouse gas and energy savings. Especially for the cultivation of giant reed, investing in an efficient drying facility is a promising option to improve the environmental performance. Reducing the moisture content of giant reed by open air-drying prior to technical drying e.g. by intermediate storage of the harvest on the field improves the results even more than the installation of an efficient drying facility. As the moisture content of Miscanthus, switchgrass and cardoon is already low prior to technical drying, little optimisation potentials are given for these crops with respect to drying. For instance, open air-drying may deteriorate the environmental performance of these crops due to biomass losses related to intermediate storage.

5.4.2.2 Pelleting

In this section optimisation potentials for biomass pelleting are discussed. As explained in section 4.2, the efficiency of the pelleting facility is varied. Furthermore, innovative technology termed “wet pelleting” is assessed. Finally, for the use options “2nd generation ethanol” and “PDO”, biomass feedstock may be processed in the form of bales. Fig. 5-13 displays the influence of these variations. It allows for the following results to be obtained:

- An increased pelleting efficiency improves the LCA results of the investigated scenario. However, the impact is small.
- Assuming that wet pelleting can be conducted under the set conditions, it improves the LCA results of the investigated scenario. The improvement is greater than achievable by the installation of a more efficient conventional pelleting facility. However, the impact on the net result is small.

- If pelleting can be avoided completely, a greater improvement can be achieved than achievable by wet pelleting. This option may only be realisable for the use options “2nd generation ethanol” and “PDO”. The impact on net results is recognisable. However, even if pelleting is avoided, the use options “2nd generation ethanol” and “PDO” still compare unfavourably to the use option “CHP”.

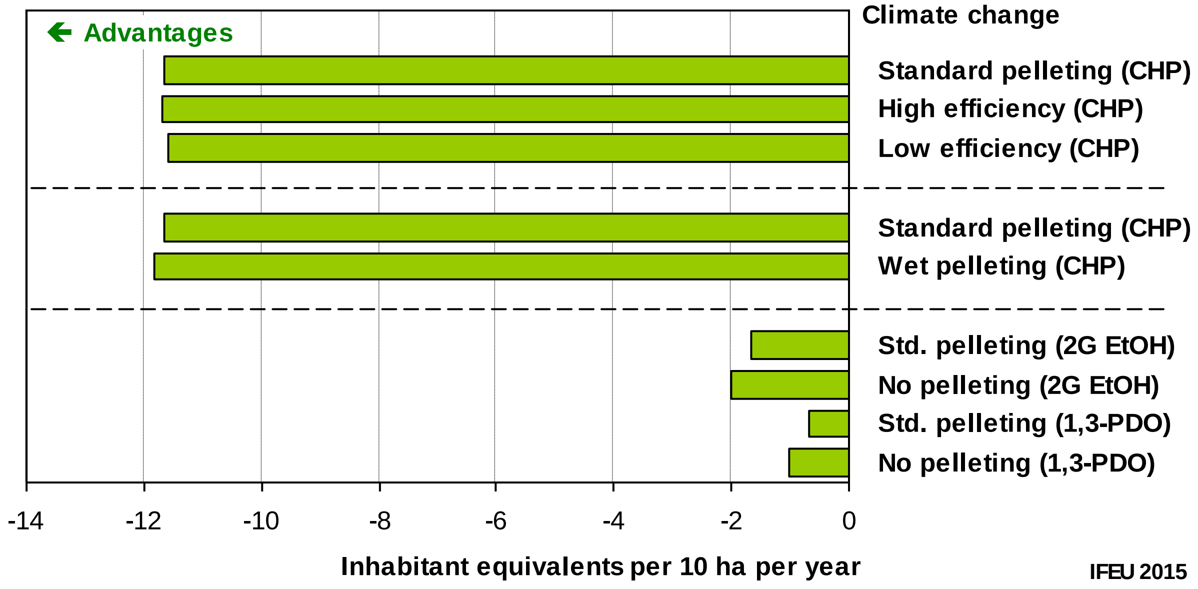

Fig. 5-13 Impact of pelleting variations on the results for the impact category climate change of the scenarios “Miscanthus → Small CHP”, “Miscanthus → 2G EtOH” and “Miscanthus → 1,3-PDO”. 2G EtOH: 2nd generation ethanol. CHP: Combined heat and power. Std.: Standard.

Conclusion:

Efforts to optimise pelleting lead to only small environmental improvements compared to other life cycle stages. Wet pelleting leads to larger improvements than installation of a more efficient pelleting facility. If the operating conditions proof to be realisable on a large scale, the technology may be a promising option despite only small improvements. The LCA results can be somewhat improved if pelleting is completely left out. It should thus be clarified whether the receiving conversion plant allows for the processing of baled instead of pelletised biomass.

5.4.3 Biomass conversion and use

Important parameters for the life cycle stages conversion and use that are analysed in depth based on sensitivity analyses in this section include biomass conversion efficiencies (section 5.4.3.1), as well as the provision of conventional reference products, namely the energy carrier used for heat production and the substituted power mix (section 5.4.3.2), the comparison of biomass CHP plants to fossil CHP plants (section 5.4.3.3) and the substitution of fossil 1,3-PDO (section 5.4.3.4). Further sensitivity analyses are conducted with respect to the sequestration ratio of biochar (section 5.4.3.5) and for co-firing a coal power plant with biomass (section 5.4.3.6).

5.4.3.1 Variation of biomass conversion efficiencies

In the following, the influence of the biomass conversion efficiency on the LCA results is discussed. As described in sections 0 to 4.3.7, depending on the use option, varied parameters include e.g. thermal conversion efficiency, resource demand, and the amount and type of co-products. From Fig. 5-14 the following results can be obtained:

- The conversion efficiency has a significant effect on the greenhouse gas balance of the displayed scenarios.
- The results show a high bandwidth. For both displayed use options, achievable greenhouse gas savings vary by approx. 6 IE / ha / year.
- A variation of conversion efficiency may even cause an overall advantage to turn into an overall disadvantage.
- Improving conversion efficiency may e.g. save emissions related to the energy demand during conversion or it may enable the generation of additional power or 1,3-PDO compared to the standard case.
- As to other impact categories, influence of conversion efficiency can be strong as well as marginal (not shown).
- Greenhouse gas savings can be achieved for the cultivation of Miscanthus at yield level “marginal 1” even when low conversion efficiency is applied except for the use option “1,3-propanediol” (not shown).

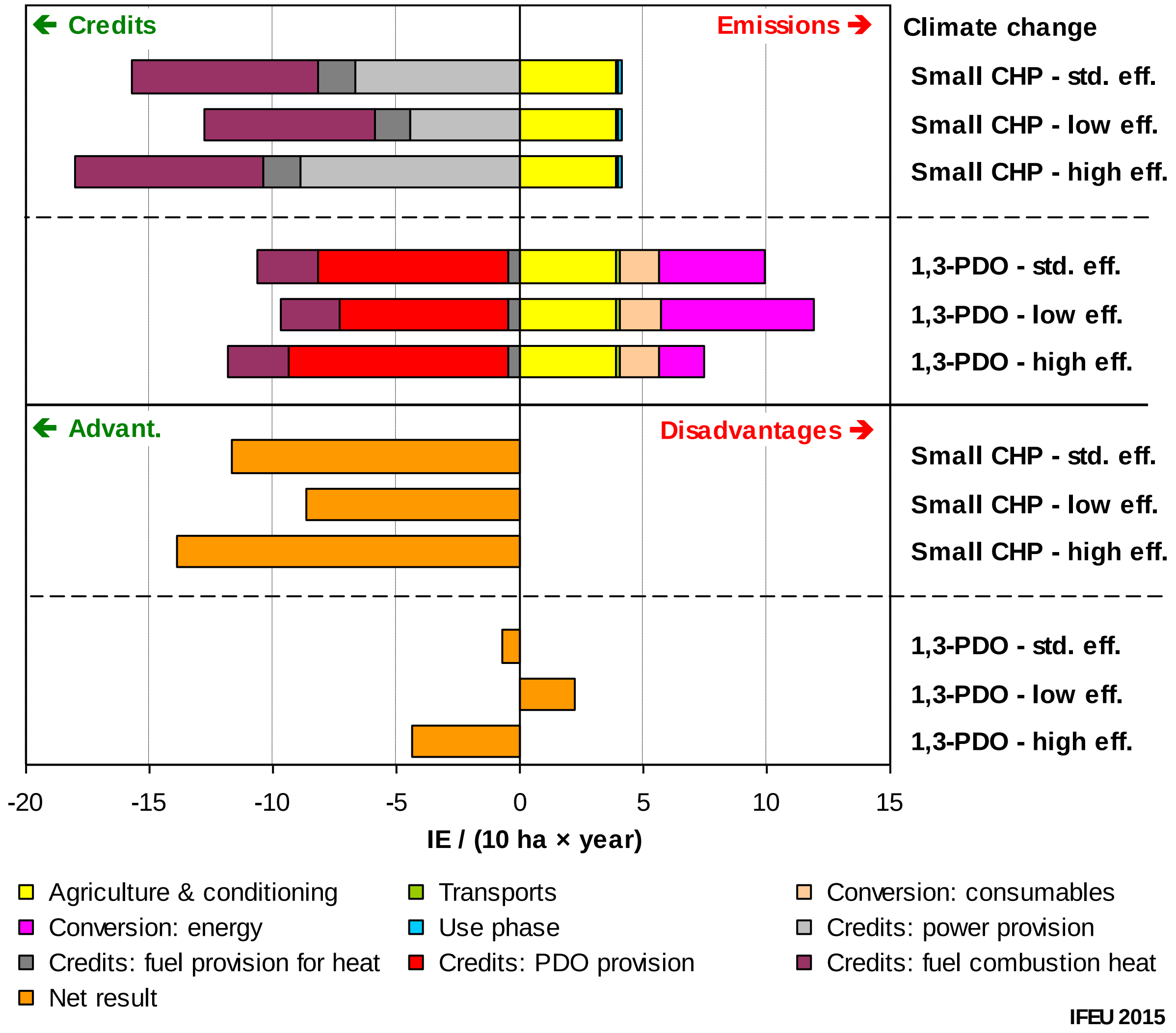

Fig. 5-14 Impact of conversion efficiency on results for the impact category climate change of the scenarios “Miscanthus → Small CHP” and “Miscanthus → 1,3-PDO”. Eff.: Efficiency. Std.: Standard.

Conclusion:

The conversion efficiency has a strong influence on the LCA results. It may even determine whether a scenario is advantageous or disadvantageous with respect to a given impact category. It is thus strongly recommendable to install best available processing technology.

5.4.3.2 Variation of reference products: substituted heat and power production

As indicated in section 4.3, the substituted conventional heat and power production are influencing parameters to be analysed in depth by variation in a sensitivity analysis. For the standard case, substituted heat is provided by combustion of natural gas. In this sensitivity analysis, substituted heat is provided by combustion of light fuel oil. Furthermore, for the standard case, substituted power is defined as a marginal power mix including natural gas and hard coal (see 3.2.3). In this sensitivity analysis, substituted power is provided by the combustion of hard coal. In Fig. 5-15, the influence on selected LCA results is displayed for the use option “CHP (small scale)”. It allows for the following results to be obtained:

- Both the selection of energy carriers for conventional heat provision and the substituted power mix significantly impact LCA results. Net results may vary up to 6 IE / ha / year.
- If conventional heat is provided by the combustion of light fuel oil instead of natural gas, the environmental performance of the investigated OPTIMA scenario improves. This is because the provision and especially the combustion of light fuel oil are related to larger CO_2, NO_x, and SO_2 emissions per MJ of produced heat than the combustion of natural gas.
- Similarly, if biogenic power provision substitutes for power provided by the combustion of hard coal instead of a marginal power mix including both hard coal and natural gas, the environmental performance of the investigated OPTIMA scenario improves. First, the provision and combustion of hard coal are related to greater environmental burdens than the provision and combustion of natural gas. Second, the marginal power mix is defined to have a larger share of cogeneration (25 %) than coal power plants, which also leads to higher burdens associated with coal power.
- For some impact categories like marine eutrophication, the selection of energy carriers for conventional heat provision and the substituted power mix are hardly relevant.
- Since other use options, namely “domestic heat production” and “1,3-propanediol” also provide heat (see sections 0, 0 and 4.3.6) the energy carrier used for conventional heat production also has an impact on the LCA results for these use options (not shown). The impact is greatest for the use option domestic heat as it focuses on heat production.
- The actual substituted conventional energy carrier varies from household to household. Also the mix of energy carriers used in a given area varies within the Mediterranean region. Thus, light fuel oil may serve as a worst case conventional reference that yields highest advantages if replaced by biomass based heat production.
- Similarly, replacing hard coal may serve as a worst case conventional reference as to the substituted provision of power.

