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Integrated Sustainability Assessment of Growing Industrial Crops on Marginal Lands in Europe

This report was produced as Deliverable 6.7 within Work Package 6 “Integrated sustainability assessment” of the EU-funded project MAGIC (“Marginal lands for Growing Industrial Crops”)

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Executive Summary

Land availability is a major factor which limits the cultivation of industrial crops for bioenergy and bio-based products. Competition for arable land is likely to intensify worldwide over the coming decades. This conflict could partially be alleviated by using so-called marginal land – provided that the land is currently not used for the cultivation of crops. Against this background, the EU-funded MAGIC project ("Marginal lands for Growing Industrial Crops", GA No. 727698) aims at promoting the sustainable development of resource-efficient and economically profitable industrial crops grown on marginal land, considering that industrial crops can provide valuable resources for high value products and bioenergy.

However, cultivating industrial crops and using them for bioenergy and bio-based products does not automatically imply that the overall sustainability performance is better than if conventional energy carriers and products were used, simply because biomass is a renewable resource. Therefore, the MAGIC project included a comprehensive integrated life cycle sustainability assessment (ILCSA) to determine which biomass-related use options of marginal land are sustainable from an environmental, societal and economic point of view. To this end, nine value chains (combinations of industrial crops and biomass conversion technologies) were selected and subjected to three individual analyses of environmental, economic and social impacts associated with them. The biomass-based value chains were compared to conventional value chains on the basis of scenarios modelling future, industrial-scale, mature processes. This study joins the detailed findings of those three individual analyses into an overall picture and analyses them collectively to provide an integrated view on the sustainability impacts associated with the selected value chains.

A large number of results are presented in chapters 4 and 5. On this basis, conclusions and recommendations are deducted (chapter 6), which are outlined in the following.

Key conclusions:

- The use of marginal land in Europe can help in achieving several sustainability goals. If done right, **cultivating industrial crops on marginal land can result in positive impacts**, e.g. in terms of energy and greenhouse gas emission savings, or with regard to social indicators. However today, economic viability of the investigated value chains is difficult to be achieved without government commitment and a long-term strategy, which encourages private investments in the agricultural and the industrial sector, respectively. This is the main bottleneck in the use of marginal land.
- From an **environmental** point of view, the use of marginal land for the cultivation of industrial crops is mostly associated with the same environmental impacts as the use of standard land for the same purpose: the well-known pattern of environmental advantages and disadvantages for bioenergy and bio-based products from standard land also applies to marginal land.

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However, environmental benefits are only achieved by cultivation on unused, low carbon stock marginal land, which avoids so-called indirect land-use changes (iLUC) and associated negative environmental impacts.

- From a **social** perspective, the use of marginal land offers great opportunities in terms of rural development and sustainable employment, including the related indicators jobs, income diversification and social benefits.
- From an **economic** point of view, under current market conditions, only few of the feedstock production chains are able to reach break-even as independent activities, unless they are considered as complementary ventures to existing farm production lines, i.e. crop cultivation using marginal land patches and farm idle capacity. Compensating for the economic disadvantages compared to cultivation on standard land is therefore imperative and must be addressed as a matter of priority. Likewise, it is rather unlikely to find in the EU very large concentrations of marginal land available for industrial crop cultivation, sufficient to feed single-feedstock, dedicated conversion plants. Thus, industrial conversion of biomass becomes economically feasible when supplementing the operation of similar, already existing large-scale conversion plants.
- In order to develop marginal land in the future, corresponding support programmes would have to be set up by politics. This need for financial support opens up the possibility to **link the provision of financial support for marginal land to the fulfilment of environmental and social sustainability criteria**.
- Accompanying (or as part of) support programmes, differentiated **land use and land allocation plans** are needed both at the EU level and at the national, regional and local levels, which define the role of the future cultivation of industrial crops with regard to the essential but increasingly scarce resources of land, water and phosphate

Recommendations:

- If it is politically decided that the potential of marginal lands should be tapped, **it is absolutely essential to establish support programmes** that close the gap in terms of economic viability, both in terms of biomass production cost and with regard to the competitiveness of the resulting bioenergy carriers and bio-based products.

  - Under such support programmes, EU legislation should **link the provision of financial support for marginal land to the fulfilment of environmental sustainability criteria.** The following aspects should be considered as eligibility criteria:
    - in defining the criteria by which marginal land is identified, the **fundamental condition** should be imposed, **that financial support is only granted if the marginal land in question has not been used at all**, not even extensively, **in the last five years**. Biophysical criteria alone are not sufficient since they do not tell whether the land is used or not. Only cultivation of unused land avoids iLUC.

- **the transformation of land that is worthy of environmental protection** should be **excluded**. This concerns several types of land which are not necessarily congruent, e.g. (i) land with high carbon stock and peatland, (ii) land with high biodiversity value and (iii) high nature value farmland (HNV).

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- **the use of land for which payments under agri-environmental programmes have been made in the last ten years** should be excluded.
- in determining the level of financial support, **CO_2 abatement costs should be used as a guideline**, as these increase with the degree of marginality / more severe biophysical constraints. A lower threshold towards very marginal land needs to be defined, below which CO_2 abatement costs would rise to extreme levels.

* **Land use and land allocation plans should be prepared as part of publicly funded support programmes and concrete projects**. This is needed both at the supranational (EU) level and at the national, regional and local level: the more fine-grained the level, the more differentiated. Such plans can help to address and resolve trade-offs between nature conservation objectives, industrial crops cultivation and other alternative uses of marginal land. Moreover, **stakeholder processes** for the integration of local and regional actors are highly recommended.

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* **Guidelines for environmentally compatible cultivation of industrial crops on ecologically sensitive sites are necessary.** The so-called 'good farming practice' is not sufficient for the use of marginal land, at least not for ecologically sensitive sites. Therefore, guidelines need to go beyond the existing requirements.
* **Capacity building**: For the sustainable establishment of industrial crops on marginal land, it is essential to build up competencies regarding the selection of suitable crops and varieties. This holds both for state agricultural advisers and for farmers. Both could benefit from the MAGIC Decision Support System (DSS) which is an excellent starting point for this.
* In order to allow further research on marginal land, **appropriate research funding should be provided**.

Further specific conclusions and recommendations can be found in chapter 6.

This study shows that action is needed to ensure the environmental compatibility of the use of marginal land for bioenergy and bio-based products, but also for other competing uses of the same land. In addition, social aspects such as rural development and sustainable employment should be considered. This will help to ensure the development of marginal land for the benefit of the environment and society.

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1 Introduction

The EU-funded project "Marginal lands for Growing Industrial Crops" (MAGIC, GA No. 727698) aims at the promotion of a sustainable development of resource-efficient and economically profitable industrial crops grown on marginal lands. The use of marginal lands is promoted – despite lower yields compared to many other cultivation sites – because marginal lands are frequently unused. Therefore, the cultivation of industrial crops on marginal lands does not intensify the already prevailing competition for land. The industrial crops harvested can be used in various different ways, for instance to provide valuable resources for high added value products or to produce bioenergy.

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This project's work on the identification of most promising crop species, on the creation of new breeding tools, on the optimisation of appropriate agronomic practices and supply chains, amongst other aspects, is accompanied by an integrated sustainability assessment. One major goal of the sustainability assessment is to give a comprehensive overview of the potential implications for environment, society and economy if the MAGIC concepts were implemented in the future. It thus serves as a valuable basis for decision makers and stakeholders.

The objective of this report is to analyse all sustainability implications associated with selected bioenergy carriers and bio-based products from industrial crops grown on marginal land in Europe. It aims to provide answers to the goal questions defined earlier in the project (see [Rettenmaier 2018] and section 2.2.1).

The integrated sustainability assessment in MAGIC is based on a life cycle approach. It takes into account the entire life cycle from "cradle" (= biomass cultivation) to "grave" (e.g. end-of-life treatment) including the use of co-products. The analysis of the life cycles within MAGIC follows the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015] (see chapter 2 for details) which is applied to the systems described in chapter 3. This report joins the detailed analyses of environmental, economic and social aspects [Rettenmaier et al. 2021; Soldatos et al. 2021; Panoutsou et al. 2021] (see chapter 4 for summaries) into an overall picture and analyses them collectively to give an integrated view on the sustainability of the investigated MAGIC value chains (chapter 5). Finally, chapter 6 provides conclusions and recommendations regarding the use of marginal land for growing industrial crops in Europe.

