Integrated sustainability 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

Background

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, the sustainability of biogenic products (bioenergy and bio-based products) produced from perennial grasses, cultivated on marginal land in the Mediterranean region, was investigated.

Scientific approach

This study considers the entire life cycle of the products from cultivation through conversion and on to utilisation (and disposal, where applicable) and is based on generic scenarios, modelling technologies maturing in the future and processes in 2020. For the 28 scenarios in total, four crops with seven utilisation options were combined, whereby in all scenarios drying and pelletisation were adopted following the biomass harvest:

- Crops: giant reed, Miscanthus, switchgrass or cardoon.
- Products: domestic heat, combined heat and power (large or small CHP), upgraded pyrolysis oil, 2nd generation bioethanol, biochar or 1,3-propanediol.

The bioenergy or bio-based products are then compared to conventional, generally fossil fuel-based energy or products, which have also been balanced through their entire life cycle. These scenarios were evaluated based on 30 selected indicators from the fields of technology, the environment, the economy and society. Optimisation options were also derived from the results. In addition to the sustainability of the scenarios themselves, barriers to the implementation of these scenarios in their studied forms, either in their entirety or which may lead to less sustainable implementation, were investigated.

Results

Perennial grasses grown on previously abandoned land in the Mediterranean region provide potentials for climate change mitigation and social benefits in rural areas in particular. Abandoned land does not need to be ‘marginal’ in terms of biophysically inferior properties to entail such benefits, but the achievement of the OPTIMA project is to bring low-quality, previously abandoned land into production by adopting selected crops and agricultural practices. If use options such as efficient stationary energy generation are chosen, benefits can be achieved which are associated with minor other negative environmental impacts. This is a big advantage compared to many other bioenergy pathways, and in some cases even economic profits are attainable.

However, several boundary conditions must be met:

- Only idle (unused) marginal land without high biodiversity value should be cultivated to avoid harmful direct and/or indirect land use changes.
- Irrigation may not contribute to local water shortages with indirect effects on other water users.
- Risks must be managed and shared along the whole added value chain to increase yield stability, reduce production downtimes and limit potential losses for single stakeholders, in particular farmers.
- Several processes from agriculture to biomass use still need to be brought to technical maturity.
- Biomass should be used for efficient, stationary energy generation (as detailed above) until boundary conditions for the assessed innovative use options improve substantially or other, better options are found.

If the above is the case, the use of abandoned marginal land for bioenergy is largely safe from a sustainability perspective. Other assessed use options may also be sustainable in certain settings under altered conditions, which will require further specific analyses.

Further optimisation of the cultivation of perennial grasses on marginal land is therefore necessary, but also possible, and altogether a promising option. However, the great advantage of perennial crops, resulting from the long plantation lifetimes of 15 years and more, also means that long-term research, development and pilot projects must be carried out and financed. Some specific crop characteristics allow for specialty applications, in which cultivation itself may serve environmental protection purposes (erosion protection, phytoremediation, capturing nutrients). Moreover, under certain conditions and given appropriate technological maturity, profitable use options are available even without funding, such as co-firing grass pellets in existing biomass-fired CHP plants or pellet-fired domestic heating systems. These should be utilised in pilot projects.

Thus, the cultivation and use of perennial grasses on abandoned marginal land can lead to substantial overall gains in sustainability if promoted and managed properly by politics, stakeholders and developers in science as well as in businesses.

2 Introduction, goal and scope

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 sustainable *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 2011] 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. In this report on integrated assessment of sustainability, the results of all separate assessments of individual sustainability aspects are combined into an overall view on sustainability.

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 are to 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?

For clarity, these questions are not addressed one by one but the answers are part of the overall discussion of results.

3 Methodology

3.1 The ILCSA approach

This integrated assessment of sustainability follows the methodology of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015]. The ILCSA procedure follows the principle of life cycle thinking and builds on and extends the procedure defined for LCAs in ISO standards 14040:2006 and 14044:2006 [ISO 2006a; b]. It addresses impacts on sustainability 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). The goal of ILCSA is to provide comprehensive ex-ante decision support from a sustainability point of view in the process of establishing new technologies, processes or products.

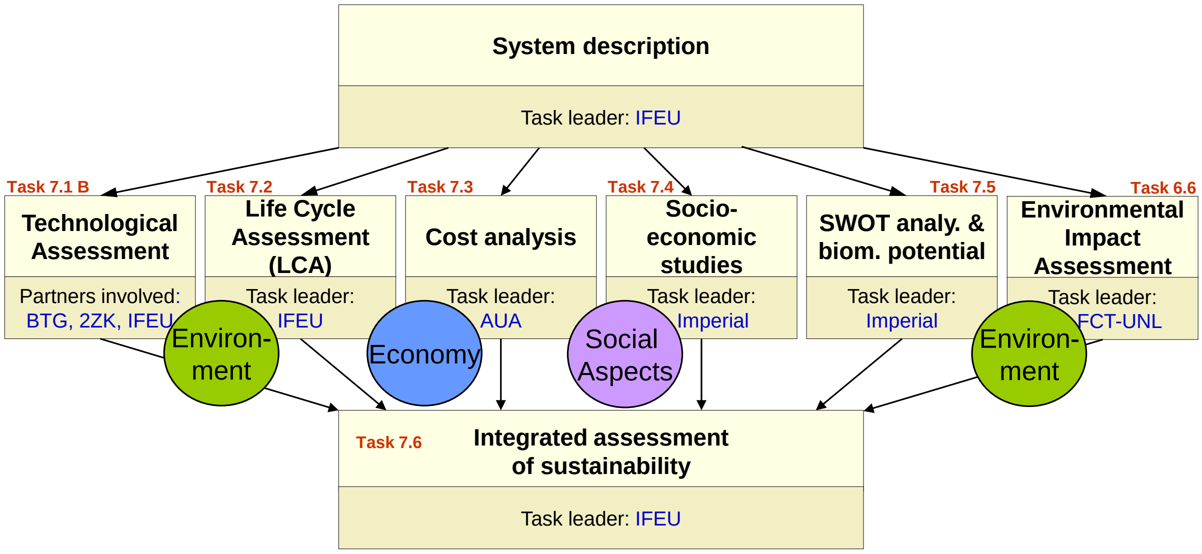

Fig. 3-1 Structure of the integrated life cycle sustainability assessment in OPTIMA .

As outlined in Fig. 3-1, a common set of scenarios is subjected to an assessment of various aspects of sustainability based on the same settings and definitions. Indicators and results from these separate assessments are subsequently combined to form an overall picture. The assessment procedure can be divided in three steps:

1. **Definitions and settings**
   Common definitions and settings are specified that apply to all parallel assessments of the various sustainability aspects to ensure the compatibility of results. This includes goal and scope questions (chapter 2), descriptions of assessed scenarios (chapter 4) and further definitions and settings (chapter 3.2). Importantly, scenarios depict potential future implementations of mature technology, i.e. the alternatives relevant to strategic decision making, not the current status of development.

2. **Parallel assessment of various sustainability aspects**
   The assessments include impacts on environment, economy and society (chapters 5.2 to 5.5), which are commonly referred to as the three pillars of sustainability. The implementation of scenarios that are found to be sustainable in a sustainability assessment may however still cause unexpected and sometimes undesirable consequences if they cannot be implemented in the intended form[1] or if operations stop after a short time[2]. To increase the value for decision support, the scenarios are additionally assessed for several barriers that could hinder their implementation in the intended form. In this study, the barrier analysis includes technological aspects, biomass potentials and a SWOT analysis (chapters 5.1 and 5.6).

3. **Result integration**
   A dedicated procedure has been developed to join all assessment results into an overall picture and derive conclusions and recommendations for decision support. See chapter 3.3 for a detailed description and chapter 5.7 for the results.

For a detailed description of the ILCSA methodology and its advantages over LCA or life cycle sustainability assessment (LCSA) please refer to [Keller et al. 2015]. The parallel assessments of various sustainability aspects within the framework of this ILCSA study have also been published in separate reports [van den Berg, de Jamblinne, et al. 2015; Fernando, Boléo, Barbosa, Costa, & Duarte 2015; Panoutsou 2015a; b; Rettenmaier et al. 2015; Soldatos & Asimakis 2015]. Please refer to these reports for further details and for the descriptions of specific methodologies used.

3.2 Definitions and settings

This chapter specifies the common definitions and settings that apply to all parallel assessments of the various sustainability aspects. Further definitions and settings can be found in the separate reports on these assessments [van den Berg, de Jamblinne, et al. 2015; Fernando, Boléo, Barbosa, Costa, & Duarte 2015; Panoutsou 2015a; b; Rettenmaier et al. 2015; Soldatos & Asimakis 2015].

3.2.1 Goal definition

Intended applications and goal and scope questions

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

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[1] Example: Unsustainable biomass is used in an efficient combined heat and power plant because of shortages in sustainable biomass supply and economic pressure.

[2] Example: Plantations are established but the only customer goes bankrupt.

- Comparisons of specific cultivation systems, which are potential results of ongoing production systems development, and biomass use options
- Identification of key factors for sustainable 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 chapter 2.

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).

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

All life cycle comparisons, e.g. between biogenic and fossil products, are based on equal function 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 ha · a or 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 sustainability assessment 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).

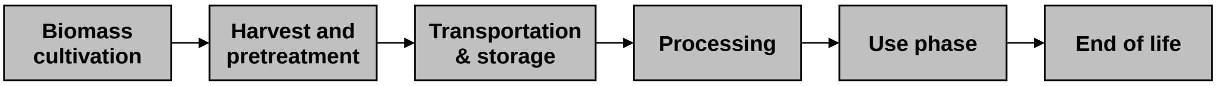

Fig. 3-2 System boundaries applied in the case of OPTIMA

Assessed systems

Assessed systems are described in chapter 4.

3.2.3 Settings for system modelling

System modelling in ILCSA refers to a part of the life cycle inventory analysis (LCI) step known from LCA. It is quantitative modelling of foreground processes, which is common for all assessments of individual sustainability aspects (including e.g. complete mass and energy balances for any unit process). Its settings are described in this section. System modelling is followed by the generation of impact-specific inventories from those models for each assessment methodology (e.g. yielding primary energy demand for LCA or energy costs for LCC). The settings for this step are specific for each methodology and thus not described here.

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, e.g. 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 ILCSA of OPTIMA systems requires a multitude of data. Primary data is obtained from the following sources:

- Data on biomass cultivation, yields and irrigation stem from OPTIMA partners and have been cross-checked with literature data. All other data on cultivation, e.g. the amount of fertiliser input stem 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. Sources for secondary data such as prices of or emissions related to process inputs are specific for each used assessment methodology.

3.3 Result integration

3.3.1 General approach

There are two general options to integrate a multitude of indicators on certain scenarios:

Weighting and mathematical integration

All indicators could be mathematically combined into one score using weighting factors or ranked otherwise according to a weighting algorithm. These approaches, in particular the required weighting factors or schemes, cannot be entirely based on scientific facts but depend on personal value-based choices defined beforehand. Furthermore, conflict situations do not become apparent and decisions regarding these conflicts depend on weighting factors, which are hard to understand for decision makers not involved in the study. Therefore, this approach is not applied.

Structured discussion

All strengths, weaknesses and conflicts of the options can be discussed verbally argumentatively. This can make conflicts transparent and enable their active management. Considering the amount of options and indicators, this requires a structured approach. This approach is followed in this study. This section describes the methodology used for the structured comparison and presentation of decision options based on a multi criteria analysis.

3.3.2 Collection of indicators and results

Indicators and results for all scenarios are provided by the parallel assessments of various sustainability [van den Berg, de Jamblinne, et al. 2015; Fernando, Boléo, Barbosa, Costa, & Duarte 2015; Panoutsou 2015a; b; Rettenmaier et al. 2015; Soldatos & Asimakis 2015]. They are collected in overview tables. In some cases, indicators are selected or aggregated by the authors of the respective individual assessment to focus on the most relevant aspects for decision support.

The integrated sustainability assessment of this project is based on:

- 4 semi-quantitative and 3 qualitative technological indicators
- 9 quantitative environmental indicators from life cycle assessment
- 4 semi-quantitative environmental indicators from environmental impact assessment
- 4 quantitative economic indicators
- 1 quantitative and 3 qualitative social indicators
- 4 qualitative indicators on further aspects from the SWOT analysis

These are a subset of all possible indicators, which were assessed in previous steps of the sustainability assessment and found to be relevant for the decision process. No further adjustments are made except for rescaling quantitative data to a common basis if necessary. Thus, all specific settings, methodological choices including underlying estimates, and data sources apply unchanged as documented in the respective reports.

For comparability to qualitative indicators, quantitative indicators are categorised and the table is coloured accordingly. Results are rated advantageous (green) if the assessed scenario is better than the respective conventional reference scenario and the difference is bigger than 10 % of the bandwidth of all results for this indicator under standard conditions. Disadvantageous results are rated analogously and the rest is rated neutral. Economic indicators are categorised individually because indicator results have different meanings for different perspectives (e.g. household for domestic heating or utilities industry for large-scale CHP). To be able to identify front-runner scenarios, indicator results are coloured alternatively according to the degree of deviation from the average of all OPTIMA scenarios.

Results are collected for all assessed main scenarios. Additional results such as from sensitivity analyses based on dedicated scenarios, which are only relevant for one aspect of sustainability, are not collected. Results from these very specific analyses, e.g. identified boundary conditions that are necessary to reach the environmental performance of a certain main scenario, are part of the result summaries in chapter 5. They are taken into account for the overall conclusions and recommendations presented in chapter 6.

3.3.3 Additional indicators

Climate protection under the condition of limited financial resources has to use the available financial resources as efficiently as possible. Efficiency means here to achieve the highest possible greenhouse gas (GHG) emission savings with the lowest monetary expenditures necessary for that. GHG abatement costs are frequently used as indicator for this purpose. GHG abatement costs are defined as quotient of the differential costs for a GHG reduction measure and the avoided GHG emissions by this measure.

In analogy to GHG abatement costs, similar additional efficiency indicators can be defined for other quantitative sustainability indicators. In this case, such indicators are available from the screening LCA like for example acidification (basis for acidification abatement costs) or resource depletion (basis for non-renewable energy savings costs). The same methods apply for those indicators as discussed in the following for the example of GHG abatement costs.

GHG abatement costs are used for microeconomic decisions as well as for the decisions in energy policy. Microeconomic decisions are always based on business analyses. If political decisions like the implementation of support programmes are concerned, the valuation is often more difficult, as the macroeconomic dimension, possible external effects as well as second- and third-round effects have to be considered. For the determination of GHG abatement costs, different methodological characteristics have to be considered concerning:

- The determination of a reference, which is e.g. for biofuels the use of fossil fuels.
- The inclusion of different cost items (e.g. full costs vs. additional costs).
- The inclusion of temporal dynamics of systems under consideration (e.g. developments of investment costs of systems, of prices for energy carriers, etc.).
- The different perspectives – especially microeconomic and macroeconomic approaches.

However, it is important to keep in mind that GHG abatement costs do not integrate the information of the original indicators (climate change and costs or profits of involved businesses) but provide additional information. They indicate the efficiency of reaching a certain target (e. g.: How expensive is it to avoid greenhouse gas emissions?) but not the efficacy of reaching it (e. g.: How far can emissions be reduced?). Therefore, GHG abatement costs do not represent a single combined indicator but only one additional criterion. GHG abatement costs from a microeconomic perspective are calculated as follows:

$$\text{GHG abatement costs} = \frac{\text{costs} - \text{costs (reference)}}{\text{GHG emissions} - \text{GHG emissions (reference)}}$$

GHG abatement costs are expressed in euro per tonne of CO_2 equivalents. Costs refer to the support in € maximally required to make an investment attractive (i.e. to reach an expected rate of return of 25 % without green premium product prices unless specified otherwise) and GHG emissions expressed in CO_2 equivalents.

One methodological option is to discount the avoided GHG emissions for the calculation of the abatement costs as well, in order to create a preference for temporally preceding measures. Otherwise a later implementation of the measure could be reasonable for decision makers. Moreover, a discounting reflects an assumed uncertainty about the degree and the time point of the environmental impact.

$$GHG\,em - GHG\,em(benchmark) = \sum_{t=0}^{n} \frac{\Delta GHG\,em(t)}{(1+i)^t}$$

Generally, a discounting of the environmental costs results in higher GHG abatement costs as without discounting. However, for further calculations in this study it is assumed that the discounting is neutralised by the fact that the environmental impact increases parallel to the so called social preference rate. The social preference rate consists of the time discounting and the growth accounting [Fankhauser 1995; IPCC 1996; Nordhaus 1994]. Therefore, the method without discounting is used.

As GHG abatement costs represent an efficiency indicator, they are only defined in the case that the primary goal is met, this is, that there are greenhouse gas emission savings by the process under investigation compared to the benchmark. If the goal is not met, one obviously cannot define an indicator on how efficiently the goal is reached. This means, the GHG abatement costs can be interpreted or not depending on the results of the numerator and the denominator.

Table 3-1 shows that out of nine possible result options only two allow an interpretation of the abatement costs. If negative abatement costs occur it has to be reconsidered if this results from the lower total costs or from the possibly higher emissions. Differences approaching zero make a calculation of abatement costs impossible. If two differences are compared to each other, it can lead to disproportionately high influences of uncertainties. This is especially the case if either the emissions or the costs of the compared pathways are very similar. If for example the GHG emissions of the two pathways differ by 10 % then a 5 % error of estimating these emissions can lead to a deviation in GHG abatement costs of 100 %. Furthermore, small emission savings mathematically lead to very high and at the same time very uncertain abatement costs. Therefore, abatement costs are only then a reliable indicator if the uncertainties of emissions and the costs are small compared to the respective differences between the pathways.

Table 3-1 Different result options for the calculation of GHG abatement costs (modified from [Pehnt et al. 2010]).

Δ profit **Δ emissions**	**> 0**	**≈ 0**	**< 0**
< 0	Calculation possible (less costs than for reference)	No calculation possible	Calculation possible
≈ 0	No calculation possible	No calculation possible (similar systems)	No calculation possible
> 0	No GHG abatement (not defined)	No GHG abatement (not defined)	No GHG abatement (not defined)

The second limitation is that abatement costs are very prone to changes in the course of time because they can generally be very sensitive to changes as discussed above and they depend on the technological developments as well as market changes for two different systems. Therefore, it is especially important only to compare abatement costs if they are determined for the same timeframe and under the same conditions. This makes it difficult to find comparable abatement costs outside of this study although there is plenty of data on abatement costs in literature. This especially applies to analyses of technologies not yet implemented for a timeframe more than a decade ahead as it is the case in this study.

Taken together, abatement costs for environmental burdens such as greenhouse gas emissions can help to decide how mitigations of environmental burdens can be reached for the lowest price or even with profits. However, abatement costs have to be interpreted carefully because in many situations their robustness and comparability are poor.

For further details and a critical review of the method see [Pehnt et al. 2010].

3.3.4 Benchmarking

The benchmarking step compares all scenarios to one benchmark scenario. This serves the purpose to answer questions such as “What are the trade-offs if the economically most favourable scenario would be implemented?”. Benchmarking tables focus the attention on one decision option and deliver additional information on the robustness of differences.

The benchmark is chosen according to the questions to be answered and the respective perspectives of various stakeholders. Depending on the question to be answered, overview tables may contain all or a part of the indicators and scenarios. The unit of reference underlying the comparison of quantitative indicators is chosen according to the question.

A subsequent categorisation of the benchmarking results reflects the robustness of advantages or disadvantages over the benchmark. For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question whether a scenario performs better than the benchmark regarding a certain indicator. Therefore, these quantitative differences are categorised into very advantageous [++], advantageous [+], neutral [0], disadvantageous [-], or very disadvantageous. Two results are rated as not substantially different if the difference is below a threshold of 10 % of the bandwidth from the best results to the worst result among all scenarios regarding a specific indicator. The certainty of this rating is evaluated by additionally taking the bandwidth of the data into account. If the scenario under consideration achieves better results under less favourable conditions than the benchmark does under standard conditions, it is rated very advantageous [++]. If not, but all direct comparisons under identical conditions show better results than the benchmark, it is rated advantageous [+]. If there is no bandwidth available for the scenario under consideration, it is rated very advantageous [++] if it is better than the benchmark under favourable conditions. For all qualitative indicators, rating of differences is done analogously but without applying minimum differences.

3.3.5 Overall comparison

For an overall comparison, a verbal argumentative discussion of decision options is supported by structured tables containing overviews of original indicator results or benchmarking results. Benchmarking tables can be used to deduce further concrete recommendations that could not be based on the underlying individual indicators but at the same time cannot contain all information from the underlying assessments. The deduction of recommendations from overview and benchmarking tables therefore also requires further in-depth analyses of the contributions e.g. of life cycle stages or unit processes that lead to these results. Of course, all available information on individual contributions to all results cannot be displayed in one table. This step, however, is not performed by the reader but is provided as background information in the discussion (e.g.: Differences A, B and C, which become apparent in benchmarking table, are caused by the input of substance X in process Y; therefore input X should be reduced as far as possible.). This way, overview and benchmarking tables provide additional insight, support the discussion, help not to miss any relevant aspect and make recommendations comprehensible.

4 OPTIMA scenarios

The following chapter is adopted from [van den Berg, de Jamblinne, et al. 2015]*. For details please refer to the original assessment report.*

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 within Task 7.1.2 in a common process for all parts of the sustainability assessment [Müller-Lindenlauf et al. 2012]. This section describes the investigated scenarios.

A set of main scenarios (pathways) combines the most relevant feedstocks, cultivation systems and processing pathways. These main scenarios are listed in Table 4-1 and described in detail below. Additionally, sensitivity analyses are assessed, which differ between the assessments.

Table 4-1 Overview of main and alternative scenarios.

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)

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). Technological performance of the investigated systems particularly depends 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.

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 4-2 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.

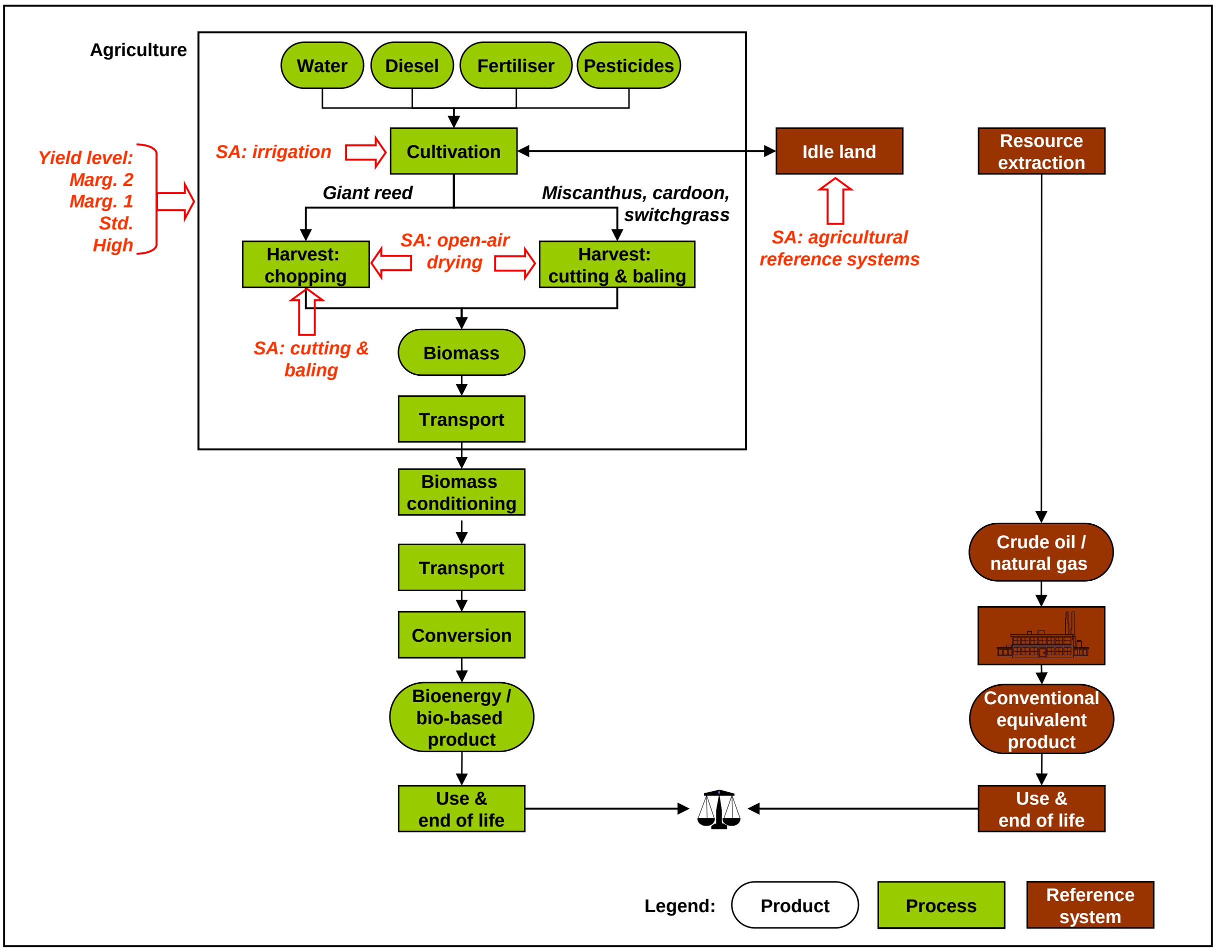

Fig. 4-1 Generic life cycle comparison scheme with focus on biomass production. Scenarios and sensitivity analyses are marked in red. Marg.: Marginal. SA: Sensitivity analysis. Std.: Standard.

Table 4-2 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 4-3 summarises important data on the agricultural system.

4.1.1.1 Giant reed (*Arundo donax* L.)

Giant reed is a C_3 grass[3], 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 silage 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

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[3] “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.

other crops. In contrast, its demand for nitrogen is high. Like Miscanthus, switchgrass is baled after harvest.

Table 4-3 Data on the agricultural system. 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 no / ha	 10,000	 10,000	5	4
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	m^3 / (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.

* Irrigation assumed for the purpose of environmental assessment even though this crop is intended for dry farming (see sections 4.1.1.4 and 5.2.2).

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.

4.1.2 Agricultural reference system

For the 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 further parameters and processes (see Table 4-4).

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 (see Part B of D 7.10 for further details).

Irrigation

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. This leads to considerable technology demand related to provision and application of water. However, in some parts of the Mediterranean region, irrigation may not be necessary due to sufficient rainfall.

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.

Table 4-4 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
	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 %

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 4-3), 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 pelleted 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 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 %, technical drying is still necessary though energy expenditures are lower.

With respect 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].

Pellets are subsequently transported to a conversion facility by truck. Fig. 4-2 summarises the process steps in the life cycle phase logistics and biomass conditioning and Table 4-5 lists the related sensitivity analyses.

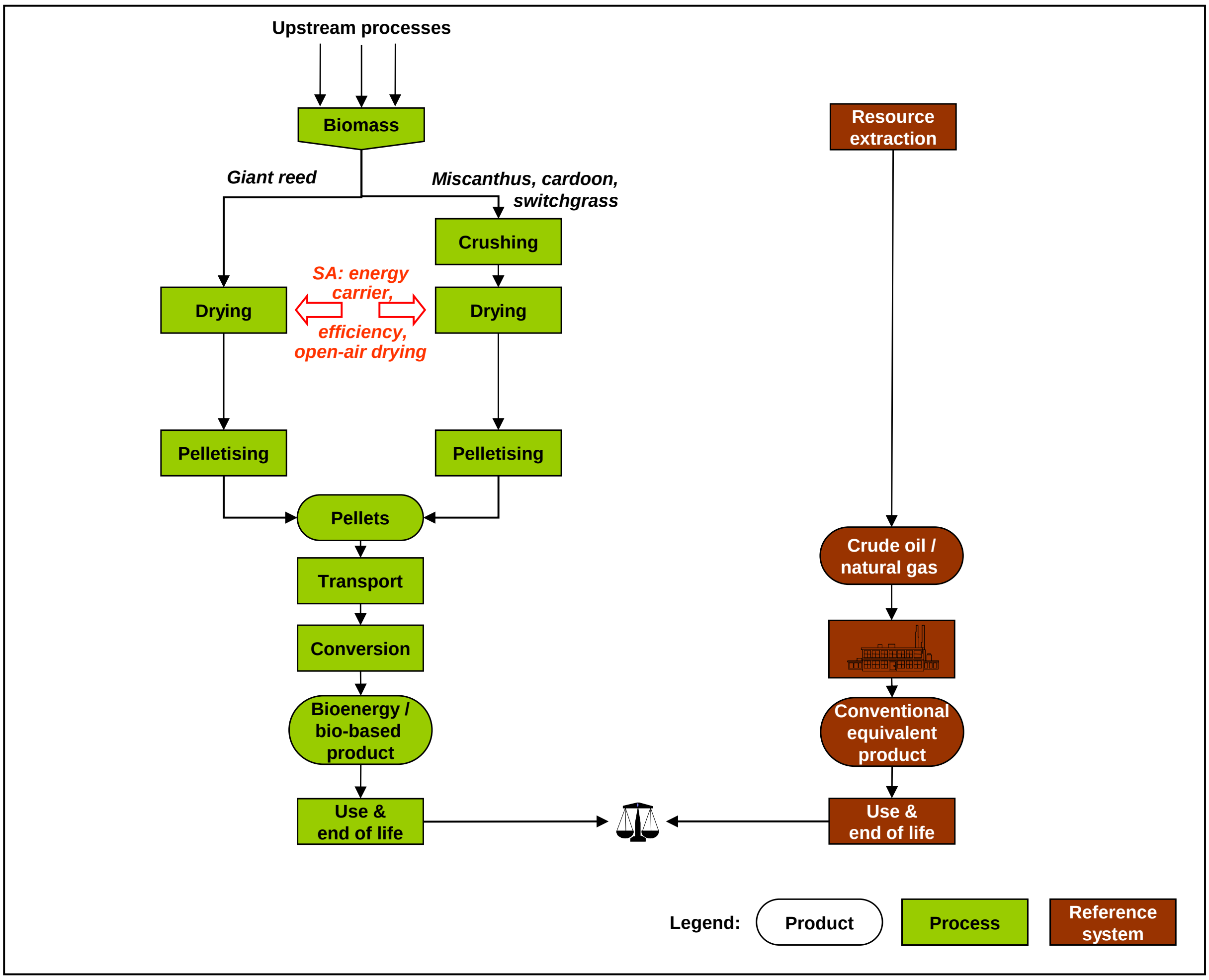

Fig. 4-2 Generic life cycle comparison scheme with focus on logistics and biomass conditioning. SA: sensitivity analysis.

Table 4-5 Overview of all sensitivity analyses and excursuses

	Varied parameters	**Possible settings (default in bold)**
	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 %
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

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). Each use option is explained in detail in the following sections 4.3.1 to 4.3.7.

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 4-6. Further varied parameters are summarised in Table 4-7. 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.

Transport distances from the pelleting facility to the conversion plant are set to the same generic values independent of the use option. However, transport distances depend on the conversion efficiency.

Table 4-6 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

Table 4-7 Overview of all sensitivity analyses and excursuses.