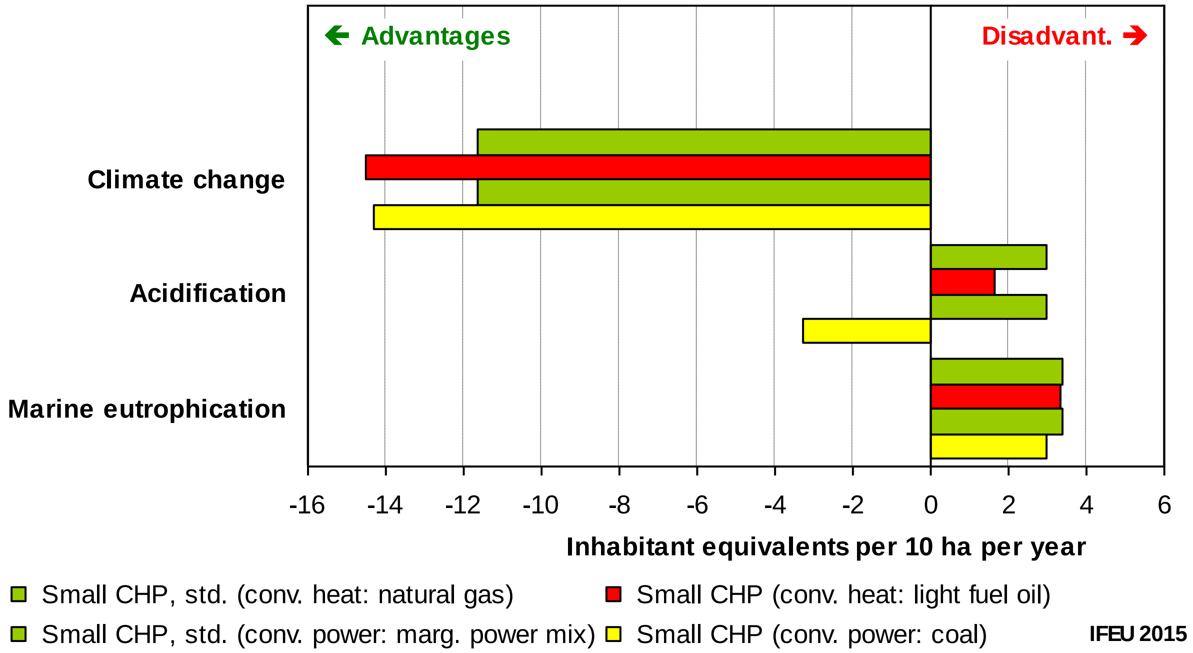

Fig. 5-15 Impact of the energy carrier used for conventional heat production and the substituted power mix on the results for the impact categories climate change, acidification and marine eutrophication of the scenario “Miscanthus → Small CHP”.

Conclusion:

The energy carrier used for conventional heat production and the substituted power mix have a strong influence on the LCA results of those scenarios that provide heat or power. The substitution of light fuel oil is related to greater overall advantages and lower disadvantages than the substitution of natural gas. Similarly, the substitution of power that is provided by hard coal plants is related to greater overall advantages and lower disadvantages than the substitution of the marginal power mix defined for the standard cases. Potential policy frameworks supporting energy production from perennial grasses should thus ideally aim at replacing heating systems or power plants with bigger environmental footprints such as oil-fired boilers or coal-fired power plants first.

5.4.3.3 Alternative scenario: substitution of fossil fuel-fired CHP

As described in section 4.3.2, this alternative scenario is analysed in order to estimate the impact of conventional energy provision on LCA results. Heat and power produced in a CHP by combustion of biomass may replace heat and power provided by a variety of production methods. For the main scenario it is defined that heat produced in a CHP replaces heat produced in a conventional boiler while power produced in a CHP replaces power from grid. In this alternative scenario, it is assumed that the heat and power produced in a biomass CHP replace heat and power produced in a CHP from fossil energy (see section 4.3.2 for further details). This analysis is relevant only for the use options “CHP (small scale)” and “CHP (large scale)”. The comparison of a biomass fired CHP to a fossil fuel fired CHP requires a careful analysis of the products to ensure an equal function provided by both systems. Both systems are primarily installed to provide a certain amount of heat e.g. to an industrial facility. However, a biomass fired CHP produces less power per amount of heat than a fossil fuel fired CHP. Thus, in the assessed scenario, a biomass fired CHP plus a certain amount of power from the grid is compared to a fossil fuel fired CHP.

Fig. 5-16 allows for the following results to be obtained:

- The definition of reference system has a very strong influence on LCA results of the displayed impact categories.
- A fossil fuel fired CHP plant needs more fossil fuel than a boiler in the standard case. Thus, credits related to the provision of fossil fuel are larger in case of a fossil fuel fired CHP (compare light grey and red bars).
- Similarly, the combustion of fossil fuel in a CHP plant is related to greater burdens than the combustion of fossil fuel in the conventional boiler. Thus, the fossil CHP scenario benefits from larger credits for direct emissions with respect to the displayed impact categories (compare grey and pink bars).
- On the other hand, the fossil CHP plant produces more power than the biomass CHP plant. To make sure that both systems provide the same amount of power, further power has to be provided from grid in addition to the power produced in the biomass CHP plant. This leads to significant burdens in the displayed impact categories for the additionally provided power instead of credits for substituted power in the standard case (compare dark blue and black bars).
- In total, the fossil fired CHP is of course more efficient than separate heat and power production from fossil fuels. For the fossil system, the additional fuel use of a CHP compared to a boiler pays off because of the additional power production. Thus, from the perspective of the biomass system, the disadvantages caused by the additional power production in the biomass system are greater than the advantages caused by the additional fuel use in the fossil CHP plant. Therefore, net results are significantly worse if a biomass CHP is compared to a fossil CHP instead of a boiler.
- In the investigated scenarios, greenhouse gas savings can still be achieved. However, they decrease by approx. 50 % compared to the standard case.

- The impact on the LCA results is so strong that in certain environmental impacts, a net advantage may turn into a net disadvantage.
- Achievable greenhouse gas and energy savings by biomass use in a biomass CHP plant are lower than for the use options “domestic heat” and “upgraded pyrolysis oil” but still greater than for the use options “2nd generation ethanol” and “1,3-propanediol” (see Fig. 5-6). Thus, biomass combustion in a CHP plant becomes much less advantageous compared to other use options if compared to a fossil fuel fired CHP plant.

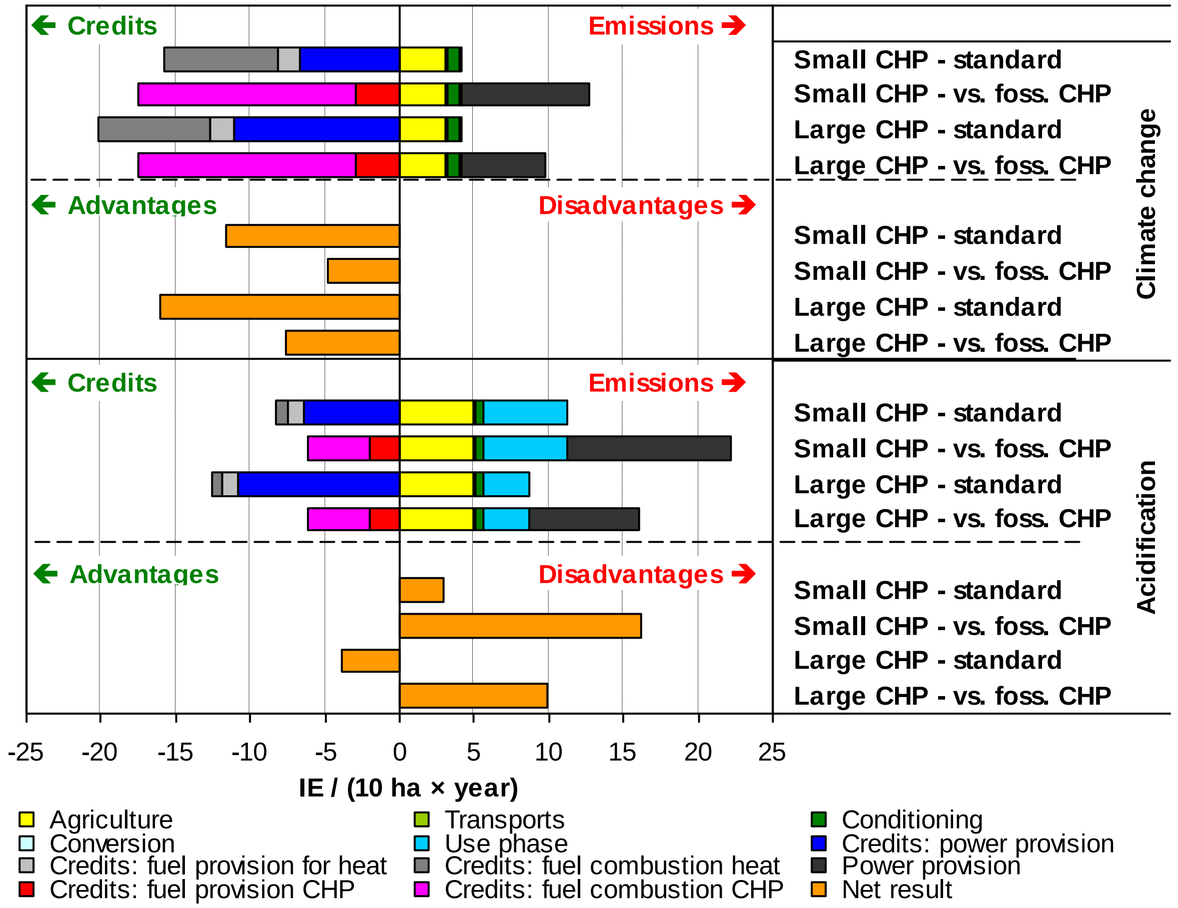

Fig. 5-16 Impact of the provision of conventional reference products on the results for the impact categories climate change and acidification of the scenarios “Miscanthus → Small CHP” and “Miscanthus → Large CHP”. Adapted from [Schmidt et al. 2015].

Conclusion:

The modelling of the conventional energy provision has a very strong impact on the LCA results. If the biomass CHP plant is compared to a fossil CHP plant instead of to separate heat and power production, LCA results significantly deteriorate. An existing fossil CHP plant should thus not be replaced by a biomass CHP because it is one of the most efficient use options for fossil fuels. Many less efficient use options exist that should be replaced first. Nevertheless, if a fossil fuel fired boiler has to be replaced, a biomass fired CHP should be installed instead of a fossil fuel fired CHP.

5.4.3.4 Alternative scenario: reference product for 1,3-PDO

As stated in section 4.3.6, 1,3-PDO from biomass may either be used for the production of PTT, which substitutes for PET or may substitute for 1,3-PDO produced from fossil resources such as crude oil (here short “fossil PDO”). Even in the medium-term future, the latter case is unlikely to take place on relevant scales because fossil 1,3-PDO is not produced in large quantities and because the availability of 1,3-PDO from biomass will likely increase further in the future. Nevertheless, this alternative scenario is analysed to cover this aspect. Fig. 5-17 allows for the following results to be obtained:

- If bio-based 1,3-PDO replaces fossil 1,3-PDO, the results of all displayed impact categories are improved.
- Except for marine eutrophication, the effect is distinctly visible for all displayed impact categories.
- However, even if fossil 1,3-PDO is defined as the conventional reference product, the use option still compares unfavourably to other use options, e.g. small CHP. This is valid even if a high conversion efficiency is assumed for the production of 1,3-PDO from biomass (not shown).