2 Methods

The analysis of the life cycles within MAGIC follows the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015], which is summarised in section 2.1. The sustainability assessment is based on common goal, scope, definitions and settings for the environmental, economic and social analyses. This common basis a prerequisite of an overall integrated sustainability assessment and is described in section 2.2. Specific definitions and settings that are only relevant for the environmental, economic and social assessment are described in the respective reports [Rettenmaier et al. 2021; Soldatos et al. 2021; Panoutsou et al. 2021]. Finally the steps applied for the integrated sustainability assessment are explained in section 2.3.

2.1 ILCSA approach

The analysis of the life cycles within MAGIC follows the integrated life cycle sustainability assessment (ILCSA) methodology (Figure 1). The methodology, described in detail in [Keller et al. 2015], builds upon existing frameworks. It is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP/SETAC guidelines for social life cycle assessment [Andrews et al. 2009]. ILCSA extends them with features for ex-ante assessments such as the identification of implementation barriers that increase the value for decision makers. This flexibility allows for focussing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. Furthermore, it introduces a structured discussion of results to derive concrete conclusions and recommendations. See section 2.3 for details on the procedure selected in this study.

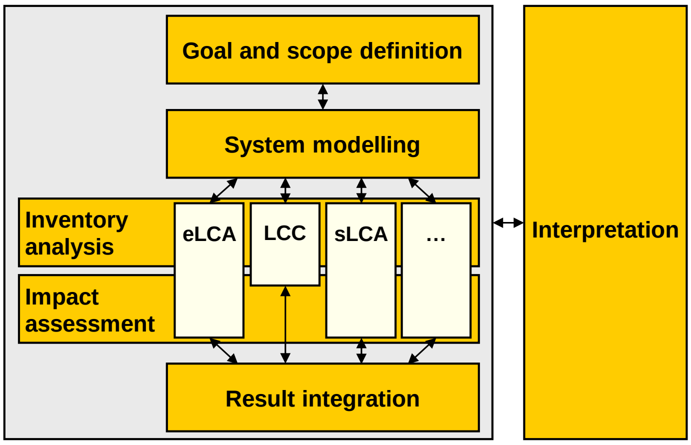

Figure 1: Schematic workflow of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015]. It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle assessment, (e)LCA, life cycle costing, LCC, social life cycle assessment, sLCA and analyses of other sustainability-relevant aspects.

2.2 Common definitions and settings

A well-founded sustainability assessment requires common definitions and settings on which the environmental, economic and social assessment are based. These general definitions and settings have been described in Deliverable D 6.1 [Rettenmaier 2018]. For additional *specific* definitions, settings and methodological aspects of the assessments of environmental, economic and social aspects please refer to the respective detailed reports [Rettenmaier et al. 2021; Soldatos et al. 2021; Panoutsou et al. 2021].

The goal and scope definition is the first phase of any sustainability assessment and is relevant for all three sub-analyses on the environmental, economic and social impacts. In the following sections, these definitions and settings are summarised as far as they are relevant for the integrated sustainability assessment.

2.2.1 Goal definition

The comprehensiveness and depth of the sustainability assessment can differ considerably depending on its goal. Therefore, the following aspects are described in detail in this section:

– I Intended applications and goal questions
– II Target audiences
– III Reasons for carrying out the study and the commissioner

I Intended applications and goal questions

The sustainability assessment within the MAGIC project aims at several separate applications. The subject of the first group of applications is the project-internal support of ongoing production systems development:

- Comparisons of specific cultivation systems, which are potential results of ongoing production systems development, and biomass use options.
- Identification of key factors for 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 MAGIC project to external stakeholders, i.e. 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 goal questions have been agreed upon by the MAGIC consortium. They are listed in the following. Their purpose is to guide the sustainability assessment in WP6:

- Which MAGIC value chains (bio-based products and bioenergy from industrial crops cultivated on marginal land) are sustainable from an environmental, societal and economic point of view,
  a) along the entire life cycle ('cradle-to-grave analysis')?
  b) in the agricultural stage ('cradle-to-farm gate analysis')?

The assessment along the entire life cycle ('cradle-to-grave analysis') is the main goal and follows internationally accepted guidelines of the International Organization for Standardization (ISO) and the Society of Environmental Toxicology and Chemistry (SETAC) [Andrews et al. 2009; ISO 2006a; b] and aims at reliable policy recommendations. An additional focus is laid on the agricultural stage ('cradle-to-farm gate analysis') to analyse the compliance of produced transportation fuels with the sustainability criteria set out in Annex V of the recast Renewable Energy Directive ("RED II") [European Parliament & Council of the European Union 2018].

This main question leads to the following sub-questions:

- Which life cycle stages or unit processes dominate the results significantly and which optimisation potentials can be identified?
- Do some MAGIC value chains show a better 'life cycle sustainability performance' than others?
- Which trade-offs within and between the pillars of sustainability have to be made?
- Which industrial crops would a farmer choose from an agronomic point of view?
- Which technological, logistical or other potential barriers may hinder the large-scale industrial deployment?
- Which boundary conditions have to be met in order to advocate large-scale cultivation of industrial crops on marginal land from a sustainability point of view?
- Do the MAGIC value chains targeting biofuels comply with the sustainability criteria set out in the RED II? Should the greenhouse gas (GHG) emission savings threshold equally be applied to biofuels from marginal land?

II Target audience

The definition of the target audience helps identifying the appropriate form and technical level of reporting. In the case of the MAGIC project, the target audience can be divided into project partners and external stakeholders (EC staff, political decision makers, other stakeholders, interested laypersons).

III Reasons for carrying out the study and commissioner

The sustainability assessment is carried out because the MAGIC consortium has decided to supplement the establishment of suitable innovative land use strategies for a sustainable production of plant-based products on marginal lands with a corresponding analysis. The study is supported by the EU Commission, which signed a grant agreement with the MAGIC consortium.

2.2.2 Scope definition

With the scope definition, the object of the sustainability assessment (i.e. the exact product or other system(s) to be analysed) is identified and described. The scope should be sufficiently well defined to ensure that the comprehensiveness, depth and detail of the study are compatible and sufficient to address the stated goal.

The analysis of the life cycles within the MAGIC project is based on international standards such as ISO standards on product life cycle assessment [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the recast Renewable Energy Directive (RED II) [European Parliament & Council of the European Union 2018], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP / SETAC guidelines for social life cycle assessment [Andrews et al. 2009].

For the analysis of the MAGIC scenarios, definitions and settings are necessary. They are used in the subsequent analyses to guarantee the consistency between the different assessments of environmental, economic and social implications. The definitions and settings are described and explained below, including the following aspects:

- I Investigated systems and settings for system modelling
- II Geographical coverage
- III Technical reference
- IV Time frame
- V System boundaries
- VI Alternative land use
- VII Function, functional unit and reference unit
- VIII Data sources

I Investigated systems and settings for system modelling

The MAGIC project investigates various industrial crops suitable for the cultivation on marginal land under various growing conditions. Also, several energy and material use options are considered. Therefore, there is not just one single MAGIC product system to be analysed. Instead, there is a wide spectrum of potential implementations combining several of the elements leading to 40–80 possible crop-technology combinations. This large amount has been reduced to the nine most promising value chains on the basis of selection criteria such as the technology readiness level (TRL) and the expected market volume [van den Berg et al. 2020]. The selection has been discussed in the framework of an internal project workshop on selection of value chains and interlinkages (MS6.2 / MS18).

Against this background, the application of a scenario-based assessment is most suitable for the MAGIC WP6. The analysed product systems represent generic scenarios which consider typical conditions that can be found across Europe (see II) so that reliable general statements and recommendations concerning bio-based products and bioenergy from industrial crops cultivated on marginal land in Europe can be derived. When deriving the mass and energy flow data for these generic scenarios, data obtained from field trials, pilot plants, case studies and databases and literature are taken into consideration, but mostly not used directly (i.e. only after extrapolation). The analysed value chains are described in chapter 3.

II Geographical coverage

Geography plays a crucial role in many sustainability assessments, determining e.g. agricultural conditions, transport systems and electricity generation.

It is the aim of the MAGIC project to establish a basis for cultivation of marginal lands in Europe. For this reason, geographical coverage for the sustainability assessment is focused on European countries and the differing growing conditions and cultivation practises in Europe are taken into account. This is achieved by categorising the various conditions and yield potentials that can be found in Europe based on the climatic zones identified by [Metzger et al. 2005]. For the MAGIC project, these climatic zones are aggregated into three large agro-ecological zones (AEZ) as specified in Figure 2. On the one hand more distinctions would exceed the scope of the analysis and on the other hand conditions vary strongly across Europe.