	Varied parameters	Possible settings (default in bold)
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	**Power mix** | coal | natural gas
	Carbon sequestration ratio for biochar	Low | **standard (std.)** | high

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. 4-3. 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[4]. 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 4-6). 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.

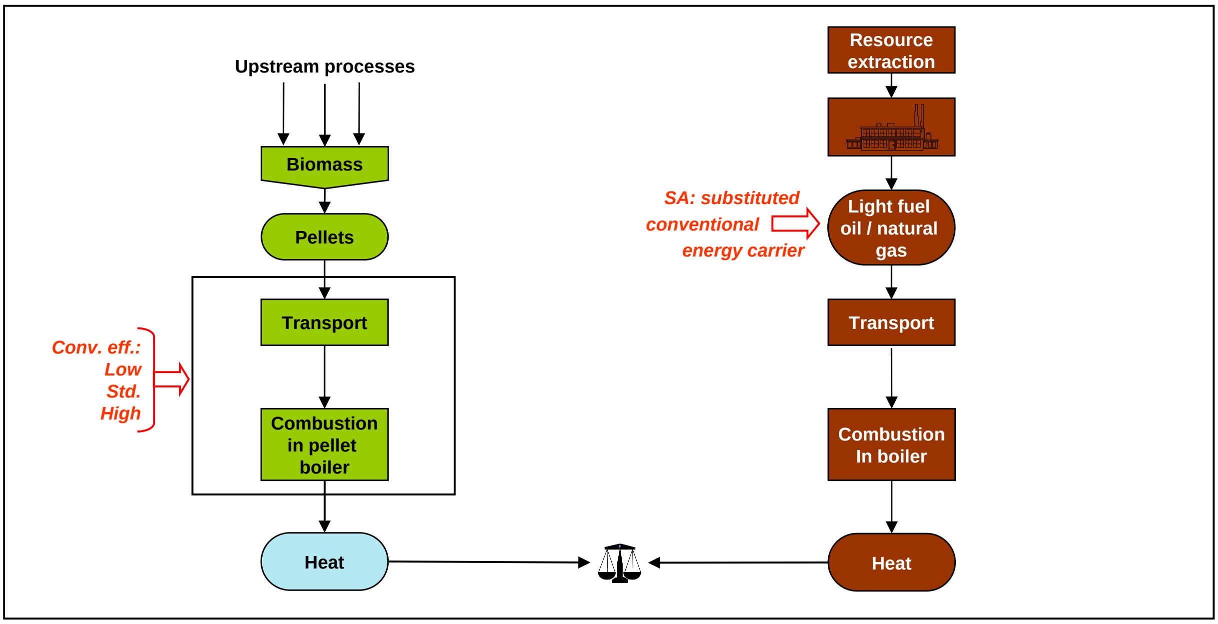

Fig. 4-3 Life cycle comparison scheme for the conversion and use option domestic heat. SA: Sensitivity analysis; Conv. eff.: Conversion efficiency; Std.: Standard.

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[4] 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. 4-4. 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.

Similar to the use option described in section 4.3.1, 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 sustainability assessment 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 4.3.1. Second, the substituted power mix is varied. This variation is conducted because the substituted power mix can have a strong influence on some sustainability assessment 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.

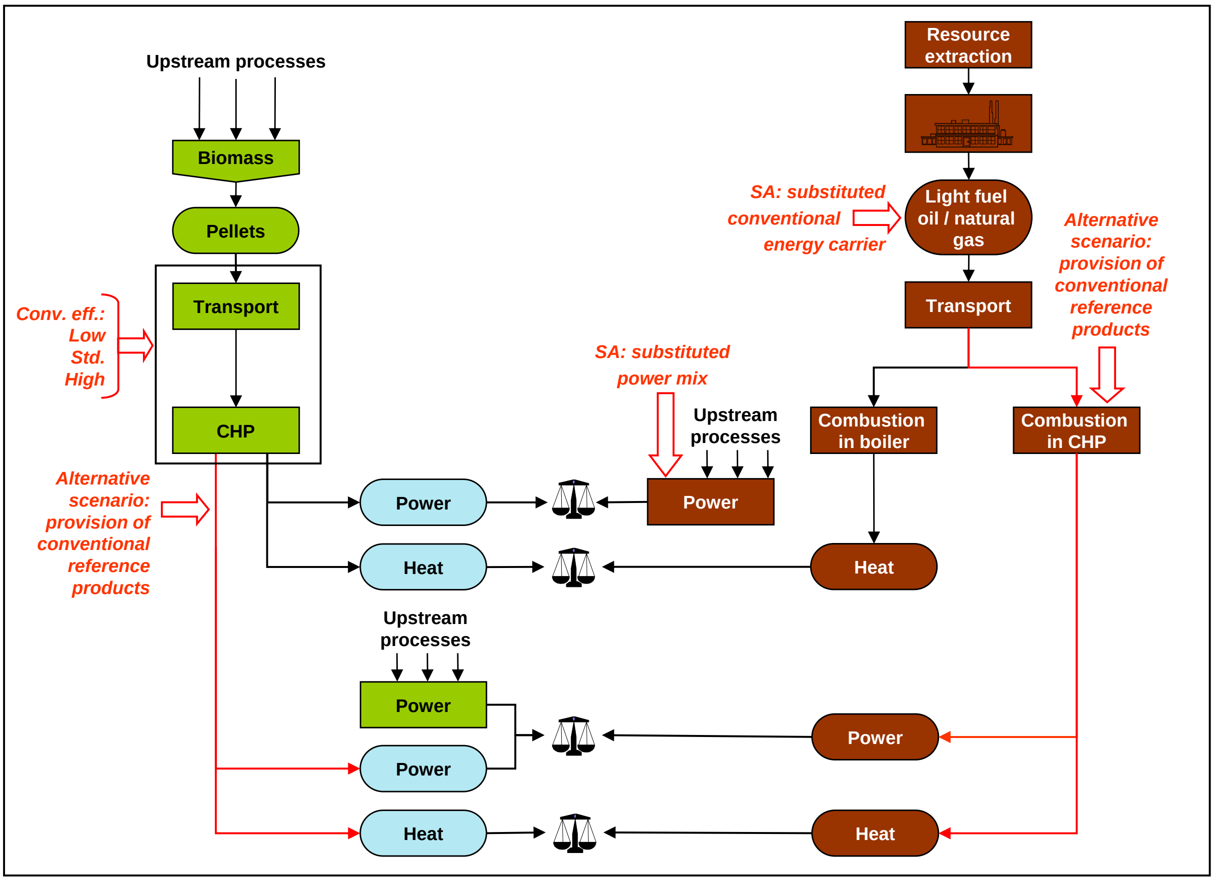

Fig. 4-4 Life cycle comparison scheme for the use options 'small CHP' and 'large CHP'. Conv. eff.: Conversion efficiency; SA: Sensitivity analysis; Std.: Standard.

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. 4-5, 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.

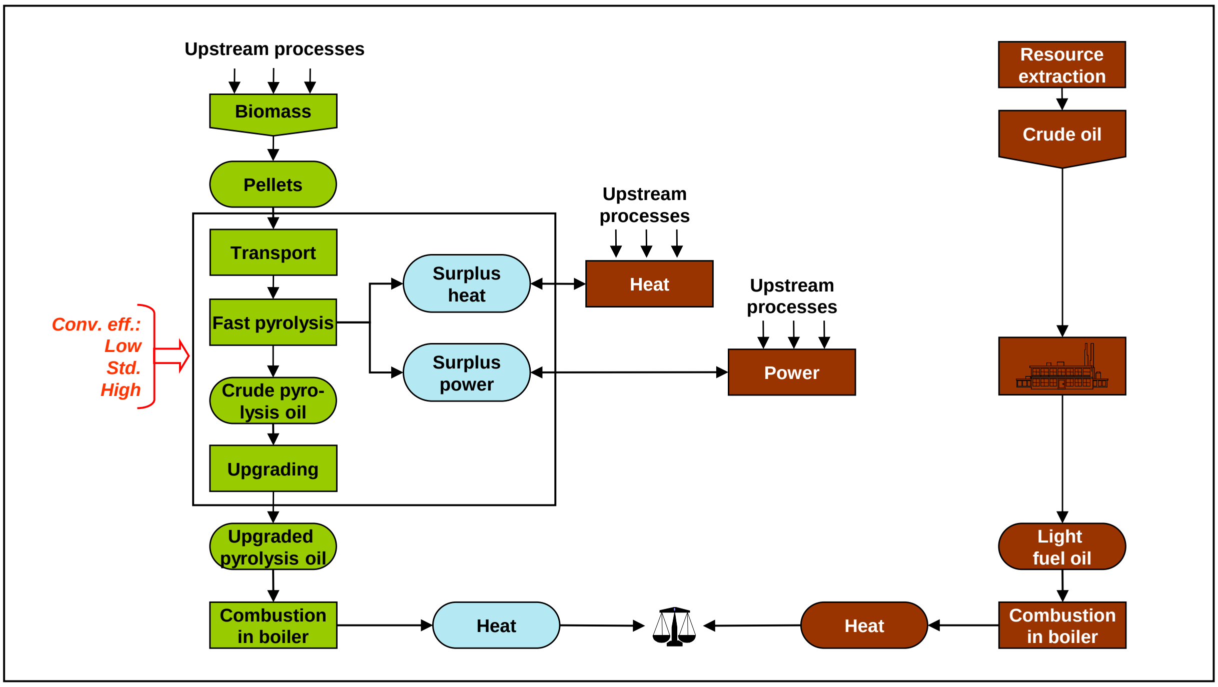

Fig. 4-5 Life cycle comparison scheme for the conversion and use option 'upgraded pyrolysis oil'; Conv. eff.: Conversion efficiency; Std.: Standard.

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. 4-6, 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.

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 %.

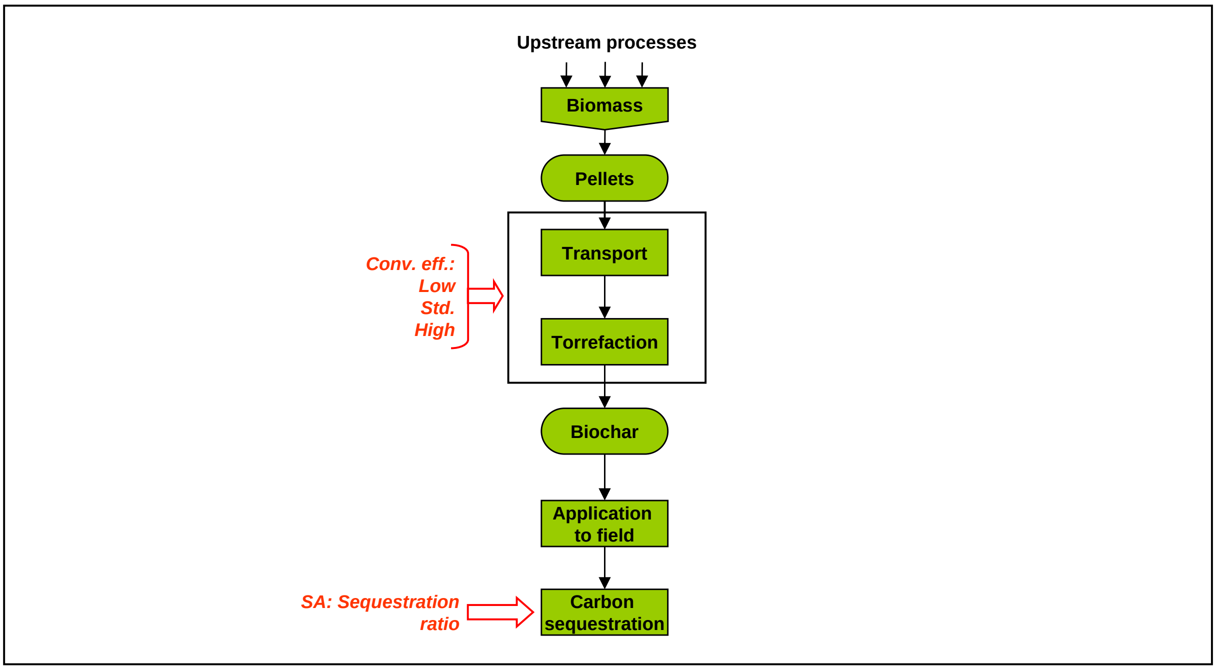

Fig. 4-6 Life cycle comparison scheme for the conversion and use option biochar. Conv. eff.: Conversion efficiency; SA: Sensitivity analysis; Std.: Standard.

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 implementation. 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. 4-7. 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.

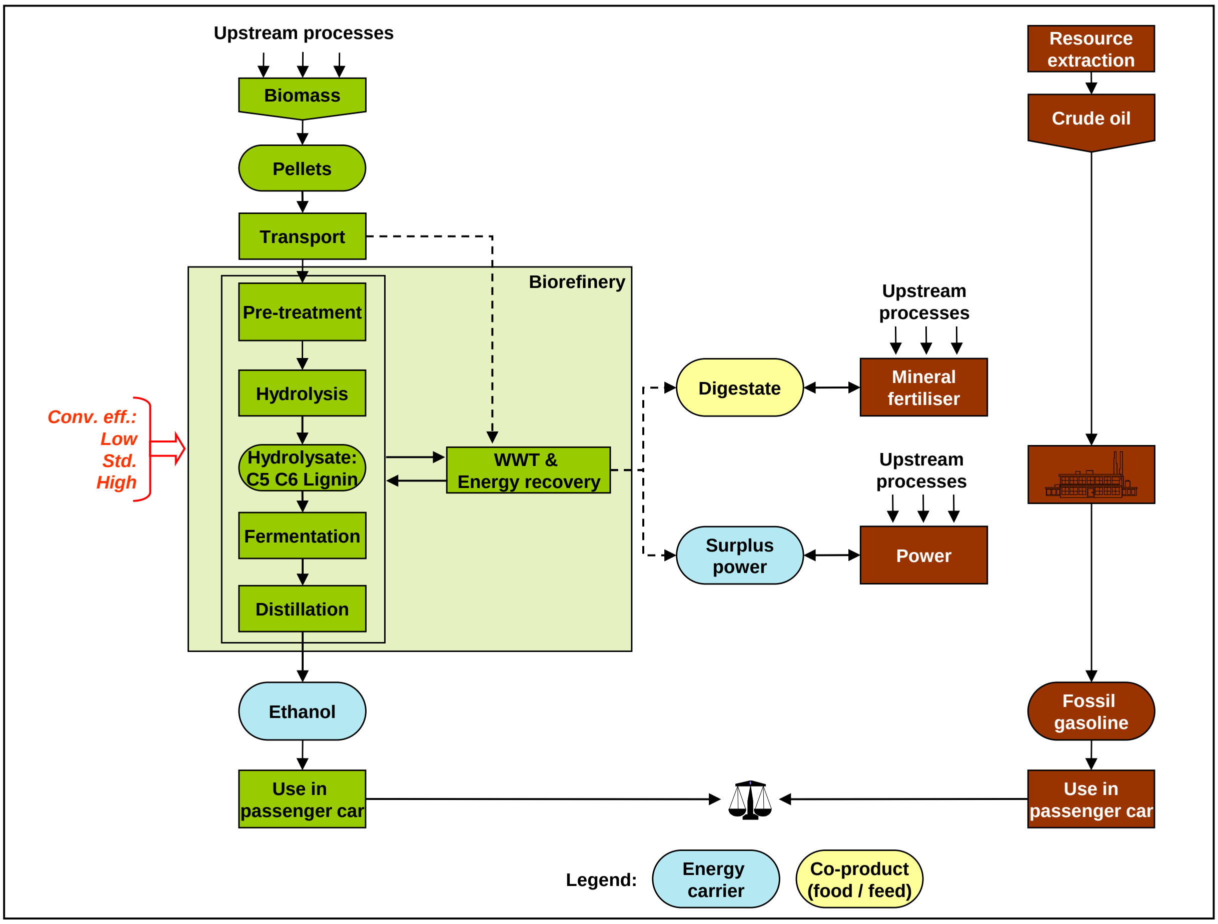

Fig. 4-7 Life cycle comparison scheme for the conversion and use option 2nd generation ethanol. Dotted lines indicate material flows that do not occur in all scenarios. C5: Pentose sugars; C6: Hexose sugars; Conv. eff.: Conversion efficiency; Std.: Standard; WWT: Wastewater treatment.

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 the grid.

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. 4-8). 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.

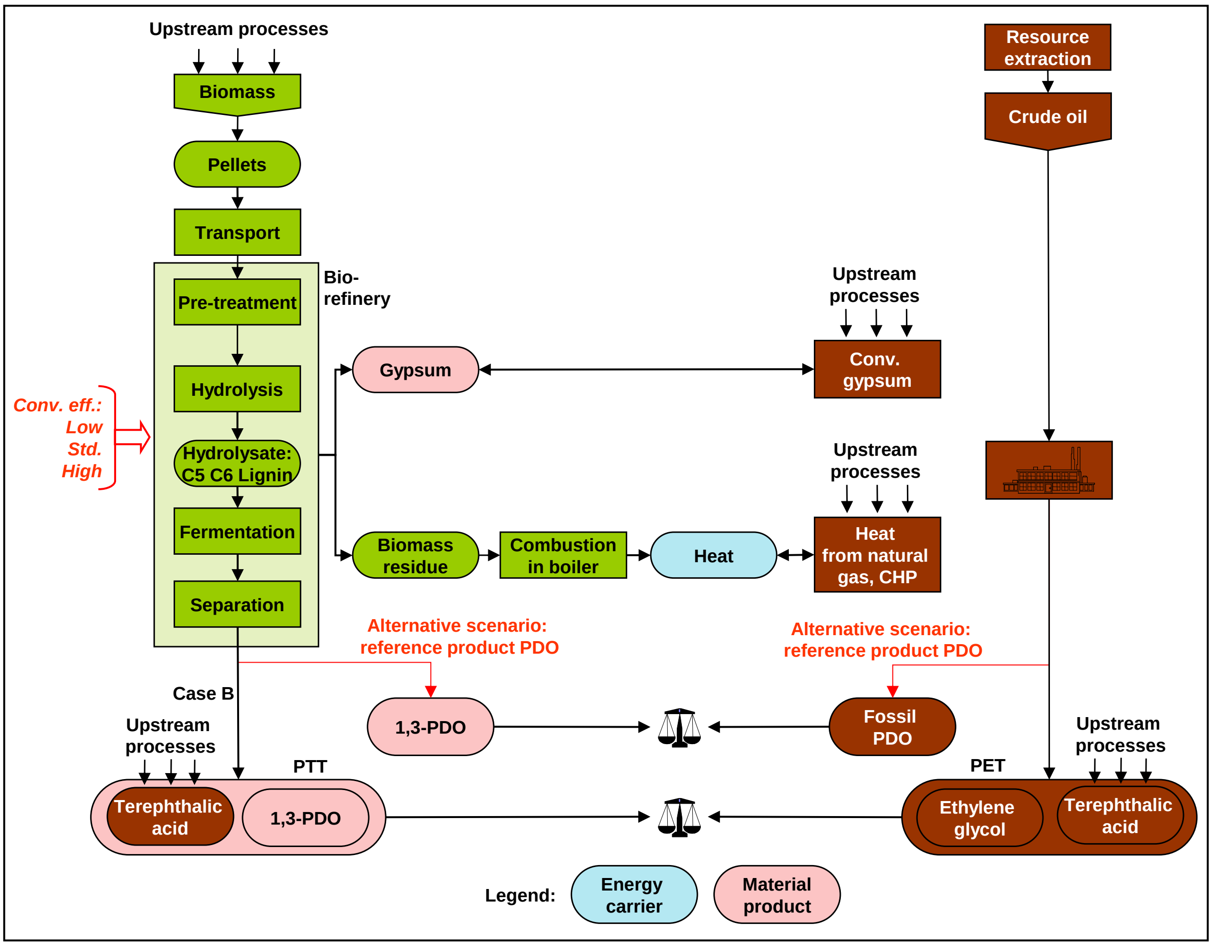

Fig. 4-8 Life cycle comparison scheme for the use option 1,3-propanediol. C5: Pentose sugars; C6: Hexose sugars; Conv. eff.: Conversion efficiency; PDO: 1,3-propanediol; Std.: Standard; WWT: Wastewater treatment.

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.

5 Results

The integrated sustainability assessment builds on results of several assessments of individual sustainability aspects (see also Fig. 3-1). These have been published in separate reports [van den Berg, de Jamblinne, et al. 2015; Fernando, Boléo, Barbosa, Costa, & Duarte 2015; Panoutsou 2015a; b; Rettenmaier et al. 2015; Soldatos & Asimakis 2015]. Their results are summarised in chapters 5.1 – 5.6. Chapter 5.7 joins these individual results into an overall picture and analyses them collectively.

5.1 Summary: technological assessment

The following chapter is adopted from [van den Berg, de Jamblinne, et al. 2015]*. For detailed results and background information please refer to the original assessment report.*

Within the work task "system description and technological assessment", a number of scenarios was developed that combine the production and use options of the crops considered in the OPTIMA project. The scenarios include the biomass pre-treatment step (densification) and the conversion into heat and power, biofuels and bio-based products. Since these scenarios form the basis of all other assessment steps, these results are not summarised in this chapter but detailed in chapter 4 of this report.

Additionally, a technological assessment was made of the densification step and the conversion pathways, based on the experimental results in WP5. Its results are summarised in this chapter.

5.1.1 Biomass densification

The technological assessment made by 2ZK was based on its own investigations. The guide line of the research was targeting the development of a mobile and flexible solution (biomass agnostic), relying on existing devices or development (TRL 6 and over).

The development of the micromill technology has confirmed some hypotheses:

- The energy consumption is lower than the classic "dry" pelletizing, the fine milling and final drying are performed in one device (two in one).
- The densification by means of screw extruder and the related polymerisation is providing a higher mechanical strength of the material by comparison with the pellets.
- The water is a catalyst of the process what is reducing the "glass transition" of the organic polymers, the mixture of organic polymers (cellulose, hemi-cellulose and lignin).

With the improvement of this technology, the samples obtained are solid organic bio-fuels, which have a higher quality than pelletized biomass with the classic dry pressing method.

There is a significant reduction of energy consumption in the production of solid fuel. In this case, the waste kinetic energy is used to evaporate the moisture. Usually, the experience has shown that the main element in the production cost was the grinding and shredding for the destruction of the intercellular structure of the materials.

This is opening interesting perspectives for the production of pellets, briquettes for energy but also for the preparation of the feedstock for bioethanol by using a mechanical cracking at a friendly low cost.

An embedded solution is currently under preparation (July 2015) for installing such device on a self-propelled harvester as described in the prior deliverable “logistics model” [de Jamblinne 2015].

Therefore a complete solution would be available for the harvesting and the densification of various kinds of biomass, with “in situ” operation. The CargoMill is developed with existing technologies with the aim to reach a TRL averaging 6-7.

Conclusion

For the densification step, the reports have highlighted some technological and organizational gaps between the stakeholders. The biomass mobilization is still a key issue and is rising across Europe. The development of the multi-feedstock conversion technologies (i.e. pyrolysis,...) is allowing the usage of different raw material. If these raw material are not from a captive source (by products of an industrial process like saw dust, sugar beet pulp), the mobilization will become the corner stone of any bio-based policy. Currently, it’ is very complex to establish a fair discussion between the European stakeholders, biomass owners and biomass converters. Both may have benefit of a proactive cooperation, nevertheless the lack of bridges is slowing down the development of the bio-based economy in Europe.

5.1.2 Biomass conversion

In the OPTIMA project a number of thermochemical conversion processes is considered for conversion of the four perennial crops into energy and green products. The selection consists of both proven technologies that are already in use for (woody) biomass as well as more innovative technologies that are currently under development and on which experimental work was done in WP5:

- Small-scale boiler for heat
- Combustion system with steam turbine for CHP
- Combustion system with ORC and turbine for CHP
- Downdraft gasifier with gas engine for CHP
- Fast pyrolysis for production of pyrolysis oil
- Upgrading of pyrolysis oil for biofuels
- Torrefaction for biochar

The state of development of the conversion processes differs. An indication of the state of development is presented in Table 5-1 below based on the Technology Readiness Levels

(TRL's) as defined by the EC. Note that the presented TRL's refer to the use of woody biomass as a feedstock. For the herbaceous energy crops considered in the OPTIMA project hardly any experience on a commercial scale or even demonstration scale is available.

Table 5-1 Technology Readiness Level (TRL) of considered conversion processes

	conversion process	**TRL (woody biomass)**
1	small scale boiler	9
2	combustion & steam turbine	9
3	combustion & ORC	8 - 9
4	downdraft gasifier & gas engine	7 - 9
5	fast pyrolysis	7 - 8
6	upgrading of pyrolysis oil	3 - 4
7	Torrefaction	5 - 8

The typical capacity of the conversion processes also differs, ranging from small-scale heat boilers of several tens of kW_{th} for domestic use up to industrial size pyrolysis plants of 20 MW_{th}. In Table 5-2 ranges are presented of the typical capacities. For the life cycle assessment, the efficiencies of the conversion technologies have a considerable impact on the results, and therefore in Table 5-2 also typical thermal, electric and product efficiencies are presented for the considered technologies.

Table 5-2 Data on thermochemical conversion pathways (Source: BTG data)

Technology	**Application**	**Scale**	**ηth %**	**ηel %**	**Other η%**	**Total η%**
Small-scale boiler	Heat	20-500 kW_{th}	91	-	-	**91**
Combustion + Steam turbine	CHP	> 1 MW_e	60	27	-	**87**
ORC + turbine	CHP	0.2 – 3 MW_e	69	15	-	**84**
Downdraft gasifier + gas engine	CHP	0.6 – 1.2 MW_e	50	25	-	**75**
Fast-pyrolysis	Bio-oil	20 MW_{th}	28	2	50	**80**
Bio-oil upgrading	Biofuel	20 MW_{th}	-	-	88*	**88**
Torrefaction	Biochar	-	-	-	89	**89**

**based on pyrolysis oil as feedstock*

On the basis of the considered conversion processes, five biomass conversion pathways were developed for the four perennial crops in OPTIMA. For these pathways a life cycle comparison is made with the fossil reference in WP7 as described in the previous chapter.

For each pathway the starting point is pelletized crop material. The exception is the upgrading of pyrolysis oil. This is considered as a second step after pyrolysis of the pelletized material, and the starting point is therefore pyrolysis oil.

The mass and energy balances have been calculated for each individual conversion pathway and used as input for the life cycle calculations. A summary of the mass and energy balances is presented in Table 5-3. In Deliverable 5.2 "*Report on technology pathways"* [van den Berg, van Sleen, et al. 2015] more background information can be found about the mass and energy balances.

Table 5-3 Mass and energy balances for the selected conversion pathways

			mass (t/hr)		**energy (MWh/hr)**	
	conversion process	**Product**	**in**	**out**	**in**	**out**
1	small scale boiler	Pellets	0.007		0.00274	
		Air	0.0481			
		Ash		0.0001		
		Fluegas		0.055		0.00024
		useful heat				0.0025
		Total	0.0551	0.0551	0.00274	0.00274
		Efficiency				*91%*
2	combustion & steam turbine	Pellets	4.7		18.39	
		Air	32.3			
		Ash		0.1		
		fluegas&losses		36.9		2.39
		useful heat				11.03
		Electricity				4.97
		Total	37	37	18.39	18.39
		Efficiency				*87%*
3	fast pyrolysis	pellets	5.6		21.93	
		heat for dryer			0.81	
		pyrolysis oil		2.75		11.46
		Ash		0.1		
		fluegas and losses		2.75		4.61
		useful heat				6.25
		Electricity				0.42
		Total	5.6	5.6	22.74	22.74
		Efficiency				*80%*
4	upgrading of pyrolysis oil	pyrolysis oil	9.97		46.53	
		Hydrogen	0.07		2.33	
		Electricity			0.8	
		natural gas			1.2	
		upgraded pyrolysis oil		5.9		44.58
		Losses		4.14		6.28
		Total	10.04	10.04	50.86	50.86
		Efficiency				*88%*
5	Torrefaction	Pellets	10			
		gas/oil	1.1			
		Biochar		8.9		
		fluegas/losses		2.2		
		Total	11.1	11.1		
		Efficiency		*89%*		

5.2 Summary: life cycle assessment

The following chapter is adopted from [Rettenmaier et al. 2015]*. For detailed results and background information please refer to the original assessment report.*

A screening LCA for the cultivation and use of three selected perennial grasses, Miscanthus, giant reed and switchgrass, as well as of the perennial plant cardoon was conducted as part of the sustainability assessment of the OPTIMA project. As a basic set of scenarios, 28 combinations of 4 crops and 7 use options have been analysed (see chapter 4) for their impacts on 7 environmental indicators in a screening LCA.

5.2.1 Exemplary OPTIMA scenario vs. conventional reference system

In this chapter, results for one exemplary scenario are analysed in detail to clarify how the emissions and credits of individual process steps or life cycle stages add up to the net results for each impact category.

Fig. 5-1displays the LCA results for the complete life cycle of Miscanthus used for heat and power production in a small CHP compared to the conventional reference system (see chapter 4.3.2). In the figure’s upper panel, emissions and credits related to individual process steps or life cycle stages for both the bioenergy system and the conventional reference system are shown. In the lower panel, the net results for all investigated impact categories are given.

As can be derived from the upper panel, for each impact category, individual process steps or life cycle stages contribute to the net results to a varying extent. Agriculture (yellow and green bars) plays a major role with respect to all impact categories. While the provision of power needed for irrigation significantly contributes to climate change, acidification, particulate matter emissions and non-renewable energy use, field emissions like N_2O or NH_3 are responsible for eutrophication and ozone depletion. For the given scenario, the life cycle stage logistics and conditioning (blue bars) is of minor importance: visible contributions are recognisable for climate change and non-renewable energy use (drying and pelleting) and freshwater eutrophication (pelleting). The impact of transports, in contrast, is insignificant. Since downstream processing is not necessary when biomass pellets are directly combusted for energy provision, no burdens are related to the life cycle stage conversion. Emissions related to use of the bioenergy carrier, in this case pellet combustion (red bar), lead to relevant burdens with respect to the impact categories acidification, ozone depletion and particulate matter, mainly caused by emitted NO_x. Credits are given for the avoided environmental burdens associated with conventional energy provision, which are in this scenario the provision of heat and power. Largest credits are achieved for the impact categories climate change and non-renewable energy use.

The lower part of Fig. 5-1reveals that the scenario leads to both environmental advantages and disadvantages depending on the impact category. While climate change and non-renewable energy use are decreased, acidification, eutrophication, ozone depletion and particulate matter emissions are increased. Therefore, no scientifically justified, objective decision for or against the biogenic 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 a mix of fossil resources.