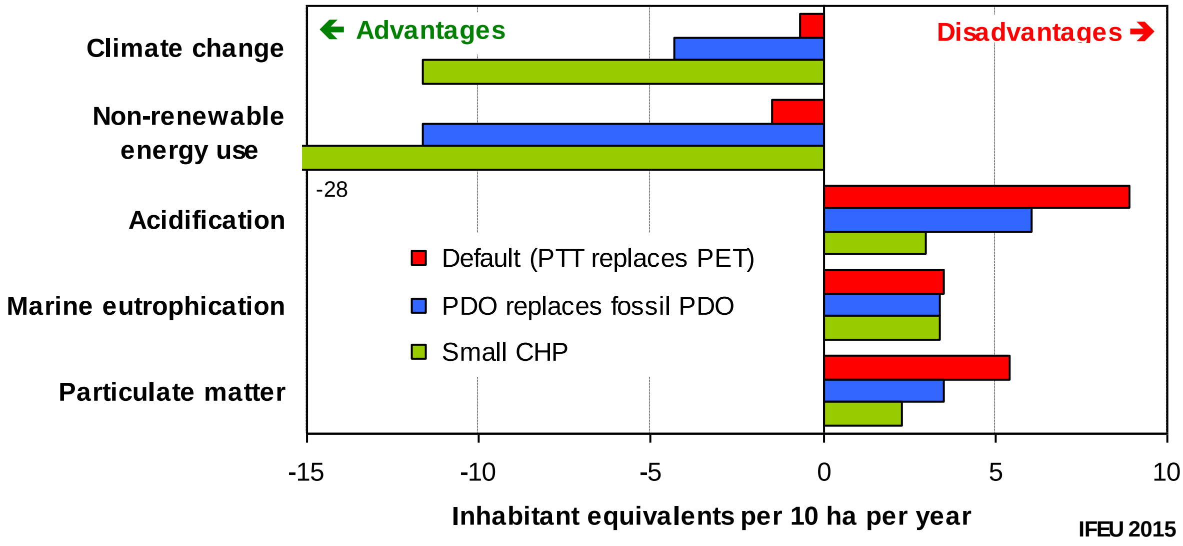

Fig. 5-17 Impact of conventional reference product on the results for selected impact categories of the scenario “Miscanthus → 1,3-PDO” compared to the scenario “Miscanthus → Small CHP”.

Conclusion:

If 1,3-PDO from biomass replaces 1,3-PDO produced from fossil resources, the environmental performance considerably improves. However, the global scale of 1,3-PDO production from fossil resources is rather small and its replacement does thus not offer big potentials. Furthermore, this use option still compares unfavourably to other use options.

5.4.3.5 Variation of sequestration ratio for biochar

The share of carbon contained in biochar that stays in the ground for more than 100 years is very uncertain as underlined by the range of values identifiable in literature. For this reason, this analysis is conducted, varying the sequestration ratio from 20 % to 80 % (for further details and references see section 4.3.4). From Fig. 5-18 the following results can be obtained:

- The impact of sequestration ratio on the greenhouse gas balance of the displayed scenario is strong. The results for the favourable and the unfavourable cases differ from each other by 15 IE / ha / year.
- If only 20 % of contained carbon stays in the ground for more than 100 years, hardly any net greenhouse gas savings can be achieved.
- On the other hand, if 80 % of contained carbon stays in the ground for more than 100 years, greenhouse gas savings are greater than achievable by biomass use for heat and power production in a small CHP and any other main scenario (see Fig. 5-6).
- The greenhouse gas balance also highly depends on the chosen methodology. In this particular analysis, CO_2 emissions occurring after 100 years are not taken into account at all. If biochar production and use should become a viable option, the actual duration of carbon sequestration and its effect beyond 100 years have to be studied in more detail.
- Independent of the sequestration ratio, the use option biochar does not provide any advantages related to any other impact category.

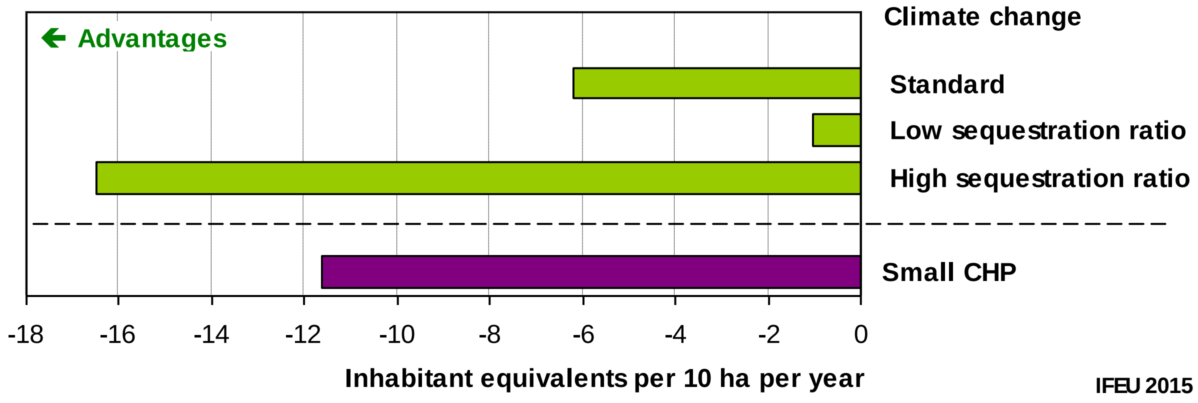

Fig. 5-18 Impact of sequestration ratio of biochar on the results for the impact category climate change of the scenario “Miscanthus → Biochar” compared to the scenario “Miscanthus → Small CHP”.

Conclusion:

The share of carbon contained in biochar that stays in the ground for more than 100 years largely determines this use option’s greenhouse gas balance. Both zero emission savings and greater savings than achievable by any other investigated main scenario may be realised. On the one hand, biochar production and application to fields as a means of climate change mitigation should be studied further. On the other hand, no clear conclusions can be drawn as long as actual sequestration ratios cannot be predicted more precisely.

5.4.3.6 Excursus: Use option: Co-firing for power generation

In this excursus, the environmental implications related to co-firing of biomass pellets substituting for hard coal in a hard coal power plant are discussed. This use option is already applied in the United Kingdom though currently not incentivised for the Mediterranean region. However, depending on the price development for the EU Emissions Trading System certificates and further political boundaries, this use option may become a relevant opportunity in the next few years.

The excursus is based on the following settings:

- Miscanthus is the crop used for co-firing.
- A transport distance from conditioning facility to hard coal power plant of 50 km is defined, which is greater than for all other use options because of the typically large scale of hard coal power plants.
- Biomass co-fired in the hard coal plant is set to make up 20 % by weight of the feedstock material combusted in the plant (approximate technical limit without further biomass processing).
- Efficiency of the power plant is set to 40 %.

Fig. 8-5 in the annex (section 8.3.2.3) displays environmental impacts related to the use option “co-firing” compared to other investigated use options in the OPTIMA project. The following results can be obtained:

- The use option allows for higher greenhouse gas savings than any other investigated use option.
- Only the use options CHP (small and large scale) allow for higher energy savings.
- Also with respect to all other investigated impact categories, co-firing compares favourably to most other investigated use options.

However, the question arises, whether power generated from hard coal plants including co-firing of biomass is an advantageous use option in terms of environmental impacts. For this reason, in the following it is discussed, which environmental impacts are related to co-firing of 20 % biomass in a hard coal power plant for generation of 1 kWh compared to the generation of 1 kWh in a natural gas power plant. With respect to this question, Fig. 5-19 allows for the following results to be obtained:

- If biomass is co-fired in a hard coal plant, LCA results for most impact categories including climate change and energy savings significantly improve. Only for marine eutrophication, LCA results deteriorate, which is caused by nutrient leaching during agricultural production.
- However, even if biomass is used in a hard coal plant for power generation, the greenhouse gas balance of power generated in a natural gas power plant is still superior.
- With respect to the impact category non-renewable energy use, co-firing compares favourably to a natural gas plant.

- Independent of the share of biomass co-fired, power generation in a hard coal plant is related to significant disadvantages compared to power generation in a natural gas plant with respect to the impact categories climate change, acidification and particulate matter.
- The impact category non-renewable energy use is the only one for which the co-firing of biomass turns a former disadvantage into an advantage.

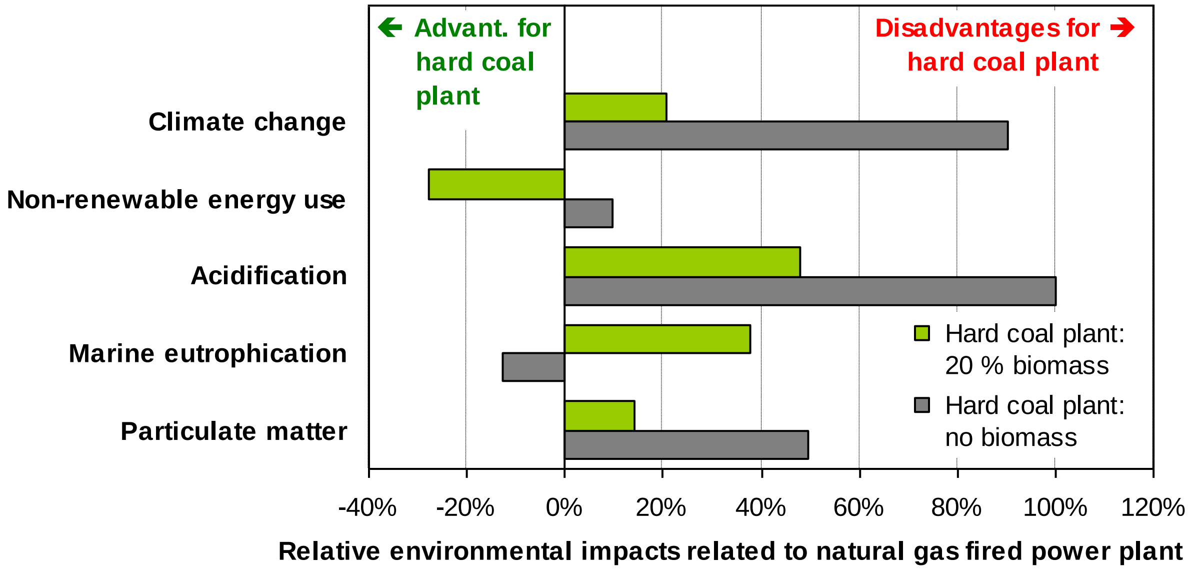

Fig. 5-19 Environmental advantages and disadvantages for selected impact categories related to the generation of 1 kWh in a hard coal plant compared to a natural gas power plant with and without co-firing of biomass in the hard coal plant. Source: [Schmidt et al. 2015].

Conclusion:

The construction of a new natural gas power plant is mostly environmentally advantageous compared to the construction of a new hard coal power plant with or without co-firing of biomass, particularly regarding climate change. Similarly, co-firing of biomass is no valid argument against shutting down coal power plants in favour of more environmentally friendly options of power generation such as natural gas power plants or even renewables. Nevertheless, co-firing can provide substantial advantages in a transition period until coal power can be replaced on a large scale. The shown advantages are, however, only valid if exclusively biomass from sustainable sources is used.

5.5 Synopsis

In this section, the results presented in the previous sections are summarized and compared to each other.