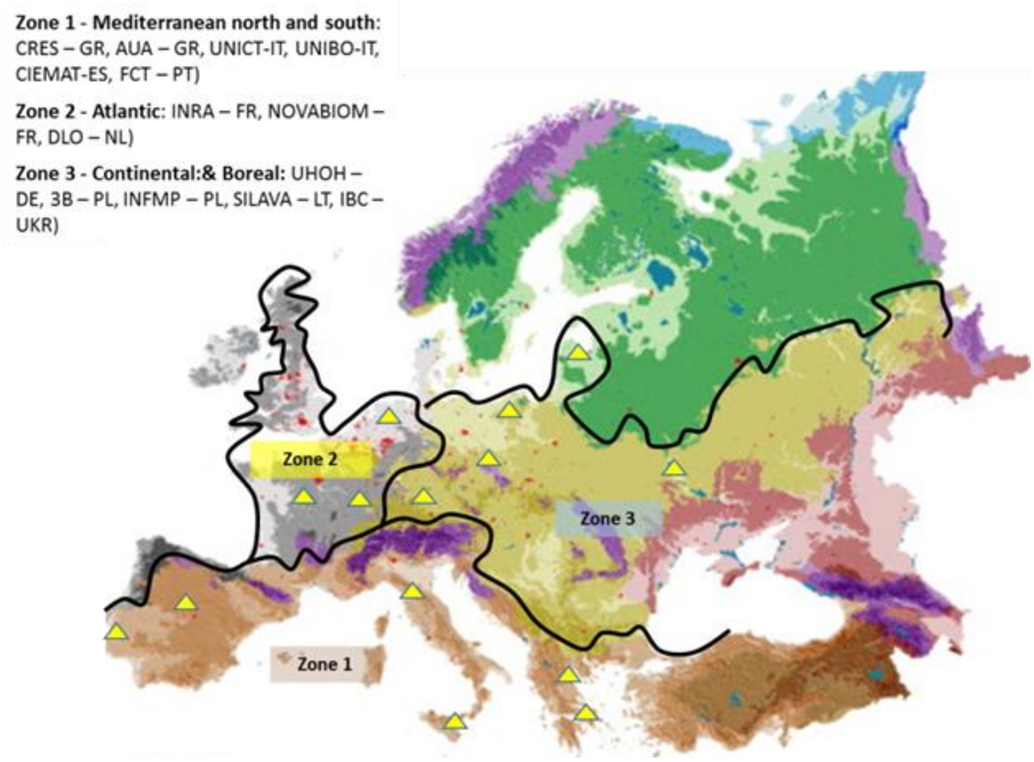

Figure 2: Major geographical/climatic zones in Europe; yellow spots indicate new and established field trials. Source: MAGIC Description of the Action (DoA)

The following three aggregated agro-ecological zones are defined for the MAGIC project:

- AEZ 1 – Mediterranean (MED),
- AEZ 2 – Atlantic (ATL), and
- AEZ 3 – Continental & Boreal (CON).

Within these zones, different biophysical constraints are prevailing which hamper the growth of industrial crops. The two most important constraints in each zone have been identified by [von Cossel et al. 2018] and corresponding yields were set by the partners, see section 2.2.2 VIII.

With respect to the provision of conventional reference products, the geographical scope is broadened in order to represent the generic (e.g. European or global) production of each replaced commodity. In some cases, country-specific conditions may be chosen for the estimation of a single parameter's influence on the overall results, e.g. related to labour costs or environmental burdens related to irrigation.

III Technical reference

The technical reference describes the agricultural practise and the conversion technology to be assessed in terms of development status and maturity.

Assessing the sustainability of a pilot case is not an appropriate approach to answer the key questions listed under the goal definition (section 2.2.1) because many parameters might differ quite considerably from future implementation. In order to evaluate whether the cultivation of marginal lands is worth being further developed or supported, it is essential to obtain information how possible future implementations will perform compared to established reference product provision pathways which are operated at industrial scale. This is to avoid an unbiased comparison between the bio-based products and conventional reference products. Therefore, mature agriculture practise and mature industrial-scale plants are set as technical reference.

IV Time frame

Typically, the time frame has a strong influence on the assessment of pilot projects because it takes several years to ramp up production volumes in order to benefit from economies of scale and to improve production with respect to resource efficiency.

Cultivation and processing of industrial crops on marginal lands are currently still in an immature state and thus cannot compete with established energy provision production chains. The year 2030 was set as a reference because this is considered a time point at which the analysed value chains could be mature as chosen for the technical reference (see III).

V System boundaries

System boundaries specify which unit processes are part of the production system and thus included into the assessment settings as well as the processes excluded based on cut-off criteria. Within the MAGIC project, two alternatives of system boundaries are considered (see Figure 3):

a) Cradle-to-grave approach and
b) Cradle-to-farm gate approach.

Regarding the *cradle-to-grave* approach, the sustainability assessment of the MAGIC system takes into account the products' entire value chain (life cycle) from cradle to grave, i.e. from resource extraction for fertilisers applied during cultivation to the utilisation and end of life of the bio-based products following the principle of life cycle thinking (see chapter 3). The system boundary also covers the so-called alternative land use (see VI), including land use change effects and associated changes in carbon stocks. Also, for the equivalent conventional reference products, the entire life cycle is taken into account. The cradle-to-grave analysis is carried out for selected value chains.

The concept of life cycle thinking integrates existing consumption and production strategies, preventing a piece-meal approach. Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium or protection target to another.

Furthermore, greenhouse gas emissions are additionally calculated for the agricultural stage from *cradle-to-farm gate*. These data are implemented in the MAGIC decision support system and allow a compliance-check according to the RED II.

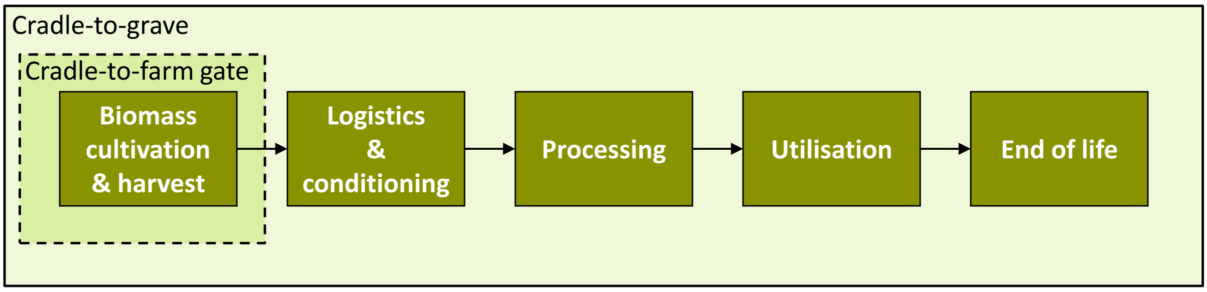

Figure 3: System boundaries from cradle-to-grave and from cradle-to-farm gate applied within the MAGIC project. Source: ifeu, own illustration

VI Alternative land use

For sustainability assessment of biomass production systems, the alternative land use is a crucial parameter for the outcome of the investigation. The alternative land use describes what the cultivation area would be used for (including non-commercial use such as nature preservation) if the crops under investigation were not cultivated [Jungk et al. 2002; Koponen et al. 2018]. If the MAGIC concepts are implemented, land that was formerly used for certain purposes will be used for production of industrial crops instead. By consideration of the alternative land use, the sustainability assessment guarantees a sound evaluation of the implications related to this land use change. The assessment is carried out through a comparison of the proposed agricultural land use with the alternative land use (see Figure 5 on page 27).

Alternative land use and the related environmental, social and economic impacts are taken into account in all scenarios, e.g. by consideration of greenhouse gas emissions, opportunity costs or social impacts on local inhabitants. However, one major benefit of marginal lands is that there is little competition for their use and in many cases they are currently unused.

Therefore, as a baseline setting cultivation is set to take place on former idle land. In this project, idle land is defined as land that is currently not in use. Thus, the MAGIC industrial crops would not displace food or fodder crops to other, previously unused areas and indirect land use changes (iLUC) can be excluded from this assessment. However, potential impacts from land use and land use changes (LULUC) are analysed by comparing the direct land use change/land use (dLUC/dLU) and attributional land use and land use change (aLULUC) approaches. For this purpose, the alternative vegetation on marginal land is defined as either grassland or woody grassland / shrubland.

VII Function, functional unit and reference unit

Defining a common reference unit for all sustainability assessments, i.e. life cycle assessment (LCA), life cycle – environmental impact assessment (LC-EIA) and life cycle costing (LCC), is vital for comparability and consistency of the individual results.

In LCA studies, results are referenced to the so-called functional unit, which is a measure for the function of the studied system. It quantifies the function (i.e. utility) of the products provided by the investigated system. In the case of lignocellulosic biomass used as biofuel, a typical output-related functional unit could e.g. be the provision of 1 MJ of fuel energy. All comparisons of products and reference products are based on a specific functional unit for each product.