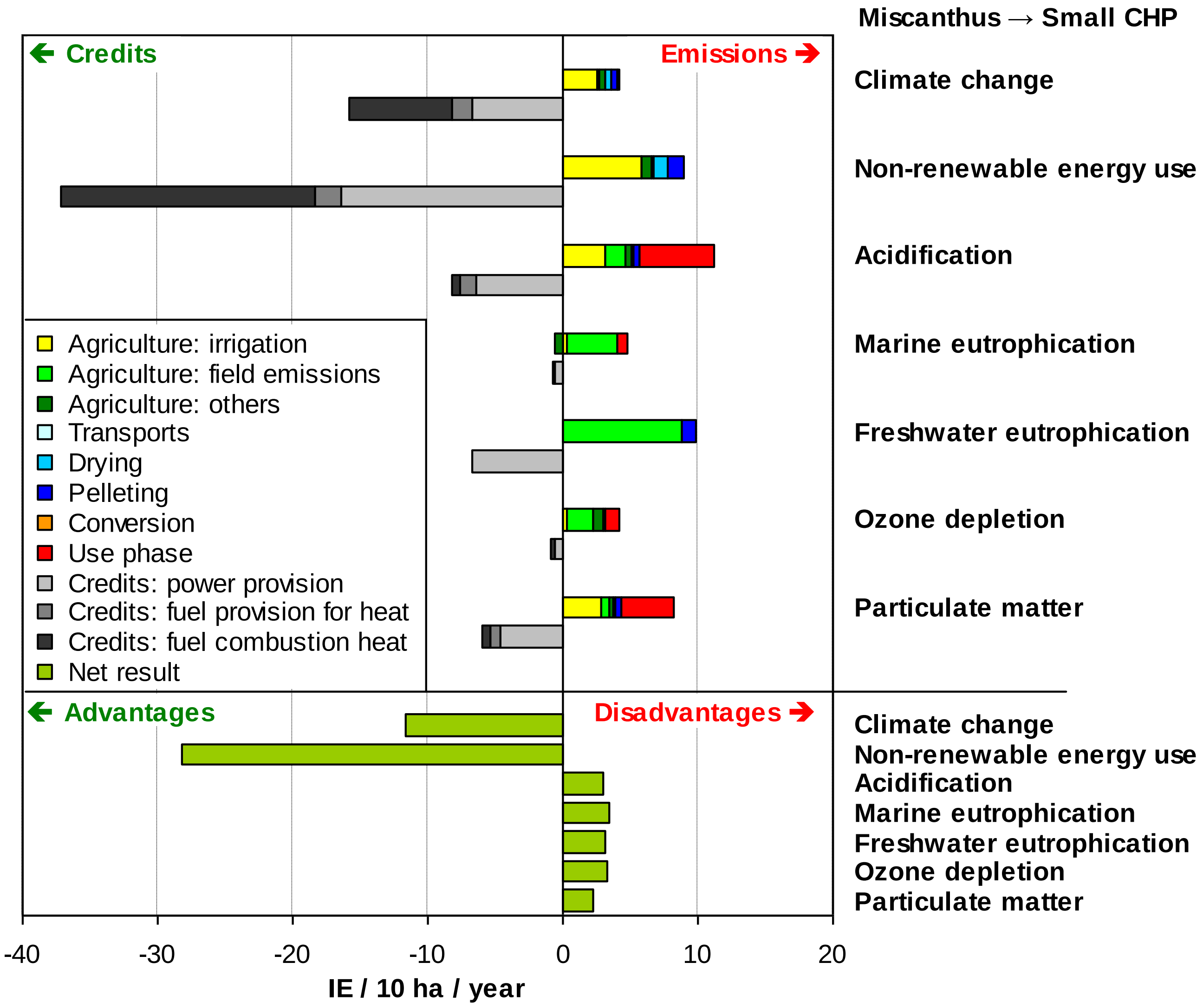

Fig. 5-1 Screening LCA results for the life cycle comparison of combined heat and power production from Miscanthus in a small CHP to the conventional reference system (power from the grid and heat from natural gas-fired heat plant). Normalised results are given in inhabitant equivalents (IE) per 10 hectares per year. Upper panel: Emissions caused by the biogenic life cycle are compared to credits (avoided emissions) due to replaced conventional energy provision. Lower panel: Resulting net advantages (emission / resource savings) or disadvantages (additional emissions / resource use). Adapted from: [Schmidt et al. 2015].

5.2.2 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 herbaceous crop cardoon is investigated for comparison (see chapter 4.1.1 for further details).

Fig. 5-2 shows how a certain area of marginal land can be used most productively to achieve environmental advantages. As can be found in Fig. 5-2, 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[5]) need for irrigation improves its performance despite the low yield.

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.

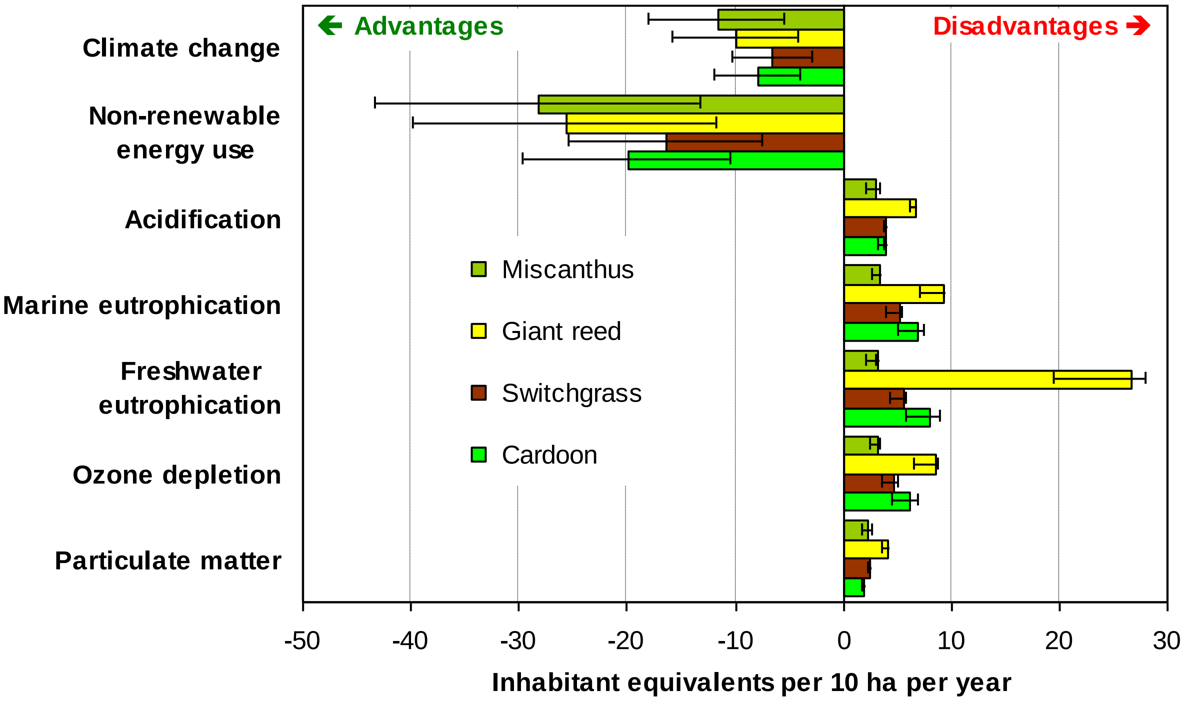

Fig. 5-2 Overall net results of the scenario "Biomass → Small CHP" compared to the fossil equivalent with different feedstock types per agricultural area. Error bars indicate variation of results due to yield levels. Source: [Schmidt et al. 2015].

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

5.2.3 Overall comparison

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. 5-3 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.

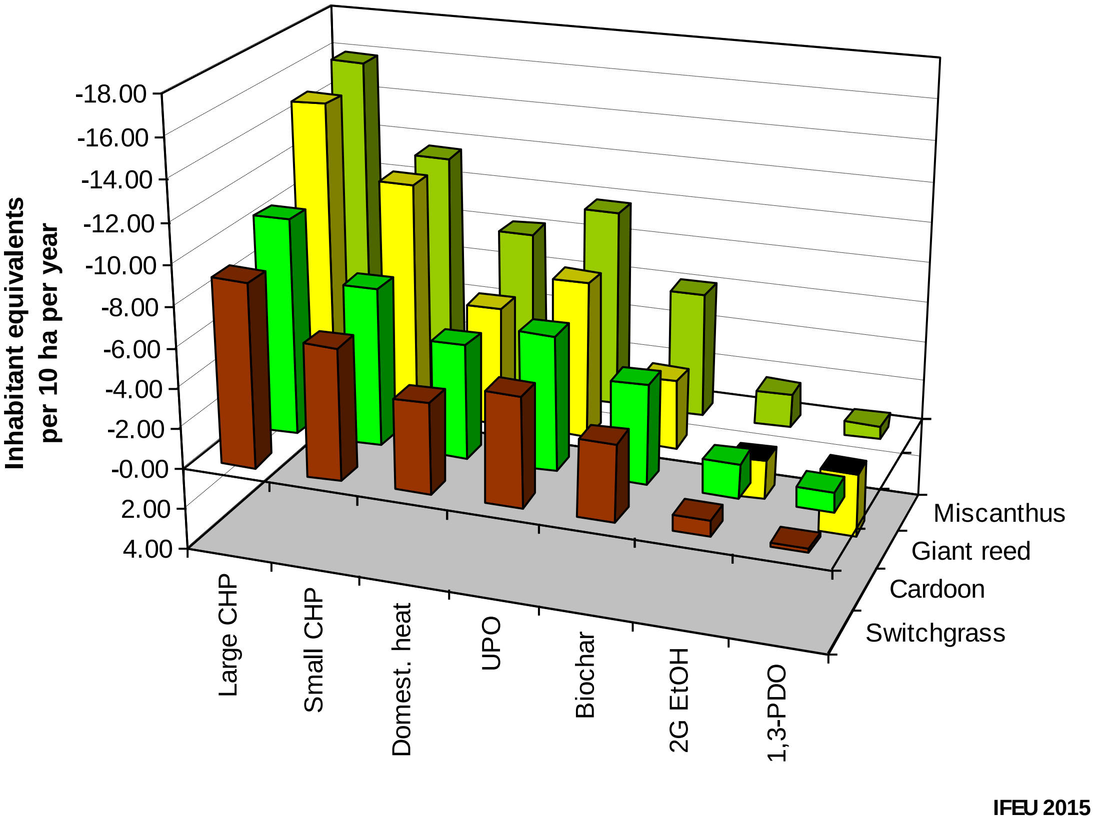

Fig. 5-3 Overall greenhouse gas savings (upward columns, negative numbers) or extra emissions (downward columns, positive numbers) of all main scenarios with the biomass feedstock cultivated on marginal land used in the use option with standard conversion efficiency, each compared to its fossil equivalent 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. 5-4 gives an overview over the basic scenarios in the OPTIMA project: all perennials and conversion / usage options investigated are displayed. It shows that both the choices of conversion / use option and of the perennial crops used substantially influence the results.

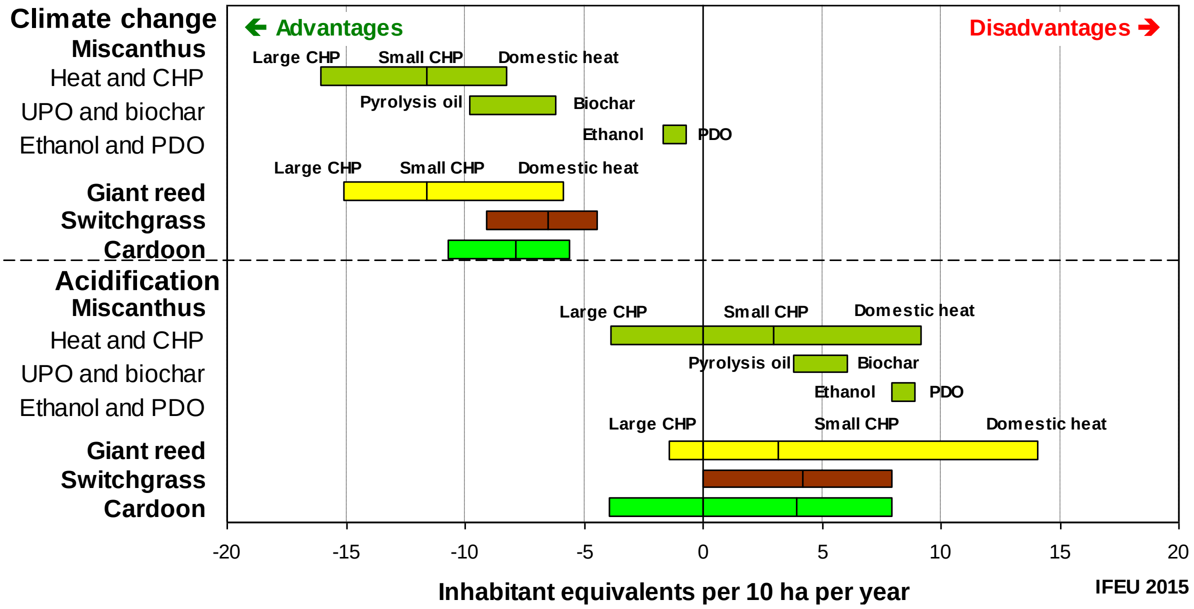

Fig. 5-4 LCA results for the basic scenarios: the different cultures and conversion / use options. Conversion / use options are shown for standard conversion efficiency based on the cultivation of Miscanthus (yield level “low” on marginal land); agricultural options are shown for yield level “low” (marginal 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. 5-5 displays the most important sensitivity analyses (for details see [Rettenmaier et al. 2015]). 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). Furthermore, co-firing of biomass in coal power plants was studied in an excursus. It comes to the conclusion that co-firing of biomass is no valid argument against shutting down coal power plants. Nevertheless, co-firing can provide substantial advantages in a transition period until coal power can be replaced on a large scale if sustainably produced biomass is used (for details see [Rettenmaier et al. 2015]).

5.2.4 Conclusions

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 provided with only minor environmental impacts from perennial grasses on marginal land. From an LCA 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. Local environmental impacts such as on water availability or biodiversity can however not be adequately captured by current LCA methods or is not yet sufficiently supported by data required for these methods. Therefore, local environmental impacts were studied using elements of EIA (see chapter 5.3).

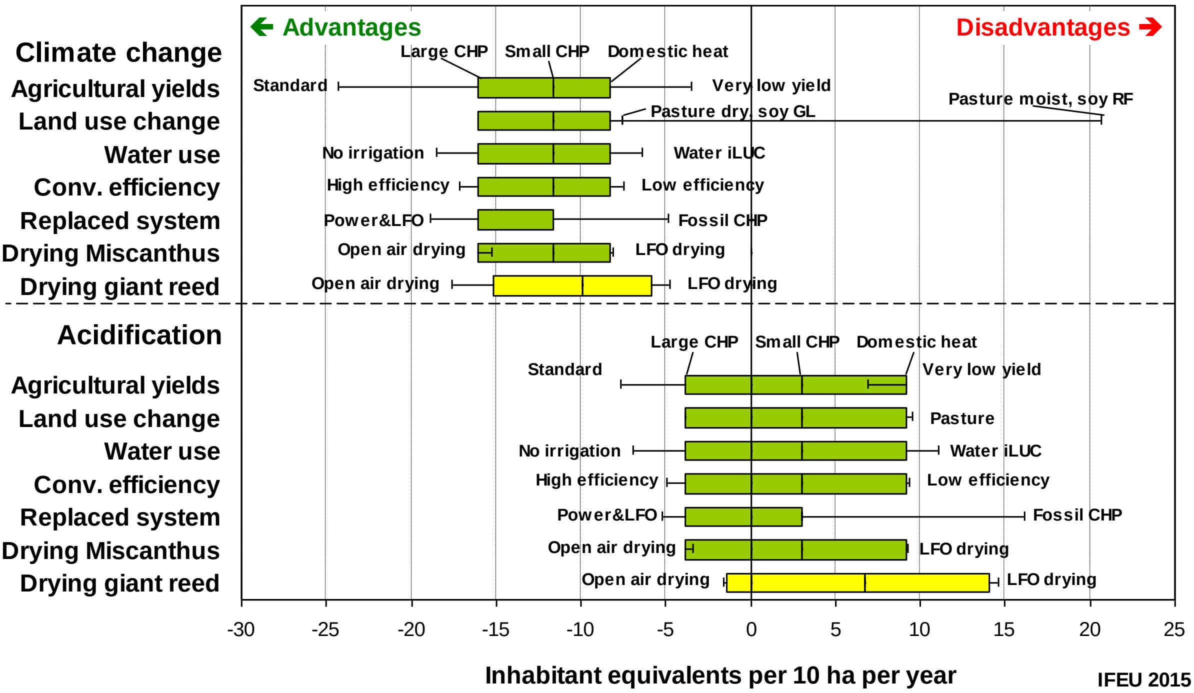

Fig. 5-5 Overview of LCA results for sensitivity analyses and bandwidths of results. Green bars show the standard results for the heat and power use options “Large CHP”, “Small CHP” and “Domestic heat”. Scenarios are based on the cultivation of Miscanthus (yield level “low” on marginal land) except for 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.

5.3 Summary: local environmental impacts

The following chapter is adopted from [Fernando, Boléo, Barbosa, Costa, & Duarte 2015]. *For detailed results and background information please refer to the original assessment report.*

The aim of this work was to assess the local environmental impacts related with the production and use of perennial grasses cultivated on marginal lands in the Mediterranean region using elements of environmental impact assessment. The study focusses on the local impacts on biodiversity, soil quality and erosion, the use of water and landscape. To determine the environmental impact of the cultivation of perennial grasses on marginal land and their use, different categories were studied: effects on the quality of soil, use of water resources, and biological and landscape diversity, following the methodology developed by [Biewinga & van der Bijl 1996], and adjusted by [Fernando et al. 2010]. Each of these categories comprises different indicators. The collection of data comprised literature review, expert consulting and own experience. To harmonize the evaluation of local impacts, a normalization procedure was applied to all categories. The conventional system received "0" and the idle land "-10". Category results obtained for the different biogenic systems were scaled taking in consideration both the idle land and the conventional system. Differences to "-10" show the gap related to the idle land. Results higher than zero indicate higher impact than conventional system, results below zero show advantages regarding the conventional system.

The following chapters 5.3.1 - 5.3.4 summarise the local environmental impacts of the whole life cycles of cultivation and use of the four perennial crops under investigation exemplarily for the use option small CHP. Chapter 5.3.5 compares the impacts of the assessed biomass use options.

5.3.1 Biodiversity

A multitude of factors related to both bio-based and conventional fossil-based life cycles influences biodiversity. In total, the impacts for bio-based life cycles are similar to the impacts of the conventional systems with biggest contributions of the life cycle stage cultivation / extraction (Fig. 5-6). All assessed feedstocks perform similarly with slightly bigger advantages for cardoon and slightly smaller ones for switchgrass due to lower yields. As an overview, all important factors contributing to these results are listed in this summary (Table 5-4). All contributions are discussed in detail in [Fernando, Boléo, Barbosa, Costa, & Duarte 2015].

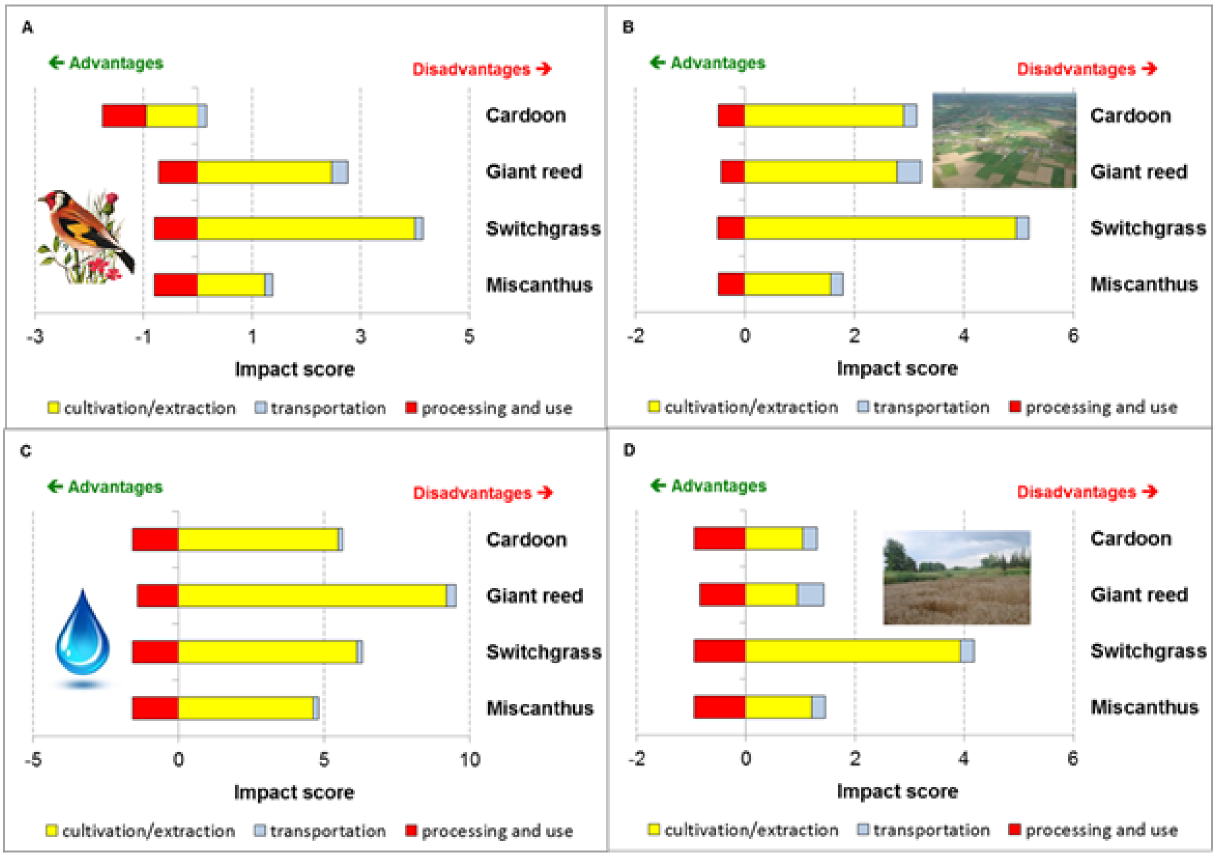

Fig. 5-6 Overall net EIA results of the cultivation of several perennial grasses on marginal land and their use. (A) Biodiversity; (B) Soil quality; (C) Water use; (D) Landscape. The use of biomass for combined heat and power production in a small CHP was compared with fossil equivalent. Bandwidths indicate results for very low and standard yield levels. Source: [Fernando, Boléo, Barbosa, Costa, Duarte, et al. 2015].

Table 5-4 Factors contributing to impacts on biodiversity.

Perennials to CHP (vs. idle land)	Fossil energy (vs. previous land cover)
+ High above and belowground biomass favours diversity and occurrence of soil micro-organisms and soil fauna and provide shelter for invertebrates, birds and small mammals.	- High magnitude and duration of impacts, mostly irreversible
+ Cardoon: Blossomed crop should attract insects and birds.	- Toxic contaminations of soil and water through extraction and transport
+ Cardoon: native to the Mediterranean region	- Risks associated with accidents and leakages are significantly higher.
- Intensive pesticide use to destroy rhizomes after cultivation period (less pronounced for cardoon)	- Higher transport distances
- Marginal land can harbour high levels of biodiversity.	
- Giant reed: invasiveness (in certain environments)	

5.3.2 Soil quality

Similar to biodiversity, impacts on soil quality from bio-based life cycles are similar to the impacts from conventional systems, with biggest contributions of the life cycle stage cultivation / extraction (Fig. 5-6). Again, all feedstocks show rather similar results with Miscanthus being somewhat more advantageous than giant reed and cardoon. Switchgrass presents the highest impact, compared to the conventional system, due to the low yields obtained. As an overview, all important factors contributing to these results are listed in this summary (Table 5-5). All contributions are discussed in detail in [Fernando, Boléo, Barbosa, Costa, & Duarte 2015].

Table 5-5 Factors contributing to impacts on soil quality.

	Perennials to CHP (vs. idle land)		**Fossil energy (vs. previous land cover)**
+	Perennials accumulate high amounts of soil organic matter.	**-**	Acidification of soils due to emissions to air
+	Rhizomes provide structural integrity and beneficial deposits to the soil.	**-**	High impacts around extraction sites (wells, pits, …)
+	Protection against erosion and runoff due to continuous soil cover	**-**	Risk of mineral oil contaminations.
0	Only reduced or no tillage needed, thus little soil compaction		
0	No pH changes		
-	Fertilisation required. Particularly pronounced for giant reed.		

5.3.3 Water use

Bio-based life cycles mostly require more water use than fossil-based life cycles with biggest contributions of the life cycle stage cultivation / extraction (Fig. 5-6). Differences between feedstocks mainly result from different irrigations needs but also on crop traits, such as the rhizome and roots apparatus that can influence the hydrological cycle (namely the aquifers refill). As an overview, all important factors contributing to these results are listed in this summary (Table 5-6). All contributions are discussed in detail in [Fernando, Boléo, Barbosa, Costa, & Duarte 2015].

Table 5-6 Factors contributing to water use.

Perennials to CHP (vs. idle land)	**Fossil energy (vs. previous land cover)**
+ Surface runoff is largely prevented and taken up by plants instead.	**+** Only minor water use during drilling.
(+) Potential to use wastewater for irrigation because these crops are not part of the food chain.	**-** Potential impacts of shale oil and gas development on water stocks.
(+) Potential to plant perennials as buffer strips intercepting water and nutrient output from annuals and livestock.	**-** Impervious surfaces created for processing facilities and roads.
- Irrigation required in many regions. Amounts are significant although perennials have comparatively low water demands.	
- Rainwater use efficiency due to deep rooting slows down refill of aquifers.	
- Giant reed: Higher water demand than other assessed crops.	
- Impervious surfaces created for processing facilities and roads.	

5.3.4 Landscape

Bio-based life cycles show disadvantages regarding their impacts on landscape compared to fossil-based life cycles with again biggest contributions of the life cycle stage cultivation / extraction (Fig. 5-6). Marginal advantages exist for cardoon compared to the other crops, due to the blossoming period. As an overview, all important factors contributing to these results are listed in this summary (Table 5-7). All contributions are discussed in detail in [Fernando, Boléo, Barbosa, Costa, & Duarte 2015].

Table 5-7 Factors contributing to impacts on landscape.

Perennials to CHP (vs. idle land)	**Fossil energy (vs. previous land cover)**
+ Perennials add to landscape diversity.	**-** Important driver of negative landscape change (pits, wells, roads, pipelines …).
+ Perennials add to habitat diversity.	
+ Cardoon: Colourful blossoms contribute to landscape value.	
(+) On degraded land particularly strong positive impact.	

5.3.5 Comparison of biomass use options

Fig. 5-7 displays the EIA results of all investigated use options based on the cultivation of Miscanthus, which was considered the best performing crop, both in terms of EIA results and in terms of LCA results (see section 5.2).

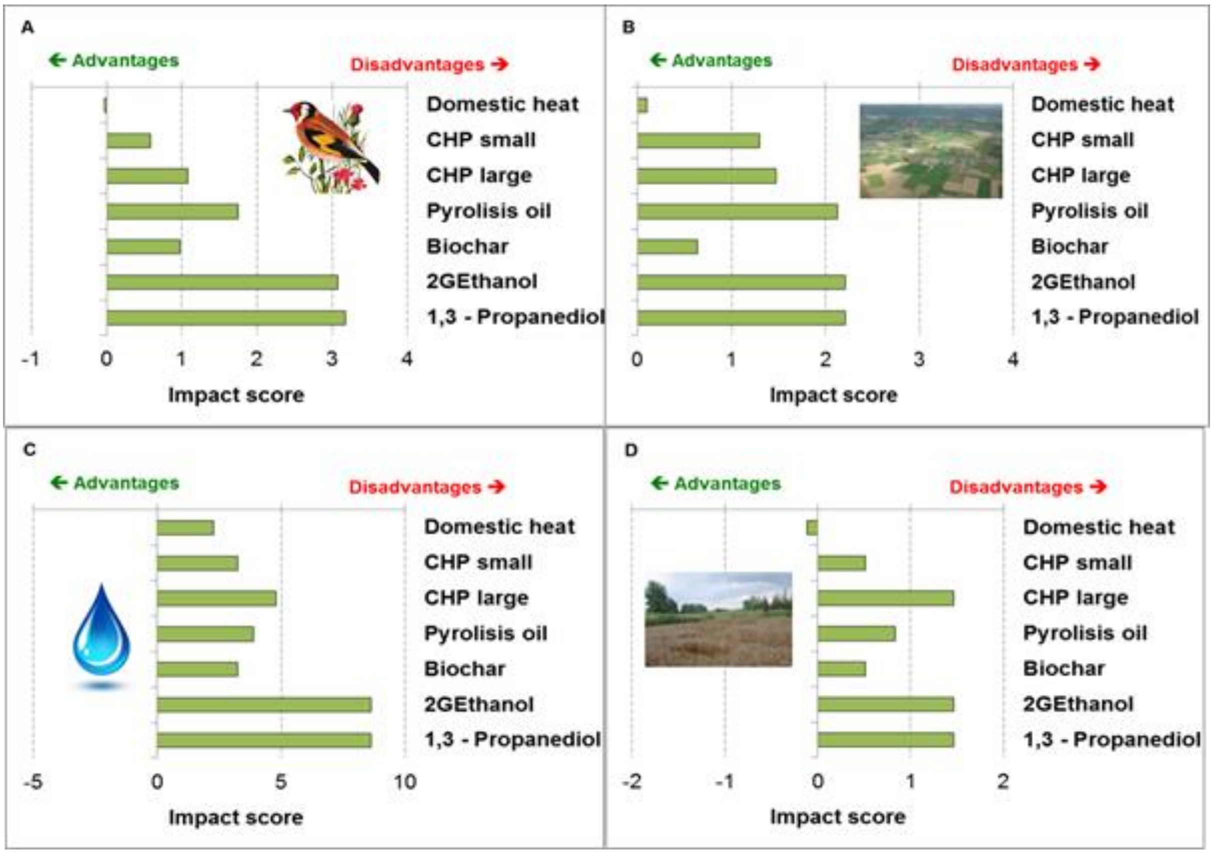

Fig. 5-7 Overall net EIA results of the cultivation of Miscanthus on marginal land and their use. (A) Biodiversity; (B) Soil quality; (C) Water use; (D) Landscape. Different use options were compared with fossil equivalent. Source: [Fernando, Boléo, Barbosa, Costa, Duarte, et al. 2015].

Regarding the different categories studied (biodiversity, soil quality, water use and landscape), the lower disturbance of the native systems presented by small CHP and domestic heat, as also biochar (Fig. 5-7), benefits these end uses. Application of ash (from CHP plants) and biochar in the soil, as a means to achieve a balanced nutrient status also provides bonus to these systems. The application of biochar to soils is being considered as a means to sequester carbon while concurrently improving soil functions, including water detainment. The remaining end uses show higher impact, especially 2nd generation ethanol and 1,3-propanediol. All contributions are discussed in detail in [Fernando, Boléo, Barbosa, Costa, & Duarte 2015].