In order to give a general impression of the impact of the agricultural processes with respect to the conversion and usage processes on climate change, Fig. 5-20 gives an overview in a 3D diagram. It shows that the differences in the results of the seven usage options are larger than the differences between the biomass types. Furthermore, the significance of the higher greenhouse gas savings with direct combustion (CHP and heat) with respect to indirect usages (thermo- or biochemical conversion prior to usage; UPO, biochar, 2G ethanol and 1,3-propanediol) becomes evident: the combination of the “best” biomass with the “best” indirect usage (Miscanthus for UPO) saves more greenhouse gases than any option with the “worst” direct usage (any crop for domestic heat). However, it performs similar to the “worst” biomass with the “best” direct usage (switchgrass in large CHP). On the other hand, the “worst” biomass in the “worst” direct usage saves still much more greenhouse gases than any crop in the “worst” indirect usages (2G EtOH and 1,3-PDO). With respect to the ranking of crops and use options, it has to be underlined that some scenario settings such as drying and pelleting of all biomass significantly influence the results. Depending on the case-specific circumstances, logistics chains could be designed differently.

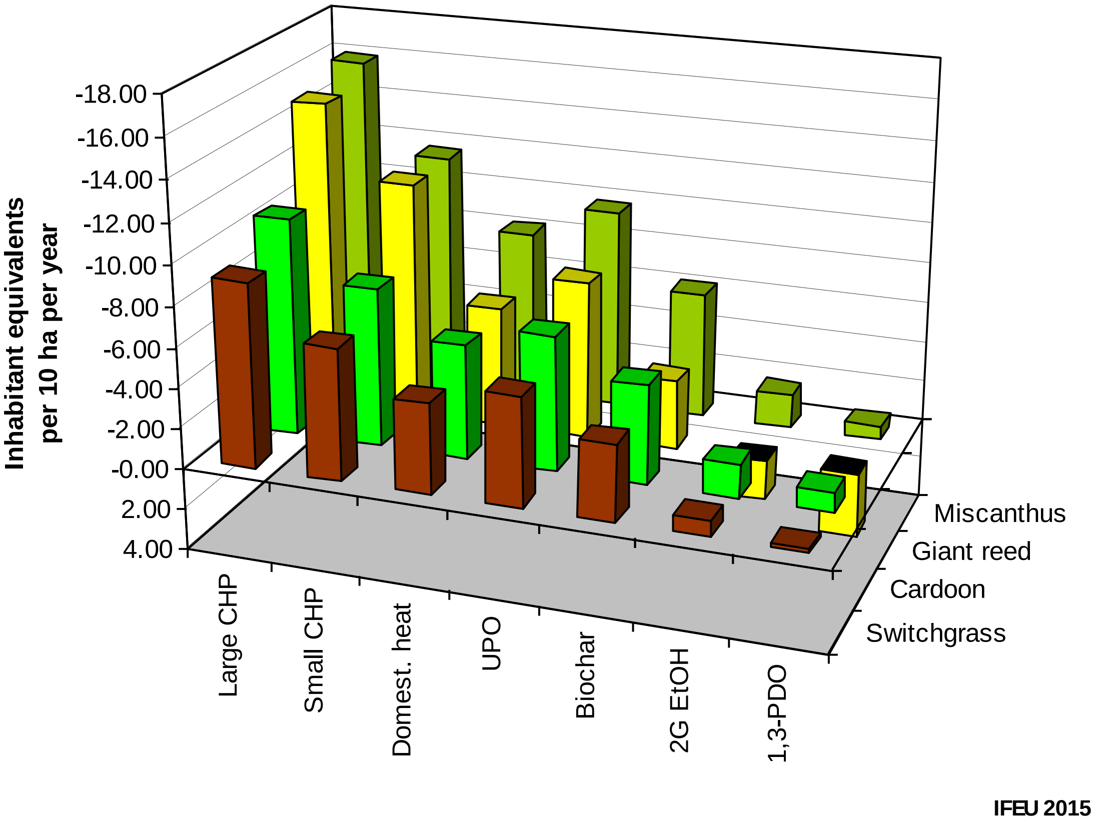

Fig. 5-20 Overall greenhouse gas savings (upward columns, negative numbers) or extra emissions (downward columns, positive numbers) of all main scenarios with the biomass feedstock cultivated on marginal land used in the use option with standard conversion efficiency, each compared to its fossil equivalent product.

While this figure shows a remarkable result matrix of the standard scenarios, but only in one environmental impact and not for the sensitivity analyses, the following figures give more details in different aspects of interrelations between the results.

Fig. 5-21 gives an overview over the basic scenarios in the OPTIMA project: all perennials and conversion / use options investigated are displayed. It shows that both the choices of conversion / use option and of the perennial crops used substantially influence the results.

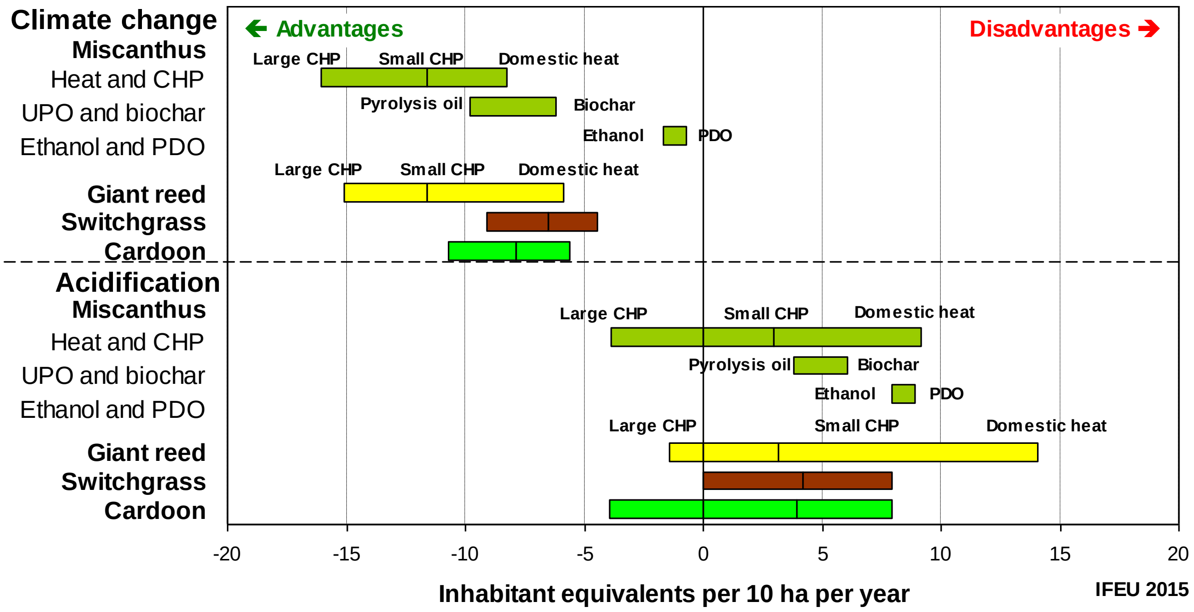

Fig. 5-21 LCA results for the basic scenarios: the different cultures and conversion / use options. Conversion / use options are shown for standard conversion efficiency based on the cultivation of Miscanthus (yield level “low” on marginal land); agricultural options are shown for yield level “low” (marginal land) based on heat and power use options. CHP: combined heat and power production, UPO: upgraded pyrolysis oil, PDO: 1,3-propanediol.

In order to get a closer look, Fig. 5-22 displays the most important sensitivity analyses explained in section 5.4. This shows that the specific conditions, under which a scenario is implemented, can influence the results in some cases even more than the choices of crop and conversion / use option. The most important of these conditions are: previous land and water use and resulting potential land use changes, achieved agricultural yield and replaced systems, which depend on investor choices, political boundary conditions etc. The achieved conversion efficiency is less variable and thus less decisive for mature power and heat use options but leave more room for optimisation and result variation for the other more innovative options (not shown).

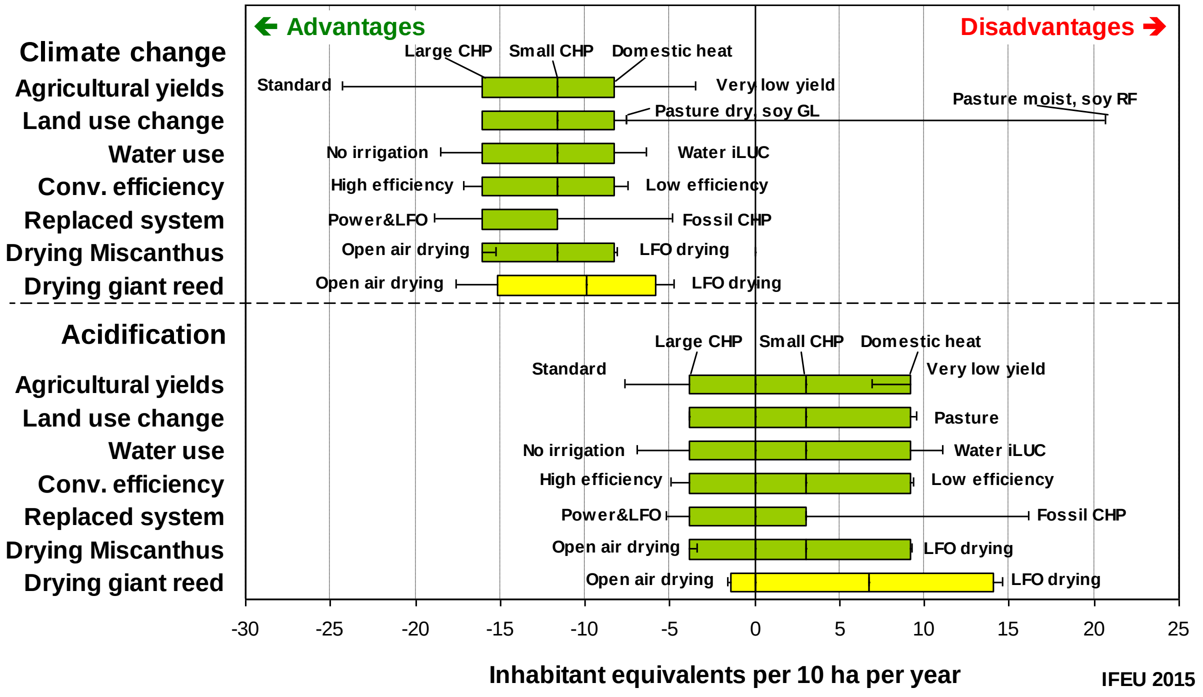

Fig. 5-22 Overview of LCA results for sensitivity analyses and bandwidths of results. Green bars show the standard results for the heat and power use options “Large CHP”, “Small CHP” and “Domestic heat”. Scenarios are based on the cultivation of Miscanthus (yield level “low” on marginal land) except for the last, which is based on giant reed as indicated. Results for the sensitivity analyses are presented with the single-line deviation bars. iLUC: indirect land use change, GL: grassland, RF: rainforest, LFO: light fuel oil.

6 Conclusions and recommendations

This screening life cycle assessment (LCA) is part of the overall sustainability assessment within the OPTIMA project. It assesses global and regional environmental impacts throughout whole life cycles from the cultivation of perennial grasses on marginal land, through biomass conversion into bioenergy or biomaterials, to their use and, if applicable, to their disposal. To this end, the screening LCA analyses scenarios on potential future biomass production, conversion and use in 2020 in the Mediterranean region and compares them to impacts caused by equivalent products.

Conclusions on the following topics are presented in this section:

- Comparison of OPTIMA scenarios to the provision of equivalent products (section 6.1)
- Optimisation of the assessed OPTIMA scenarios (section 6.2)
- Comparison of OPTIMA scenarios to each other to determine the most environmentally friendly ones (section 6.3).

Details on the goal and scope questions that motivated the analysis of these topics can be found in chapter 2.

Additionally, section 6.4 provides recommendations for different stakeholders.

6.1 Conclusions: OPTIMA scenarios vs. conventional product provision

OPTIMA focuses – in contrast to other projects – on the cultivation of perennial grasses **on marginal land** in the Mediterranean region, in particular in order to not present competition to food and animal feed production. The possibility of lower environmental impacts being associated with this was investigated as part of the screening life cycle assessment. Advantages can be seen for cultivation on idle land (not to be equated with the land quality descriptor 'marginal', but often affecting the same areas), because potentially highly detrimental indirect land use changes are avoided. In these terms, the achievement of the OPTIMA project is to bring low-quality land into production by adopting selected crops and agricultural practices.