The value chains analysed in MAGIC each provide different products. Therefore, a common reference unit is needed to be able to compare the systems. If the focus is set on the input, 1 tonne oven-dry biomass could be used as reference unit. Alternatively, land is a main factor limiting the production of bioenergy and bio-based products in Europe. Therefore, referencing the results to 1 hectare is most suitable. Hence, the reference unit of 1 hectare of occupied land for 1 year for biomass production systems is applied within the MAGIC project. For RED-related analyses, the output-based reference unit of 1 MJ fuel is used as specified in the RED II.

Results related to these reference units are well comparable to other biomass production systems. Transformation into other reference units is possible where needed.

VIII Data sources

The sustainability assessment of the MAGIC systems requires a multitude of data. Primary data (on the foreground system) is obtained from the following sources:

- Quantitative data on agricultural cultivation, harvesting, logistics and conditioning, up to the biorefinery inlet gate (cradle-to-biorefinery inlet gate) are provided by CRES and CREA.
- Quantitative data on biomass conversion as well as qualitative and/or quantitative information on use and end of life (biorefinery inlet gate-to-grave) are provided by BTG, ARKEMA and NOVA [van den Berg et al. 2020].

It is important to note that the original data (e.g. coming from field trials or pilot plants) is not used directly but only after extrapolation for the year 2030. The extrapolation was done by expert judgements, resulting in datasets which represent mature agricultural practice and industrial processing units (see section 2.2.2 III and IV).

For each of the agro-ecological zones (AEZ), the two most important biophysical constraints which hamper the growth of industrial crops were identified by [von Cossel et al. 2018].

AEZ 1 (Mediterranean)

- Adverse rooting conditions (rooting): e.g. unfavourable texture, shallow rooting depth
- Adverse climate (climate/drought): ratio precipitation / pot. evapotranspiration ≤0.5

AEZ 2 (Atlantic)

- Excessive soil moisture (wetness) : soil moisture above field capacity for >210 days
- Adverse rooting conditions (rooting) : e.g. unfavourable texture, shallow rooting depth

AEZ 3 (Continental+Boreal)

- Adverse climate (climate/low temp.): number of days or thermal time sum >5°C
- Excessive soil moisture (wetness) : soil moisture above field capacity for >210 days

Partners have set corresponding yields that can be attained under these specific biophysical constraints based on their expertise. These are summarised in the following Table 1:

Table 1: Expected yields under specific biophysical constraints

	AEZ 1 (MED)		AEZ 2 (ATL)		AEZ 3 (CON)	
Crop	**Rooting**	**Climate**	**Wetness**	**Rooting**	**Climate**	**Wetness**
Miscanthus	11.5	8.0	0.0	12.0	6.5	0.0
Switchgrass	6.0	6.0	5.5	5.5	5.0	5.0
Poplar	4.0	4.0	5.0	4.0	5.5	5.5
Willow	5.0	4.0	6.0	5.0	7.0	6.5
Castor	1.2	1.2	n.a.	n.a.	1.0	1.5
Safflower	0.8	0.8	0.7	0.9	0.9	0.8
Hemp	6.0	6.0	5.0	6.0	4.0	5.0
Sorghum	5.0	8.0	6.0	7.0	10.0	6.5
Lupin	-	-	-	-	-	-

Depending on the data requirements of each individual assessment of environmental, economic and social sustainability aspects, further primary as well as secondary data are taken from databases or literature.

2.3 Integrated sustainability assessment

This study joins the detailed findings of those three individual analyses into an overall picture and analyses them collectively to provide an integrated view on the sustainability impacts associated with the selected value chains. Within the framework of MAGIC, a technological assessment was not carried out because this is largely independent of the question of whether biomass provision takes place on marginal sites or standard agricultural land, at least as far as biomass conversion technologies are concerned.

General approach

There are two general options to integrate a multitude of indicators on certain scenarios, either weighting and mathematical integration or structured discussion.

- **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.

Collection of indicators and results

Indicators and results for all scenarios are provided by the parallel assessments of individual sustainability aspects [Rettenmaier et al. 2021; Soldatos et al. 2021; Panoutsou et al. 2021]. The following indicators are collected in an overview table:

- 10 quantitative environmental indicators from life cycle assessment
- 4 semi-quantitative environmental indicators from life cycle environmental impact assessment
- 6 quantitative economic indicators
- 5 qualitative social indicators

A sixth qualitative social indicator ‘sustainable employment’ was added in the course of the integrated sustainability assessment by combining the indicators ‘income diversification’ and ‘social benefits’ of the social assessment (see below). 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 tables are coloured accordingly. Dark and light green boxes represent overall advantageous results, i.e. an improvement compared to a situation without MAGIC. Orange and red boxes represent overall disadvantages, i.e. a deterioration compared to a situation without MAGIC. Yellow boxes represent a minor sustainability impact. This way of categorising results supports the identification of options that perform best among all studied options but also maintains the quantitative information on the sustainability of a scenario. Results are collected for all assessed 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 4. They are taken into account for the overall conclusions and recommendations (chapter 6).

Condensation of indicators and benchmarking

In view of the large number of collected indicators, a condensation to a more easily interpretable number of indicators was carried out. The aim was to provide the reader with a more condensed overview while at the same time avoiding a (over-)simplification, e.g. by applying a dashboard with only three displays, one each for environment, economy and society.

As part of an iterative process, qualitative composite indicators were formed on the basis of or in knowledge of the results for all available indicators from section 5.1:

- Qualitative composite indicators were formed, either because indicators correlated or belonged together thematically:
  - An example is the composite indicator ‘GHG and energy balance’, which assesses the impact on ‘climate change’ as well as ‘non-renewable energy use (NREU)’ jointly since those are governed by the same key drivers.
  - Another example is the combination of several indicators, which are essentially controlled by emissions of various nitrogen species, into 'airborne emissions'.
- An additional social indicator ‘sustainable employment’ was formed by combining the indicators ‘income diversification’ and ‘social benefits’ of the social assessment [Panoutsou et al. 2021]. Sustainable employment is a priority within the funding objectives of the European Regional Development Fund and the European Social Fund.
- Some indicators that do not contribute significant additional information to the sustainability assessment were not considered further in the following analysis:
  - For example, the economic indicator 'net present value (NPV)', which only allows limited comparative statements on the economic sustainability of the individual value chains due to the significant differences in the size of the plants.
  - Another example is the social indicator 'natural resources', which is already sufficiently considered in the environmental indicators. The social indicators 'innovation' and 'governance' are already partly included in the economic assessment.

Thus, in the integrated sustainability assessment, those indicators were chosen from the set of available indicators, which give additional information that is relevant for decisions between the assessed options.

Furthermore, the definition of the composite indicators was based on the concept of planetary boundaries [Rockström et al. 2009], which describes the scientifically and socially most important environmental problems. In the further development of this concept [Steffen et al. 2015] , the so-called safe operating space of the four processes climate change, biosphere integrity (biodiversity loss), biogeochemical flows and land-system change was defined as already exceeded (see Figure 4). Therefore, these features should be an important part of this Integrated Life Cycle Sustainability Assessment. Furthermore, the management of globally available resources is an important component of a holistic sustainability assessment.