5.3.6 Conclusions

From the findings presented in the results, a major conclusion can be drawn related to the influence of the life cycle phases on the level of environmental impacts: the local environmental impacts are mainly influenced by biomass cultivation and extraction of conventional raw materials. Qualitatively a typical pattern can be identified: compared to the conventional reference systems the cultivation and use of the investigated perennial crops provides disadvantages regarding biodiversity, soil, landscape and water use. However, if a different time length for the land restoration under the conventional system will be used, different results would be achieved, and the biogenic system would be more beneficial than the conventional one (this aspect is discussed in detail in [Fernando, Boléo, Barbosa, Costa, & Duarte 2015]. Nevertheless, if crops and end uses were to be sorted according to their performance, the results would remain unchanged, and the profile would be the same. Miscanthus performs well at the local level because of its low nutrient demand and high yield. However, other crops perform better regarding specific impacts, e.g. because of cardoon’s flowering effect on biodiversity and landscape. Regarding the best performing use option, small CHP and domestic heat use options are considerably more beneficial than conversion to 2nd generation ethanol or 1,3-propanediol. Particular attention should be addressed to the cultivation phase when bioenergy and bio-based products from perennial grasses are to be cultivated on marginal land in the Mediterranean region. Especially concerning the irrigation and water use options, limiting irrigation as far as possible and if necessary and justifiable by adopting water- and energy saving techniques. Adequacy among crop, location and crop management options, should therefore be accurately assessed in order to overcome negative impacts at local level.

5.4 Summary: cost analysis

The following chapter is adopted from [Soldatos & Asimakis 2015]*. For detailed results and background information please refer to the original assessment report.*

The present text is a summary of the Report on the Economic (Cost) Analysis of the production and conversion of biomass from perennial crops into useful bio-products, such as fuels in various forms and other non-energy products. The identification of promising pathways is within the main goals of the “OPTIMA” EU project.

With regard to agricultural production, a thorough literature review has been undertaken in order to bring together all recent experimental work, especially in the South of Europe and elsewhere, mainly the US, with similar climatic conditions. Many recent publications have been studied and used for the compilation of this report.

The numerical results concerning costs and revenues are necessarily based on current information with regard to costs of inputs and market selling prices, which, however, fluctuate substantially from year to year. Therefore, they have to be regarded as best approximations of highly uncertain magnitudes. This fact, party explains the great variability of estimates of other researchers in the same field.

In this report, a rather rigid approach has been adopted, including all costs and expenses associated and charged to the examined activities, such as administrative costs, communication, contingencies, required constructions, travel, energy usage, machinery trips before and after operation, etc. A profit margin of 23% (30% mark-up) has been assumed for the farmer and the conversion plants, which is included in selling prices of produced feedstocks or final products. Externally provided inputs are charged at market prices.

5.4.1 Biomass production

The financial position of giant reed, Miscanthus, switchgrass and cardoon has been studied and analysed. Although the European experience with Miscanthus and switchgrass is not long, these plants have been adapted quite well to Mediterranean conditions and we already know enough to appreciate the potential and prospects of these crops. High yielding giant reed, which is native in south Europe, is rather controversial, because of its invasive nature in certain environments and handling difficulty.

The significance of perennial grasses is due to the fact that they are capable of giving satisfactory yields under stress conditions on less fertile land and that they are not particularly demanding in agricultural inputs. After establishment, they practically only need to be harvested and possibly fertilised every year and they require minimal attention during their whole life. Biomass yields are similar in volume to yields of short rotation forestry (SRF) and they already play a role, mainly in power generation in several European countries. They appear as a possible alternative source of energy, not only in electricity generation stations but also in many other industrial and domestic uses.

Under the current food vs. fuel controversy the question of economic sustainability of perennial grasses cultivation on (non-food) marginal lands is posed from many directions. It was found (as expected) that the cost per tonne of all plants is higher in marginal lands than in standard agricultural land due to lower soil fertility, since reduced rent and expenses do not compensate for yield losses. It was also found that in almost all cases, from a financial point of view, marginal land cultivation with perennial grasses is not particularly attractive to the farmer, who cannot easily earn the opportunity cost of his land. Besides, in view of the high risk of a relatively new venture, he would probably be in need of further incentives and secure long term contracts to decide allocating part of his land to perennial grasses.

The following table summarises the costs of perennial grasses production in South Europe including transport to the market (delivered). Also estimates total cost per dry tonne (DT).

Table 5-8 Production cost of perennial grasses.

in annual equivalent €/ha	**GIANT REED**				**MISCANTHUS**				**SWITCHGRASS**				**CARDOON**			
	M0	**ML**	**MH**	**SH**	**M0**	**ML**	**MH**	**SH**	**M0**	**ML**	**MH**	**SH**	**M0**	**ML**	**MH**	**SH**
Initial investment	198	198	204	204	198	198	204	204	57	57	61	62	48	48	48	48
Fertilisation	113	113	159	159	113	113	159	159	113	113	159	159	31	94	127	127
Irrigation	11	178	253	253	11	178	253	253	11	126	178	178	8	95	95	95
Harvesting	198	243	276	300	142	198	243	276	107	139	198	249	107	135	176	213
Transport	134	177	220	306	96	120	144	192	72	96	120	144	72	96	117	177
Land rent, restoration and overheads	131	133	136	240	151	157	164	281	141	147	157	270	155	160	164	269
TOTAL COST, €/ha (delivered)	**786**	**1043**	**1247**	**1462**	**710**	**966**	**1166**	**1364**	**501**	**677**	**874**	**1063**	**422**	**627**	**727**	**930**
Yield, Dry Tonnes/ha (delivered)	12	15	20	25	10	12	16	20	7	9	12	16	6	8	10	14
Total Cost €/DT (delivered)	**65**	**70**	**62**	**58**	**71**	**80**	**73**	**68**	**72**	**75**	**73**	**66**	**70**	**78**	**73**	**66**

M0: Marginal land, minimal irrigation, ML: Marginal land, Low input, MH: Marginal land, High input, SH: Standard Agricultural land, High input

Giant reed is more productive and in spite of higher production expenses, its cost per tonne is lower (below 65 €/tonne line in the high input scenarios). On the other hand, Miscanthus is about as costly per tonne of output as switchgrass (around 65-80 €), because although it is more productive than switchgrass, it is also more expensive to grow. It is worth observing that cultivation on marginal land is in general more costly per tonne of produced biomass, in spite of the lower opportunity cost (rent) of land and generally smaller amounts of agricultural inputs. The Table below shows the breakdown of costs by main operation category only on Marginal Lands (average). It illustrates the relative significance of fertilisation, irrigation and harvesting, making up about 50% of average annual cost of perennial grasses.

Table 5-9 Average cost of production in marginal land.

in Annual Equivalent €/ha	**Giant Reed**	**Miscanthus**	**Switchgrass**	**Cardoon**
Initial investment	199.94	199.94	57.89	48.48
Fertilisation	128.54	128.54	128.54	83.91
Irrigation	147.37	147.37	105.28	65.91
Harvesting	239.36	194.48	147.96	138.99
Transport	176.78	120.03	96.22	95.22
Land rent etc.	133.36	157.19	148.27	159.65
Total Average Cost	**1025.35**	**947.55**	**684.16**	**592.16**
Average Yield (DT/ha)	15.67	12.67	9.33	8.00
Average Cost per DT	65.79	74.81	73.22	74.02

The selling price of biomass depends primarily upon the market it is being sold. Nevertheless, a price around 65 € per dry tonne, as repeatedly recorded for example in the energy market, seems to be a meaningful average. At this price, only giant reed may break even, which can hardly be regarded as satisfactory return on equity or return to risk and management. At this price, the other three crops do not cover their cost of delivered product. The need for some kind of financial support on grounds of environmental benefits and strategic goals is obvious.

5.4.2 Biomass conditioning

The production of pellets transforms herbaceous biomass into a commercial product that may be transported at lower cost, can be easily handled and is suitable for space heating in large or medium burners either alone or mixed with other wood pellets.

The cost of pelleting is dominated by the cost of feedstock, which may exceed 50% of the Total. The following table is indicative of the costs of a medium size (20,000 tonnes) pelleting plant.

Giant reed pellets can be retailed at around 200 €/tonne (including wholesaler and retailer margins). However, they may preferably be used in electricity generation at wholesale prices lower than imported pellets from America, which include a 50€/tonne freight which raises their cost to around 200 €/tonne.

Table 5-10 Pelleting plant total cost (feedstock: giant reed).

Capacity: 20,000 tonnes/yr	**Amount**	**%**
Capital Cost (€/yr)	175,367	7%
Operating Cost (€/yr)	720,000	28%
Feedstock (€/yr)	1,710,624	66%
TOTAL COST (€/yr)	2,605,991	100%
Cost per tonne (€/tonne)	130	

5.4.3 Conversion and use options

Based on biomass feedstock at cost including average farmer's margin (23%), several biomass conversion technologies into final products have been examined and evaluated against current alternatives.

Domestic heating

Today there are some domestic heating systems that may burn pellets form herbaceous grasses. Most will accept mixed pellet fuel (with wood pellets). The investment cost of biomass burners are much higher than oil systems, but the running costs are lower, since one tonne of oil, which is bought at about 800 € is equivalent to 2+ tonnes of pellets (in heating value terms), which have a cost of around than 500-600 €. In South Europe, where heating demand is low, the cost advantage of pellets is relatively small, especially at current, unusually low oil prices). As a result, the payback period for investments in biomass burners is very long, exceeding ten years.

Depending on pellet quality controls and the prices of heating oil, pellet burners may be a strong competitor to oil heating systems.

CHP small and large scale

The goal of Combined Heat and power systems is to capture and utilise the surplus heat produced at electricity generation. Their evaluation depends upon the value of the required investment vis-à-vis the value of useful annual heat produced, which in turn depends upon the load of heat demand. District heating is not economic in South Europe, but CHP may be financially attractive in the case of industrial uses, in hospitals, hotels, etc. where the heat demand load is favourable.

Fast Pyrolysis

The cost of producing bio-oil is dominated by the cost related to feedstock (raw material and equipment and energy for treating the biomass). It may be done in small or large scale. The estimates show that bio-oil can be produced at a cost similar to the oil-equivalent selling price, which shows that it can only compete with fossil oil only if it is taxed at a much lower rate (or not taxed) in order to cover the equity cost and all marketing and sales expenses.

Bioethanol

The analysis of costs and revenues is based on the assumption that the value of bio-ethanol is proportional to its energy content as compared to the energy content of fossil petrol (the energy content of ethanol is 65% of the energy content of petrol). Also, assumed selling price for ethanol is set according to the pre-tax selling price of petrol, which is today equal to 0.571 €.[6] Under the assessed conditions, the scenario was found to be not financially viable without incentives or subsidies.

Biochar

The cost analysis of biochar medium scale production (5,500 tonnes / year) is indicating too high costs per tonne, difficult to compete with e.g. compost for large quantities applications (farmers). Biochar would need a selling price of at least 700 € / tonne to be financially viable. However this can only be achieved through small retail gardening shops.

5.4.4 Summary

Economic analysis has shown that financial sustainability of the cultivation of perennial grasses in Europe is related and depends upon EU policies with regard to the security of energy supply and the protection of the environment. In EU today, the cost of delivered biomass from perennial grasses is somewhere between 65 and 75 € per dry tonne, which makes it a rather expensive alternative raw material for energy use within the existing framework of energy prices. Fluctuating oil prices and currency exchange rates increase the uncertainty of any economic forecast and raise the risk of economic and financial strategies.

Our extensive review of biomass production from perennial grasses around the world showed that most economic reports indicate that there is need for some kind of incentive or subsidy in order to persuade the farmer to invest time and money in a relatively novel and financially risky business such as growing perennial grasses. Biofuels had to be generously subsidised in order to get the biofuel industry up and running, and today we are witnessing endless debates with regard to the usefulness of their introduction in the energy sector. After all, even the fossil fuels energy chains are subsidised today, regardless of the environmental damage that they cause.

In addition, the examination of economic performance of growing bioenergy crops on marginal lands (i.e. lands of lower productivity and opportunity cost) is more complicated, because there is no commonly established definition of marginal lands (e.g. degree of marginality) and consequently more difficult to assign costs and estimate productivity for cultivation on such lands. In general, it has been estimated that growing energy crops on marginal or abandoned lands increases the cost per tonne of produced biomass in spite of the lower rent (opportunity cost) of these naturally or economically inferior lands.

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[6] It is naturally expected that 2G bio-ethanol will enjoy some tax exceptions, but the estimates here explore its financial viability before any incentives or subsidies.

The advantage of growing perennial grasses on marginal land helps to preserve food supplies and relieves inflationary pressures on food prices. An environmental and societal incentive strategy could therefore be established to encourage the cultivation of these energy crops on marginal land, on grounds of food and environmental safety. This has been adopted recently e.g. in the UK, under the Energy Crops Schemes, (2000-06 and 2007-13), and as a result, an area of almost 10,000 hectares has been planted with Miscanthus and Switchgrass, mainly for electricity generation.

This study reviews a large number of published research reports on the economics of perennial grasses and compares their findings to the experience and current experimental results of the members of the Consortium of the OPTIMA project.

In spite of the fact that crop yields seem to differ quite substantially in the cases that have been examined, the cost per tonne of biomass produced somehow converges to a more reasonable range. This cost differentiation may be explained by the differences in the amounts of inputs used, varying climate and land productivity in different regions as well as other case specific particulars, such as land rent, labour cost, cost of other inputs, etc.

Key conclusions can be summarized as follows:

- The cultivation of perennial grasses in marginal lands of South Europe may provide useful raw materials for several technologies for the conversion of biomass into useful products. However, the low rental of marginal lands is accompanied with lower biomass yields resulting in higher costs per harvested tonne.
- It is estimated that the cost of delivered biomass from perennial grasses in marginal lands, ranges between 65 and 75 €, relatively high in comparison with feedstocks of waste wood, and wastes from wood related industrial processes. The cost per tonne of herbaceous biomass cultivated in standard agricultural land with usual agronomic treatment is lower, indicating that the loss of yield is not compensated by the lower marginal land rent.
- Today Europe is by far the largest wood pellet producer, consumer and importer. It produces about 50% of global production and consumes a little less than twice as much, importing about 8 million tonnes, mainly from North America. Half the amount of imports is directed to domestic heating and most of the rest is consumed in power generation plants. Biomass from perennial grasses could be transformed into pellets at a total cost lower than the cost of imports and supply the needs of electricity generation stations. Thus, EU environmental targets in power generation could be served at a lower cost.
- The use of biomass from perennial grasses can be used in CHP industrial applications, achieving economic feasibility under conditions of favourable heat load curves (allowing the equipment to operate for at least 50-60% of the time. Produced electricity is assumed to be supplied to the national grid.
- Cellulosic ethanol, pyrolysis oil and biochar are new technologies supported by various grants. Today they are in the demonstration stage and it is expected that soon they will reach financial sustainability.

5.5 Summary: socio-economic analysis

The following chapter is adopted from [Panoutsou 2015b]*. For detailed results and background information please refer to the original assessment report.*

5.5.1 Employment effects

This section discusses the employment effects using the reference units from the OPTIMA analysis:

- in terms of total job equivalents per value chain,
- per 1,000 tonnes of biomass input

for the four under study perennial crops. It also provides detailed information for how these jobs are structured in terms of direct, indirect and net induced per value chain, crop, yielding capacity (from marginal to standard agronomic practice and higher intensified systems) and logistics. Across the analysis presented here, yields are based on the scenario Marginal 1, unless there is a dedicated sensitivity involving this parameter. All figures are expressed as net job equivalents per value chain (created jobs minus lost jobs due to replaced previous uses of the land).

5.5.1.1 Job equivalents per value chain

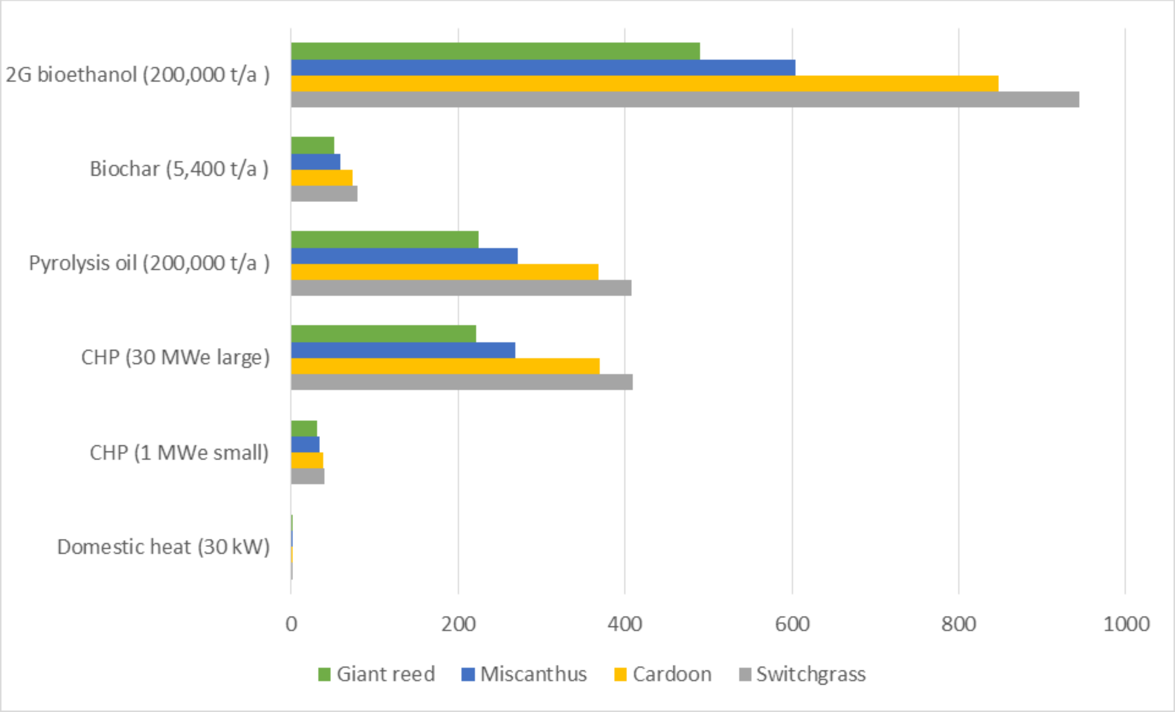

Fig. 5-8 Full job equivalents for each of the studied value chains

Fig. 5-8 shows the total (direct, indirect and induced) job equivalents for the under study value chains.

As expected, jobs increase as scales and amount of annually required biomass supply increases. Giant reed fuelled value chains always exhibit lower number of jobs as the crop yields (reported within the OPTIMA research teams) at marginal land are 17.5 t/ha/year, while Miscanthus yields are 14t/ha/year and switchgrass and cardoon much lower at 8.75 and 9.8 t/ha/year, respectively.

Fig. 5-9 presents the direct, indirect and induced jobs for the four under study crops in the domestic heat, CHP (small) and biochar value chains.

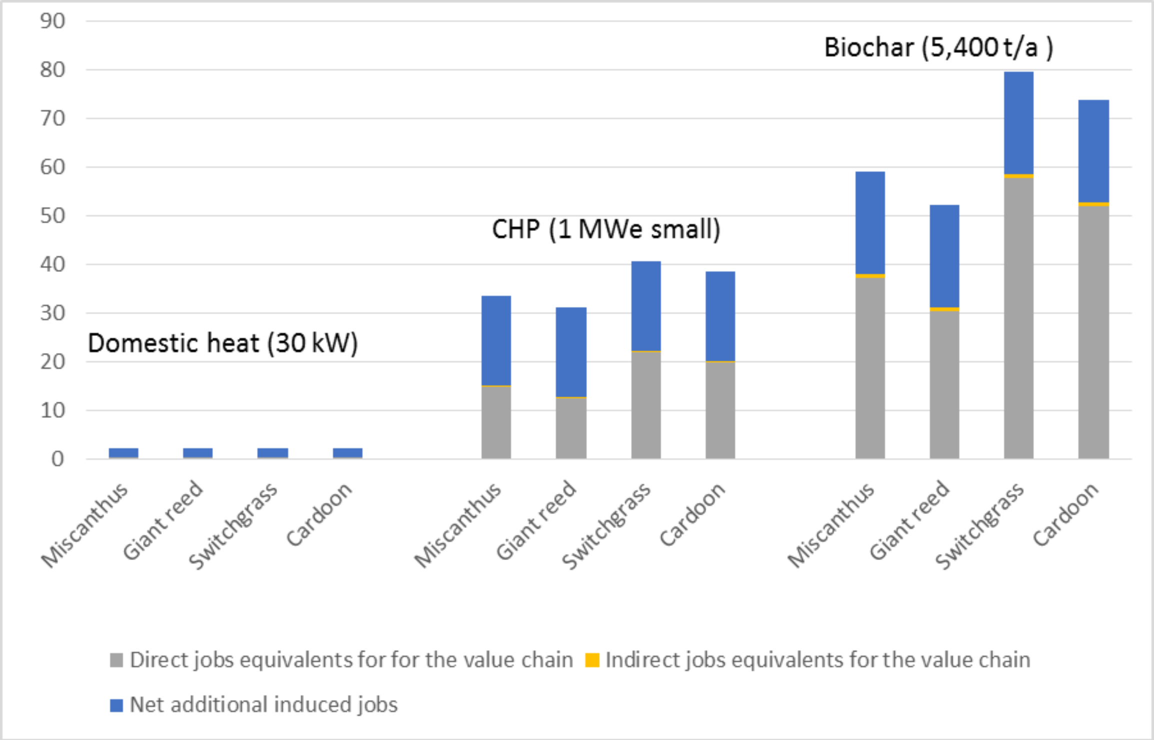

Fig. 5-9 Direct, indirect and induced jobs for the four under study crops in the domestic heat, CHP (small) and biochar value chains

In domestic heat the total number of job equivalents is around 2-2.3 with the number of direct jobs being in the range of 0.3 and the net additional induced jobs being around 2.

In small scale CHP direct jobs are approximately equal with the induced ones, deriving mainly from biomass production [Christian & Riche 1999]. In this value chain (as the previous was rather small and differences among crops were negligible) the influence of yields to the number of job equivalents shows differentiation in particular for giant reed as it exhibits a much higher yielding capacity (17.5 t/ha/year) than the other three- so less land is required to secure fuel supply for the power plant with subsequent lower number of direct job equivalents. The respective numbers of direct job equivalents range from 12 in the giant reed fuelled chain, to 15 in the Miscanthus, 20 in the cardoon and 22 in the switchgrass ones.

The number of total job equivalents for the biochar value chain ranges from 52 (giant reed) to 80 (switchgrass) with the same logic for the influence of yields in the direct job equivalents.

Net additional induced jobs have been estimated at 2 for domestic heat, 18 in small scale CHP and 21 in biochar (accounting mostly for equipment manufacturers, maintenance and service).

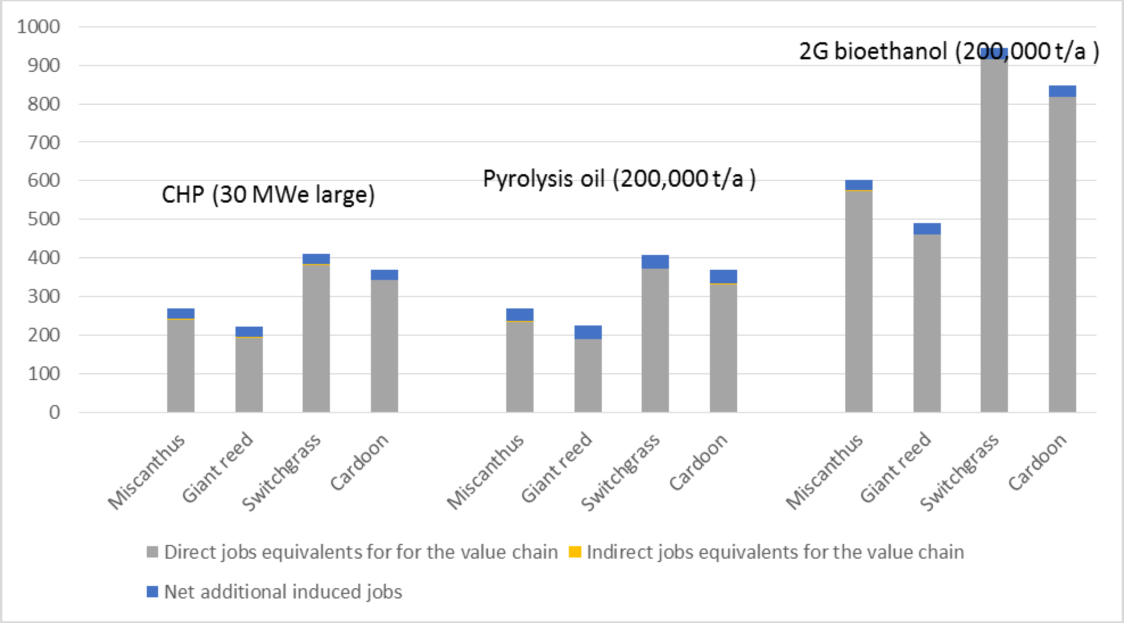

Fig. 5-10 Direct, indirect and induced jobs for the four under study crops in the CHP (large), pyrolysis and 2G bioethanol value chains

Fig. 5-10 shows the job equivalents for the large CHP, pyrolysis and 2G bioethanol value chains.

It is clear that as scales and respective amounts of required biomass supply increase the direct jobs have the major share in the total number of job equivalents as they reflect the large amounts of raw material. For reference, the full operation of both the pyrolysis and the second generation ethanol plant are estimated to generate 50-70 full time employees while building the plants themselves is expected to create almost 1,000 additional jobs during the construction phase. These figures are close to the ones from the Vivergo biofuels plant in the UK which started operation recently (during 2014).

Net additional induced jobs have been estimated at 26 in small scale CHP, 28 in pyrolysis oil and 29 in 2G bioethanol (accounting mostly for equipment manufacturers, maintenance and service).

5.5.1.2 Job equivalents per 1,000 tonnes of biomass input

In the case of total job equivalents per 1,000 tonnes of cropped biomass input, it has been estimated that the smaller scale value chains generate more local employment as they refer to small scale logistic channels and local infrastructures with much less efficiencies than international transport, storage, distribution. In this element we should also add that there are strong aspects of seasonality and part time employment in these scales which are not part of this analysis but should be take into account for future research, policy formation and local planning.

Both domestic heat boilers and small scale CHP result to an average of 4.5-6 total job equivalents for each 1,000 tonnes of biomass produced, handled and converted to end product, the majority of them being placed towards upstream production.

The larger scale value chains (i.e. bioethanol and pyrolysis) result to an average of 1.5-3 equivalents for each 1,000 tonnes of biomass produced, handled and converted to end product, the majority of them still in the upstream but with much higher share (45% instead of 15% in the smaller scales) for the logistics/ handling value chain component.

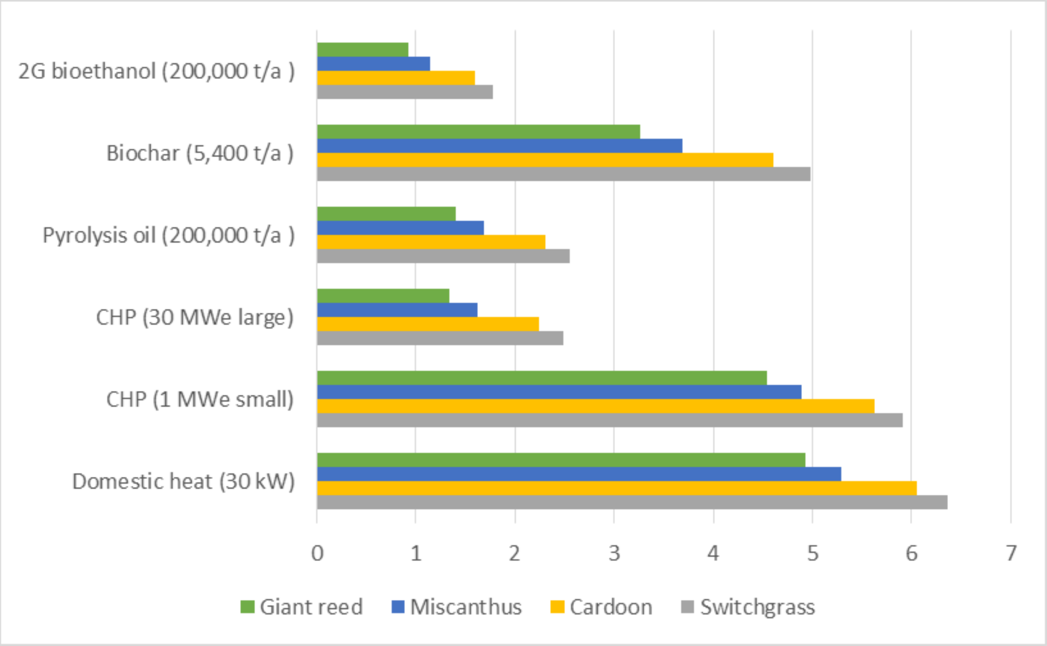

Fig. 5-11 Total job equivalents per 1,000 tonne of biomass input for the under study value chains

Table 5-11 Job equivalents per 1,000 tonne of biomass input for the domestic heat and 2G ethanol value chains averaged across the four under study crops.

Value chain component	Domestic heat (30 kW)	2G bioethanol (200,000 t/ha)
Direct		
Crop production (incl. harvesting)	2.5	0.5
Handling - Logistics	0.8	1.2
Conversion	0.2	0.1
Indirect		
	1.5	0.7
Total	**5**	**2.5**

5.5.1.3 Crops and yielding capacities

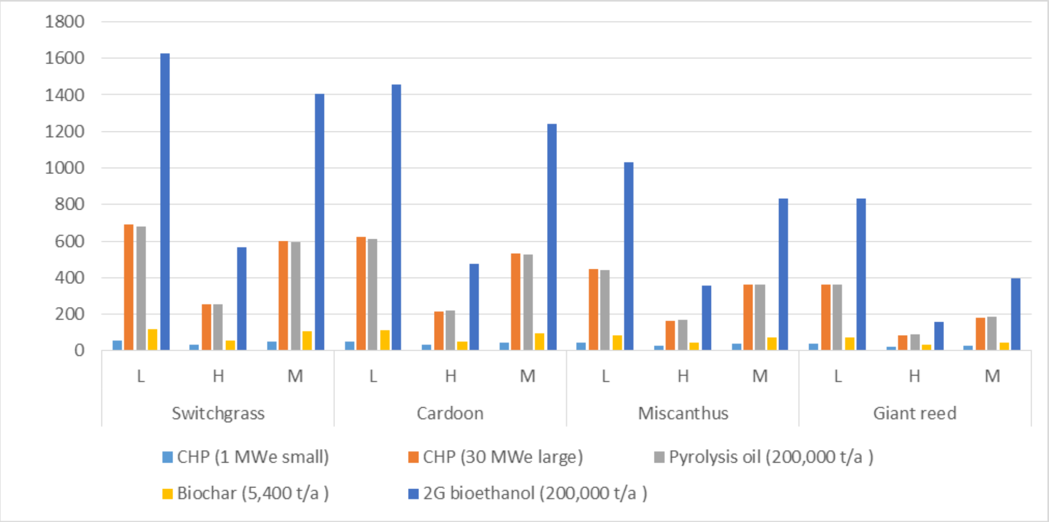

Fig. 5-12 Total job equivalents based on the different yielding capacities of the four under study perennial crops

Fig. 5-12 presents the variation in total job equivalents based on the different yielding capacities of the four under study perennial crops.