Compared to a conventional product provision, the OPTIMA scenarios display highly diverse results in the screening life cycle assessment:

- In general, the **result bandwidth is very large** and for individual impact categories such as global warming it can range from advantages (emission savings) to disadvantages (additional emissions). The reason for this is that the investigated scenarios are highly diverse and the conversion and use options, in particular, cover a broad spectrum ranging from bio-based products through biofuels to liquid and solid bioenergy carriers. A considerable part of the range of results therefore represents freedom for future decision-making. This freedom should be actively exploited to use the available marginal land in the Mediterranean region and other resources, such as the available water, as productively as possible, and to environmental advantage.

- Viewed across all impact categories, practically all OPTIMA scenarios are **associated with both environmental advantages and disadvantages**. In the majority of scenarios, the advantages and disadvantages follow a **typical pattern**, which can often be observed for bioenergy: clear environmental advantages can generally only be achieved in terms of energy savings and global warming –deleterious effects, in part even substantially, can be observed for almost all of the remaining environmental impacts analysed, such as acidification and eutrophication. In the majority of scenarios the environmental advantages in terms of energy savings and global warming thus cannot be achieved without other disadvantages. Because comparative weighting of the environmental impacts requires a value-based approach, the approval of bioenergy and bio-based products in general assumes a preference for climate- and energy-related targets compared to other environmental targets. However, compared to the cultivation of annual crops, the expenditures and resulting environmental disadvantages of perennial crops are smaller.
- In a few scenarios, however, there are both positive and negative **deviations from the general pattern of environmental impacts**. Notable deviations result for the following conversion and use options:
  - \+ Large CHP[5]: In addition to the typical benefits, balanced results or even advantages are possible depending on the crop, and cultivation and conditioning options, even given acidification, particulate matter emissions and freshwater eutrophication. This conversion and use option is therefore highly recommended.
  - – PDO and 2nd generation ethanol[6]: Compared to other use options, only small environmental advantages for energy savings and global warming can be achieved which are accompanied by large typical disadvantages. These conversion and use options are therefore less recommended. Results may improve recognisably but not decisively if pelleting and drying (the latter depending on the season) are not required, because moist bulk material might serve as appropriate feedstock for conversion to 1,3-PDO and 2nd generation ethanol. However, the biomass moisture content must not exceed critical levels of e.g. 20 % due to storage requirements.
  - – Biochar[7]: The balanced utility is only carbon sequestration. Environmental advantages can therefore only be identified for global warming. Disadvantages occur in all other impact categories. It is not currently certain to what degree and possibly under which conditions these disadvantages can be compensated for by

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[5] Combustion of biomass in a large combined heat and power plant that provides heat to industrial plants and feeds power into the grid.

[6] Conversion of biomass into polymer precursors (1,3-propanediol) or biofuel (2nd generation ethanol) via a biotechnological process.

[7] Conversion of biomass into biochar in a thermochemical process (torrefaction).

a possible additional function as a soil improver. Until such a benefit can be reliably verified and fertiliser application reduced as a result, conversion to biochar cannot be recommended.

- However, from a qualitative perspective, **the same typical pattern**, but clear quantitative differences, can be seen under the majority of conditions for **all cultivated crops**. They are discussed in Section 6.3 where the scenarios are compared.
  In particular, the typical patterns of advantages and disadvantages are, on the whole, independent of the **yield of the marginal land areas**. In the low-yield scenarios investigated, the environmental advantages are weaker, but do not convert to disadvantages as a result of area-specific, fixed expenses, when used efficiently, for example for stationary energy generation. Moreover, generally lesser disadvantages occur as a result of the less intensive use. However, the ratio of advantages to disadvantages tends to be more beneficial on higher yield marginal land. If higher yield marginal land is predominantly used, for example for economic reasons, this contributes to achieving environmental targets.

The points raised above demonstrate that it is not possible to condone the cultivation and use of perennial grasses across the board. However, screening life cycle assessments help to optimise the individual use options (Section 6.2) and identify the pathways associated with the weakest environmental impacts (Section 6.3). For example, given **efficient, stationary energy generation**, it is possible to achieve environmental advantages in terms of energy savings and global warming with only minor, and sometimes even without, disadvantages to the other analysed environmental aspects. These scenarios should therefore be preferentially implemented. Detailed implementation recommendations can be found in Section 6.4.

6.2 Conclusions: Result contributions and optimisation potentials

Environmental impacts at global / regional level occur at all stages of the life cycle, however, the extent to which each life cycle stage contributes to the overall balance and to its variability varies both *between scenarios* and *between environmental impact categories*. The life cycles analysed in OPTIMA can be separated into two relatively independent stages: agriculture and production of the intermediate pellet product on one side, and pellet conversion to end products and their uses on the other. The result contributions of all life cycle stages were investigated for this project. Detailed optimisation potentials, as well as less controllable external influences, are only discussed below for agriculture and pellet production, because they represented the main points of interest.

Result contributions according to environmental impacts

Some impact categories are primarily influenced by biomass cultivation (marine eutrophication and ozone depletion), while human toxicity from particulate matter is primarily influenced by the use option. Both parts of the life cycle clearly contribute to the results for energy savings, global warming and acidification. Easily implementable optimisation measures should nevertheless be adopted in all life cycle stages; however, where optimisation conflicts are possible, in particular, the input parameters identified as being most important ('hot spots') should be preferentially optimised.

Hot spots and optimisation potentials in agriculture and pellet production

In terms of agriculture and pellet production the governing result contributions depend on agricultural yield, the required quantity of fertilisers and irrigation, and, in part, the necessary drying effort. These points should therefore be preferentially optimised. In terms of pellet conversion to end products, and their uses, the conversion efficiency, the necessary material and energy expenses and the direct emissions represent the primary governing factors, depending on the use option and impact category. Optimisation of the use options, such as even lower emissions during biomass combustion, is not discussed in this section, because this project focuses on the biomass provision.

- The **yield** on marginal land areas predominantly depends on the site conditions. Nevertheless, it can be enhanced to a certain extent by very good cultivation practice. This should be exploited to an extent that does not result in other environmental harm. For example, this may be the case where excessive fertilisation or irrigation is used that does not lead to a corresponding increase in yield.
- The impacts of any **irrigation** vary widely between different biomass production sites. If substantial irrigation is necessary[8], it may considerably reduce the achievable greenhouse gas and energy savings due to the pumping expense, but will not generally overcompensate it. Optimisation of irrigation efficiency is therefore especially important. If yield cannot be raised without irrigation or harvest failures are avoided, it is first of all reasonable. However, industrial biomass should only be irrigated if sufficient water is available in the respective region, which also is the case in certain parts of the Mediterranean region. However, if already scarce water is nevertheless used to irrigate crops for industrial purposes, such as those studied in OPTIMA, this may result in significant environmental harm. Eventually, there may not be sufficient water remaining for other agricultural purposes, leading to yield losses. If this then affects food cultivation, increased food imports result from water scarcity, which may lead to indirect land use changes similar to those resulting from land use competition.
- **Fertilisers:** Nitrogen fertilisers, in particular, lead to high environmental impacts both in their production and in field emissions. Depending on the soil conditions, a large proportion of the nitrogen fertiliser not taken up by the crops is lost through water and air emissions from the field and thus causes additional environmental harm. Although the amount of fertiliser required by perennial crops is comparatively low, its use should be optimised as far as possible, for example by optimising application techniques and times.
- The environmental impacts of **biomass drying** can be reduced on three levels.
    1. The harvest should be optimised with the aim of minimising the biomass water content.

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[8] Irrigation using up to 6,000 m³ / ha / a was investigated in the scenarios.

2. An efficient drying process should be adopted.
3. As far as possible an environmentally friendly energy carrier for heat provision should be employed. Open air-drying, where possible, offers clear advantages, while innovative processes such as wet pelleting can at least achieve certain improvements. Depending on the use option and impact category, combustion of part of the biomass to generate drying heat leads to environmental advantages or disadvantages, making it necessary to investigate this type of energy provision on a case-by-case basis. When optimising, care should also be taken that the biomass is quickly dried following the harvest, in order to prevent losses caused by decomposition / rotting.

Importance of external influences

In addition to the important parameters ('hot spots') that can be influenced by farmers and pellet producers as discussed above, less controllable external factors may also contribute to the results. The most important, in some cases much discussed, factors are considered in more detail below.

- **Indirect land use changes** have the greatest potential impacts. These can occur when marginal land used for industrial crop cultivation was previously subject to other uses and the goods produced there are then produced in another part of the globe by expanding farmland. A similar effect can also occur if scarce water is withdrawn from previous agricultural uses. One aim of the project is to utilise unused marginal land. However, firstly, many 'unused' land areas are nevertheless extensively used and, secondly, it is difficult to define and verify the 'unused' status in any possible support programmes. It is therefore possible, depending on the implementation, that existing uses are displaced, even on marginal land. This can cause natural land to be converted to arable land through indirect land use changes in other regions of the globe. Rainforests and other vegetation in South America, which are cleared for growing food and animal feed for exports (for example replacing local meadow feed with imported soy feed), are in special danger. As sensitivity analyses demonstrate, the resulting greenhouse gas emissions depend heavily on the respective displaced use and its intensity. If more extensive meadow grazing or cereals cultivation on dry, low-yield marginal biomass production sites are displaced, the danger is considerably less than if moist sites with higher grass yields are affected. In this case, high additional greenhouse gas emissions may even be caused as an end result. The displacement of more extensive grazing may nevertheless reduce the advantages regarding global warming to such a degree that they no longer represent an acceptable relationship to the adverse environmental impacts. For example, these include adverse impacts on biodiversity, even though they cannot currently be quantified by means of life cycle assessment. The exploitation of sites with existing uses and scarce water resources should therefore be avoided as far as possible – even if they are marginal sites.
- **Reference products:** The advantages achievable by using perennial grasses depend heavily on which conventional products they replace. This is in turn influenced by market conditions, the political framework and investor decisions. Sensitivity analyses have

demonstrated that considerable differences in results can occur in almost all scenarios if the reference products are changed. However, advantages regarding global warming can be identified in all cases of the stationary energy use of biomass – assuming no other renewable energy carriers are replaced. It is therefore important that the political framework is developed such that more environmentally harmful conventional products are replaced first. In terms of the replaced reference products, the degree to which uncertainty influences the choice of use options is discussed in Section 6.3.

- The **sequestration of carbon in soils** is a particular site-specific effect, which was also considered in this study due to its relevance for global warming. Whether and to what extent additional carbon can be stored in the ground by cultivating perennial grasses, for example in the root system, depends heavily on local conditions and is currently the subject of controversial debate among experts. However, even making generous assumptions the influence on global warming is minor, for example compared to fossil fuel savings. Carbon sequestration cannot therefore serve as a decisive argument for cultivating perennial grasses.

6.3 Conclusions: Comparison of the different OPTIMA scenarios

The investigated pathways incorporate various biomass provision options and various options for its use. These options can generally be freely combined, because the intermediate biomass pellet product is highly versatile. Below, therefore, the biomass provision options are first compared, followed by the use options.

In terms of **biomass cultivation**, decisive differences in the results primarily arise from the differences in yield and nutrient content, and the associated fertiliser and water demand. The conclusions are based, in particular, on the following individual results:

- **Miscanthus** displays both a high yield and a low nutrient content. If used in large CHP plant this can even lead to achieving major environmental advantages without significant disadvantages in other analysed impact categories. This is very unusual for bioenergy and can therefore be recommended without restriction given a suitable local environmental framework.
- Because of the yield, **giant reed** can achieve similarly large advantages regarding global warming as Miscanthus, although different harvesting techniques and a higher water content make an energy-intensive conditioning necessary. However, this necessitates an adapted and specifically optimised biomass drying strategy with the use of as little non-renewable energy as possible. In turn, however, giant reed causes substantial environmental disadvantages in other impact categories, because of the high nutrient content compared to other perennial crops, which currently offers no prospect of reduction. Where possible, Miscanthus should therefore be given priority.
- **Cardoon and switchgrass** display slightly lower yields, and thus environmental advantages, than Miscanthus and giant reed. Robust differences between switchgrass

and cardoon cannot be derived from this scenario analysis. In terms of their nutrient content and the associated disadvantages, they lie between giant reed and Miscanthus. No environmental advantages can be identified compared to Miscanthus. There are minor advantages and disadvantages compared to giant reed. However, per tonne of dried biomass or a given product quantity, the advantages and disadvantages of the three crops are comparable in the majority of impact categories, with certain benefits for cardoon, in particular in terms of global warming and non-renewable energy use. In addition, cardoon displays water demand benefits. In contrast, giant reed requires less cultivation area but causes substantially larger nutrient input into water bodies.