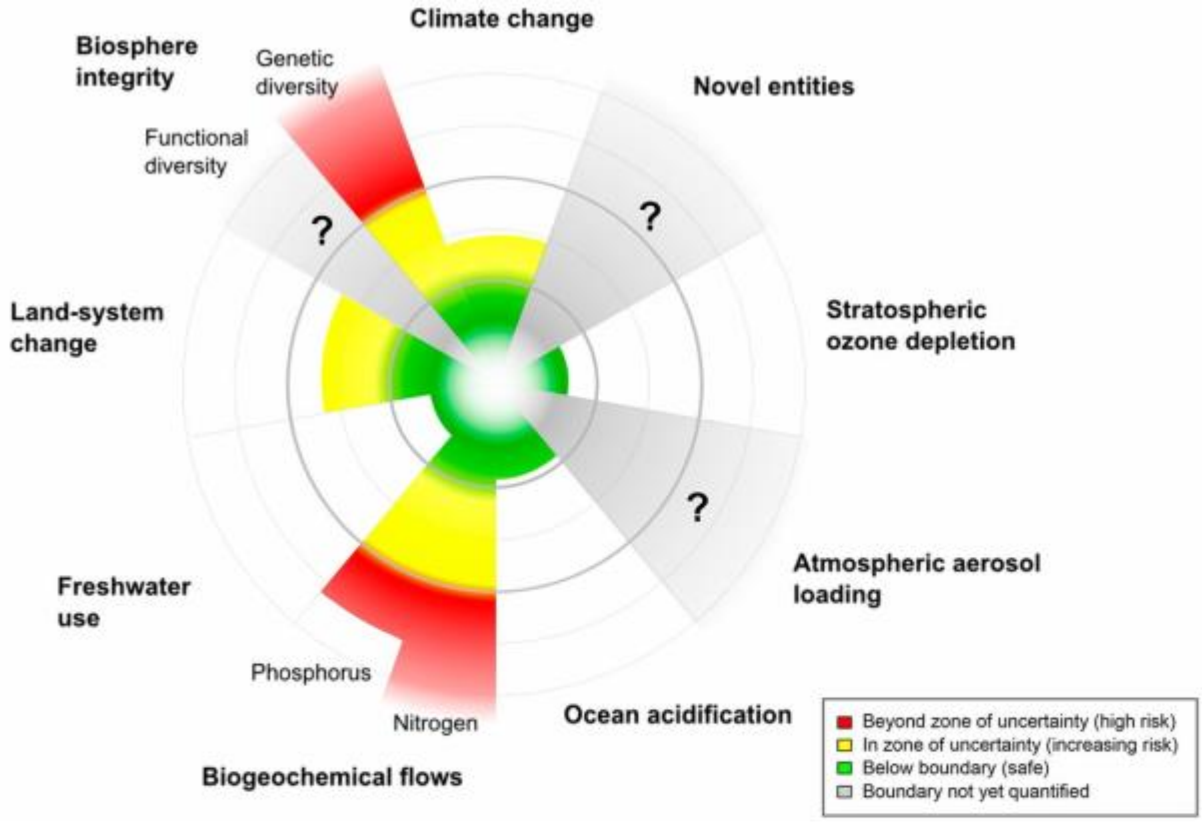

Figure 4: Current status of the control variables for seven of the planetary boundaries according to [Steffen et al. 2015]. The green zone is the safe operating space, the yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone. The planetary boundary itself lies at the intersection of the green and yellow zones.

The concept of planetary boundaries was taken up by [Raworth 2012, 2017] as an ecological ceiling and supplemented by a social foundation, below which lies critical human deprivation such as hunger, ill health, illiteracy, and energy poverty. Between social and planetary boundaries lies an environmentally safe and socially just space in which humanity can thrive. Raworth derived 12 social indicators from internationally agreed minimum standards for human wellbeing, as established in 2015 by the UN Sustainable Development Goals [United Nations 2015]. These served as a source of inspiration when selecting the social indicators.

This iterative process was concluded with a SWOT analysis (analysis of strengths, weaknesses, opportunities and threats) was performed evaluating this condensation of indicators.

Benchmarking and overall interpretation

In the benchmarking step, the results for bioenergy carriers and bio-based products from marginal land are benchmarked against the results for the same products from standard land. Standard land is chosen as the benchmark since the main focus of the MAGIC project is to level out the burdens associated with the cultivation of industrial crops on marginal land (as compared to standard land) and ideally turning them into an opportunity.

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 value chain on marginal land and the benchmark (the same value chain on standard land). These comparisons should serve as a decision support to answer the question whether a value chain performs better than the benchmark regarding a certain indicator. Therefore, these quantitative differences are categorised into advantageous [+], neutral [○] or disadvantageous [-], which is also reflected by a traffic light colouring, i.e. green [+], yellow [○] and red [-]. Two results are rated as not substantially different if the difference is below a threshold of 2% 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. For all qualitative indicators, rating of differences is done analogously but without applying minimum differences.

For the overall interpretation, a verbal-argumentative discussion of decision options is supported by structured tables containing overviews of original indicator results as well as the benchmarking results (see section 5.3 for details).

3 Analysed systems

The integrated sustainability assessment is performed for a number of defined systems. In the following, these MAGIC systems are qualitatively described. As indicated in [Rettenmaier 2018], the MAGIC systems follow the principle of so-called life cycle comparisons. A schematic overview of a life cycle comparison scheme is shown in Figure 5. The entire life cycles of the MAGIC system and the obtained products are assessed – starting from industrial crops cultivation through harvesting, pre-treatment, further processing, to product use and – if applicable – end-of-life treatment and final disposal ('cradle-to-grave approach'). All material and energy inputs into and outputs from the system are taken into account. All products and co-products replace conventional reference products that provide the same function. For the reference products, the entire life cycle is taken into account as well. Through such a systematic overview and life cycle thinking (LCT) perspective, the unintentional shifting of environmental burdens, economic benefits and social well-being between life cycle stages or individual processes can be identified and possibly mitigated or at least minimised.

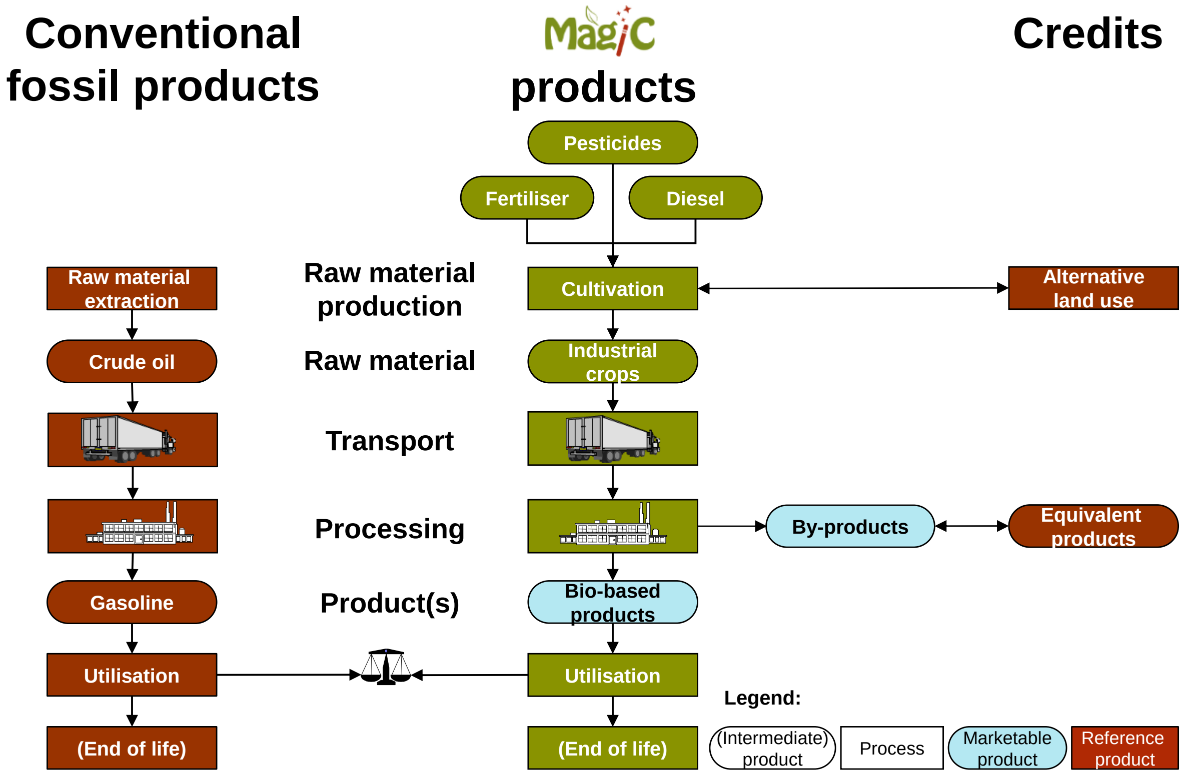

Figure 5: Sustainability assessment within the MAGIC project. The MAGIC bio-based products are compared to conventional reference products, both along the entire life cycle. Source: ifeu, own illustration

Selection of value chains for the integrated sustainability assessment

The value chain selection process consists of the following steps: First, the most promising industrial crops for marginal lands were selected by [Alexopoulou & Monti 2018]. The selection includes 20 industrial crops, grouped in three categories: lignocellulosic crops, oil crops & carbohydrate/multipurpose crops. These crops can be used for various products including bioenergy, biofuels, biochemicals and biomaterials.

Second, an analysis was conducted to identify all suitable conversion pathways for each of the 20 selected crops. As summarised by [Spekreijse et al. 2018], 140 feasible combinations of crop and conversion pathway were identified. Out of those 140 value chains, 82 were assessed to be the most promising candidates. The other 58 value chains were assessed to be also promising, but generally have better alternatives due to another crop matching better with the technology or another technology matching better with that crop. Reasons include the properties of the crop, TRL, market potential of the end product, or data availability.