Domestic heat is not presented in the figure as the values are very small (ranging from 2- 2.4 job equivalents for the value chain) with negligible variations across crops and yields.

High yielding capacities (in intensified agricultural production with high inputs and good quality land) result to the lower number of job equivalents across the value chains and the four perennial crops.

5.5.2 Social sustainability

Social sustainability evaluates the impacts of the value chain to society and rural development. The analysis in OPTIMA took into account the following criteria:

- Contribution to rural economy: Employment is a major issue in rural economies. Certain value chains may induce more regional job creation, stimulating the rural economy, while other value chains may be more directed to large scale industry, often in the hands of international players/multinationals.
- Local embedding: The capacity of the local economy to develop and operate a full value chain or part of it (e.g. in the OPTIMA case the production of perennial crops).
- Proximity to markets: The indicator expresses the difference between a more local approach with low distances (feedstock converted and consumed locally) on the one side, and on the other side a more international/industrial approach where the feedstock is transported to large industrial sites, or to harbour areas to be exported.

All four under study perennial crops are considered highly beneficial to the three social sustainability criteria as they are expected to diversify farming activities, provide new opportunities for farmers and the rural economy and facilitate to improved infrastructure for harvesting, storage, transport and logistics.

Table 5-12 illustrates the performance of the under study value chains in the social sustainability criteria.

Domestic heat and small scale CHP rank high in all three criteria, as both the full value chain and the end product offer very good prospects to the rural economy with the production of perennial crops, the manufacturing and/ or increased market for biomass boilers/ related equipment and the provision of service for their operation and maintenance.

Large scale CHP value chains rank moderate in the contribution to local economy as they can be beneficial for the local economy in terms of partially supplying the plant with raw material and generating jobs for building and operating the plant while the major part of biomass supply and plant equipment is brought into the region from other regions or countries. The value chain ranks high in embedding to the local system and proximity to markets as it can provide heat to a district heating (if available) and electricity to the grid or industrial sites/ businesses.

The value chains of pyrolysis oil, biochar and 2G bioethanol rank low in embedding to the local system and proximity to markets as they are larger plants that the major part of their raw materials and respective sales of end product will be from outside the region/ local economy.

Table 5-12 Performance of the under study value chains in social sustainability

	Contribution to rural economy	Local embedding	Proximity to markets
Domestic heat	🟩	🟩	🟩
CHP (1 MWe small)	🟩	🟩	🟩
CHP (30 MWe large)	🟨	🟩	🟩
Pyrolysis oil	🟨	🟥	🟥
Biochar	🟨	🟥	🟥
2G bioethanol	🟨	🟥	🟥

5.5.3 Conclusions

Which is the best crop option?

Regarding employment effects giant reed fuelled value chains always exhibit lower number of jobs as the crop yields in all OPTIMA scenario cases are higher ranging from 10 to 30 t/ha/year, while Miscanthus yields range from 8 to 25 t/ha/year, switchgrass from 5 to 15 t/ha/year and cardoon from 5.6 to 18 t/ha/year, respectively.

From the sensitivity analysis for the impact of yields to employment, it is shown that high yielding capacities (in intensified agricultural production with high inputs and good quality land) result to the lower number of job equivalents across the value chains and the four perennial crops. Here, it should be stressed out the man effort required across the crops is rather similar, with slight differences in establishment of giant reed with rhizomes.

All four under study perennial crops are considered highly beneficial to the three social sustainability criteria as they are expected to diversify farming activities, provide new opportunities for farmers and the rural economy and facilitate the development of improved infrastructure for harvesting, storage, transport and logistics.

Which value chain performs best in terms of employment?

The under study value chains have different impact on employment as their scales and biomass requirements on an annual basis vary significantly. A general comment from the analysis is that as scales and respective amounts of required biomass supply increase the direct jobs have the major share in the total number of job equivalents as they reflect the large amounts of raw material. Therefore the three larger value chains, i.e. large scale CHP, pyrolysis oil and 2G bioethanol result in significantly higher number of jobs.

However, the results from the analysis can also be interpreted by addressing the issue of restricted land availability so the focus should be placed on establishing value chains which have the potential to generate higher jobs per biomass produced. From that perspective, as illustrated in Figure 4 domestic heat and small CHPs create most jobs provided the raw material is sustainable sourced and they are economically viable.

In detail, it has been estimated that the smaller scale value chains generate more local employment as they refer to small scale logistic channels and local infrastructures with much less efficiencies than international transport, storage, distribution. In this element we should also add that there are strong aspects of seasonality and part time employment in these scales which are not part of this analysis but should be take into account for future research, policy formation and local planning.

How do value chains perform in terms of social sustainability?

Smaller scale value chains like domestic heat and small CHP perform best in all the under study social sustainability criteria as both the full value chain and the end product offer very good prospects to the rural economy. The three larger scale perform low and moderate since they concern large production units with more “open market” end product orientation so their immediate benefits are not directly provided to the local community but to the society and environment as a whole.

Which are the gaps and what research is required to improve the knowledge base?

Calculating job equivalents requires clear definition of value chains and very detailed data provision at implementation scales. Therefore, it is considered important for future analysis to focus on value chains which can be comparable in terms of outputs and implementation scales and analyse impacts at local scales where the net implications for jobs and rural development can best be quantified.

Getting from job equivalents and social sustainability criteria to net job creation and quantification of income generated and induced in a region due to biomass value chains is more complicated and also requires clear definition of the reference system that the proposed value chain will displace.

5.6 Summary: SWOT analysis and biomass potentials

The following chapter is adopted from [Panoutsou 2015a]*. For detailed results, background information and recommendations please refer to the original assessment report.*

5.6.1 SWOT analysis

An analysis on strengths, weaknesses, opportunities, and threats (SWOT) is performed to identify the key internal and external factors that will determine the success of the OPTIMA pathways and the most promising reference systems. The analysis covers the full value chain with focus on the upstream aspects of the under study crops. The results are summarised in the following SWOT tables.

Table 5-13 SWOT analysis for giant reed, Miscanthus and switchgrass in the Mediterranean region.

	Favourable	**Unfavourable**
Internal	**Strengths**	**Weaknesses**
	For both systems Benefits might arise from the establishment of perennial grasses in a local agricultural system by diversification of activities, provision on new crop opportunities [Bassam 1998], etc. Perennial crop plantations can be designed to minimize negative impacts on water use. Higher lignin and cellulose contents in perennial grasses allow the crop to stand upright at scarcity of water. High water use efficiency due to deep and well developed root system. Due to their dense root system perennials can i)easily immobilize nutrients thus increasing the nutrient use efficiency, ii)be used as buffer strips, iii) exploit wastewater sources, iv) reduce erosion risks, v) minimize water runoff and vi) increase soil cover. Long-term presence in the field maintains soil structure and improves soil organic content. Public perception is better for large scale biorefinery applications fuelled with perennial crops (e.g. 2G ethanol, etc.) than heat and CHP.	For both systems Not fully established logistic and processes (varieties, cultivation, harvest, storage, quality control). Aquifer refilling slows down, due to deeper roots and high water needs. High productivity Exploits good land Irrigation is required to achieve good yields and maintain productivity. Direct competition with food and feed Low productivity Low yielding capacity in low input systems, especially under dry farming conditions in environments with low precipitation Mostly uneconomic for farmers

	High productivity Provide good yielding capacity and minimizes the demand for land use Low productivity No direct competition with food/ feed as land is mostly marginal and not currently in production	
	Opportunities	**Threats**
External	For both systems Diversify opportunities for rural employment and development. The establishment of perennial crop systems: i) reduces soil tillage (over long term), ii) minimizes use of agrochemicals, iii) favours soil micro fauna and iv) has been reported as giving shelter to invertebrates and birds. Combining energy and industrial uses for the crops improves the economics thus providing new resources for the industry and energy sectors. High productivity Improved varieties with selected traits through genetics development and use of high technological skills (genetic engineering, etc.). Improved agricultural practices. Low productivity Exploit certain types of low productivity land with optimized inputs and techniques.	For both systems Lack of strong communication channels with the agricultural community. Low commercial and industrial activity could present difficulties in the supply of components. Low level of interrelation between the agricultural and energy policies leads to non-efficient use or no use at all of the existing financial support mechanisms. Monoculture of any crop type (including the under study perennials) is a threat to biodiversity High productivity Direct competition with land for food and feed crops. Use of GMO to increase yields and adaptation is considered negative. Low productivity Increased fertilizer and other chemical inputs to achieve adequate yields in marginal land.

Table 5-14 SWOT analysis for the use of the four under study crops for small scale heat.

	Favourable	**Unfavourable**
Internal	**Strengths**	**Weaknesses**
	For the crops Use of indigenously produced material to displace coal/ oil in the small scale heat market delivers carbon reductions. Pellets are regarded as the best option for domestic, especially in urban areas due to convenience in handling and use. For the market segment Modern biomass heat technology is proven at a wide range of scales, with thousands of applications throughout Europe. The technologies vary from relatively low cost manual systems through to highly automated, advanced systems. Technologies are commercially available at most scales with technical reliability comparable to fossil fuels [Obernberger & Biedermann 2005].	For the crops Not well established logistic and processes (varieties, cultivation, harvest, storage, quality control). Fuel quality and standardisation issues for the use of grasses for small scale boilers are not well developed [Christian & Riche 1999]. The extra cost for the production of pellets can be prohibiting in small scale investments. For the market segment Biomass heat producing technologies have a slower response than gas or oil fired systems, but comparable to coal systems. However in practice, the gap is closed by installing buffer vessels with the biomass system. Biomass for heat requires more room than alternative fossil fuels for the boiler itself (with its buffer vessel if relevant), as well as for fuel storage, and for fuel delivery vehicles' access.
External	**Opportunities**	**Threats**
	For the crops Employment creation is invariably stressed as a key driver for biomass and especially perennial crops uptake but this is case-specific and it should be analysed as such in the different policy setting agendas. For the market segment The replacement of old inefficient boilers with high emissions levels can be seen as an opportunity for bioenergy. Capital grants and fiscal incentives are so far the most commonly means used to specifically support biomass heat boilers. Emissions trading and renewable certificate schemes can also be considered as good external drivers for future investments into biomass heat.	For the crops Increased emissions, vehicle movements associated with raw material transport, noise associated with fuel deliveries and aesthetic impacts (e.g. flues) may be critical constraints or concerns that need addressed. For the market segment Concentration of small scale biomass heat boilers impacts on local gaseous / particulate emission levels (especially in urban areas) with potential consequences on public health [Carbon Trust 2009].

Table 5-15 SWOT analysis for the use of the four under study perennial crops for large scale CHP.

	Favourable	Unfavourable
Internal	**Strengths**	**Weaknesses**
	For the crops Use of indigenously produced material delivers carbon reductions. Good potential of integrating perennial crops into agro-industrial or other forest based industrial CHP plants and combining them with the exploitation of residual streams. For the market segment CHP has a long history and so they are well known and developed. CHP technologies enable the fuel switch from coal, oil or natural gas to biomass in existing CHP systems. High potential of biomass CHP in terms of contribution to RES targets.	For the crops Not well established logistic and processes (varieties, cultivation, harvest, storage, quality control). Health and safety issues for handling large quantities of variable quality and bulky material. For the market segment Substantial heat demand is required to fully exploit the benefits of CHP plants; this frames the options for large scale CHP plants to locations where the generated heat can be used either for district heating or for industrial purposes.
External	**Opportunities**	**Threats**
	For the crops Employment creation is invariably stressed as a key driver for biomass and especially perennial crops uptake but this is case-specific and it should be analysed as such in the different policy setting agendas. Biomass from perennial crops can be a promising “complementary material” option for industries that are related or in close proximity to forest or agriculture based activities (forest products processing, etc.) and already use biomass for electricity/ process heat. For the market segment Increasing price of natural gas, oil and electricity A rather strong position of industrial CHP, opportunities for fuel switch, i.e. to biomass CHP.	For the crops Increased emissions, vehicle movements associated with raw material transport, noise associated with fuel deliveries and aesthetic impacts (e.g. flues) may be critical constraints or concerns that need addressed. These issues are considered particularly important in the services sector. The mobilisation of the agricultural sector to deliver to energy markets. Especially in relation to perennial crops, where there is a general feeling that farmers are reluctant to commit to grow them for a policy-driven bioenergy market in the context of high and rising prices in traditional agricultural markets. For the market segment Planning, design, authorisation, construction and commissioning of new dedicated biomass CHP plants can take a number of years and involve

		significant costs. Barriers to achieve planning permission for a large biomass electricity plant are: time and cost for planning studies, no planning precedents, local opposition by both politicians and local public, lack of joined-up policies between government agencies, inexperience and lack of resources in the planning authorities. Harmonised regulations and coherent policies are considered crucial to the future implementation of biomass CHP.

Table 5-16 SWOT analysis for the use of the four under study perennial crops for biofuels and bioliquids.

	Favourable	**Unfavourable**
Internal	**Strengths**	**Weaknesses**
	For the crops Use of indigenously produced material delivers carbon reductions. Good potential of integrating perennial crops into agro-industrial or other forest based second generation biofuel plants and combining them with the exploitation of residual streams. For the market segment Technology is considered very reliable[7] for first generation biofuels, while there is some reluctance to the maturity of the production capabilities for second generation biofuels up to 2020.	For the crops Not well established logistic and processes (varieties, cultivation, harvest, storage, quality control) Security of year round supply from perennial crops is considered a risk for large scale plants (pyrolysis, 2G ethanol, etc.). For the market segment Commercial maturity of second generation biofuels still faces difficulties in terms of scaling up facilities mainly due to the economic crisis and reduced cash flow liquidity. Balancing biomass material needs and various sustainability concerns is perceived as a major challenge for the future development of the second generation biofuels.

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[7] 'Reliable technology' related to end-user reflects fuel-engine compatibility while reliable technology for biofuel production is mainly addressing ability to increase the volumes produced.

	Opportunities	**Threats**
External	For the crops Development of new varieties with optimized traits for biofuels Employment creation is invariably stressed as a key driver for biomass and especially perennial crops uptake but this is case-specific and it should be analysed as such in the different policy setting agendas. For the market segment When considering future biofuel penetration it is important to consider the full chain GHG balances and take into account their respective performance. The 2016 increase in the overall sustainability threshold may be a limiting factor for first generation biofuel availability in the market and present a good opportunity for second generation ones based on lignocellulosic material (including perennial grasses).	For the crops Increased emissions, vehicle movements associated with raw material transport, noise associated with fuel deliveries and aesthetic impacts (e.g. flues) may be critical constraints or concerns that need addressed. The mobilisation of the agricultural sector to deliver to energy markets. Especially in relation to perennial crops, where there is a general feeling that farmers are reluctant to commit to grow them for a policy-driven bioenergy market in the context of high and rising prices in traditional agricultural markets. Health and safety issues for handling large quantities of variable quality and bulky material. For the market segment Developing second generation biofuel facilities will take time as the industry moves up the learning curve. Likewise, the economic viability of next generation biofuel facilities will improve overtime. Well-thought support mechanisms are needed to commercialize the technologies. Continued financial support for renewable energy will be a challenge in times of tight public budgets.

Table 5-17 SWOT analysis for the use of the four under study perennial crops for biomaterials.

	Favourable	**Unfavourable**
Internal	**Strengths**	**Weaknesses**
	For the crops Use of indigenously produced material delivers carbon reductions. Good potential of integrating perennial crops into agro-industrial or other forest based second generation biofuel plants and combining them with the exploitation of residual streams. For the market segment Strong drivers for biotechnology from the chemical industry. Ecological benefits from the use of biomaterials Europe is very strong in biotechnology both at industrial and R&D levels.	For the crops Not well established logistic and processes (varieties, cultivation, harvest, storage, quality control) For the market segment The market is not yet fully developed. Conflicts with food, feed and bioenergy/ biofuels may pose hurdles to rapid uptake of biomaterials. Not enough start- up companies
External	**Opportunities**	**Threats**
	For the crops Employment creation is invariably stressed as a key driver for biomass and especially perennial crops uptake but this is case-specific and it should be analysed as such in the different policy setting agendas. For the market segment The chemical industry seeks feedstock flexibility Development of industries for specialized plant products for niche markets. Accelerate partnering and technology transfer.	For the crops Increased emissions, vehicle movements associated with raw material transport, noise associated with fuel deliveries and aesthetic impacts (e.g. flues) may be critical constraints or concerns that need addressed. Land use for industrial plant cultivation is under scrutiny both at political and at industrial level. Health and safety issues for handling large quantities of variable quality and bulky material. For the market segment Investment in new technologies is limited at current financial situation in Europe.

5.6.2 Biomass potentials

Recent work in the Biomass Futures project stated that dedicated cropping with perennials for bioenergy production is most likely to take place on land that is not needed for the production of food and feed production nor biofuel crops. In order to estimate the amount of land that can be exploited in 2020 and 2030 a post-model analysis was made in the project for the agricultural production area as modelled in CAPRI 2020 baseline and 2030 reference scenario and 2004. By comparing the size of different types of land uses in the future years with the 2004 situation an estimate was made of the amount of land released, but also of the type of categories of land released. Low quality land is expected to be released for perennial crops like vineyards, olives and fallow.

Two scenarios have been elaborated for the below presented land potentials, the reference and the sustainability. In the sustainability scenario stricter sustainability criteria were applied to all bioenergy carriers, including solid and gaseous ones. An important difference with the reference scenario is that this GHG mitigation requirement should also include compensation for emissions from indirect land use changes caused by biomass cropping in the EU.

Table 5-18 Dedicated cropping potential (1,000 ha) in 2020 and 2030 in reference and sustainability scenarios.

	2020		**2030**	
1,000 ha	**Reference**	**Sustainability**	**Reference**	**Sustainability**
	grassy	**grassy**	**grassy**	**grassy**
Greece	763	361	460	208
Spain	2,660	1,592	1,919	1,037
Italy	1,453	1,144	1,665	669
Portugal	128	66	94	43
Sub- total	**5,004**	**3,163**	**4,139**	**1,957**
EU-27	**10,389**	**7,844**	**10,086**	**7,291**

The land potential estimates in this work excluded a further potential of land that has been abandoned already before 2004 and therefore not included in the total utilised agricultural area figures of 2004 used in the CAPRI modelling exercise. This abandoned land resource is expected to be considerable especially in the CEEC and the Mediterranean and could also add significantly to future potentials. This however has not been taken into account in the potential presented in Table 5-18.

In order to come to a total land use potential for dedicated cropping in the two scenarios different criteria were applied to select the final perennial crop mix. This mix firstly fits with the soil and climate characteristics per region, but to determine the final mix in the reference scenario priority was given to the cheapest crop mix per region, while in the sustainability scenario the crops with the highest mitigation potential were selected, with cost level as secondary selection criterion. In the sustainability scenario there is less land available to use for dedicated cropping and/or there are more regions where the mitigation requirement is not reached.

5.7 Results integrated assessment

The integrated assessment joins the results of the assessments of individual sustainability aspects (chapters 5.1 to 5.6) into an overall picture. It identifies the most sustainable solutions from various viewpoints and highlights trade-offs. To this end, OPTIMA scenarios are first compared to conventional alternatives to derive general advantages and disadvantages (chapter 5.7.1). Then the significance of shown results for decision making are discussed (chapter 5.7.2) and, based on this, front-runner scenarios from various perspectives are identified (chapter 5.7.3). Finally, trade-offs are discussed that occur when deciding for any of the front-runner scenarios (chapter 5.7.4).

5.7.1 Comparison of OPTIMA scenarios to conventional alternatives

The integrated sustainability assessment is based on a life cycle comparison of providing a certain product either from biomass by processes studied in OPTIMA or from mostly fossil resources by conventional processes. These life cycle comparisons were comprehensively

Table 5-19 Overview of selected sustainability indicators.

Impact category	Short description
Technology	
Maturity (of cultivation on marginal land / harvest + logistics / conversion)	Technical maturity of involved processes on EU technology readiness level (TRL) scale from 1: basic principles observed to 9: actual system proven in operational environment.
Feedstock compatibility	Degree of technical adaptation that is required because of using a feedstock other than the standard feedstock (e.g. wood, wheat straw).
Required development work	Average number of TRL levels in the whole value chain until maturity (TRL 9) is reached.
Complexity	Indicates how easily the plant can be operated under / adapted to non-optimal conditions and how easily it can be optimised.
Suitability for small scale	Indicates how well the technology is suitable for local small scale use.
Environment: life cycle assessment (LCA)	
Energy use	More specific: non-renewable energy use (NREU). Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Climate change	Climate change as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide (CO_2), a number of other gases like methane (CH_4) and nitrous oxide (N_2O) are included.
Acidification	Shift of the acid / base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword ‘acid rain’).
Marine / freshwater eutrophication	Input of nutrients into marine or freshwater directly or via input into soils and gaseous emissions. E.g. nitrogen and phosphorous species contribute to this (keyword ‘algal bloom’).

Impact category	Short description
Summer smog	Photochemical formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword 'ozone alert').
(Stratospheric) Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword 'ozone hole').
Particulate matter formation	Damage to human health due to air pollutants such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, keyword 'winter smog' or 'London smog').
Land use	In this case: Occupation of marginal land by production of energy crops. This category is only displayed if results are shown per t of biomass.
Environment: environmental impact assessment (EIA)	
Biodiversity	Local biodiversity among animals and plants.
Soil	Soil quality is affected e.g. by erosion, compaction or organic matter content.
Water	Local water availability for ecosystems and its quality.
Landscape	Characteristics and diversity of the landscape.
Economy	
Return on investment	Return on investment is a measure for the economic feasibility of the scenario.
Internal Rate of Return (IRR)	The interest rate at which the Net Present Value (NPV) of the project equals zero. i.e. the cost of capital (interest rate), over which the investment is unprofitable. It is a measure of investment attractiveness.
Payback period	The number of years it takes for profits to repay the initial investment. It is an indicator for capital recovery and risk of the investment.
Total Assets Turnover	The total assets turnover is an indicator of efficiency. It is only meaningful in a commercial environment but not for households.
Society	
Job equivalents	Net created jobs including direct jobs (those employed by the project itself), indirect jobs (those employed in supplying inputs to the project), and induced jobs (those employed to provide goods and services to meet consumption demands of additional directly and indirectly employed workers).
Contribution to rural economy	Certain value chains may induce more regional job creation, stimulating the rural economy, while other value chains may be more directed to large scale industry, often in the hands of international players / multinationals.
Local embedding	The capacity of the local economy to develop and operate a full value chain or part of it (e.g. in the OPTIMA case the production of perennial crops).
Proximity to markets	The indicator expresses the difference between a more local approach with low distances (feedstock converted and consumed locally) and a more international / industrial approach where the feedstock is transported to large industrial sites, or to harbour areas to be exported.
SWOT	
Public perception	General current perception and acceptance of a scenario.
Use of GMO	Acceptance of a potential use of genetically modified organisms.
Health & Safety	Occupational health and safety issues.
Security of feedstock supply	Market availability of suitable feedstock at any time when required by the respective logistics concept.

assessed regarding many sustainability aspects, which led to results for many sustainability indicators. A selection of the most relevant indicators is presented in Table 5-19 and the results[8] of the life cycle comparisons to equivalent conventional product life cycles are shown in Table 5-20. Particularly in the socio-economic assessment, these indicators represent only a small selection of all possible indicators.

The comparison of OPTIMA scenarios to conventional scenarios shows rather similar patterns of advantages and disadvantages. Thus, improvements of sustainability in some aspects will always come at the cost of additional impacts regarding other aspects. The following general strengths and weaknesses of providing energy and material products from perennial biomass cultivated on marginal land can be seen although they do not apply to all scenarios:

General strengths and weaknesses: Sustainability

- Environment
  - Most scenarios achieve a mitigation of global warming and reductions in the depletion of fossil energy resources. At the same time, most other environmental impacts are worse than for conventional provision of the same products. This effect is commonly seen for products of intensive agriculture. The impact on water resources is negative if irrigation is needed.
- Economy
  - The economic performance largely depends on the use option of the biomass. Some scenarios can compete well with equivalent conventional options; others are not expected to be profitable under the assessed conditions. Thus, profitability is neither a general strength nor weakness of cultivating and using perennial grasses but has to be analysed in detail.
- Society
  - Regionality has strong implications for social impacts and can be made a strength of the assessed value chains. This is reflected in the indicators contribution to rural economy, local embedding and proximity to markets. The scenarios show high advantages if regionally produced biomass is used in comparatively small scale units. If large scale conversion plants are involved, impacts are not as favourable.
  - Job creation is another advantage of the OPTIMA scenarios. A major contribution to job creation is also expected from a general strengthening of the rural economy.

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[8] In case several alternatives for one scenario have been assessed in the individual assessments of sustainability aspects, scenarios with identical settings were chosen for the integrated assessment although they may be part of sensitivity analyses instead of standard scenarios in the original assessment report.

Table 5-20 Overview of sustainability assessment results. Results are shown for cultivation on marginal land (marginal 1) and standard conversion conditions. Categorisation and respective colouring of quantitative results reflects differences to the conventional alternative. TRL: technology readiness level, GMO[9]: genetically modified organism, N/A: not applicable, N/D: no data.

Area	Indicator	Unit	Giant reed						
			Giant reed → Domestic heat	Giant reed → Small CHP	Giant reed → Large CHP	Giant reed → Pyrolysis oil	Giant reed → Biochar	Giant reed → 2G Ethanol	Giant reed → 1,3-Propanediol
Technology	Maturity cultivation (marg. land)	TRL	6	6	6	6	6	6	6
	Maturity harvest+logistics	TRL	5	5	5	5	5	5	5
	Maturity conversion	TRL	9	9	9	7	7	7	5
	Feedstock compatibility	(qualitative)	○	○	○	○	○	○	○
	Required development work	TRL	2,7	2,7	2,7	3,3	3,3	3,3	4,0
	Complexity	(qualitative)	+	○	○	– –	○	– –	– –
	Suitability for small scale	(qualitative)	++	+	–	–	○	– –	– –
Environment: LCA	Energy use	GJ / ha / yr	-149	-221	-317	-81	152	47	50
	Climate change	t CO_2 eq. / ha / yr	-13,2	-14,9	-17,0	-6,6	-3,9	2,2	3,5
	Acidification	kg SO_2 eq. / ha / yr	40	18	-5	29	36	43	47
	Marine eutrophication	kg N eq. / ha / yr	9,8	9,3	8,8	9,5	9,5	11,2	9,5
	Freshwater eutrophication	kg P eq. / ha / yr	1,5	1,1	0,9	1,4	1,4	1,7	1,7
	Summer smog	kg NMVOC eq. / ha / y	30	16	3	24	23	23	22
	Ozone depletion	g R11 eq. / ha / yr	57	58	60	57	57	106	69
	Particulate matter formation	kg PM10 eq. / ha / yr	11,6	4,6	-1,6	8,9	10,4	11,6	11,6
Envir.: EIA	Biodiversity	- (score)	1,5	2,0	2,5	3,1	2,4	4,3	4,4
	Soil	- (score)	1,7	2,8	2,9	3,5	2,2	3,6	3,6
	Water	- (score)	7,3	8,1	9,5	8,7	8,1	12,9	12,9
	Landscape	- (score)	0,0	0,6	1,4	0,9	0,6	1,4	1,4
Economy	Return on investment	- (ratio)	14%	7%	17%	1%	3%	-24%	N/D
	Internal rate of return	- (ratio)	12%	8%	15%	1%	2%	N/A	N/D
	Payback period	years	7,4	9,8	6,3	19,0	16,0	N/A	N/D
	Total assets turnover	- (ratio)	0,25	0,34	0,56	0,94	0,94	0,61	N/D
Society	Job equivalents	jobs / 1000 ha	77	71	21	20	51	15	N/D
	Contribution to rural economy	(qualitative)	○	++	○	○	○	○	○
	Local embedding	(qualitative)	++	++	○	– –	– –	– –	– –
	Proximity to markets	(qualitative)	++	++	○	– –	– –	– –	– –
SWOT & biomass potentials	Public perception	(qualitative)	+	+	+	++	++	++	++
	Use of GMO	(qualitative)	– –	– –	– –	– –	– –	– –	– –
	Health & Safety	(qualitative)	○	○	–	– –	–	– –	–
	Security of feedstock supply	(qualitative)	○	○	–	– –	○	– –	○
	Cropping potential	Mha	7,8	7,8	7,8	7,8	7,8	7,8	7,8

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[9] GMOs are not but could theoretically be used in the assessed scenarios. That would lead to a negative public perception.