Miscanthus therefore proves to be **the most environmentally friendly crop** in this investigation. If Miscanthus cultivation is not possible, climate protection can also be achieved by the **alternatives giant reed, cardoon and switchgrass.** However, **larger environmental disadvantages in other impact categories** must be accepted for those crops. If, in a necessarily subjective weighting of the advantages and disadvantages, the decision falls in favour of climate protection, giant reed should be preferred, because the greatest effect can be achieved on a limited area. However, the to-date less studied and less optimised crop cardoon displays great potential as an additional alternative crop if the yields can be improved or additional specific benefits can be exploited, e.g. by application of harvesting technologies to separate the oil containing seeds from the rest of the biomass in order to produce an oil-based liquid fuel. At biomass production sites with high drought stress and no environmentally compatible irrigation options, cardoon may even be the only energy crop cultivation option due to its particular resistance to drought.

In terms of the **use options**, stationary energy generation is considerably more beneficial among the conditions investigated than conversion to 2nd generation ethanol, 1,3-PDO or biochar, meaning that biomass should primarily be used for stationary energy generation. The following decisive boundary conditions lead to this result:

- No material use options that maintain and productively utilise the high-quality components of biomass, such as fibres or lignin, were investigated. In this case even a more energy- and / or material intensive conversion process may be highly beneficial. However, such processes are not optimised for the investigated biomass types and are barely used even with established biomass, or still require substantial development prior to industrial-scale deployment.

- In order to facilitate comparison among use options, pellets were defined as intermediate feedstock product for conversion necessitating technical drying of biomass prior to pelleting. For the default scenarios, this implies disadvantages for the use options 2nd generation ethanol and 1,3-PDO compared to other use options investigated because moist bulk material might be an appropriate feed material, partially making conditioning redundant.

- Currently, an additional function of biochar as a soil improver cannot be relied upon. This option therefore causes numerous disadvantages, as discussed in Section 6.1. Moreover, under the majority of conditions the achievable advantages regarding global warming are less than those for the energy use options, meaning that conversion to biochar is not recommended under these boundary conditions.

- The environmental impacts of power and heat from conventional generation remain so high that their replacement provides the greatest environmental advantages. Unavoidable conversion losses also cause that 2nd generation ethanol and 1,3-PDO are at a disadvantage in comparison. However, in future it will be possible to provide power and heat predominantly from other renewable sources, which is only possible to a limited degree for fuels and chemical products. From an environmental perspective, as long as substantial shares of heat and in particular power are produced from coal or oil, bioenergy carriers should thus be utilised as an alternative in these fields.

To the same degree that power and heat are saved in future, or can be provided by other renewable sources, biomass can be utilised for other purposes such as conversion to 2nd generation ethanol and 1,3-PDO. However, some of these processes must be considerably optimised in order to achieve robust environmental advantages under practical conditions.

Stationary energy uses in comparison

Which of the stationary energy use options achieves the best results depends on how efficiently which conventional energy carriers are replaced. In terms of power generation, in particular, this depends on a wide range of regulatory, political and economic boundary conditions. It is particularly beneficial when conventional large heating plants, for example as used in industry, are replaced by biomass CHP. The biomass is efficiently utilised thanks to the additional power generation and more non-renewable energy carriers are replaced. However, the advantages are more minor in nature if a biomass-fired CHP plant is built instead of a natural gas-fired CHP plant, among other things because natural gas-fired CHP plants can achieve higher efficiencies. Given the same site, therefore, the boundary conditions are decisive. Regardless of this, biomass utilisation in CHP plants sets the scene for the future, because industrial heat demand often cannot be reduced by more than a certain degree by implementing efficiency measures, nor be provided by other renewable sources such as solar thermal, as a result of required temperature level and availability. Combined and heat and power production in smaller facilities is almost as beneficial, even if the high efficiencies, and thus benefits, cannot be achieved. Co-firing of biomass in coal-fired power plants is controversial. In the short term, the highest environmental advantages per tonne of biomass can be achieved here. However, biomass co-firing should not be allowed to serve as an argument for switching off coal-fired power plants at a later date, or even building new ones, because even other fossil-fuel power plants, such as natural gas power plants, are more environmentally friendly than coal-fired power plants with biomass co-firing. What's more, creating a high demand for biomass provides an incentive for also using non-sustainably produced biomass, which may eradicate the original environmental advantages.

The other end of the spectrum of direct energy use results from the use of biomass pellets for domestic heat, where otherwise an efficient natural gas-fired central heating system would have been installed. Despite the lower efficiency, clear and robust advantages regarding climate change and energy savings can be achieved here, but greater disadvantages in other impact categories must also be accepted. In addition, the heat demand in the majority of residential properties could be drastically lowered by refurbishment, which, from an environmental perspective, should be preferred to the use of limited-availability biomass.

Converting biomass pellets to upgraded pyrolysis oil and its subsequent stationary energy use in the place of light fuel oil represents a further use option. Due to unavoidable conversion losses this option is only approximately as beneficial as direct energy use for domestic heat, but at least not foreseeably worse. Additional markets and savings potentials can be developed thanks to this option, if more efficient uses are already covered. If it is also technically possible to adopt UPO, without great additional effort, in mobile applications such as lorries or ships, this would massively increase future viability, because barely any renewable energy sources besides biomass are on the horizon here. Compared with conversion to 2nd generation ethanol, considerably fewer expenses and losses are involved, whereby the quality of the liquid energy carrier, however, is not comparable, at least currently.

Overall, then, direct use of the pellets for stationary energy generation is the most beneficial option under current conditions, and probably also in the medium term.

In summary, it can be said that the cultivation of perennial grasses on marginal land and their use in stationary energy generation, such as combined heat and power generation, can achieve substantial greenhouse gas emission mitigation and non-renewable energy savings for low additional other environmental impacts. Conversion into and use of 2nd generation ethanol, biochar or precursors for biopolymers, for example, show mixed results. Advantages are particularly high if crops such as Miscanthus, that have a low nutrient demand and can be harvested with a low water content to reduce energy intensive drying, are used. Where necessary, irrigation must be managed cautiously because it can cause high impacts and may not be justifiable at all depending on local water availability. Given the correct boundary conditions, bioenergy, in particular, can be generated with only minor environmental impacts from perennial grasses on marginal land. From an environmental perspective cultivation and / or use should therefore be supported, if necessary, under these boundary conditions, particularly including the efficient use and prevention of any competition for land and water.

Limitations:

A complete analysis of the following points is outside of the scope of this study and may require additional investigations:

1) **Implementability:** All scenarios are based on the assumption that it is technically feasible to implement them with the assumed efficiencies and adhering to all regulations, such as emissions limits. This implies that state of the art equipment is used, e.g. no old boilers. Even then, it is very likely that only mixed pellets can be used (see section 4.3). to fulfil technical specifications and emission limits. When adopting innovative use options, such as conversion to bioplastics, special challenges are anticipated. However, problems may still occur in relation to the combustion of grass pellets in technically far more mature domestic heating systems, because emissions limits could be exceeded and no options for complex exhaust gas treatment are available for smaller installations. Moreover, it may not be possible to use cardoon in existing thermochemical plants, for example in the production of pyrolysis oil. It is therefore possible that individual analysed scenarios cannot be implemented at all or only with modifications. However, this can only be determined through additional

research and development in the fields involved. It is therefore important that any implementation or promoting strategies are not currently tailored to individual measures or technologies, but that general boundary conditions for the sector are defined instead.

2) Currently, life cycle assessments cannot adequately represent **local and site-specific environmental impacts**, for example on flora, fauna, the soil and the hydrologic balance. Such environmental impacts are anticipated in the Mediterranean region, **in particular due to land use changes on the marginal sites**. Whether these are positive, negative or neutral, however, depends on the site (for example on the prevalent vegetation succession or the erosion hazard). However, general differences between land use changes in the Mediterranean region (mostly sparse vegetation, i.e. perennial crops with generally low local impacts) and in South America (partially very dense vegetation, i.e. annual crops with generally high local impacts) can be identified – including because the changes in the Mediterranean region will be smaller-scale than rain forest deforestation in South America. Therefore, local impacts are also assessed in a complementary study within work package 6 of the OPTIMA project for the biomass provision part of the life cycle using environmental impact assessment (EIA) methodology.
3) The additional benefits resulting from **bioremediation** cannot be quantified in this analysis. If the use of marginal land includes the cultivation of crops on chemically polluted soils then significant advantageous impacts on human toxicity and ecotoxicity are to be expected. Their extent depends on previous local soil conditions and concrete implementation conditions of the bioremediation measure. Hence, they cannot be quantified in generic scenarios. Furthermore, the primary function of crop cultivation may in such cases be phytoremediation and bioenergy may rather be a by-product. Therefore, the analysis of such impacts would require a dedicated assessment.

6.4 Recommendations

Whether the described potentials can be realised to create environmental benefits through the cultivation of perennial grasses on marginal land and their use in various applications depends on several stakeholder groups. Politics, industry and farmers are particularly influential. They can contribute to sustainable implementation of the assessed systems in particular in the following ways:

To politics:

Cultivating perennial grasses on marginal land can provide bioenergy with only minor environmental impacts. However, a number of boundary conditions must be adhered to. From an environmental perspective, cultivating perennial grasses on marginal sites should therefore be supported, if necessary from an economical perspective, taking these boundary conditions into consideration, in order to become established at a relevant scale. When developing the support programmes the following points should be observed:

- The use of marginal sites is not beneficial to the environment because of their quality (soil properties, etc.). Only truly unused sites are beneficial, because they cannot cause indirect land use changes. However, the majority of unused land is also located on marginal sites. Possible support programmes for industrially used, perennial grasses should therefore take previous use into consideration as a condition, rather than site qualities (“marginality”).
- In addition to land competition, water competition may also cause indirect land use changes, on top of local environmental damages. In regions where water is scarce supporting additional agricultural activities, such as cultivating perennial grasses, should be coordinated with the water use concept and the associated regulations. If such a concept does not exist we strongly recommend compiling one.
- From an environmental perspective there is no reason to exclude low-yield land in general, as long as local peculiarities such as a high ecological value do not oppose it and the biomass is efficiently used.
- Policy measures must ensure that biomass does not displace any more environmentally friendly renewable energy sources. In addition, energy saving measures, especially in buildings, should be preferentially supported.
- As long as a large proportion of power and heat is generated from coal and oil, efficient, stationary power and heat generation from biomass should be given priority support over other investigated use options for large-scale implementation. Because of long-term perspectives, support for research and development of other options is nevertheless recommended. If material uses of perennial biomass are established, for example maintaining and productively utilising high-quality biomass components such as fibres or lignin, the preference for stationary heat and power generation should be reviewed.

To industry:

- A concept detailing the supply of sustainable biomass must be presented for any plant using biomass. Otherwise high economical pressure to also use non-sustainably produced biomass results at times of low biomass supply.
- New plants for stationary energy use should be designed for heat demand instead of maximised power generation.
- Installing a CHP plant operating with perennial biomass should be considered for supplying industrial facilities with high-temperature heat, in particular.

To farmers:

- When selecting sites ensure that they were previously unused. If they are already extensively used, for example for grazing, they should not be converted to a different use unless other unused sites are available for the replaced existing use.