Third, out of 82 most promising candidates, ten value chains were finally selected for in-depth analysis within the sustainability assessment in the framework of an internal project workshop on selection of value chains and interlinkages [Rettenmaier et al. 2019]. An overview of the ten selected value chains is given in Table 2. It shows a good representation of:

1. Crop categories (lignocellulosic crops, oil crops & carbohydrate/multipurpose crops)
2. Products categories: energy, fuels, chemicals & materials

Table 2: Final selection of value chains for in-depth analysis within the sustainability assessment

Crop	Conversion technology	Main products[1]	Type
Miscanthus	Pyrolysis	Energy (industrial heat)	
Poplar	Gasification	Energy (SNG)	
Switchgrass	Fermentation	Ethanol	
Willow	Pyrolysis	Biochemicals (biotumen)	
Safflower (high oleic)	Oxidative cleavage	Azelaic and pelargonic acid	
Camelina (high oleic)	Metathesis	Methyl decenoate	
Castor	Alkaline cleavage	Sebacic acid	
Industrial hemp	Mechanical processing	Insulation material	
Sorghum	Anaerobic digestion	a) heat & power b) biomethane	
Lupin	Extraction	Adhesives	/

A qualitative description of the analysed systems can be found in [Alexopoulou et al. 2020]. For the readers' convenience, the value chain descriptions were also put into the annex of this report (chapter 9).

Subsequently, quantitative data for biomass conversion for nine out of ten value chains has been provided in [van den Berg et al. 2020]. The voluntary tenth value chain (Methyl decenoate from camelina) had to be skipped because it was not feasible to provide data on the biomass conversion. Information on quantitative inputs and outputs, i.e. on mass and energy flows, are summarised in section 2.2.2 VIII. It is important to note that both the qualitative and quantitative description represent mature agriculture practise and mature industrial-scale plants of the year 2030, as already determined in D 6.1 [Rettenmaier 2018] and summarised in the scope definition in section 2.2.2 III and IV.

The value chains (or life cycles) are divided into two parts: i) biomass provision and ii) biomass conversion, product use and end-of-life (EoL). The biorefinery inlet gate is defined as the interface between the two parts.

Biomass provision and alternative land use

The first part of the life cycle covers all processes from **biomass production** through **harvesting**, **logistics** and **conditioning** up to the biorefinery inlet gate.

Since a broad range of crops is investigated in MAGIC (perennial and annual crops, lignocellulosic, oil and carbohydrate / multipurpose crops, etc.), cultivation and harvesting practices as well as conditioning requirements vary significantly among the crops. In addition, agricultural co-products and their use are described as well in D 6.2 [Alexopoulou et al. 2020].

Biomass conversion, product use and end-of-life

The second part of the life cycle covers all processes from **biomass conversion** (the biorefinery inlet gate is defined as the interface) through **product use** and **end of life (EoL)**. The **conventional reference system(s)** is/are also covered in order to obtain full **life cycle comparisons**.

Quantitative data for biomass conversion (mass and energy flows) including all main products and co-products is provided in D 6.3 [van den Berg et al. 2020].

4 Summaries of specific assessments and SWOT analysis

As a basis for further analyses, this chapter contains summaries of the assessments of individual sustainability aspects (sections 4.1 - 4.3).

4.1 Summary: environmental assessment

This assessment by the project partners IFEU and FCT NOVA analysed all environmental implications of the scenarios described in chapter 3. For a summary on the applied methods, e.g. the used life cycle impact assessment method, and further details please refer to the original environmental assessment report [Rettenmaier et al. 2021].

The environmental assessment consists of two parts: a screening life cycle assessment (LCA) which addresses impacts at global level and a so-called life cycle environmental impact assessment (LC-EIA) for impacts at local level. The most important results and conclusions which are based on both assessments are summarised in the following.

4.1.1 Life cycle assessment: Results and key findings

Figure 6 shows the normalised screening LCA results for bio-based value chains (compared to conventional reference products) and all impact categories across all yields and agro-ecological zones. The figure shows burdens caused by the MAGIC value chains on the right hand side and credits that are assigned due to the substituted conventional reference products on the left hand side.

The screening Life Cycle Assessment (LCA) examined the cultivation of nine industrial crops in Europe, the processing and use of the products and the substitution of the corresponding reference products. A total of ten environmental impact categories were evaluated in the screening LCA. The analysis provided a number of key findings which are listed below.

Comparison between marginal land and standard land

No significant qualitative differences: LCA results for bioenergy and bio-based products from marginal land are qualitatively similar to LCA results for bioenergy and bio-based products from standard land (in both cases compared to conventional reference products). This is because even low-input agricultural systems on marginal land require inputs such as fertilisers, pesticides and fuel which are of course scaled to the expected yield but often specifically higher per tonne of harvested biomass than on standard land.

Exceptionally wide result range: LCA results for biomass use from marginal land show an exceptionally wide range: if displayed per hectare per year (as done here), the results scale with yield. Due to the extremely diverse climatic and soil conditions on marginal land across Europe, the achievable yield is within a wide range.

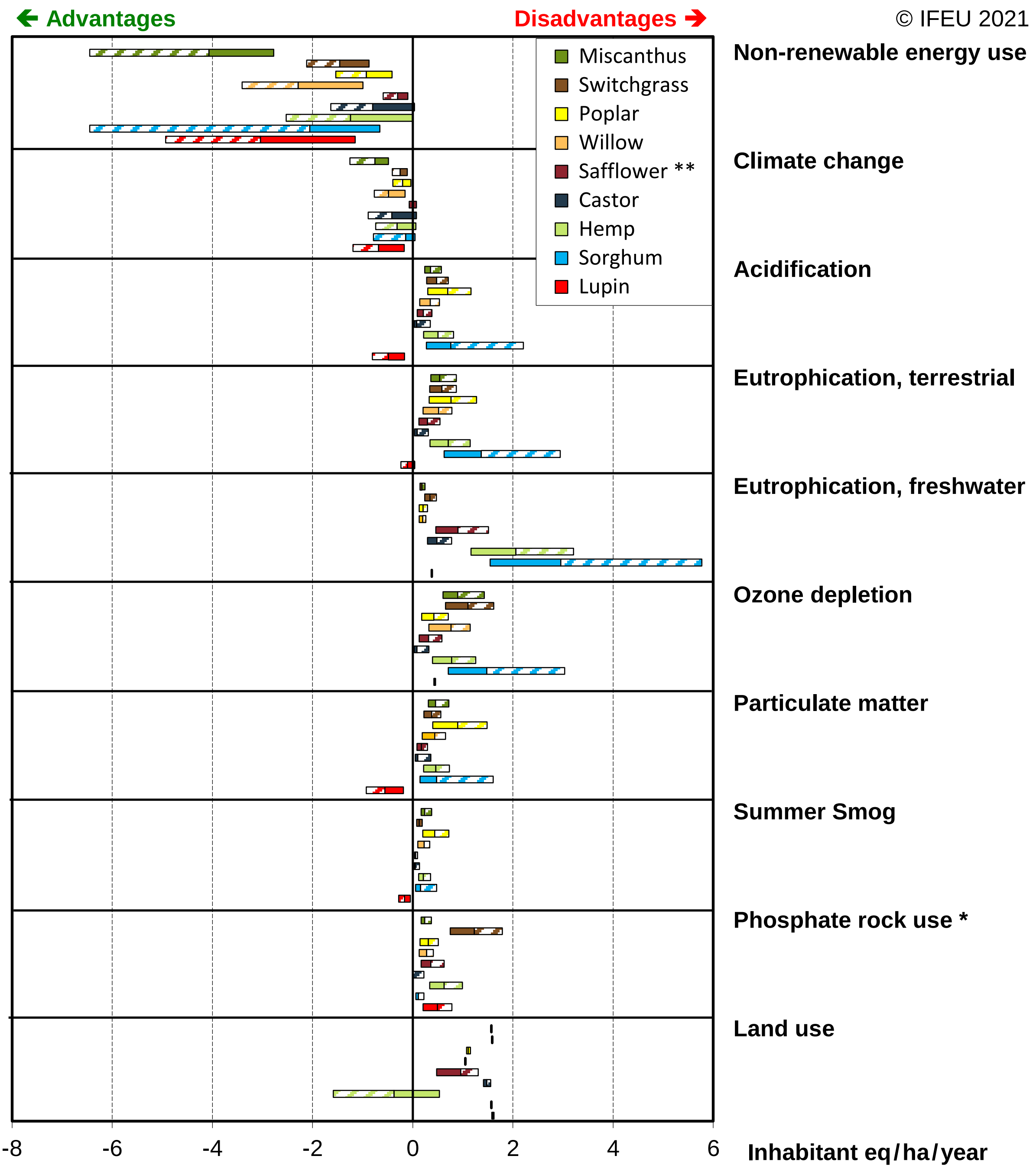

Figure 6: Ranges of LCA results for all bio-based value chains (compared to conventional reference products) and all impact categories across all agro-ecological zones. The fully coloured bar sections indicate the result ranges for marginal land (yield levels 'very low' and 'low' as introduced in [Rettenmaier et al. 2021]) whereas the shaded bar sections indicate a transition zone towards standard land (yield level 'standard'). * results for phosphate rock use: multiply by 10. ** reference product of safflower value chain: animal fat.