Table 5-20 (continued)

Miscanthus							Switchgrass							Cardoon						
Miscanthus → Domestic heat	**Miscanthus → Small CHP**	**Miscanthus → Large CHP**	**Miscanthus → Pyrolysis oil**	**Miscanthus → Biochar**	**Miscanthus → 2G Ethanol**	**Miscanthus → 1,3-Propanediol**	**Switchgrass → Domestic heat**	**Switchgrass → Small CHP**	**Switchgrass → Large CHP**	**Switchgrass → Pyrolysis oil**	**Switchgrass → Biochar**	**Switchgrass → 2G Ethanol**	**Switchgrass → 1,3-Propanediol**	**Cardoon → Domestic heat**	**Cardoon → Small CHP**	**Cardoon → Large CHP**	**Cardoon → Pyrolysis oil**	**Cardoon → Biochar**	**Cardoon → 2G Ethanol**	**Cardoon → 1,3-Propanediol**
6	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
9	9	9	7	7	7	5	9	9	9	7	7	7	5	9	9	9	7	7	7	5
○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	– –	–	– –	– –
2,3	2,3	2,3	3,0	3,0	3,0	3,7	2,3	2,3	2,3	3,0	3,0	3,0	3,7	2,7	2,7	2,7	3,7	3,7	3,7	4,3
+	○	○	– –	○	– –	– –	+	○	○	– –	○	– –	– –	+	○	○	– –	○	– –	– –
++	+	–	–	○	– –	– –	++	+	–	–	○	– –	– –	++	+	–	–	○	– –	– –
-180	-240	-321	-123	74	-15	-12	-104	-140	-188	-70	48	-10	-8	-130	-169	-222	-93	36	-27	-26
-14,8	-16,3	-18,0	-9,2	-6,9	-1,9	-0,8	-8,4	-9,2	-10,2	-5,0	-4,2	-0,9	-0,2	-10,0	-10,9	-12,0	-6,3	-5,5	-1,9	-1,1
24	6	-13	15	21	27	31	22	11	-1	16	19	23	26	23	10	-2	16	19	24	26
3,8	3,4	3,0	3,6	3,6	5,0	3,6	5,5	5,2	5,0	5,3	5,3	6,3	5,3	7,2	6,9	6,7	7,0	7,0	8,0	7,0
0,5	0,1	-0,1	0,4	0,4	0,6	0,6	0,4	0,2	0,1	0,4	0,4	0,5	0,6	0,6	0,3	0,2	0,5	0,5	0,6	0,7
21	9	-2	16	15	15	14	16	9	3	12	12	11	11	15	7	0	11	10	10	10
21	22	24	21	21	63	31	32	32	34	32	32	59	38	42	42	44	41	42	71	48
8,1	2,2	-3,0	5,8	7,1	8,1	8,0	6,5	3,0	-0,2	4,9	5,7	6,3	6,3	5,9	2,1	-1,4	4,1	5,0	5,7	5,7
0,0	0,6	1,1	1,7	1,0	3,1	3,2	2,7	3,3	3,8	4,5	3,7	5,8	5,9	-2,2	-1,6	-1,1	-0,4	-1,2	0,9	1,0
0,1	1,3	1,5	2,1	0,6	2,2	2,2	3,5	4,7	4,9	5,5	4,0	5,6	5,6	1,4	2,6	2,8	3,5	2,0	3,6	3,6
2,3	3,2	4,8	3,9	3,2	8,6	8,6	3,8	4,7	6,3	5,4	4,7	10,1	10,1	3,1	4,1	5,7	4,7	4,1	9,5	9,5
-0,1	0,5	1,5	0,8	0,5	1,5	1,5	2,6	3,2	4,2	3,5	3,2	4,2	4,2	-0,3	0,4	1,3	0,7	0,4	1,3	1,3
13%	6%	15%	-7%	-2%	-34%	N/D	13%	6%	15%	-6%	-2%	-34%	N/D	13%	6%	15%	-6%	-2%	-34%	N/D
11%	7%	13%	N/A	N/A	N/A	N/D	11%	7%	14%	N/A	N/A	N/A	N/D	11%	7%	14%	N/A	N/A	N/A	N/D
8,0	7,8	6,8	73,0	26,0	N/A	N/D	7,9	10,2	6,7	51,0	24,0	N/A	N/D	7,9	10,3	6,8	58,0	24,0	N/A	N/D
0,25	0,34	0,56	0,94	0,94	0,61	N/D	0,25	0,34	0,56	0,94	0,94	0,61	N/D	0,25	0,34	0,54	0,94	0,94	0,61	N/D
69	64	21	20	49	16	N/D	54	50	21	21	42	16	N/D	56	52	21	20	43	15	N/D
○	++	○	○	○	○	○	○	++	○	○	○	○	○	○	++	○	○	○	○	○
++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –
++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –
+	+	+	++	++	++	++	+	+	+	++	++	++	++	+	+	+	++	++	++	++
– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –
○	○	–	– –	–	– –	–	○	○	–	– –	–	– –	–	○	○	–	– –	–	– –	–
○	○	–	– –	○	– –	○	○	○	–	– –	○	– –	○	○	○	–	– –	○	– –	○
7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8	7,8

How to read Table 5-20, environmental indicator acidification:

Cultivation of giant reed and its use for domestic heat generates 40 kg of SO_2 equivalents per hectare per year more than the same amount of domestic heat from light fuel oil. Similarly for most other scenarios, the cultivation and use of perennial biomass creates higher burdens regarding acidification than the production and use of alternative conventional products (red background). In some cases, bio-based and conventional products are considered not substantially different because the difference in smaller than 10 % of the overall bandwidth of results (yellow background).

Remarks on qualitative and economic indicators:

Qualitative results are coloured according to the rating from ‘++’ to ‘--‘. Results for economic indicators are categorised individually because of the different meaning of the numbers in different business contexts and coloured accordingly.

General strengths and weaknesses: Barriers towards implementation

The implementation of generally sustainable scenarios may still cause unexpected and sometimes undesirable consequences if they cannot be implemented in the intended form or if operations stop after a short time. The following barriers were found to be relevant:

- Although there are substantial cropping potentials on marginal land in the EU, their extent is limited, too. Furthermore, not all marginal land will be usable in practise e.g. because parts are scattered over a large area. The extent of available land also depends on how strict the applied sustainability criteria are (see also chapter 5.6.2). On the contrary, future plans for many sectors including power, heat, fuels and chemicals rely on increased biomass use. This demand most likely exceeds cropping potentials on available regular and marginal land. Thus, the availability of marginal land will be limiting once suitable policies and technologies exist to support its cultivation. Consequently, achievable sustainability benefits are limited by the availability of marginal land.
  Seen the other way around, insufficient local biomass supply after implementation of a scenario may lead to the use of less suitable or unsuitable land with higher impacts on sustainability than assessed in this study. Depending on the logistics concept, scenarios depend to a different degree on the security of feedstock supply. Some show potentially severe implications (mainly large continuously operated facilities with limited storage capacity) while others are less affected (e.g. domestic heat with storage for a whole season).
- None of the OPTIMA scenarios is fully mature and established in practise. For some scenarios, in particular those that involve energy provision via direct combustion, the required development work is limited to agriculture and certain technological adaptations. For other scenarios, in particular involving innovative conversions, there is still substantial work to be done. Some scenarios may turn out to be technically unfeasible in the assessed forms if expected technological development stays behind expectations.
  This also means that process parameters underlying the assessed scenarios are to some extent uncertain. Therefore, sustainability impacts of future mature technology may

deviate from the results of this assessment although bandwidths were used for the calculation of many quantitative parameters (see also Table 8-1 in the annex).

- For most use options, biomass from perennial grasses will very likely have to be mixed with other biomass to fulfil technical specifications. This interlinkage with other value chains may cause some friction but may also generate synergies if existing infrastructure or distribution channels can be used.
- A regional use of the produced biomass results in positive social impacts as discussed above. However, not all of the assessed use options are suitable for use on a small scale or are complex to optimise and operate. This could hinder a successful implementation of some scenarios in particular in remote rural areas, where marginal land is often located.
- Potential occupational health and safety issues were identified the SWOT analysis. These have to be solved not to risk negative impacts.
- Public perception of all assessed scenarios is currently positive. However, the use of genetically modified organisms, which is not part of the assessed scenarios, would probably not be accepted by the public. Depending on implementation conditions, including the potential use of genetically modified organisms as one example, public perception may therefore turn quickly from strength into weakness.

5.7.2 Significance of results for decision support

Scenarios are possible futures that can result from certain choices. Naturally, there is also uncertainty as to the effect of these choices. This uncertainty is reflected in bandwidths for many quantitative indicators (see also Table 8-1 in the annex). These bandwidths are taken into account in the comparison metrics used for the benchmarking analysis in chapter 5.7.4.

Furthermore, the reports on the assessment of individual sustainability aspects contain a number of sensitivity analyses on parameters that are important for the sustainability indicators analysed in the respective study [van den Berg, de Jamblinne, et al. 2015; Fernando, Boléo, Barbosa, Costa, & Duarte 2015; Panoutsou 2015a; b; Rettenmaier et al. 2015; Soldatos & Asimakis 2015]. It was impossible to include all of them in the summary chapters 5.1 – 5.6. Nevertheless, the conclusions from these analyses are taken into account for the overall conclusions and recommendations in chapter 6. Exemplarily, one important sensitivity analysis that affects both economic and life cycle assessment indicators is summarised in Table 5-21. It highlights the importance of the substituted energy carrier for heat provision. The effect on LCA indicators is considerable but not decisive for the comparison of the shown scenarios to the conventional reference system or the comparison among the shown scenarios. For the economic performance of the scenario small CHP it is, however, decisive. It shows that combined heat and power plants fuelled with biomass pellets from perennial grasses can be profitable or not depending on a number of parameters including scale and competing options. These parameters can differ within the Mediterranean region. For example, natural gas is not available in many places, where heat plants thus largely depend on light fuel oil. In such places, it is comparatively more economic to build biomass-fired small CHPs.

Table 5-21 Sensitivity analysis on the reference system of heat provision. Selected scenarios are compared to power provision from the grid and heat provision by heat plants fuelled with natural gas (NG) or light fuel oil (LFO). Indicators not shown here are not or only marginally affected. N/D: no data.

			Giant reed				Miscanthus				Switchgrass				Cardoon			
			Giant reed → Small CHP		Giant reed → Large CHP		Miscanthus → Small CHP		Miscanthus → Large CHP		Switchgrass → Small CHP		Switchgrass → Large CHP		Cardoon → Small CHP		Cardoon → Large CHP	
Area	**Indicator**	**Unit**	**NG**	**LFO**	**NG**	**LFO**	**NG**	**LFO**	**NG**	**LFO**	**NG**	**LFO**	**NG**	**LFO**	**NG**	**LFO**	**NG**	**LFO**
Environment: LCA	Energy use	GJ / ha / yr	-211	-221	-317	-327	-232	-240	-321	-330	-135	-140	-188	-193	-164	-169	-222	-228
	Climate change	t CO_2 eq. / ha / yr	-11,1	-14,9	-17,0	-20,8	-13,1	-16,3	-18,0	-21,2	-7,3	-9,2	-10,2	-12,1	-8,8	-10,9	-12,0	-14,1
	Acidification	kg SO_2 eq. / ha / yr	23	18	-5	-10	10	6	-13	-18	14	11	-1	-3	13	10	-2	-5
	Marine eutrophication	kg N eq. / ha / yr	9,3	9,3	8,8	8,8	3,4	3,4	3,0	3,0	5,3	5,2	5,0	5,0	6,9	6,9	6,7	6,6
	Freshwater eutrophication	kg P eq. / ha / yr	1,1	1,1	0,9	0,9	0,1	0,1	-0,1	-0,1	0,2	0,2	0,1	0,1	0,3	0,3	0,2	0,2
	Ozone depletion	g R11 eq. / ha / yr	59	58	60	59	23	22	24	23	33	32	34	33	43	42	44	43
	Particulate matter formation	kg PM10 eq. / ha / yr	6,1	4,6	-1,6	-3,1	3,4	2,2	-3,0	-4,3	3,8	3,0	-0,2	-0,9	2,9	2,1	-1,4	-2,2
Economy	Return on investment	- (ratio)	-7%	7%	17%	23%	-8%	6%	15%	20%	-8%	6%	15%	21%	-8%	6%	15%	21%
	Internal rate of return	- (ratio)	N/A	8%	15%	18%	N/A	7%	13%	17%	N/A	7%	14%	17%	N/A	7%	14%	17%
	Payback period	years	N/A	9,8	6,3	5,3	N/A	7,8	6,8	5,7	N/A	10,2	6,7	5,7	N/A	10,3	6,8	5,7
	Total assets turnover	- (ratio)	0,20	0,34	0,56	0,62	0,20	0,34	0,56	0,62	0,20	0,34	0,56	0,62	0,20	0,34	0,54	0,62

In some cases, additional specific aspects have to be taken into account when interpreting the data for decision support:

- In the environmental impact category 'summer smog', low net advantages or disadvantages result from relatively high emissions and credits. Due to this uncertainty, the biomass path cannot be reliably rated advantageous or disadvantageous compared to the fossil path regarding summer smog.
- For some indicators, results for all OPTIMA scenarios are identical or not sufficiently different taking uncertainty into account. Thus, these indicators can only yield information regarding strengths or weaknesses of OPTIMA scenarios compared to conventional ways of providing the same products but not for comparing OPTIMA scenarios to each other. Therefore, the indicators 'cropping potential', 'use of GMO' and 'summer smog' are not displayed any more in the following.
- Local environmental impacts on biodiversity, soil, are hard to assess. Severe permanent disturbances of small areas, as they are observed for fossil resource extraction, have to be compared to less severe and largely reversible disturbances of large areas mainly by agricultural operations on marginal land. There are no natural science arguments to prefer one over the other. Hence, any comparison heavily depends on value-based weights assigned to quality, magnitude, extent and duration of impacts. Nevertheless, cultivation options can be compared and optimised based on these indicators.

Excursus: Greenhouse gas abatement costs

The combination of economic and selected environmental indicators into abatement costs can yield additional information on the efficiency e.g. of potential policy measures. For example, greenhouse gas (GHG) abatement costs could indicate, how much reduction in emissions could be achieved per Euro of incentives. The calculation of such indicators is detailed in chapter 3.3.3. In this case, ‘costs’ would refer to additional monetary incentives to be covered by the society including direct subsidies and higher consumer prices due to regulatory measures such as mandatory quota. However, particularly the energy, fuel and agricultural sector are already highly regulated and / or subsidised. This applies to both fossil- and bio-based value chains and is furthermore substantially different from country to country within the EU. Additionally, market actors take investment decisions based on completely different criteria in the contexts of e.g. domestic heat or large industrial facilities. Therefore, required subsidies for any of the assessed scenarios to become sufficiently attractive for investors heavily depend on the context. Any generalised number for the Mediterranean region would oversimplify these issues. In consequence, GHG abatement costs are not calculated in this study but only qualitatively discussed in this excursus.

The categorisation of the economic assessment results (background colours in Table 5-20) take the different perspectives of e.g. households and utilities industry on the attractiveness of investments into account. Furthermore, results of the bio-based value chains are calculated on a cost basis without direct subsidies. Thus, scenarios with mostly green results would not require monetary support. The more results are yellow or red, the more incentives are needed including potentially existing ones. Compared to the environmental indicator ‘climate change’, two qualitative trends can be identified:

1. High and low greenhouse gas emission savings often correlate with good and bad economic performance, respectively. This is due to the respective efficiency over the whole life cycle.
2. In particular domestic heat deviates from this trend as it shows a good economic performance at intermediate greenhouse gas savings. In this case, the much smaller scale of the individual investment contributes positively to the results.

In summary, GHG abatement costs do not add much information on a general level because greenhouse gas emission savings and economic performance largely correlate. Further detailed studies are necessary to add decision-relevant information on how public money could be invested most productively to mitigate climate change, which is beyond the scope of this assessment. These studies will also have to analyse country-specific existing subsidies of both fossil- and bio-based energy, fuels and other products. Abatement costs are not shown in this assessment to avoid misleading conclusions.

5.7.3 Identification of front-runner OPTIMA scenarios

If general weaknesses and disadvantages of OPTIMA pathways compared to their conventional alternatives (as detailed in chapter 5.7.1) are considered acceptable to achieve the general benefits, then the most sustainable of the OPTIMA scenarios have to be identified. In Table 5-22, all quantitative results are categorised and colour-coded according to deviations from the average of all OPTIMA scenarios. Thus, this table shows the *relative* performance of all OPTIMA scenarios.

It is obvious from Table 5-22 that there is no scenario, which is better than all other scenarios in all aspects. Therefore, no most sustainable scenario can be identified based on entirely scientific criteria. Instead of necessarily value-based weighting of different impacts, several front-runner scenarios are identified and further discussed in this study.

Front-runner scenarios from various perspectives are:

- From an environmental perspective: Miscanthus → Small CHP
- From an economic perspective: Giant reed → Large CHP
- From a social perspective: Giant reed → Small CHP

This list already shows that front-runner scenarios are very similar. The selection is based on superiority regarding most indicators. Other scenarios could be selected when assigning a higher weight to individual indicators. Therefore, the selected front-runner scenarios are to be seen as suitable benchmarks but not as unanimously most sustainable. These scenarios are analysed for trade-offs in the following chapter.

Please note that the selection is largely independent of the unit of reference. In early implementations, the available land may not be limiting but rather the amount of marketable biomass. From this perspective, achievable sustainability improvements should be compared per amount of biomass produced instead of per area of land use (see Table 8-2 in the annex). In this case, from a social perspective, switchgrass or cardoon may be chosen in the front-runner scenario instead of giant reed due to small advantages in job equivalents.

How to read Table 5-22, environmental indicator acidification, first three scenarios:

Cultivation of giant reed and its use for domestic heat generates 40 kg of SO_2 equivalents per hectare per year more than the same amount of conventional domestic heat. These results are worse than for the average of all OPTIMA life cycle comparisons (red background). If used for combined heat and power production in a small or large plant, this results in additional emissions of 18 kg SO_2 eq. / ha / a or savings of 5 kg SO_2 eq. / ha / a, respectively. These results do not differ by more than 10 % from the average (yellow) or are better than average (green), respectively.

Remark on qualitative indicators:

Qualitative results are coloured according to the rating from ‘++’ to ‘--‘.

Table 5-22 Relative performance of OPTIMA scenarios. Results are shown for cultivation on marginal land (marginal 1) and standard conversion conditions. Categorisation and respective colouring of quantitative results reflects differences to average results of OPTIMA scenarios. TRL: technology readiness level, GMO: genetically modified organism, N/A: not applicable, N/D: no data

			Giant reed						
Area	**Indicator**	**Unit**	**Giant reed → Domestic heat**	**Giant reed → Small CHP**	**Giant reed → Large CHP**	**Giant reed → Pyrolysis oil**	**Giant reed → Biochar**	**Giant reed → 2G Ethanol**	**Giant reed → 1,3-Propanediol**
Technology	Maturity cultivation (marg. land)	TRL	6	6	6	6	6	6	6
	Maturity harvest+logistics	TRL	5	5	5	5	5	5	5
	Maturity conversion	TRL	9	9	9	7	7	7	5
	Feedstock compatibility	(qualitative)	○	○	○	○	○	○	○
	Required development work	TRL	2,7	2,7	2,7	3,3	3,3	3,3	4,0
	Complexity	(qualitative)	+	○	○	– –	○	– –	– –
	Suitability for small scale	(qualitative)	++	+	–	–	○	– –	– –
Environment: LCA	Energy use	GJ / ha / yr	-149	-221	-317	-81	152	47	50
	Climate change	t CO_2 eq. / ha / yr	-13,2	-14,9	-17,0	-6,6	-3,9	2,2	3,5
	Acidification	kg SO_2 eq. / ha / yr	40	18	-5	29	36	43	47
	Marine eutrophication	kg N eq. / ha / yr	9,8	9,3	8,8	9,5	9,5	11,2	9,5
	Freshwater eutrophication	kg P eq. / ha / yr	1,5	1,1	0,9	1,4	1,4	1,7	1,7
	Ozone depletion	g R11 eq. / ha / yr	57	58	60	57	57	106	69
	Particulate matter formation	kg PM10 eq. / ha / yr	11,6	4,6	-1,6	8,9	10,4	11,6	11,6
Envir.: EIA	Biodiversity	- (score)	1,5	2,0	2,5	3,1	2,4	4,3	4,4
	Soil	- (score)	1,7	2,8	2,9	3,5	2,2	3,6	3,6
	Water	- (score)	7,3	8,1	9,5	8,7	8,1	12,9	12,9
	Landscape	- (score)	0,0	0,6	1,4	0,9	0,6	1,4	1,4
Economy	Return on investment	- (ratio)	14%	7%	17%	1%	3%	-24%	N/D
	Internal rate of return	- (ratio)	12%	8%	15%	1%	2%	N/A	N/D
	Payback period	years	7,4	9,76	6,25	19	16	N/A	N/D
	Total assets turnover	- (ratio)	0,25	0,34	0,56	0,94	0,94	0,61	N/D
Society	Job equivalents	jobs / 1000 ha	77	71	21	20	51	15	N/D
	Contribution to rural economy	(qualitative)	○	++	○	○	○	○	○
	Local embedding	(qualitative)	++	++	○	– –	– –	– –	– –
	Proximity to markets	(qualitative)	++	++	○	– –	– –	– –	– –
SWOT	Public perception	(qualitative)	+	+	+	++	++	++	++
	Health & Safety	(qualitative)	○	○	–	– –	–	– –	–
	Security of feedstock supply	(qualitative)	○	○	–	– –	○	– –	○

Table 5-22 (continued)

Miscanthus							Switchgrass							Cardoon						
Miscanthus → Domestic heat	Miscanthus → Small CHP	Miscanthus → Large CHP	Miscanthus → Pyrolysis oil	Miscanthus → Biochar	Miscanthus → 2G Ethanol	Miscanthus → 1,3-Propanediol	Switchgrass → Domestic heat	Switchgrass → Small CHP	Switchgrass → Large CHP	Switchgrass → Pyrolysis oil	Switchgrass → Biochar	Switchgrass → 2G Ethanol	Switchgrass → 1,3-Propanediol	Cardoon → Domestic heat	Cardoon → Small CHP	Cardoon → Large CHP	Cardoon → Pyrolysis oil	Cardoon → Biochar	Cardoon → 2G Ethanol	Cardoon → 1,3-Propanediol
6	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
9	9	9	7	7	7	5	9	9	9	7	7	7	5	9	9	9	7	7	7	5
○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	– –	–	– –	– –
2,3	2,3	2,3	3,0	3,0	3,0	3,7	2,3	2,3	2,3	3,0	3,0	3,0	3,7	2,7	2,7	2,7	3,7	3,7	3,7	4,3
+	○	○	– –	○	– –	– –	+	○	○	– –	○	– –	– –	+	○	○	– –	○	– –	– –
++	+	–	–	○	– –	– –	++	+	–	–	○	– –	– –	++	+	–	–	○	– –	– –
-180	-240	-321	-123	74	-15	-12	-104	-140	-188	-70	48	-10	-8	-130	-169	-222	-93	36	-27	-26
-14,8	-16,3	-18,0	-9,2	-6,9	-1,9	-0,8	-8,4	-9,2	-10,2	-5,0	-4,2	-0,9	-0,2	-10,0	-10,9	-12,0	-6,3	-5,5	-1,9	-1,1
24	6	-13	15	21	27	31	22	11	-1	16	19	23	26	23	10	-2	16	19	24	26
3,8	3,4	3,0	3,6	3,6	5,0	3,6	5,5	5,2	5,0	5,3	5,3	6,3	5,3	7,2	6,9	6,7	7,0	7,0	8,0	7,0
0,5	0,1	-0,1	0,4	0,4	0,6	0,6	0,4	0,2	0,1	0,4	0,4	0,5	0,6	0,6	0,3	0,2	0,5	0,5	0,6	0,7
21	22	24	21	21	63	31	32	32	34	32	32	59	38	42	42	44	41	42	71	48
8,1	2,2	-3,0	5,8	7,1	8,1	8,0	6,5	3,0	-0,2	4,9	5,7	6,3	6,3	5,9	2,1	-1,4	4,1	5,0	5,7	5,7
0,0	0,6	1,1	1,7	1,0	3,1	3,2	2,7	3,3	3,8	4,5	3,7	5,8	5,9	-2,2	-1,6	-1,1	-0,4	-1,2	0,9	1,0
0,1	1,3	1,5	2,1	0,6	2,2	2,2	3,5	4,7	4,9	5,5	4,0	5,6	5,6	1,4	2,6	2,8	3,5	2,0	3,6	3,6
2,3	3,2	4,8	3,9	3,2	8,6	8,6	3,8	4,7	6,3	5,4	4,7	10,1	10,1	3,1	4,1	5,7	4,7	4,1	9,5	9,5
-0,1	0,5	1,5	0,8	0,5	1,5	1,5	2,6	3,2	4,2	3,5	3,2	4,2	4,2	-0,3	0,4	1,3	0,7	0,4	1,3	1,3
13%	6%	15%	-7%	-2%	-34%	N/D	13%	6%	15%	-6%	-2%	-34%	N/D	13%	6%	15%	-6%	-2%	-34%	N/D
11%	7%	13%	N/A	N/A	N/A	N/D	11%	7%	14%	N/A	N/A	N/A	N/D	11%	7%	14%	N/A	N/A	N/A	N/D
7,97	7,75	6,79	73	26	N/A	N/D	7,9	10,2	6,69	51	24	N/A	N/D	7,9	10,3	6,8	58	24	N/A	N/D
0,25	0,34	0,56	0,94	0,94	0,61	N/D	0,25	0,34	0,56	0,94	0,94	0,61	N/D	0,25	0,34	0,54	0,94	0,94	0,61	N/D
69	64	21	20	49	16	N/D	54	50	21	21	42	16	N/D	56	52	21	20	43	15	N/D
○	++	○	○	○	○	○	○	++	○	○	○	○	○	○	++	○	○	○	○	○
++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –
++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –
+	+	+	++	++	++	++	+	+	+	++	++	++	++	+	+	+	++	++	++	++
○	○	–	– –	–	– –	–	○	○	–	– –	–	– –	–	○	○	–	– –	–	– –	–
○	○	–	– –	○	– –	○	○	○	–	– –	○	– –	○	○	○	–	– –	○	– –	○

5.7.4 Trade-offs of front-runner OPTIMA scenarios

None of the assessed OPTIMA scenarios is superior to all other scenarios in all aspects. Therefore, the implementation of any scenario means that achievable advantages of other scenarios cannot be realised – as it is the case for almost any decision in real life. It is the approach of the used methodology of integrated life cycle sustainability assessment (ILCSA, [Keller et al. 2015]) to highlight these trade-offs enabling decision makers to take informed decisions. This way, of course none of the scenarios can be selected as single 'most sustainable' option[10]. Instead, potentially preferred selections from different perspectives, the front-runner scenarios selected above, are analysed for their specific trade-offs in the following benchmarking analysis.

Trade-offs occur where other scenarios are superior compared to the benchmark, which is indicated by "+" or "++" for the respective indicator. The following trade-offs are necessary when implementing the scenario Miscanthus → Small CHP, the selected front-runner scenario from an environmental perspective (Table 5-23):

- Technology: The use option 'domestic heat' is less complex. However, as the social indicator 'local embedding' shows, this is not a significant disadvantage for small CHPs regarding operability in rural areas. Furthermore, domestic heat can be built on a smaller scale. Thus, it may be a better option than a small CHP in locations with little available marginal land.
- Environment: Although this scenario ranges among the best performing ones regarding global and regional environmental impacts (as determined by LCA), large CHPs operated with Miscanthus and partially also with giant reed still perform better in some of these aspects. When considering local environmental impacts, the use options 'domestic heat' and regarding soil impacts also the use option 'biochar' show less additional burdens. In terms of biomass feedstock for the CHP, cardoon performs better regarding biodiversity. This highlights a trade-off between efficiency and local environmental impacts.
- Economy: Several scenarios show a better performance.
- Society and further aspects: Small scale use of giant reed is expected to create more jobs. Otherwise, there are just few trade-offs. Only regarding public perception, most alternatives are superior.

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[10] Other approaches using multi criteria decision making algorithms do select 'best' choices based on weighting factors of various origin. However, we do not think that a political decision making process benefits from such selections because trade-offs need to be transparent to be able to balance outcomes for various stakeholders with different preferences.

Table 5-23 Benchmarking of all scenarios against Miscanthus → Small CHP. The comparison is based on results per hectare per year. Bandwidths of results for conversion technologies are taken into account. N/D: no data.

Benchmark: Miscanthus → Small CHP		**Giant reed**							**Miscanthus**							**Switchgrass**							**Cardoon**						
Area	**Indicator**	**Giant reed → Domestic heat**	**Giant reed → Small CHP**	**Giant reed → Large CHP**	**Giant reed → Pyrolysis oil**	**Giant reed → Biochar**	**Giant reed → 2G Ethanol**	**Giant reed → 1,3-Propanediol**	**Miscanthus → Domestic heat**	**Miscanthus → Small CHP**	**Miscanthus → Large CHP**	**Miscanthus → Pyrolysis oil**	**Miscanthus → Biochar**	**Miscanthus → 2G Ethanol**	**Miscanthus → 1,3-Propanediol**	**Switchgrass → Domestic heat**	**Switchgrass → Small CHP**	**Switchgrass → Large CHP**	**Switchgrass → Pyrolysis oil**	**Switchgrass → Biochar**	**Switchgrass → 2G Ethanol**	**Switchgrass → 1,3-Propanediol**	**Cardoon → Domestic heat**	**Cardoon → Small CHP**	**Cardoon → Large CHP**	**Cardoon → Pyrolysis oil**	**Cardoon → Biochar**	**Cardoon → 2G Ethanol**	**Cardoon → 1,3-Propanediol**
Technology	Maturity cultivation (marg. land	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	–	–	–	–	–	–	–
	Maturity harvest+logistics	–	–	–	–	–	–	–	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Maturity conversion	○	○	○	–	–	–	–	○		○	–	–	–	–	○	○	○	–	–	–	–	○	○	○	–	–	–	–
	Feedstock compatibility	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	–	–	–	–
	Required development work	–	–	–	–	–	–	–	○		○	–	–	–	–	○	○	○	–	–	–	–	–	–	–	–	–	–	–
	Complexity	+	○	○	–	○	–	–	+		○	–	○	–	–	+	○	○	–	○	–	–	+	○	○	–	○	–	–
	Suitability for small scale	+	○	–	–	–	–	–	+		–	–	–	–	–	+	○	–	–	–	–	–	+	○	–	–	–	–	–
Environment: LCA	Energy use	○	○	+	– –	– –	– –	– –	○		+	– –	– –	– –	– –	– –	– –	○	– –	– –	– –	– –	– –	–	○	– –	– –	– –	– –
	Climate change	○	○	○	– –	– –	– –	– –	○		○	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	○	– –	– –	– –	– –
	Acidification	– –	–	○	– –	– –	– –	– –	– –		++	○	○	– –	– –	○	○	○	○	○	– –	– –	○	○	○	○	○	– –	– –
	Marine eutrophication	– –	– –	– –	– –	– –	– –	– –	○		○	○	○	– –	○	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Freshwater eutrophication	– –	– –	– –	– –	– –	– –	– –	– –		○	○	○	– –	– –	– –	○	○	○	○	– –	– –	– –	○	○	– –	– –	– –	– –
	Ozone depletion	– –	– –	– –	– –	– –	– –	– –	○		○	○	○	○	○	○	– –	– –	○	○	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Particulate matter formation	– –	○	+	– –	– –	– –	– –	– –		++	○	– –	– –	– –	○	○	○	○	○	– –	–	○	○	○	○	○	– –	–
Envir.: EIA	Biodiversity	–	–	–	–	–	–	–	○		○	–	○	–	–	–	–	–	–	–	–	–	+	+	+	+	+	○	○
	Soil	○	–	–	–	–	–	–	+		○	–	+	–	–	–	–	–	–	–	–	–	○	–	–	–	–	–	–
	Water	–	–	–	–	–	–	–	○		–	○	○	–	–	○	–	–	–	–	–	–	○	○	–	–	○	–	–
	Landscape	+	○	–	○	○	–	–	+		–	○	○	–	–	–	–	–	–	–	–	–	+	○	–	○	○	–	–
Economy	Return on investment	+	○	+	○	○	–	N/D	+		+	–	–	–	N/D	+	○	+	–	–	–	N/D	+	○	+	–	–	–	N/D
	Internal rate of return	+	○	+	–	–	–	N/D	+		+	–	–	–	N/D	+	○	+	–	–	–	N/D	+	○	+	–	–	–	N/D
	Payback period	○	○	○	–	–	–	N/D	○		○	–	–	–	N/D	○	○	○	–	–	–	N/D	○	○	○	–	–	–	N/D
	Total assets turnover	–	○	+	+	+	+	N/D	–		+	+	+	+	N/D	–	○	+	+	+	+	N/D	–	○	+	+	+	+	N/D
Society	Job equivalents	+	+	–	–	–	–	N/D	○		–	–	–	–	N/D	–	–	–	–	–	–	N/D	–	–	–	–	–	–	N/D
	Contribution to rural economy	–	○	–	–	–	–	–	–		–	–	–	–	–	–	○	–	–	–	–	–	–	○	–	–	–	–	–
	Local embedding	○	○	–	–	–	–	–	○		–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–
	Proximity to markets	○	○	–	–	–	–	–	○		–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–
SWOT	Public perception	○	○	○	+	+	+	+	○		○	+	+	+	+	○	○	○	+	+	+	+	○	○	○	+	+	+	+
	Health & Safety	○	○	–	–	–	–	–	○		–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–
	Security of feedstock supply	○	○	–	–	○	–	○	○		–	–	○	–	○	○	○	–	–	○	–	○	○	○	–	–	○	–	○

How to read Table 5-23, environmental indicator acidification, first three scenarios:

Even under favourable conditions, the scenario 'Giant reed → Domestic heat' performs worse than the benchmark scenario 'Miscanthus → Small CHP' under standard conditions regarding in the impact category acidification. Thus it is rated very disadvantageous (red). The scenario 'Giant reed → Small CHP' is worse than the benchmark in this category when compared under standard conditions (disadvantageous, orange). The scenario 'Giant reed → Large CHP' is not substantially different from the benchmark when applying a 10 % threshold (neutral, yellow). See chapter 3.3.4 for further details on the benchmarking procedure.