- Miscanthus should be preferentially cultivated if the site conditions are suitable. Cardoon should be examined as an alternative on dry sites. If giant reed is to be cultivated, the option of open air-drying the harvested crop on or at the field should be examined.
- Irrigation should be limited as far as possible. If still necessary and justifiable given local water availability, water- and energy-saving techniques should be adopted.
- Fertiliser application techniques and times should therefore be optimised to minimise fertiliser losses, in particular on permeable, sandy soils.
- The time of harvesting should be selected such that the biomass has a minimum water content.

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8 Annex

8.1 Normalisation

Table 8-1 EU 28 inhabitant equivalents (IE) for the year 2000.

Impact category	Notation this report	Inhabitant equivalent Hierarchist	
Climate change (ReCiPe) [Goedkoop et al. 2014]	Climate change	11,215	kg CO_2 eq. / yr
Ozone depletion [Ravishankara et al. 2009]	Ozone depletion	0.07	kg R11 eq. / yr
Photochemical oxidant formation (ReCiPe)	Summer smog	56.85	kg NMVOC eq. / yr
Particulate matter formation (ReCiPe)	Particulate matter	14.90	kg PM10 eq. / yr
Terrestrial acidification (ReCiPe)	Acidification	34.37	kg SO_2 eq. / yr
Acidification (CML) [CML 2015]	Acidification (CML)	49	kg SO_2 eq. / yr
Freshwater eutrophication (ReCiPe)	Freshwater eutrophication	0.41	kg P eq. / yr
Marine eutrophication (ReCiPe)	Marine eutrophication	10.12	kg N eq. / yr
Terrestrial eutrophication (CML)	Terr. eutrophication	6	kg PO_4 eq. / yr
Aquatic eutrophication (CML)	Aq. eutrophication	38	kg PO_4 eq. / yr
NREU: Non-renewable energy use [Eurostat 2007]	Energy use (NREU)	82.09	GJ / yr
Agricultural land occupation (ReCiPe)	Agr. land occupation	4,518	$m^2 \cdot yr / yr$

8.2 Data on agricultural systems

This section contains an overview of important agricultural data for the life cycle assessment. The cultivation of biomass is assessed in the way that full expenditures of crop cultivation are ascribed to the harvested crop based on a sustainable cultivation practise. This includes that nutrients replaced by fertilisation compensate the amount removed by harvest as well as emissions to air and water. They exceed the deposition of nutrients from the atmosphere (in case of nitrogen) [Müller-Lindenlauf et al. 2014].

Table 8-2 LCA input data on cultivation. Adapted from [Schmidt et al. 2015].

Parameter	Yield level	Unit	Miscanthus	Giant reed	Switchgrass	Cardoon
Cultivation life time	Each yield level	years	15	15	15	15
Seeds / Seedlings	Each yield level	kg / ha			5	4
		no / ha	10,000	10,000		
Nitrogen fertiliser	Marginal 2	kg N / (ha×year)	28	86	46	62
	Marginal 1		38	111	63	85
	Standard		39	112	66	93
Phosphorus fertiliser	Marginal 2	kg P_2O_5 / (ha×year)	11	42	11	14
	Marginal 1		16	60	16	21
	Standard		18	68	19	26
Potassium fertiliser	Marginal 2	kg K_2O / (ha×year)	58	220	13	112
	Marginal 1		102	385	22	196
	Standard		146	550	31	280
Calcium fertiliser	Marginal 2	kg CaO / (ha×year)	18	12	10	6
	Marginal 1		31	21	18	10
	Standard		44	30	25	14
Pesticides (sum of first and last year)	Each yield level	kg active matter / ha	2	2	2	5
Diesel for field work	Marginal 2	L / (ha×year)	53	63	48	40
	Marginal 1		58	75	50	43
	Standard		63	88	53	45
Water irrigated	Each yield level	m³ / (ha×year)	6,000	6,000	4,000	2,000*
Diesel for irrigation	Each yield level	L / (ha×year)	300	300	200	100*
Yield (fresh matter)	Marginal 2	t fm / (ha×year)	10	22	6	7
	Marginal 1		18	39	10	12
	Standard		25	56	15	17
Moisture content	Each yield level	%	20	55	15	15
Transport distance to conditioning	Marginal 2	km	30	30	30	30
	Marginal 1		30	30	30	30
	Standard		20	20	20	20
Storage loss	Each yield level	% dm	5	10	2.5	5

fm: fresh matter; dm: dry matter.

* Cardoon is intended for dry farming (see sections 4.1.1.4 and 5.2.1).

8.3 Additional results

8.3.1 Alternative impact assessment

As described in section 3.2.4, certain environmental impacts of the OPTIMA scenarios are assessed using the ReCiPe and the CML methodologies: acidification and eutrophication. Fig. 8-1 shows the results for Miscanthus used in small CHP.

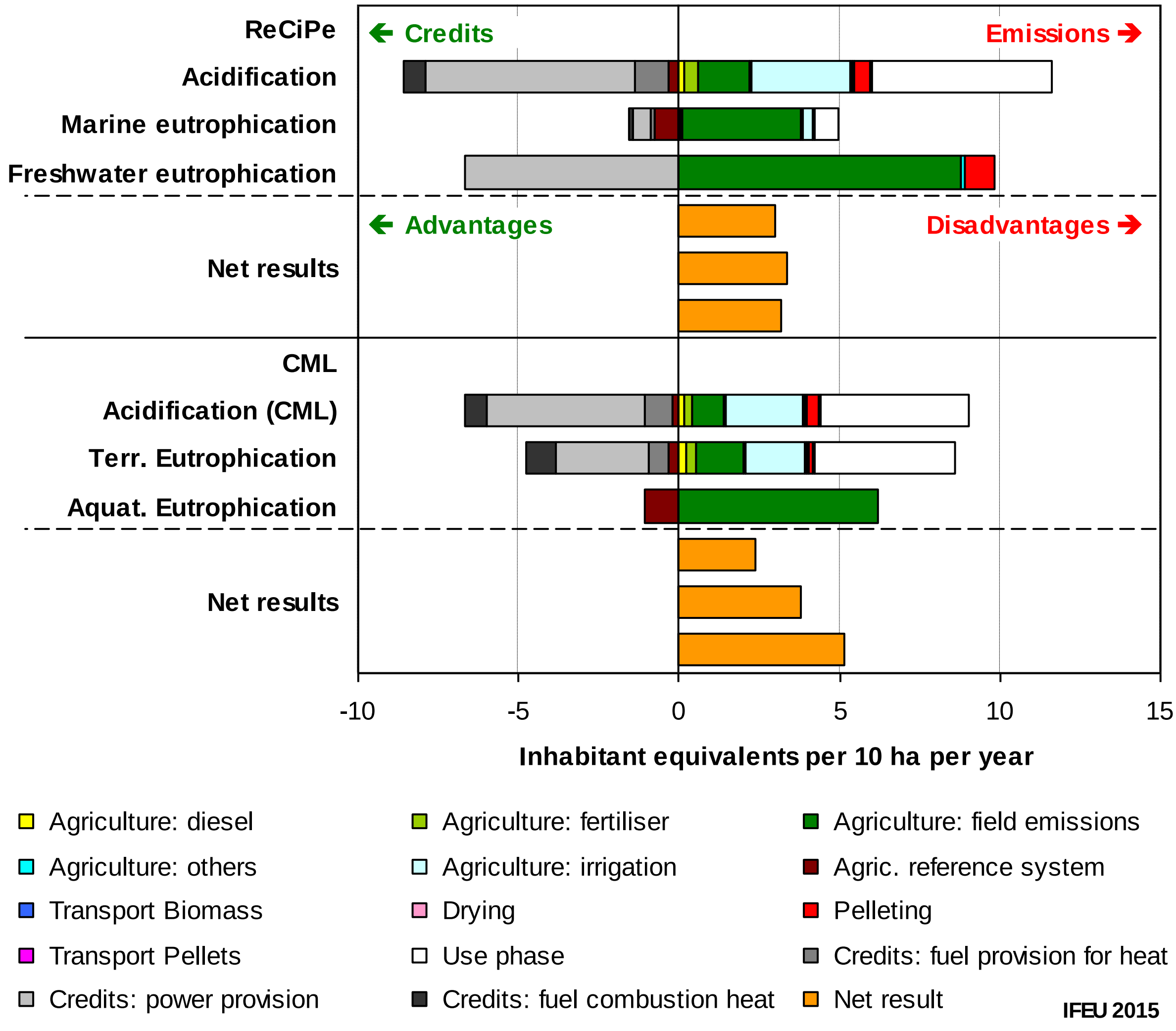

Fig. 8-1 Results for the impact categories acidification and eutrophication of the scenario “Miscanthus → Small CHP” according to the ReCiPe methodology and the CML methodology.

The results for acidification in the both methods are quite similar to each other, different mainly in scaling. For eutrophication, the results cannot be compared between the ReCiPe and the CML methodology since ReCiPe differentiates between two types of aquatic eutrophication, but does not consider terrestrial eutrophication, whereas CML calculates one aquatic and one terrestrial eutrophication.

8.3.2 Further sensitivity analyses

8.3.2.1 Diesel consumption in agriculture, pesticides and transport distances

Fig. 8-2 depicts the impact of a variation of the diesel and pesticide inputs for agriculture and the transport distances on the LCA results for selected impact categories. All related inputs are varied by a factor of 2, e.g. the transport distance from the biomass production site to the conditioning facility is increased / decreased from 20 km to 40 km and 10 km, respectively.

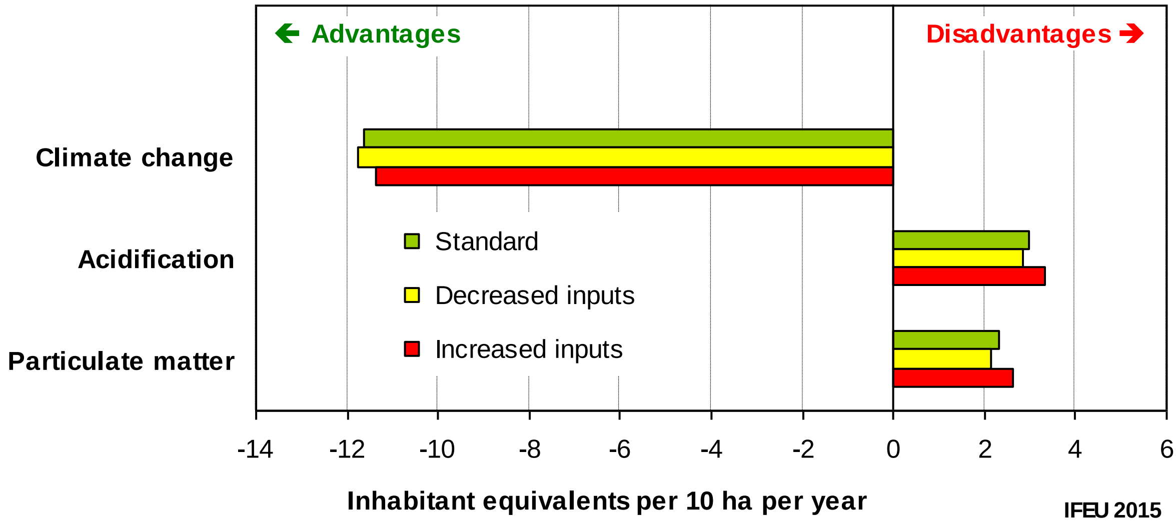

Fig. 8-2 Impact of varied diesel consumption in agriculture, pesticide input and transport distances on results for the impact categories climate change, acidification and particulate matter of the scenario “Miscanthus → Small CHP”.

Conclusion:

Diesel consumption for cultivation and harvest, pesticide input as well as transport distances have little influence on the LCA results. Optimisation efforts in other aspects may thus lead to higher improvements. Yet, impacts of pesticide use on local flora and fauna are not reflected in the applied standard LCA impact categories.

8.3.2.2 Drying

As depicted in section 5.4.2.1 for giant reed, open air-drying is the most promising option to reduce the energy demand related to drying. However, picking up the crops after open air-drying is related to biomass losses. Fig. 8-3 shows the impact of open air-drying on LCA results for the impact category climate change for the other investigated crops. For further information and an interpretation, please see section 5.4.2.1.