Comparison between biomass-based and conventional systems

Well-known pattern of environmental impacts confirmed: the pattern of environmental advantages and disadvantages, which is well-known for bioenergy and bio-based products from standard land, also applies to the same products from marginal land:

Energy and GHG emission savings are possible: typically, environmental advantages are observed in terms of fossil energy savings and global warming, except in case of large carbon stock changes due to land use changes (LUC). Ethanol from switchgrass, for which a separate GHG balance has been calculated according to the calculation rules for biofuels laid down in Annex V of the RED II, cannot achieve the required minimum GHG emission saving of 65%, unless the bonus for the use of severely degraded land can be awarded.

Tendency towards disadvantages with other environmental impacts: environmental disadvantages are typically observed in terms of the agriculture-dominated environmental impact categories. Unfavourable results in terms of acidification, eutrophication (freshwater and terrestrial) or ozone depletion are mainly due to N- and P-related emissions of fertilisation. In terms of the long-neglected environmental impacts on biodiversity, water and phosphate resources, the results for bioenergy and bio-based products also tend to be disadvantageous, again mainly due to biomass cultivation.

Environmental advantages and disadvantages increase with increasing yields: yield acts as a scaling factor for both environmental benefits and disadvantages.

Entire life cycle and all environmental impacts need to be considered: It is shown that optimisations are possible in many life cycle stages. Since, for example, relevant emissions that contribute to acidification and eutrophication occur in the biomass utilisation phase, it is essential to consider the entire life cycle. Furthermore, all relevant environmental impacts must be taken into account in order to avoid one-sided optimisation (e.g. with regard to GHG emissions) and shifting between environmental impacts. The following fields of action are most important:

- Avoidance of indirect land-use changes (iLUC) is of central importance: However, iLUC is only avoided if the marginal areas are so far unused. This is decisive for the result of the life cycle assessment. The main challenge is therefore to identify the unused areas from the totality of all marginal land.
- Only marginal land with a low carbon stock in vegetation may be taken into use: the conversion of marginal land with a high carbon stock should be avoided, as in this case the direct land use change (dLUC) can lead to additional GHG emissions, for example when growing woody biomass on grassland with a high share of shrubs.
- Renewed use of organic soils must be avoided under any circumstances

Comparison of biomass-based systems among each other and with other renewables

No ranking between industrial crops possible: due to the limited selection of value chains (one per crop), the obtained picture regarding environmental performance of certain crops is not complete. For example, the selected crop-technology combinations (value chains) are missing out on direct combustion pathways.

Other renewables can be more environmentally friendly than bioenergy: Bioenergy competes with other renewable energy systems, e.g. ground-mounted photovoltaic (PV) systems, for marginal land. The environmental advantages of bioenergy and bio-based products should be compared with the set-up of other renewable energy systems on a case-specific basis, especially with regard to local environmental impacts on biodiversity. In some areas where an electric infrastructure is available, the environmental advantages of PV electricity per unit of energy could be greater than those of bioenergy, as exemplary calculations by [Rettenmaier et al. 2021] have shown. However, the latter do not replace a systemic overall comparison (based on generic settings) which was outside the goal and scope of this study.

4.1.2 Life cycle environmental impact assessment: Results and key findings

Table 3 shows the results of the LC-EIA related with the local impacts of the different cropping systems and processing technologies, evaluating the entire value chains studied. Impacts of the different biogenic systems were compared with idle land and also with the conventional reference system life cycle (extraction, processing, use phase and end of life).

Table 3: Results of the EIA of the different value chains: impact on biodiversity, landscape, soil quality, water use and wastes production

Value chain	Biodiversity & Landscape	Wastes production	Soil Quality	Water Use
Industrial heat from Miscanthus	0	0	+ + +	–
SNG from poplar	+	–	+ +	**0**
Ethanol from switchgrass	– –	–	+	– – –
Biotumen from willow	+	0	+ +	–
Organic acids from safflower	–	– – –	– – –	–
Sebacic acid from castor oil	– – –	– – –	–	–
Adhesives from lupin	–	– –	– – –	– – –
Insulation material from hemp	–	0	0	– –
Biogas/biomethane from sorghum	– –	–	0	–

0 Similar to idle land
-/ -- / --- Compared to idle land increases the impact buy a small, medium and high amount
+/ ++ / +++ Compared to idle land reduces the impact buy a small, medium and high amount

The screening Life Cycle Environmental Impact Assessment (LC-EIA) examined the cultivation of nine industrial crops in Europe, the processing and use of the products and the substitution of the corresponding reference products. Different local impact categories were analysed in the cultivation and the processing stages, in order to provide an overall evaluation of the nine different value chains assessed in the project. The analysis provided a number of key findings which are listed below.

Comparison between marginal land and standard land

No significant qualitative differences: LC-EIA results for bioenergy and bio-based products from marginal land are overall qualitatively similar to LC-EIA results for bioenergy and bio-based products from standard land (in both cases compared to conventional reference products). Yet, introducing an industrial crop in marginal conditions render benefits in terms of biodiversity, landscape and soil quality, covering the negative impact associated with the need of a higher land area and also with the negative impacts associated with the use of a biomass that by presenting different characteristics may contribute to a higher amount of wastes. This was of relevance for the Mediterranean and the Atlantic regions due to the type of biophysical constraints associated with the marginal conditions of the soils. Nevertheless, the marginal soils to be used should present a low carbon stock and should not harbour high levels of biodiversity or very unique valuable components of biodiversity (such as food and medicinal resources for locals).

Comparison between biomass-based and conventional systems

Biogenic systems present a higher impact than the conventional-fossil ones: In terms of the local impacts associated with the value chains, the biogenic systems present overall a higher impact than the conventional-fossil ones. Yet, if a higher time length for the land to be restored to its native conditions will be used in the conventional-fossil systems, a different pattern would be achieved, and the gap of the biogenic system to the conventional-fossil one, in terms of biodiversity, landscape, soil quality and wastes production, would be smaller. Nevertheless, the negative impact on water use specially associated with the cultivation stage (of particular relevance in the Mediterranean region, due to the poorness in water resources), penalizes the biogenic routes, even if the time line applied is different. The safflower value chain presented an impact similar to the conventional value chain, which is also biogenic.

Comparison of biomass-based systems among each other and with other renewables

The higher the complexity of the technological process, the higher the impacts: Regarding the different value chains, herbaceous crops and woody crops take benefits from the cultivation phase where they present less local impacts and higher yields when comparing with idle land. Locally, it can be argued that the higher the complexity of the technological process, the higher the impacts on biodiversity, landscape, soil quality and wastes. Therefore the value chains associated with switchgrass, safflower, castor and lupin were negatively scored, also because of the amount of land area needed to feed the processing units.

Biogenic value chains offer several environmental advantages and provide a wide range of ecosystem services in marginal land: In terms of local impacts, the biomass value chains can get a positive bonus when the marginality of the soil is reversed due to the introduction of the vegetative cover. This is particularly important in terms of soil organic matter, soil erosion and provision of shelter for micro and macrofauna. On the other hand, the biomass value chains are scored negatively in terms of water use, associated with the cultivation stage. Impact reduction strategies are limited to crop management options (namely inputs) but the majority of the local impacts are site specific dependent, intertwined with crops traits. Therefore, the implementation of biogenic value chains should also evaluate the adequacy between crop and location. Beneficial bonuses linked with biomass are the crop's multipurpose options, and the release of oxygen only by the easy conversion of solar energy into sugars.

4.1.3 Conclusions

On the basis of the results and key findings in the previous sections, the conclusions outlined in the following can be drawn:

- The use of marginal land in Europe can help in achieving several sustainability goals. **Cultivating industrial crops on marginal land can result in positive impacts** in terms of energy and greenhouse gas emission savings. Regarding local environmental impacts, the establishment of a vegetation cover can have beneficial effects on soil quality, biodiversity and landscape, especially if the marginal land suffers from erosion and / or other types of degradation.
- However, these benefits are also associated with negative environmental impacts at the same time. **The central challenge is the conservation of biodiversity** since marginal land is often the 'last retreat' for many species which suffer from the intensive agricultural use of standard land. In view of (i) alarming biodiversity losses due to agricultural activities in the EU, (ii) the re-cultivation of former set-aside land after changes to the CAP in 2009 and (iii) the encroachment into grasslands, **biodiversity in Europe will be decisively affected**, among other things, **by how much the pressure on marginal land will increase** (e.g. through financial incentives for its use for bioenergy).