Seen the other way around, there are no trade-offs when implementing the benchmark scenario 'Miscanthus → Small CHP' compared to these three competing scenarios considering the impact category acidification.

Optimising the economic performance leads to many more trade-offs (forgone advantages of alternative scenarios) than the optimisation of environmental performance based on the indicators assessed here (compare green indicator values in Table 5-23 and Table 5-24). Which of these two scenarios should be preferred nevertheless depends on the perspective (e.g. business or societal perspective) and the respective subjective weights attributed to each indicator or group of indicators. The following trade-offs are necessary when implementing the scenario ‘Giant reed → Large CHP’, the selected front-runner scenario from an economic perspective (Table 5-24):

- Compared to other crops: All other crops show advantages regarding several environmental impacts and technological maturity. This is analysed in detail in Table 5-25. Giant reed in turn performs better than switchgrass and cardoon in terms of climate change and non-renewable energy use.
- Scale: Among the scenarios on direct combustion, several differences can be found that are related to scale. The bigger the conversion unit becomes the more likely its size can cause disadvantages. Large CHPs score worse than smaller units not only in terms of technological indicators such as complexity but also in local environmental impacts, social impacts related to regionality, potential workplace safety issues and security of feedstock supply. In contrast, economic performance (with the exception of efficiency as reflected by total assets turnover) and certain global / regional environmental impacts improve with larger scale.
- Compared to innovative conversion and use scenarios, there are only few trade-offs, in particular compared to ‘biochar’ regarding local environmental and social impacts.

Table 5-24 Benchmarking of all scenarios against Giant reed → Large CHP. The comparison is based on results per hectare per year. Bandwidths of results for conversion technologies are taken into account. N/D: no data.

Benchmark: Giant reed → Large CHP		Giant reed							Miscanthus							Switchgrass							Cardoon						
Area	**Indicator**	Giant reed → Domestic heat	Giant reed → Small CHP	Giant reed → Large CHP	Giant reed → Pyrolysis oil	Giant reed → Biochar	Giant reed → 2G Ethanol	Giant reed → 1,3-Propanediol	Miscanthus → Domestic heat	Miscanthus → Small CHP	Miscanthus → Large CHP	Miscanthus → Pyrolysis oil	Miscanthus → Biochar	Miscanthus → 2G Ethanol	Miscanthus → 1,3-Propanediol	Switchgrass → Domestic heat	Switchgrass → Small CHP	Switchgrass → Large CHP	Switchgrass → Pyrolysis oil	Switchgrass → Biochar	Switchgrass → 2G Ethanol	Switchgrass → 1,3-Propanediol	Cardoon → Domestic heat	Cardoon → Small CHP	Cardoon → Large CHP	Cardoon → Pyrolysis oil	Cardoon → Biochar	Cardoon → 2G Ethanol	Cardoon → 1,3-Propanediol
Technology	Maturity cultivation (marg. land	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	–	–	–	–	–	–	–
	Maturity harvest+logistics	○	○		○	○	○	○	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
	Maturity conversion	○	○		–	–	–	–	○	○	○	–	–	–	–	○	○	○	–	–	–	–	○	○	○	–	–	–	–
	Feedstock compatibility	○	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	–	–	–	–
	Required development work	○	○		–	–	–	–	+	+	+	–	–	–	–	+	+	+	–	–	–	–	○	○	○	–	–	–	–
	Complexity	+	○		–	○	–	–	+	○	○	–	○	–	–	+	○	○	–	○	–	–	+	○	○	–	○	–	–
	Suitability for small scale	+	+		○	+	–	–	+	+	○	○	+	–	–	+	+	○	○	+	–	–	+	+	○	○	+	–	–
Environment: LCA	Energy use	– –	–		– –	– –	– –	– –	– –	–	○	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Climate change	○	○		– –	– –	– –	– –	○	○	○	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –
	Acidification	– –	– –		– –	– –	– –	– –	– –	○	○	– –	– –	– –	– –	– –	– –	○	– –	– –	– –	– –	– –	– –	○	– –	– –	– –	– –
	Marine eutrophication	○	○		○	○	– –	○	++	++	++	++	++	○	++	++	++	++	++	++	○	++	++	++	++	++	++	○	++
	Freshwater eutrophication	– –	○		– –	– –	– –	– –	++	++	++	++	++	++	+	++	++	++	++	++	++	++	++	++	++	++	++	○	+
	Ozone depletion	○	○		○	○	○	○	++	++	++	++	++	○	++	++	++	++	++	++	○	++	++	++	++	++	++	○	++
	Particulate matter formation	– –	– –		– –	– –	– –	– –	– –	–	○	– –	– –	– –	– –	– –	– –	○	– –	– –	– –	– –	– –	–	○	– –	– –	– –	– –
Envir.: EIA	Biodiversity	+	○		○	○	–	–	+	+	+	○	+	○	○	○	–	–	–	–	–	–	+	+	+	+	+	+	+
	Soil	+	○		–	+	–	–	+	+	+	+	+	+	+	○	–	–	–	–	–	–	+	○	○	○	+	–	–
	Water	+	+		○	+	–	–	+	+	+	+	+	○	○	+	+	+	+	+	○	○	+	+	+	+	+	○	○
	Landscape	+	+		+	+	○	○	+	+	○	+	+	○	○	–	–	–	–	–	–	–	+	+	○	+	+	○	○
Economy	Return on investment	○	–		–	–	–	N/D	○	–	○	–	–	–	N/D	○	–	○	–	–	–	N/D	○	–	○	–	–	–	N/D
	Internal rate of return	–	–		–	–	–	N/D	–	–	○	–	–	–	N/D	–	–	○	–	–	–	N/D	–	–	○	–	–	–	N/D
	Payback period	○	○		–	–	–	N/D	○	○	○	–	–	–	N/D	○	○	○	–	–	–	N/D	○	○	○	–	–	–	N/D
	Total assets turnover	–	–		+	+	○	N/D	–	–	○	+	+	○	N/D	–	–	○	+	+	○	N/D	–	–	○	+	+	○	N/D
Society	Job equivalents	+	+		○	+	○	N/D	+	+	○	○	+	○	N/D	+	+	○	○	+	○	N/D	+	+	○	○	+	○	N/D
	Contribution to rural economy	○	+		○	○	○	○	○	+	○	○	○	○	○	○	+	○	○	○	○	○	○	+	○	○	○	○	○
	Local embedding	+	+		–	–	–	–	+	+	○	–	–	–	–	+	+	○	–	–	–	–	+	+	○	–	–	–	–
	Proximity to markets	+	+		–	–	–	–	+	+	○	–	–	–	–	+	+	○	–	–	–	–	+	+	○	–	–	–	–
SWOT	Public perception	○	○		+	+	+	+	○	○	○	+	+	+	+	○	○	○	+	+	+	+	○	○	○	+	+	+	+
	Health & Safety	+	+		–	○	–	○	+	+	○	–	○	–	○	+	+	○	–	○	–	○	+	+	○	–	○	–	○
	Security of feedstock supply	+	+		–	+	–	+	+	+	○	–	+	–	+	+	+	○	–	+	–	+	+	+	○	–	+	–	+

The benchmarking analysis against the scenario Giant reed → Small CHP, the selected front-runner scenario from a social perspective, does not yield any further systemic insights (see also Table 8-3 in the annex). Therefore, it is not discussed here.

Cultivating Miscanthus for direct combustion in domestic heating or in CHPs results in only few trade-offs under the assessed prototypical conditions (Table 5-25). These are related to biodiversity (because cardoon is a native species), particulate matter formation (because of higher irrigation needs compared to cardoon and related emissions from diesel pumps) and job creation potential (although difference between crops are small). Most indicators are not substantially influenced by the choice of the crop (rating “0” in Table 5-25).

Table 5-25 Benchmarking of all assessed crops against Miscanthus for selected use options. The comparison is based on results per hectare per year. Bandwidths of results for biomass provision are taken into account. N/D: no data.

Benchmark: Miscanthus

Area	Indicator	Giant reed → Domestic heat	Miscanthus → Domestic heat	Switchgrass → Domestic heat	Cardoon → Domestic heat	Giant reed → Small CHP	Miscanthus → Small CHP	Switchgrass → Small CHP	Cardoon → Small CHP	Giant reed → Large CHP	Miscanthus → Large CHP	Switchgrass → Large CHP	Cardoon → Large CHP
Technology	Maturity cultivation (marg. land	○		○	–	○		○	–	○		○	–
	Maturity harvest+logistics	–		○	○	–		○	○	–		○	○
	Maturity conversion	○		○	○	○		○	○	○		○	○
	Feedstock compatibility	○		○	○	○		○	○	○		○	○
	Required development work	–		○	–	–		○	–	–		○	–
	Complexity	○		○	○	○		○	○	○		○	○
	Suitability for small scale	○		○	○	○		○	○	○		○	○
Environment: LCA	Energy use	○		○	○	○		○	○	○		○	○
	Climate change	○		–	○	○		–	○	○		–	○
	Acidification	– –		○	○	–		○	○	○		○	○
	Marine eutrophication	– –		– –	– –	– –		– –	– –	– –		– –	– –
	Freshwater eutrophication	– –		○	○	– –		○	○	– –		○	○
	Ozone depletion	– –		○	– –	– –		○	– –	– –		○	– –
	Particulate matter formation	– –		○	++	○		○	○	○		○	○
Envir.: EIA	Biodiversity	–		–	+	–		–	+	–		–	+
	Soil	–		–	–	–		–	–	–		–	–
	Water	–		–	○	–		–	○	–		–	○
	Landscape	○		–	○	○		–	○	○		–	○
Economy	Return on investment	○		○	○	○		○	○	○		○	○
	Internal rate of return	○		○	○	○		○	○	○		○	○
	Payback period	○		○	○	○		○	○	○		○	○
	Total assets turnover	○		○	○	○		○	○	○		○	○
Society	Job equivalents	+		–	–	+		–	–	○		○	○
	Contribution to rural economy	○		○	○	○		○	○	○		○	○
	Local embedding	○		○	○	○		○	○	○		○	○
	Proximity to markets	○		○	○	○		○	○	○		○	○
SWOT	Public perception	○		○	○	○		○	○	○		○	○
	Health & Safety	○		○	○	○		○	○	○		○	○
	Security of feedstock supply	○		○	○	○		○	○	○		○	○

However, cultivation of perennial crops is much more dependent on local conditions than conversion of the biomass. Therefore, any prototypical conditions can only cover a part of the possible spectrum despite the use of bandwidths which are likewise necessarily prototypical. All crops have specific properties that enable them to thrive in specific niches. The following conditions have been identified under which other crops than Miscanthus may have specific advantages:

- Dry sites without irrigation option: A particular risk for perennial crops is the total loss of the plantation in a very dry year, because the high initial expenditures for establishing the plantation are lost. Drought tolerance is thus important if there is no technically or economically feasible option to irrigate even in those years. Cardoon has the highest drought tolerance of all assessed crops. Also giant reed and switchgrass are likely to survive drought better than Miscanthus depending on the conditions. The influence on various sustainability indicators depends very much on local conditions and cannot necessarily be extrapolated from drought occurrences in past decades because of climate change-dependent changes in frequencies of extreme weather.
- Sites with cold winter weather: Total loss of plantations can also be caused by freezing. Cold winters are frequent also in the Mediterranean region in particular where the influence of continental climate dominates. The assessed Miscanthus genotypes (*Miscanthus* × *giganteus*) are better adapted to temperate climates and have a considerable risk of dying from frost. This is less pronounced for the other assessed crops.
- Possibility for open air-drying: The assessed scenarios are based on a logistics concept that includes some drying to allow for subsequent pelleting. The drying process in a central conditioning facility can be optimised (e.g. in terms of used energy carrier) but always consumes considerable amounts of energy. If open air-drying is feasible under local conditions including expectable precipitation at the time after harvest, this can improve environmental and economic performance. This especially applies to giant reed because if its high water content. If open air-drying is possible, results for giant reed thus improve compared to Miscanthus.

6 Conclusions and recommendations

In this study the sustainability of biogenic products (bioenergy and bio-based products) produced from perennial grasses, cultivated on marginal land[11] in the Mediterranean region, was investigated. The study considers the entire life cycle of the products from cultivation through conversion and on to utilisation (and disposal, where applicable) and is based on generic scenarios that represent future mature technologies and processes in 2020[12]. For the 28 scenarios in total, four crops with seven use options were combined, whereby in all scenarios drying and pelletising were adopted following the biomass harvest:

- Crops: giant reed, Miscanthus, switchgrass or cardoon.
- Products: domestic heat, combined heat and power (large or small CHP), upgraded pyrolysis oil, 2nd generation bioethanol, biochar or 1,3-propanediol.

The bioenergy or bio-based products were then compared to conventional, generally fossil-based energy or products, which have also been assessed throughout their entire life cycle. These scenarios were evaluated based on almost 30 selected indicators from the fields of technology, the environment, the economy and the society. Optimisation options were also derived from the results. In addition to the sustainability of the scenarios, barriers to the implementation were investigated, which may either prevent successful implementation of the scenarios in their studied forms or may lead to less sustainable implementation.

6.1 General advantages and disadvantages of the studied scenarios

Products produced from perennial grasses, cultivated on marginal land in the Mediterranean region, may possess sustainability advantages and disadvantages compared to conventional products generally based on fossil resources. In terms of the investigated sustainability indicators the following picture emerges, from which the individual scenarios deviate both favourably and unfavourably:

- Sustainability benefits generally result in terms of climate change, the use of non-renewable energy resources, the regional nature of value chains with employment gains primarily in rural areas and further positive, social impacts.

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[11] Marginal land as considered here is defined as currently not used for agricultural purposes (i.e. lying idle), merely due to the prevailing regulatory framework conditions. For example, irrigation is considered physically possible but currently too costly for any kind of biomass cultivation.

[12] In many of the use options the biomass from perennial grasses will probably need to be mixed with other biomass in order to adhere to technical specifications, such as ash content, etc. The scenarios only model the production and use of grass pellets in possible mixes and not the entire mix, including a wood pellet share, for example. The estimated impacts therefore correspond to those caused by the additional use of grass pellets.

- Sustainability drawbacks generally occur for the majority of the remaining environmental impacts such as nutrient input into sensitive ecosystems and water consumption. These drawbacks are typical for energy and industrial biomass utilisation.

The described advantages, however, **are *only* valid for cultivation on currently *unused* agricultural land**. Only then are potentially highly detrimental indirect land use changes (iLUC) avoided and *additional* agricultural jobs created. The question of whether the unused land is marginal in terms of biophysical constraints (e.g. slope steepness, salinity) is of secondary importance only. However, it is clear that marginal land with biophysical constraints, which is often unused, require greater agricultural expenditures for one unit of biomass produced (e.g. fertiliser or field work) compared to sites with average or high yields, which are predominantly used. In these terms, the achievement of the OPTIMA project is to keep these expenditures as low as possible by adopting selected crops and agricultural practices. This way, abandoned low-quality land can be brought into production. In addition, greenhouse gas savings can be achieved in a life cycle comparison with alternative, fossil fuel-based products even for very low yields.

In order to achieve **economic viability**, the majority of biogenic cultivation and/or use options will require **financial incentives**. However, this is not regarded as a sustainability drawback compared to the conventional products generally based on fossil resources, because the affected sectors of energy, transport and agriculture are already very highly regulated in most countries, meaning that biogenic and fossil products do not compete under the conditions of a perfect market. With the requisite political will and assertiveness, the current regulatory and economic boundary conditions could therefore be revised to the advantage of the perennial grasses.

The general advantages and disadvantages described above do not – as previously noted – affect all the investigated scenarios equally. A positive deviation is given by the use of biomass in efficient CHP plants. The high conversion efficiency means that a large amount of conventionally generated energy, associated with substantial environmental burdens, can be replaced. In this way **disadvantages for environmental impact categories**, in which the biogenic paths typically achieve worse results than the conventional alternatives, are **largely compensated**, which only rarely occurs.

Perennial grasses on marginal land *can* therefore generally be sustainably cultivated and utilised, but not every possible configuration *is* sustainable *per se*. It is therefore important to create incentives in order to reinforce the benefits and reduce the drawbacks. Because in the majority of cases implementation of the scenarios will generally rely on financial incentives from public support, at least initially, politics has substantial shaping opportunities for supporting sustainability targeting by defining suitable frameworks. A range of options are available for this, which are listed in the recommendations. Whether or not the remaining disadvantages are acceptable in view of the advantages can only be decided politically, but not on a purely natural science basis. When attempting to implement the scenarios, we recommend adhering to the optimisation options discussed in the following section.

6.2 Options for preventing disadvantages and strengthening advantages

While investigating the general advantages and disadvantages, a broad range of impacts on sustainability was identified. There are both predominantly sustainable and less sustainable options for the cultivation and use of perennial grasses on marginal land. In addition to the uncertainty of the input data (e.g. in terms of the yield per unit area), this range is primarily given by the freedom of choice of the protagonists in implementation. This results in numerous shaping options, which should be exploited to guarantee implementation as sustainably as possible.

Basic requirements for sustainable utilisation of the perennial grasses

The following three factors are essential preconditions for the sustainability of the investigated life cycles:

1. **Sustainable land use:** In terms of the utilisation of perennial grasses, it may be economically more beneficial from the point of view of the farmer, given general public support, to cultivate them on land already used rather than on unused marginal land, or to incorporate favourably located but especially ecologically valuable land in cultivation. From an environmental perspective this can lead to considerable disadvantages, for example if it causes either direct or indirect land use changes (dLUC / iLUC), which may result in negative greenhouse gas balances, large biodiversity losses, etc. The employment effect may also be far lower or disappear.

Recommendation 1:

The necessary establishment supportive measures should guarantee sustainable land use and be configured as follows:

- In the definition of eligible land, the principal criterion should be its previous non-use (e.g. *not* used for at least 5 years, not even extensively), because sustainability benefits are only created if previously *unused* agricultural land is reused. Low land quality is only of secondary importance as a criterion. If support for unused, but high quality arable land (where it exists) should be ruled out[13], additional biophysical criteria such as slope steepness or salinity may be adopted, as they are discussed in the common agricultural policy (CAP) for classification as an ‘area facing natural constraints’ (ANC)[14].
- Land worthy of protection should be excluded from support, because of biodiversity losses as a result of renewed cultivation (see chapter 5.3.1). In the Mediterranean region this applies especially to land with high biodiversity value[15], e.g. highly

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[13] If in doubt, food crops should always be cultivated, especially on high quality arable land.

[14] See Regulation 2003/1305/EU [European Parliament & Council of the European Union 2013] and [Jones et al. 2014]

[15] See definition in Directive 2009/28/EC [European Parliament & Council of the European Union 2009]. Land with high carbon stock (e.g. wetlands, forests) and peatland are equally deserving of protection but probably play a minor role in the Mediterranean region.

biodiverse grasslands[16]. Moreover, areas taking part in the so-called *agri-environment* programmes during the last 10 years should not be used for cultivating perennial grasses. These programmes are designed to encourage farmers to protect and enhance the environment on their farmland by paying them for the provision of environmental services. An attracting effect towards the cultivation of perennial grasses, which would negate all extensification and protection efforts of recent years should be prevented at all costs.

- Where water is scarce sustainable irrigation should be ensured (also see next item).
- Industrial biomass conversion plant must present a concept detailing the continuous supply of sustainable biomass. Otherwise, high economic pressure to also use non-sustainably produced biomass results at times of low biomass supply.

2. **Irrigation** contributes substantially to environmental loads and costs. Land with sufficient natural water supplies should therefore be preferentially used. On the other hand, irrigation allows additional dry areas to be utilised, which would otherwise not be used. Compared to the environmental burdens and the costs of alternative products, irrigation appears justified, in particular where the biomass is used directly for energy, assuming enough water is available in the catchment area. However, if water is scarce, water may be withdrawn from other uses. This can lead to similar negative indirect effects as described above for land use changes. Each case must be considered separately here.

Recommendation 2:

Where necessary, highly efficient irrigation techniques should be adopted and integrated in regional water management concepts, if necessary with subordinate priority. If no such concept is available in regions with low water availability, we expressly recommend compiling a concept and furnishing it with the appropriate enforceability.

3. The evaluated crops have their own specific demands on site and climate, as discussed in Section 6.1. If these demands are not met, there is a substantial risk of total plantation failure. For perennial crops this not only means a one-off loss of harvest, but also the loss of the investment for establishing the plantation and lower yields in the years following re-establishment. The investigated scenarios assume that **sufficient cultivation experience and suitable varieties are available** to prevent such total plantation failures – otherwise the results may be substantially worse.

Recommendation 3:

Research into the cultivation and development of perennial grass varieties should continue to be supported. The prevention of total planation failures should be given priority. In view of the long plantation lifetimes and therefore long development cycles, farmers should be incorporated in the development process as early as possible.

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[16] See definition in Commission Regulation (EU) No 1307/2014 [European Commission 2014].

Primary influencing factor: Choice of use option

If these three prerequisites are met, there are several options available for optimising sustainability. A variety of options were modelled in scenarios. The study resulted in no single scenario excelling in all sustainability aspects. The sustainability of the life cycles for the majority of indicators depends predominantly on the **chosen use option**. The following preferences were identified:

- In a comparison *between* all use options, **energy generation through direct combustion** of biomass pellets comes out best in the foreseeable future in all sustainability dimensions (i.e. from an economic, social and environmental protection perspective) under the investigated conditions. Examples of direct combustion were modelled in the use options domestic heat, small CHP and large CHP. *Within* these options, certain trade-offs exist, depending on which sustainability aspect is awarded the greatest relevance. Opposing effects can be recognised in terms of scale, in particular: Large facilities generally possess advantages in terms of profitability and both global and regional environmental impacts such as climate change and particulate matter emissions. Small facilities tend to be associated with social benefits and a few lesser, local, adverse environmental effects, e.g. regarding landscape. These factors must be weighed up, taking local conditions into consideration. Here, local biomass potentials and heat or cooling customers[17] should be primarily considered. This is because year-round almost complete heat utilisation is a prerequisite for good CHP plant results.

  Another possible alternative, the co-firing of grass pellets in coal-fired power stations, could only be partly investigated in the course of this study. From an environmental perspective, co-firing can provide substantial advantages in a transition period until coal power can be replaced on a large scale. However, co-firing of biomass is not a valid point for delaying the shutdown of coal-fired power plants.

Recommendation 4:

The type and size of bioenergy generation facilities should be adapted to regional biomass potentials and heat or cooling customers.

- New biomass conversion plants for stationary energy use should be designed to meet heat demand (heat-driven operation) instead of maximised power generation. Installing a CHP plant operating with perennial biomass, for example, should be considered for supplying industrial facilities with heat (or cooling), i.e. where a high baseload of operation is needed.
- Promoting the use of perennial grasses should be embedded in regional planning and be linked to the existence of a regional biomass utilisation concept.

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[17] The viability can be greatly increased where opportunities for trigeneration / combined cooling, heat and power (CCHP) exist. In such cases, the heat from the CHP plant is also used as a primary energy source to deliver cooling by means of an adsorption chiller.

- **Innovative use options** such as 2nd generation ethanol, upgraded pyrolysis oil, biochar or 1,3-propanediol may become valuable mid- to long-term options if the following, important boundary conditions change:
  (1) Increasing the added value of the innovative use options by changing co-product utilisation in biochemical conversion processes (e.g. material use of the lignin fraction) or reliably quantifiable benefits of biochar as a soil improver (e.g. lower fertiliser requirements) is economically and environmentally beneficial.
  (2) From an environmental perspective power and heat generation from biomass is more beneficial than the analysed, innovative use options as long as this contributes to shutting down coal-fired power plants. Power and heat production should therefore currently be given priority given the limited biomass potentials. From an environmental viewpoint, innovative use options gain competitiveness to the extent by which coal becomes redundant as an important energy source in the future.
  The technological maturity of the innovative use options was assumed in the investigated scenarios.

Recommendation 5:

Innovative use options should be developed further by promoting research and development up to individual, industrial scale plant, because they may represent valuable alternatives to the crude oil/natural gas pathways in the post-coal age. Introduction at larger scales is not currently recommended, because the limited biomass can currently be utilised more sustainably elsewhere.

- The potential for improving sustainability depends not only on the sustainability of the bio-based products, but also on the sustainability of the **substituted conventional products**. Which conventional products exactly are substituted is predominantly the result of the given geographical, political and economic framework, which can change with time. For example, a natural gas grid is not available in all regions. Power from biomass could replace power from a variety of sources, from coal-fired power plants to photovoltaics and wind power. Because the impacted sectors are already heavily regulated, funded and/or taxed, politics has extensive shaping options, which should be used in the context of sustainability.

Recommendation 6:

Power market regulation should be configured such that additional renewable power sources can achieve the greatest possible sustainability benefits. It must first be ensured that conventionally (fossil) generated energy is replaced, which currently is successfully achieved in many EU countries by a feed-in priority for renewable energy in the power sector. In addition, a coordinated retreat from the use of coal should be considered, because this energy source causes especially large environmental burdens.

Irrespective of the choice of use option, the respective utilisation itself can also be optimised. However, because this project focuses on the provision of biomass, possible utilisation improvements were not studied in detail, but modelled within generic ranges. Naturally, the conversion efficiency is particularly important here (i.e. the efficiency factor of CHP plant). However, its optimisation must take many more influencing factors into consideration, depending on the technology, and must therefore be studied separately.

Subordinate influencing factor: choice of crop

Remarkable sustainability benefits can be achieved in one of the favourable uses discussed above with all four investigated crops. Therefore, **all four crops initially represent good options** and should be developed further. However, a basic requirement for utilisation is the suitability of the crop for a specific site. Otherwise, the yields assumed in the respective scenarios cannot be achieved. But the four investigated crops represent a promising repertoire of options for numerous local conditions.

If several different crops are well suited to a site, **Miscanthus comes out best in a number of aspects**, while other indicators are not substantially influenced by the choice of crop. Especially with respect to environmental impacts, Miscanthus demonstrates good performance, because relatively high yields can be achieved for relatively little expenditure. A comparatively clear difference between crops can be seen in the greenhouse gas emissions, whereby Miscanthus can achieve double the savings per unit area than switchgrass. However, Miscanthus also places higher demands on the site than do other crops. On dry sites without irrigation options and sites with cold winter weather in particular, some of the other investigated crops may therefore do better. Cardoon, as a domestic crop with low water demand, is a true alternative to the perennial grasses, in particular on dry sites.

In addition, a conversion plant using biomass from more than one crop may prove advantageous. For example, a combination of Miscanthus and cardoon with harvesting times in the early spring or autumn appears to make sense for logistical reasons. The degree to which possible synergies in storage outweigh possible additional expenditures for technical modifications, etc., would need to be investigated in further studies focusing on the logistical concept.

Recommendation 7:

Choice of crop for a given site:

- The crops suitable for a specific site should first be preselected from the repertoire of the four investigated crops. However, because the conditions at marginal sites may differ considerably, this study cannot replace specific investigations taking local conditions and the intended use into consideration. Developing expertise in selecting the most suitable crops and varieties is therefore indispensable for the sustainable establishment of perennial grasses. This could be achieved by the provision of consultation services for farmers, for example.
- The crop with the best environmental performance should then be selected (under the standardised conditions investigated here this was Miscanthus in the majority of cases).

Optimisation of agricultural production

Optimisation of agricultural production from a sustainability perspective should initially concentrate on yields, yield stability and, as far as possible, a reduction in irrigation and nitrogen fertilisation. This would allow positive effects to be achieved for the majority of the investigated sustainability indicators.

Recommendation 8:

In addition to increasing the yields and the yield stability, the following points should be optimised in agriculture:

- 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 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 minimal water content.

Additional benefits may be achieved if sites with specific characteristics are cultivated in a suitable way. The investigated systems are particularly suitable for:

- Erosion protection on heavily inclined land applying contour farming.
- Capturing nutrients between intensively farmed fields and water bodies.
- Regeneration of contaminated land (phytoremediation) with suitable biomass utilisation, where necessary with measures such as additional flue gas treatment.

In many cases, these specific benefits may even represent the primary benefit.

Recommendation 9:

Cultivation of perennial crops should be implemented first and foremost at sites where the plantations can generate additional benefits. In particular, this includes erosion protection, protection of water bodies by capturing nutrients, and phytoremediation. This should be started as soon as possible, because high yields are of only secondary importance here. However, the biomass should still be utilised. These niches offer an excellent opportunity to gather practical experience in yield-oriented cultivation on large areas. It should be investigated whether such projects can be supported in parallel for the double objective of benefiting environmental protection and technological developments.

6.3 Implementation barriers

Barriers generally exist which make the introduction of new products and value-added chains more difficult. In order to implement the life cycles investigated here the following, non-monetary barriers[18] must be overcome (1) to facilitate them being established at all and (2) so that they are not any less sustainable than was previously anticipated.

The following technological aspects should be developed further with the aid of public support:

- The investigated scenarios represent possible objectives of a successful establishment and not the current status, because **many of the investigated use options are still at the development stage**. In some scenarios, in particular those that involve energy provision via direct combustion, the required development work is limited to certain technological adaptations. Innovative conversion options, however, require substantial additional work on conversion technology.
  In terms of utilisation, the adaptation of existing combustion technology to suit the combustion characteristics of grass pellets should be addressed. The applications in which grass pellets alone can be utilised should also be clarified. If mixing with other biomass types is necessary, which shares of which other biomass types are suitable should be analysed in order to compile logistics concepts in the next step.

- An important obstacle on the way to implementation is to find a suitable logistics concept and to integrate all parties involved in value-added chain on this basis. The drying and pelleting assumed here appears promising but still needs to be optimised further, in particular in terms of energy use. Such an **energy optimised logistics concept** should take into consideration the specific properties of the respective crops and use options. The following aspects are important here:
  (1) For giant reed, in particular, reduction in the water content should be aimed for by optimising the time of harvest, for example, and the energy demand for biomass drying should be reduced. The open air drying option, in particular, should be examined here.
  (2) For some of the use options, for example bioethanol, the degree to which moist and/or non-pelletised biomass can be directly exploited should be examined.
  (3) Depending on the seasonal availability of the individual raw materials, the feasibility of occasionally using biomass with higher residual moisture content given short storage periods should be examined.
  (4) It should be taken into consideration that biomass from perennial grasses probably cannot be utilised alone in some applications, but only in mixtures with other biomass.