In addition, in order to show the strong impact that drying variations may have on the results of a complete scenario, Fig. 8-4 displays the impact of drying variations on the LCA results of 2nd generation ethanol produced from giant reed.

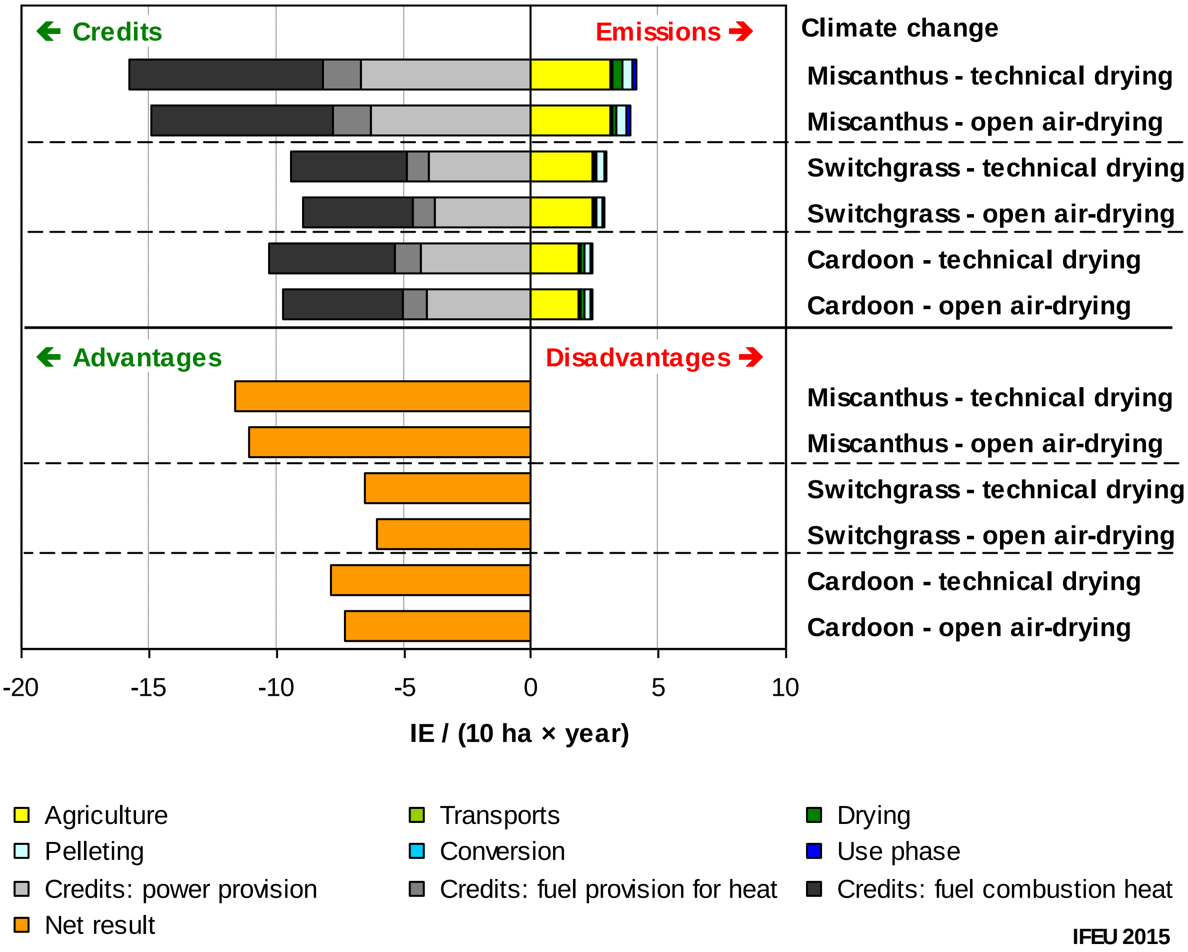

Fig. 8-3 Impact of open air-drying on the results for the impact category climate change of the scenarios "Miscanthus → Small CHP", "Switchgrass → Small CHP" and "Cardoon → Small CHP".

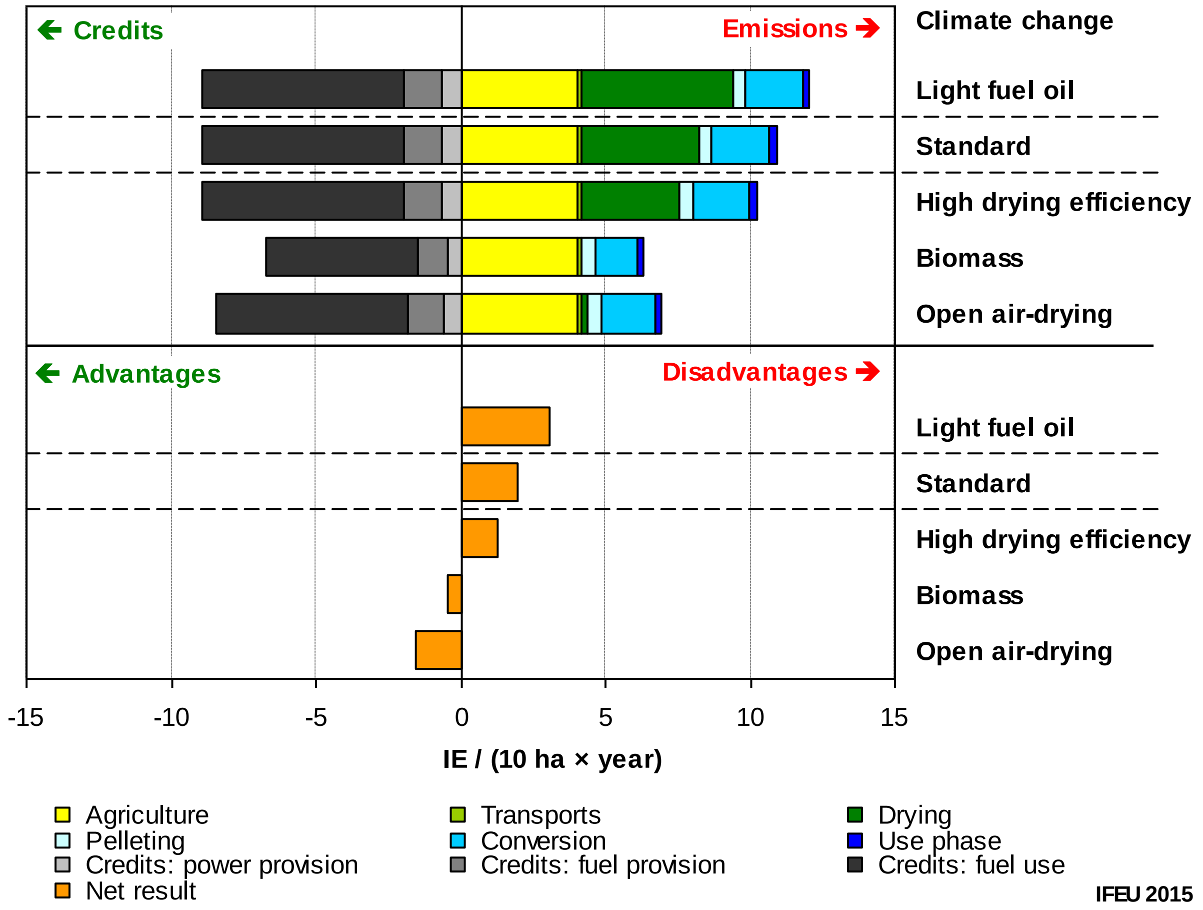

Fig. 8-4 Impact of varying energy carriers for drying, drying efficiency and moisture content prior to drying on the results for the impact category climate change of the scenario "Giant reed → 2^{nd} generation ethanol".

8.3.2.3 Co-firing

Fig. 8-5 shows LCA results for biomass use in a hard coal power plant compared to other use options. Technical parameters for this use option and an interpretation of Fig. 8-5 are given in section 5.4.3.6.

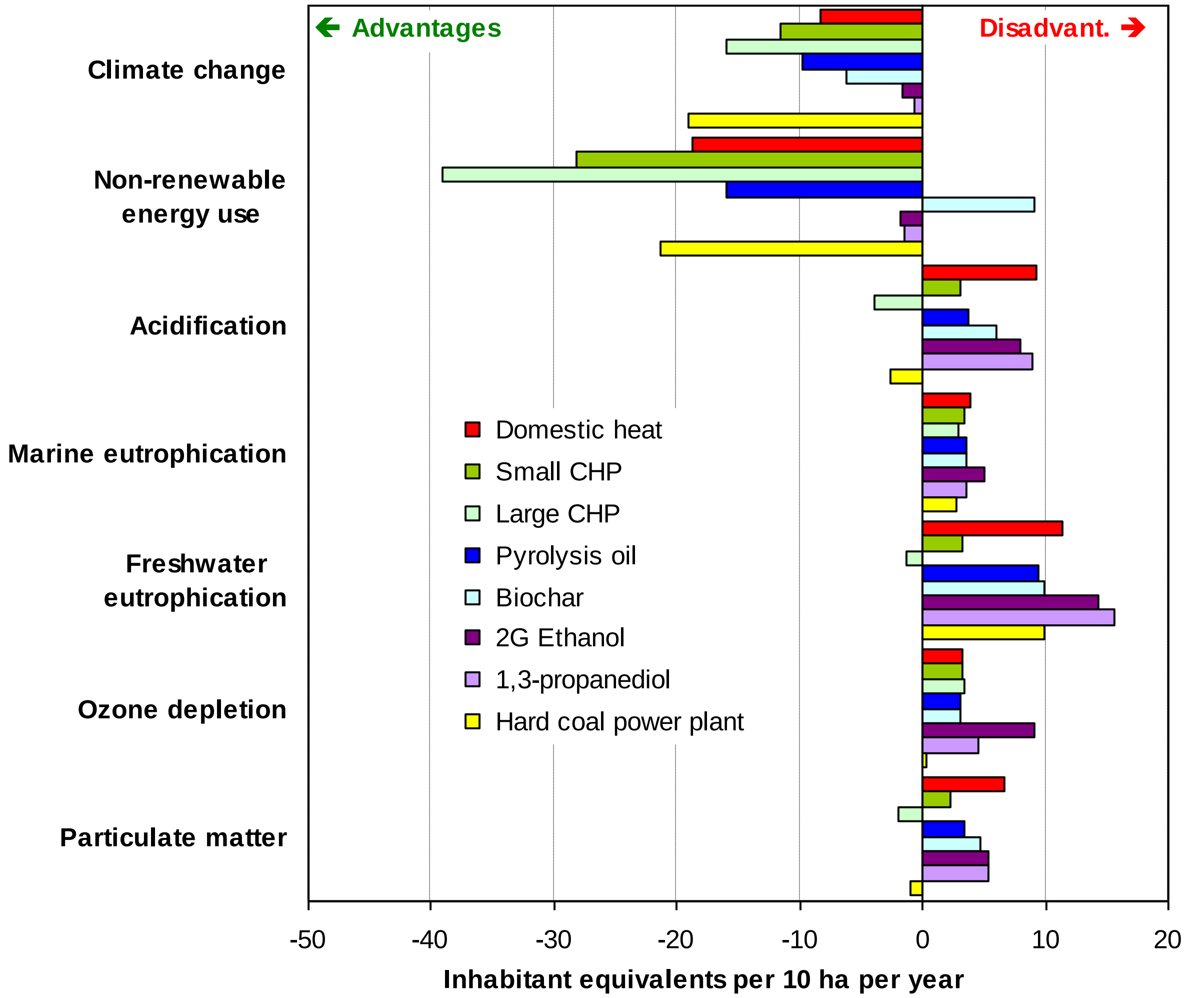

Fig. 8-5 LCA results for the use option “co-firing for power generation in a hard coal power plant” compared to other use options at standard conversion efficiency based on the cultivation of Miscanthus (yield level “marginal 1”). Adapted from: [Schmidt et al. 2015].