The following organisational aspects should also be optimised:

- A **management system** should be introduced, coordinating all stakeholders along the value-added chain. The risks, in particular, should be adequately shared by the stakeholders, especially the farmers, conversion plant operators, customers and the public.

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[18] The necessity for financial incentives was dealt with previously.

For example, the interests of all stakeholders could be bundled and balanced in suitable organisations such as associations or cooperatives. Risk sharing, in particular, appears to be a necessity. For the farmer the long plantation lifetime means less scope for decision making, for a simultaneously high initial investment. Long-term biomass purchase contracts at guaranteed prices should therefore be concluded (possibly even coupled to prices for fertiliser, etc.). However, farmers, especially in the Mediterranean region, should take into consideration anticipated, individual harvest failures, caused by dry weather for example, when planning supply quantities and contracts.

- Support should be coupled to the compilation of **regionally adapted biomass utilisation concepts** for the following reasons:
  (1) Regional use of the produced biomass results in positive social impacts but some of the assessed use options cannot be operated in remote rural areas, where marginal land is often located, because of the complexity or the necessary infrastructure. (2) For facilities operated at a larger scale, sufficient unused marginal land areas need to be available for contracting within a certain radius. If this land is scattered over a large area or if biomass customers compete in regions with little such land, high transportation expenditures or a low degree of capacity utilisation can make the biomass use unprofitable. Furthermore, this can result in high economic pressure to additionally use unsustainable biomass (e.g. from areas with high ecological value).

In addition, public perception should be addressed:

- Public perception of all assessed scenarios is currently positive. However, depending on the implementation conditions, including the potential use of genetically modified organisms as one example, public perception may turn quickly from benign to hostile. **Stakeholders should therefore be involved** in regional planning at an early stage to avoid the risk of losing acceptance.

Recommendation 10:

We recommend compiling regional concepts and regional planning based on them, because numerous important optimisation measures are heavily influenced by regional conditions. They should bundle the following, previously discussed, optimisation measures:

- The selection of suitable crops and use options within the framework of a regionally adapted biomass utilisation concept.
- Specific regulations for sustainable land and water management.
- Compilation of a logistics concept.
- Integration of all stakeholders.

6.4 Summary

Perennial grasses grown on previously abandoned land in the Mediterranean region provide potentials for climate change mitigation and social benefits in rural areas in particular. Abandoned land does not need to be ‘marginal’ in terms of biophysically inferior properties to entail such benefits, but the achievement of the OPTIMA project is to bring low-quality, previously abandoned land into production by adopting selected crops and agricultural practices. If use options such as efficient stationary energy generation are chosen, benefits can be achieved which are associated with minor other negative environmental impacts. This is a big advantage compared to many other bioenergy pathways, and in some cases even economic profits are attainable.

However, several boundary conditions must be met:

- Only idle (unused) marginal land without high biodiversity value should be cultivated to avoid harmful direct and/or indirect land use changes.
- Irrigation may not contribute to local water shortages with indirect effects on other water users.
- Risks must be managed and shared along the whole added value chain to increase yield stability, reduce production downtimes and limit potential losses for single stakeholders, in particular farmers.
- Several processes from agriculture to biomass use still need to be brought to technical maturity.
- Biomass should be used for efficient, stationary energy generation (as detailed above) until boundary conditions for the assessed innovative use options improve substantially or other, better options are found.

If the above is the case, the use of abandoned marginal land for bioenergy is largely safe from a sustainability perspective. Other assessed use options may also be sustainable in certain settings under altered conditions, which will require further specific analyses.

Further optimisation of the cultivation of perennial grasses on marginal land is therefore necessary, but also possible, and altogether a promising option. However, the great advantage of perennial crops, resulting from the long plantation lifetimes of 15 years and more, also means that long-term research, development and pilot projects must be carried out and financed. Some specific crop characteristics allow for specialty applications, in which cultivation itself may serve environmental protection purposes (erosion protection, phytoremediation, capturing nutrients). Moreover, under certain conditions and given appropriate technological maturity, profitable use options are available even without funding, such as co-firing grass pellets in existing biomass-fired CHP plants or pellet-fired domestic heating systems. These should be utilised in pilot projects.

Thus, the cultivation and use of perennial grasses on abandoned marginal land can lead to substantial overall gains in sustainability if promoted and managed properly by politics, stakeholders and developers in science as well as in businesses.

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8 Annex

This annex contains additional results supporting the integrated assessment in chapter 5.7. Table 8-1 shows bandwidths of assessment results for several quantitative indicators as an extension of Table 5-20. Table 8-2 corresponds to Table 5-22 addressing the relative performance of OPTIMA scenarios but is based on a different unit of reference. Table 8-3 shows further benchmarking results in addition to Table 5-23 and Table 5-24.

Table 8-1 Bandwidth of assessment results under various conditions (only available for LCA results)

			Giant reed						
Cond.	**Indicator**	**Unit**	**Giant reed → Domestic heat**	**Giant reed → Small CHP**	**Giant reed → Large CHP**	**Giant reed → Pyrolysis oil**	**Giant reed → Biochar**	**Giant reed → 2G Ethanol**	**Giant reed → 1,3-Propanediol**
Marginal 2, typical conversion	Energy use	GJ / ha / yr	-62	-102	-157	-23	110	50	51
	Climate change	t CO_2 eq. / ha / yr	-6,0	-6,9	-8,1	-2,2	-0,7	2,8	3,5
	Acidification	kg SO_2 eq. / ha / yr	31	18	6	25	28	33	35
	Marine eutrophication	kg N eq / ha / yr	7,5	7,2	7,0	7,4	7,4	8,3	7,4
	Freshwater eutrophication	kg P eq / ha / yr	1,0	0,8	0,7	1,0	1,0	1,1	1,2
	Summer smog	kg NMVOC eq / ha / yr	22	14	7	19	18	18	18
	Ozone depletion	g R11-Äquiv. / ha / yr	44	45	46	44	44	72	51
	Particulate matter formation	kg PM10 eq / ha / yr	9,1	5,2	1,7	7,6	8,5	9,1	9,1
Marginal 1, typical conversion	Energy use	GJ / ha / yr	-149	-221	-317	-81	152	47	50
	Climate change	t CO_2 eq. / ha / yr	-13,2	-14,9	-17,0	-6,6	-3,9	2,2	3,5
	Acidification	kg SO_2 eq. / ha / yr	40	18	-5	29	36	43	47
	Marine eutrophication	kg N eq / ha / yr	9,8	9,3	8,8	9,5	9,5	11,2	9,5
	Freshwater eutrophication	kg P eq / ha / yr	1,5	1,1	0,9	1,4	1,4	1,7	1,7
	Summer smog	kg NMVOC eq / ha / yr	30	16	3	24	23	23	22
	Ozone depletion	g R11-Äquiv. / ha / yr	57	58	60	57	57	106	69
	Particulate matter formation	kg PM10 eq / ha / yr	11,6	4,6	-1,6	8,9	10,4	11,6	11,6
Standard, typical conversion	Energy use	GJ / ha / yr	-239	-341	-480	-142	193	42	46
	Climate change	t CO_2 eq. / ha / yr	-20,8	-23,2	-26,1	-11,3	-7,4	1,3	3,1
	Acidification	kg SO_2 eq. / ha / yr	45	13	-19	29	39	50	55
	Marine eutrophication	kg N eq / ha / yr	10,1	9,4	8,8	9,8	9,7	12,2	9,7
	Freshwater eutrophication	kg P eq / ha / yr	1,7	1,2	0,8	1,6	1,6	2,0	2,0
	Summer smog	kg NMVOC eq / ha / yr	37	16	-2	28	27	26	25
	Ozone depletion	g R11-Äquiv. / ha / yr	58	59	63	58	59	129	75
	Particulate matter formation	kg PM10 eq / ha / yr	13,3	3,3	-5,6	9,4	11,6	13,3	13,3
Marginal 1, conversion low	Energy use	GJ / ha / yr	-132	-150	-272	-32	152	81	124
	Climate change	t CO_2 eq. / ha / yr	-11,9	-10,6	-14,5	-3,6	-3,2	2,0	7,3
	Acidification	kg SO_2 eq. / ha / yr	41	28	4	32	36	75	56
	Marine eutrophication	kg N eq / ha / yr	9,8	9,5	9,0	9,6	9,5	16,7	9,7
	Freshwater eutrophication	kg P eq / ha / yr	1,5	1,2	1,0	1,4	1,4	1,5	1,9
	Summer smog	kg NMVOC eq / ha / yr	31	23	9	27	23	28	27
	Ozone depletion	g R11-Äquiv. / ha / yr	57	60	62	58	57	60	70
	Particulate matter formation	kg PM10 eq / ha / yr	12,0	7,7	1,1	9,8	10,4	17,5	14,5
Marginal 1, conversion high	Energy use	GJ / ha / yr	-167	-274	-344	-131	152	29	-44
	Climate change	t CO_2 eq. / ha / yr	-14,6	-17,9	-18,5	-9,6	-4,5	0,8	-1,4
	Acidification	kg SO_2 eq. / ha / yr	39	9	-9	26	36	47	35
	Marine eutrophication	kg N eq / ha / yr	9,7	9,1	8,7	9,5	9,5	11,2	9,3
	Freshwater eutrophication	kg P eq / ha / yr	1,5	1,0	0,8	1,4	1,4	1,7	1,5
	Summer smog	kg NMVOC eq / ha / yr	29	10	0	22	24	23	16
	Ozone depletion	g R11-Äquiv. / ha / yr	56	56	60	56	57	112	67
	Particulate matter formation	kg PM10 eq / ha / yr	11,3	1,9	-2,9	8,0	10,5	12,1	7,9

Table 8-1 (continued)

Miscanthus							Switchgrass							Cardoon						
Miscanthus → Domestic heat	**Miscanthus → Small CHP**	**Miscanthus → Large CHP**	**Miscanthus → Pyrolysis oil**	**Miscanthus → Biochar**	**Miscanthus → 2G Ethanol**	**Miscanthus → 1,3-Propanediol**	**Switchgrass → Domestic heat**	**Switchgrass → Small CHP**	**Switchgrass → Large CHP**	**Switchgrass → Pyrolysis oil**	**Switchgrass → Biochar**	**Switchgrass → 2G Ethanol**	**Switchgrass → 1,3-Propanediol**	**Cardoon → Domestic heat**	**Cardoon → Small CHP**	**Cardoon → Large CHP**	**Cardoon → Pyrolysis oil**	**Cardoon → Biochar**	**Cardoon → 2G Ethanol**	**Cardoon → 1,3-Propanediol**
-80	-114	-160	-47	64	14	15	-44	-65	-92	-25	43	10	11	-66	-88	-119	-45	29	-7	-6
-7,1	-7,8	-8,8	-3,9	-2,6	0,3	0,9	-3,8	-4,3	-4,9	-1,9	-1,4	0,4	0,8	-5,1	-5,6	-6,3	-3,0	-2,5	-0,5	0,0
20	9	-2	14	18	21	23	18	11	4	14	16	18	19	17	10	2	13	15	17	19
2,8	2,6	2,4	2,7	2,7	3,5	2,7	4,0	3,9	3,8	4,0	3,9	4,5	3,9	5,2	5,0	4,9	5,1	5,1	5,7	5,1
0,3	0,1	0,0	0,3	0,3	0,4	0,4	0,3	0,2	0,1	0,3	0,3	0,3	0,4	0,4	0,2	0,2	0,3	0,3	0,4	0,4
16	9	3	13	13	13	12	12	8	5	10	10	10	9	11	6	2	8	8	8	8
16	17	18	16	16	40	22	24	24	25	24	24	39	27	30	31	32	30	30	47	34
6,7	3,3	0,4	5,4	6,1	6,7	6,7	5,3	3,3	1,5	4,4	4,8	5,2	5,2	4,4	2,2	0,2	3,4	3,9	4,3	4,3
-180	-240	-321	-123	74	-15	-12	-104	-140	-188	-70	48	-10	-8	-130	-169	-222	-93	36	-27	-26
-14,8	-16,3	-18,0	-9,2	-6,9	-1,9	-0,8	-8,4	-9,2	-10,2	-5,0	-4,2	-0,9	-0,2	-10,0	-10,9	-12,0	-6,3	-5,5	-1,9	-1,1
24	6	-13	15	21	27	31	22	11	-1	16	19	23	26	23	10	-2	16	19	24	26
3,8	3,4	3,0	3,6	3,6	5,0	3,6	5,5	5,2	5,0	5,3	5,3	6,3	5,3	7,2	6,9	6,7	7,0	7,0	8,0	7,0
0,5	0,1	-0,1	0,4	0,4	0,6	0,6	0,4	0,2	0,1	0,4	0,4	0,5	0,6	0,6	0,3	0,2	0,5	0,5	0,6	0,7
21	9	-2	16	15	15	14	16	9	3	12	12	11	11	15	7	0	11	10	10	10
21	22	24	21	21	63	31	32	32	34	32	32	59	38	42	42	44	41	42	71	48
8,1	2,2	-3,0	5,8	7,1	8,1	8,0	6,5	3,0	-0,2	4,9	5,7	6,3	6,3	5,9	2,1	-1,4	4,1	5,0	5,7	5,7
-281	-367	-484	-199	83	-44	-41	-164	-216	-285	-116	53	-30	-28	-195	-251	-327	-142	42	-48	-46
-22,8	-24,8	-27,3	-14,7	-11,4	-4,2	-2,6	-13,1	-14,3	-15,7	-8,3	-7,2	-2,5	-1,4	-15,0	-16,3	-17,9	-9,8	-8,6	-3,4	-2,3
28	1	-26	15	22	32	36	25	9	-8	16	21	27	30	26	9	-9	16	22	28	31
4,0	3,4	2,9	3,7	3,7	5,8	3,7	5,9	5,5	5,2	5,7	5,6	7,0	5,6	7,9	7,5	7,2	7,7	7,6	9,1	7,6
0,6	0,1	-0,2	0,5	0,5	0,8	0,8	0,5	0,2	0,1	0,5	0,5	0,7	0,7	0,7	0,4	0,2	0,6	0,6	0,8	0,9
25	8	-7	18	17	16	15	19	9	0	14	13	13	12	19	8	-2	13	12	11	11
21	22	26	22	22	81	36	34	34	37	33	33	72	42	45	46	49	45	45	87	55
9,1	0,7	-6,8	5,9	7,7	9,1	9,1	7,4	2,4	-2,2	5,0	6,2	7,1	7,1	7,0	1,5	-3,5	4,4	5,6	6,7	6,6
-165	-180	-283	-81	74	14	50	-95	-104	-166	-45	48	9	32	-120	-130	-198	-66	36	-7	18
-13,7	-12,6	-15,9	-6,7	-6,4	-2,0	2,5	-7,7	-7,0	-9,0	-3,5	-3,9	-1,0	1,9	-9,2	-8,5	-10,7	-4,7	-5,1	-2,0	1,2
25	14	-6	18	21	54	38	23	16	4	17	19	41	30	23	16	2	17	19	43	32
3,8	3,6	3,2	3,7	3,6	9,6	3,7	5,5	5,4	5,1	5,4	5,3	9,2	5,4	7,2	7,0	6,8	7,0	7,0	11,3	7,1
0,5	0,2	0,0	0,4	0,4	0,5	0,8	0,4	0,3	0,2	0,4	0,4	0,4	0,6	0,6	0,4	0,3	0,5	0,5	0,6	0,8
22	15	3	18	15	19	18	17	12	5	13	12	15	14	16	11	4	12	10	13	13
21	23	25	22	21	24	32	32	33	34	32	32	33	39	42	43	45	42	42	43	49
8,4	4,8	-0,8	6,6	7,0	13,0	10,5	6,7	4,6	1,2	5,3	5,7	9,5	7,9	6,1	3,8	0,1	4,6	5,0	9,2	7,4
-195	-285	-344	-164	74	-30	-91	-113	-167	-202	-94	48	-20	-59	-140	-199	-237	-120	36	-38	-82
-16,0	-18,8	-19,2	-11,8	-7,5	-3,0	-4,9	-9,0	-10,7	-11,0	-6,5	-4,6	-1,7	-2,9	-10,7	-12,5	-12,8	-8,0	-5,9	-2,7	-4,0
24	-2	-17	13	21	30	21	22	7	-3	14	19	25	19	22	6	-5	14	19	26	19
3,8	3,2	2,9	3,5	3,6	5,0	3,4	5,5	5,1	5,0	5,3	5,3	6,2	5,2	7,1	6,8	6,6	6,9	7,0	8,0	6,8
0,5	0,0	-0,1	0,4	0,4	0,6	0,5	0,4	0,2	0,1	0,4	0,4	0,5	0,5	0,6	0,3	0,2	0,5	0,5	0,6	0,6
20	4	-4	14	15	15	8	16	6	1	11	12	12	7	15	4	-1	10	11	10	6
21	21	23	21	21	68	29	31	32	33	31	32	62	37	41	41	43	41	42	74	47
7,8	-0,1	-4,2	5,0	7,1	8,5	4,9	6,4	1,7	-0,9	4,4	5,7	6,6	4,3	5,7	0,6	-2,2	3,6	5,0	6,0	3,5

Table 8-2 Relative performance of OPTIMA scenarios based on results per t of biomass (dry matter, DM). Results are shown for cultivation on marginal land (marginal 1) and standard conversion conditions. Categorisation and respective colouring of quantitative results reflects differences to average results of OPTIMA scenarios. TRL: technology readiness level, GMO: genetically modified organism, N/A: not applicable, N/D: no data.

			Giant reed						
Area	**Indicator**	**Unit**	**Giant reed → Domestic heat**	**Giant reed → Small CHP**	**Giant reed → Large CHP**	**Giant reed → Pyrolysis oil**	**Giant reed → Biochar**	**Giant reed → 2G Ethanol**	**Giant reed → 1,3-Propanediol**
Technology	Maturity cultivation (marg. land)	TRL	6	6	6	6	6	6	6
	Maturity harvest+logistics	TRL	5	5	5	5	5	5	5
	Maturity conversion	TRL	9	9	9	7	7	7	5
	Feedstock compatibility	(qualitative)	○	○	○	○	○	○	○
	Required development work	TRL	2,7	2,7	2,7	3,3	3,3	3,3	4,0
	Complexity	(qualitative)	+	○	○	– –	○	– –	– –
	Suitability for small scale	(qualitative)	++	+	–	–	○	– –	– –
Environment: LCA	Energy use	GJ / t DM	-10	-14	-20	-5	10	3	3
	Climate change	t CO_2 eq. / t DM	-0,8	-1,0	-1,1	-0,4	-0,2	0,1	0,2
	Acidification	kg SO_2 eq. / t DM	2,6	1,1	-0,3	1,9	2,3	2,8	3,0
	Marine eutrophication	kg N eq. / t DM	0,6	0,6	0,6	0,6	0,6	0,7	0,6
	Freshwater eutrophication	kg P eq. / t DM	0,10	0,07	0,06	0,09	0,09	0,11	0,11
	Ozone depletion	g R11 eq. / t DM	3,6	3,7	3,9	3,7	3,7	6,8	4,4
	Particulate matter formation	kg PM10 eq. / t DM	0,7	0,3	-0,1	0,6	0,7	0,7	0,7
	Land use	(ha·yr) / t DM	0,06	0,06	0,06	0,06	0,06	0,06	0,06
Envir.: EIA	Biodiversity	- (score)	1,5	2,0	2,5	3,1	2,4	4,3	4,4
	Soil	- (score)	1,7	2,8	2,9	3,5	2,2	3,6	3,6
	Water	- (score)	7,3	8,1	9,5	8,7	8,1	12,9	12,9
	Landscape	- (score)	0,0	0,6	1,4	0,9	0,6	1,4	1,4
Economy	Return on investment	- (ratio)	14%	7%	17%	1%	3%	-24%	N/D
	Internal rate of return	- (ratio)	12%	8%	15%	1%	2%	N/A	N/D
	Payback period	years	7,4	9,76	6,25	19	16	N/A	N/D
	Total assets turnover	- (ratio)	0,25	0,34	0,56	0,94	0,94	0,61	N/D
Society	Job equivalents	jobs / (kt DM / yr)	5	5	1	1	3	1	N/D
	Contribution to rural economy	(qualitative)	○	++	○	○	○	○	○
	Local embedding	(qualitative)	++	++	○	– –	– –	– –	– –
	Proximity to markets	(qualitative)	++	++	○	– –	– –	– –	– –
SWOT	Public perception	(qualitative)	+	+	+	++	++	++	++
	Health & Safety	(qualitative)	○	○	–	– –	–	– –	–
	Security of feedstock supply	(qualitative)	○	○	–	– –	○	– –	○

Table 8-2 (continued)

Miscanthus							Switchgrass							Cardoon						
Miscanthus → Domestic heat	Miscanthus → Small CHP	Miscanthus → Large CHP	Miscanthus → Pyrolysis oil	Miscanthus → Biochar	Miscanthus → 2G Ethanol	Miscanthus → 1,3-Propanediol	Switchgrass → Domestic heat	Switchgrass → Small CHP	Switchgrass → Large CHP	Switchgrass → Pyrolysis oil	Switchgrass → Biochar	Switchgrass → 2G Ethanol	Switchgrass → 1,3-Propanediol	Cardoon → Domestic heat	Cardoon → Small CHP	Cardoon → Large CHP	Cardoon → Pyrolysis oil	Cardoon → Biochar	Cardoon → 2G Ethanol	Cardoon → 1,3-Propanediol
6	6	6	6	6	6	6	6	6	6	6	6	6	6	5	5	5	5	5	5	5
6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
9	9	9	7	7	7	5	9	9	9	7	7	7	5	9	9	9	7	7	7	5
○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	– –	–	– –	– –
2,3	2,3	2,3	3,0	3,0	3,0	3,7	2,3	2,3	2,3	3,0	3,0	3,0	3,7	2,7	2,7	2,7	3,7	3,7	3,7	4,3
+	○	○	– –	○	– –	– –	+	○	○	– –	○	– –	– –	+	○	○	– –	○	– –	– –
++	+	–	–	○	– –	– –	++	+	–	–	○	– –	– –	++	+	–	–	○	– –	– –
-14	-18	-24	-9	6	-1	-1	-12	-16	-22	-8	6	-1	-1	-14	-18	-24	-10	4	-3	-3
-1,1	-1,2	-1,4	-0,7	-0,5	-0,1	-0,1	-1,0	-1,1	-1,2	-0,6	-0,5	-0,1	0,0	-1,1	-1,2	-1,3	-0,7	-0,6	-0,2	-0,1
1,9	0,4	-1,0	1,2	1,6	2,1	2,3	2,6	1,3	-0,1	1,9	2,3	2,7	3,0	2,4	1,1	-0,3	1,7	2,1	2,6	2,8
0,3	0,3	0,2	0,3	0,3	0,4	0,3	0,6	0,6	0,6	0,6	0,6	0,7	0,6	0,8	0,7	0,7	0,8	0,7	0,9	0,7
0,04	0,01	0,00	0,03	0,03	0,05	0,05	0,05	0,03	0,01	0,05	0,05	0,06	0,07	0,06	0,04	0,02	0,05	0,06	0,07	0,07
1,6	1,7	1,8	1,6	1,6	4,8	2,4	3,7	3,8	4,0	3,7	3,7	6,9	4,4	4,5	4,5	4,7	4,5	4,5	7,6	5,2
0,6	0,2	-0,2	0,4	0,5	0,6	0,6	0,8	0,4	0,0	0,6	0,7	0,7	0,7	0,6	0,2	-0,2	0,4	0,5	0,6	0,6
0,08	0,08	0,08	0,08	0,08	0,08	0,08	0,12	0,12	0,12	0,12	0,12	0,12	0,12	0,11	0,11	0,11	0,11	0,11	0,11	0,11
0,0	0,6	1,1	1,7	1,0	3,1	3,2	2,7	3,3	3,8	4,5	3,7	5,8	5,9	-2,2	-1,6	-1,1	-0,4	-1,2	0,9	1,0
0,1	1,3	1,5	2,1	0,6	2,2	2,2	3,5	4,7	4,9	5,5	4,0	5,6	5,6	1,4	2,6	2,8	3,5	2,0	3,6	3,6
2,3	3,2	4,8	3,9	3,2	8,6	8,6	3,8	4,7	6,3	5,4	4,7	10,1	10,1	3,1	4,1	5,7	4,7	4,1	9,5	9,5
-0,1	0,5	1,5	0,8	0,5	1,5	1,5	2,6	3,2	4,2	3,5	3,2	4,2	4,2	-0,3	0,4	1,3	0,7	0,4	1,3	1,3
13%	6%	15%	-7%	-2%	-34%	N/D	13%	6%	15%	-6%	-2%	-34%	N/D	13%	6%	15%	-6%	-2%	-34%	N/D
11%	7%	13%	N/A	N/A	N/A	N/D	11%	7%	14%	N/A	N/A	N/A	N/D	11%	7%	14%	N/A	N/A	N/A	N/D
7,97	7,75	6,79	73	26	N/A	N/D	7,9	10,2	6,69	51	24	N/A	N/D	7,9	10,3	6,8	58	24	N/A	N/D
0,25	0,34	0,56	0,94	0,94	0,61	N/D	0,25	0,34	0,56	0,94	0,94	0,61	N/D	0,25	0,34	0,54	0,94	0,94	0,61	N/D
5	5	2	2	4	1	N/D	6	6	2	2	5	2	N/D	6	6	2	2	5	2	N/D
○	++	○	○	○	○	○	○	++	○	○	○	○	○	○	++	○	○	○	○	○
++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –
++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –	++	++	○	– –	– –	– –	– –
+	+	+	++	++	++	++	+	+	+	++	++	++	++	+	+	+	++	++	++	++
○	○	–	– –	–	– –	–	○	○	–	– –	–	– –	–	○	○	–	– –	–	– –	–
○	○	–	– –	○	– –	○	○	○	–	– –	○	– –	○	○	○	–	– –	○	– –	○

Table 8-3 Benchmarking of all scenarios against Giant reed → Small CHP. Bandwidths of results for conversion technologies are taken into account. N/D: no data.

Benchmark: Giant reed → Small CHP	**Giant reed**							**Miscanthus**							**Switchgrass**							**Cardoon**						
Indicator	**Giant reed → Domestic heat**	**Giant reed → Small CHP**	**Giant reed → Large CHP**	**Giant reed → Pyrolysis oil**	**Giant reed → Biochar**	**Giant reed → 2G Ethanol**	**Giant reed → 1,3-Propanediol**	**Miscanthus → Domestic heat**	**Miscanthus → Small CHP**	**Miscanthus → Large CHP**	**Miscanthus → Pyrolysis oil**	**Miscanthus → Biochar**	**Miscanthus → 2G Ethanol**	**Miscanthus → 1,3-Propanediol**	**Switchgrass → Domestic heat**	**Switchgrass → Small CHP**	**Switchgrass → Large CHP**	**Switchgrass → Pyrolysis oil**	**Switchgrass → Biochar**	**Switchgrass → 2G Ethanol**	**Switchgrass → 1,3-Propanediol**	**Cardoon → Domestic heat**	**Cardoon → Small CHP**	**Cardoon → Large CHP**	**Cardoon → Pyrolysis oil**	**Cardoon → Biochar**	**Cardoon → 2G Ethanol**	**Cardoon → 1,3-Propanediol**
Maturity cultivation (marg. land	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	–	–	–	–	–	–	–
Maturity harvest+logistics	○		○	○	○	○	○	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Maturity conversion	○		○	–	–	–	–	○	○	○	–	–	–	–	○	○	○	–	–	–	–	○	○	○	–	–	–	–
Feedstock compatibility	○		○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	–	–	–	–
Required development work	○		○	–	–	–	–	+	+	+	–	–	–	–	+	+	+	–	–	–	–	○	○	○	–	–	–	–
Complexity	+		○	–	○	–	–	+	○	○	–	○	–	–	+	○	○	–	○	–	–	+	○	○	–	○	–	–
Suitability for small scale	+		–	–	–	–	–	+	○	–	–	–	–	–	+	○	–	–	–	–	–	+	○	–	–	–	–	–
Energy use	○		++	– –	– –	– –	– –	○	○	++	– –	– –	– –	– –	– –	○	○	– –	– –	– –	– –	○	○	○	– –	– –	– –	– –
Climate change	○		○	– –	– –	– –	– –	○	○	○	– –	– –	– –	– –	– –	– –	○	– –	– –	– –	– –	○	○	○	– –	– –	– –	– –
Acidification	– –		++	○	○	– –	– –	○	+	++	○	○	– –	–	○	○	++	○	○	○	○	○	○	++	○	○	○	○
Marine eutrophication	○		○	○	○	– –	○	++	++	++	++	++	○	++	++	++	++	++	++	○	++	++	++	++	++	++	○	++
Freshwater eutrophication	– –		○	– –	– –	– –	– –	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++	++
Ozone depletion	○		○	○	○	○	–	++	++	++	++	++	○	++	++	++	++	++	++	○	++	++	++	++	++	++	○	○
Particulate matter formation	– –		++	○	– –	– –	– –	○	○	++	○	○	– –	–	○	○	++	○	○	○	○	○	○	++	○	○	○	○
Biodiversity	○		○	–	○	–	–	+	+	+	○	+	–	–	○	–	–	–	–	–	–	+	+	+	+	+	+	+
Soil	+		○	–	+	–	–	+	+	+	+	+	+	+	–	–	–	–	–	–	–	+	○	○	–	+	–	–
Water	○		–	○	○	–	–	+	+	+	+	+	○	○	+	+	+	+	+	–	–	+	+	+	+	+	–	–
Landscape	+		–	○	○	–	–	+	○	–	○	○	–	–	–	–	–	–	–	–	–	+	○	–	○	○	–	–
Return on investment	+		+	–	○	–	N/D	+	○	+	–	–	–	N/D	+	○	+	–	–	–	N/D	+	○	+	–	–	–	N/D
Internal rate of return	+		+	–	–	–	N/D	+	○	+	–	–	–	N/D	+	○	+	–	–	–	N/D	+	○	+	–	–	–	N/D
Payback period	○		○	–	○	–	N/D	○	○	○	–	–	–	N/D	○	○	○	–	–	–	N/D	○	○	○	–	–	–	N/D
Total assets turnover	–		+	+	+	+	N/D	–	○	+	+	+	+	N/D	–	○	+	+	+	+	N/D	–	○	+	+	+	+	N/D
Job equivalents	○		–	–	–	–	N/D	○	–	–	–	–	–	N/D	–	–	–	–	–	–	N/D	–	–	–	–	–	–	N/D
Contribution to rural economy	–		–	–	–	–	–	–	○	–	–	–	–	–	–	○	–	–	–	–	–	–	○	–	–	–	–	–
Local embedding	○		–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–
Proximity to markets	○		–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–
Public perception	○		○	+	+	+	+	○	○	○	+	+	+	+	○	○	○	+	+	+	+	○	○	○	+	+	+	+
Health & Safety	○		–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–	○	○	–	–	–	–	–
Security of feedstock supply	○		–	–	○	–	○	○	○	–	–	○	–	○	○	○	–	–	○	–	○	○	○	–	–	○	–	○