- **Growing industrial crops on marginal land is not the silver bullet.** If done right, it can make a positive contribution. However, this does not automatically result in an upfront 'certificate of environmental compliance'.
- Only if **unused, low carbon stock and low biodiversity value marginal land** is cultivated, so-called indirect land-use changes (iLUC) are avoided, thus minimising negative environmental impacts.
  - Avoiding these indirect land use changes (iLUC) is decisive for the result of the life cycle assessment. It is therefore of utmost importance to identify the unused part of all marginal land.
  - The cultivation of industrial crops on marginal land is fine from a climate protection point of view - as long as no major carbon stock changes are involved.
  - The transformation of land that is worthy of environmental protection and the re-intensification of currently extensively managed agricultural land must be avoided.
- **There is competition of biomass with other renewables** (e.g. ground-mounted photovoltaic (PV) systems) **for the same marginal land**. A direct comparison between the different options needs to be made both in the framework of a systemic overall comparison (based on generic settings) and on a case-specific basis.

- In addition to quantifying the environmental impacts of products, life cycle assessment (LCA) can help in selecting suitable value chains and in identifying hot spots and optimisation potentials along them. For a comprehensive picture, local environmental impacts need to be addressed as well, e.g. by means of life cycle environmental impact assessment (LC-EIA), and complemented by other dimensions of sustainability, including the economic and social aspects.

4.2 Summary: economic assessment

An economic assessment of the MAGIC value chains was performed by the project partner AUA [Soldatos et al. 2021]. The assessment includes a macroeconomic Life Cycle Cost analysis (LCC) of the **agricultural production** of the selected MAGIC crops (Volume 1) and the corresponding **conversion of biomass to bioenergy and bio-based products**, respectively (Volume 2).

The first part examines the economic viability of the cultivation of biomass grown in EU marginal lands and its agro-industrial processes. This assessment delivers input data for the second part, which analyses the financial feasibility of the biomass conversion including all costs and expenses as feedstock storage, pretreatment processes, the conversion unit, refining processes, auxiliary facilities and more.

4.2.1 Results

The economic assessment included a cost analysis carried out for each MAGIC value chain. The resulting production costs per value chain are listed in Table 4. The particular shares of the overall costs are shown in Figure 7.

Table 4: Production cost assessment for MAGIC value chain conversion plants.

	Production cost	Unit
1. Miscanthus-to- pyrolysis bio-oil	280	€/t
2. Poplar- to- BioSNG	910	€/t
3. Switchgrass-to-ethanol	900	€/t
4. Willow-to-biotumen	1250	€/t
5. Safflower-azelaic/pelargonic	3700	€/t
6. Castor oil-sebacic acid	4900	€/t
7. Lupin - MLP	2500	€/t
8. Hemp-insulation material	1250	€/t
9a. Sorghum - bioelectricity	49	€/GJ
9b. Sorghum - biomethane	770	€/t

The outcome of the analysis indicates that the biomass feedstock cost is in the range of 40 - 60% of the overall costs, being always the major cost factor by far. One exception is insulation material from hemp where biomass feedstock costs only account for 39% of the overall costs and utilities & chemicals (including binder etc.) account for 44% of the overall costs.

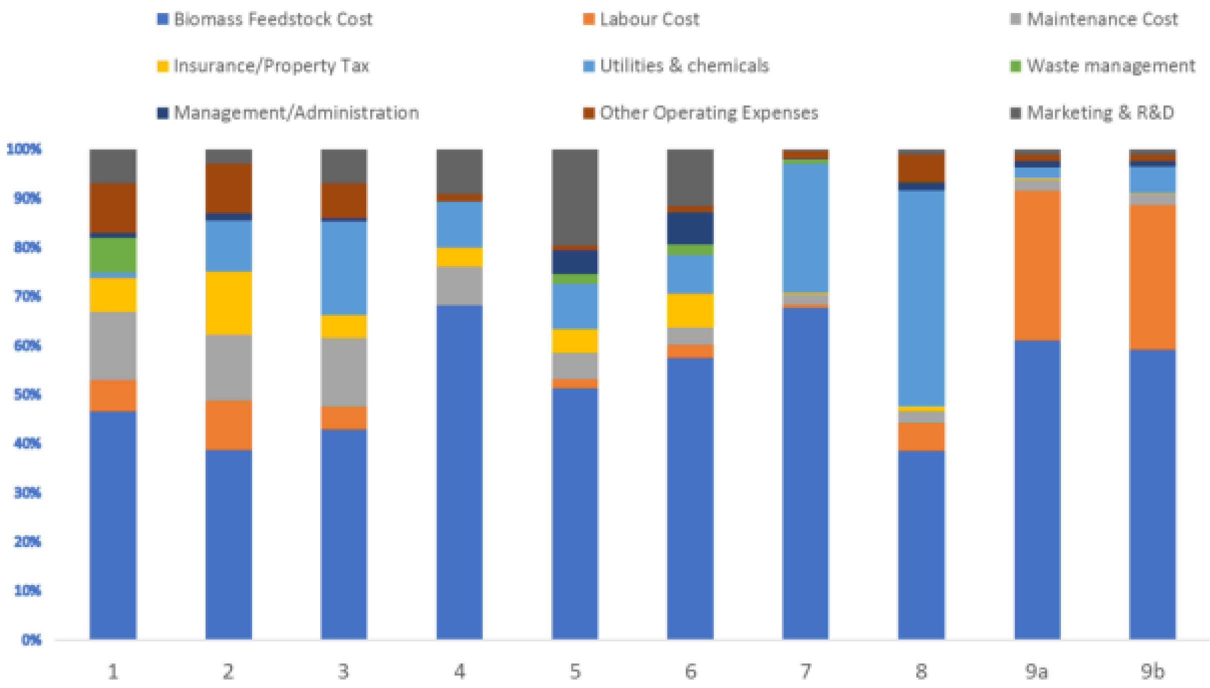

Figure 7: Cost breakdown of analysed MAGIC value chains.

The results of the analysis showed that having a large share of biomass feedstock costs in the overall costs (due to the low yield productivity of marginal land and marginal land availability boundaries) leads to probably economically unfeasible operation of the conversion plants. In these cases mixed feedstock plants and financial incentives both to farmer and conversion plants could be helpful.

Having a look at the economic assessment of the various MAGIC value chains, the analysis has shown that under the current fossil fuel prices the value chains producing energy cannot achieve economically competitive results. If the already existing subsides in the EU were expanded also to marginal land and all the potential bioenergy products, there will be chances for feasible local applications based on marginal land produced crops.

One exception is biomethane produced using sorghum as a feedstock due to well established production technology and low capital investment requirements. However, even in the case of using sorghum for biomethane production, the grid connectivity can be a crucial issue for the plant's viability. Furthermore, relevant investment should consider the competition for sorghum biomass coming from other higher value-added application fields, since under current energy market prices biomethane represents a low value added product.

Value added chemicals and other products can produce promising results even under the current market conditions. It has to be noticed that the respective price levels are fluctuating due to volatile supply-demand-relationships. Moreover, these value chains are considered having better chances of success in add-on plant approaches in existing chemical plants due to the more complex production and logistics operations.

Finally, from an economic point of view, insulation material from hemp seems the most promising value chain that has been examined, because of the following reasons:

- Relatively low capital investment requirements, combined with easily applicable operations.
- Already existing market needs and commercial products.
- Potential to use the whole mass of hemp straw in various application fields (using fractionation).
- Low-capacity production: possible local production and use leads to minimal transport and distribution requirements, especially at the start-up phase of the plant operation.
- Competitive feedstock costs, especially if the main agricultural product, hemp seeds, is also used for value added applications, creating even more favourable pricing conditions for the straw which is a field co-product.

A bottleneck in the economic feasibility of the analysed MAGIC value chains is the profitability of agricultural production of the biomass since 40 – 60% of the overall costs can be accounted to biomass cultivation and provision. Farmers will not decide to produce these agricultural products without the confidence that they will be able to sell them at a reasonable price. On the other hand, no investor would finance a conversion plant, before securing adequate flow of feedstock throughout the year at prices that allow a reasonable return to his investment.

Figure 8 and Table 5 show the annual equivalent costs the analysed MAGIC Crops with their expected revenue from sales as well as an estimate of the required selling price to break-even.

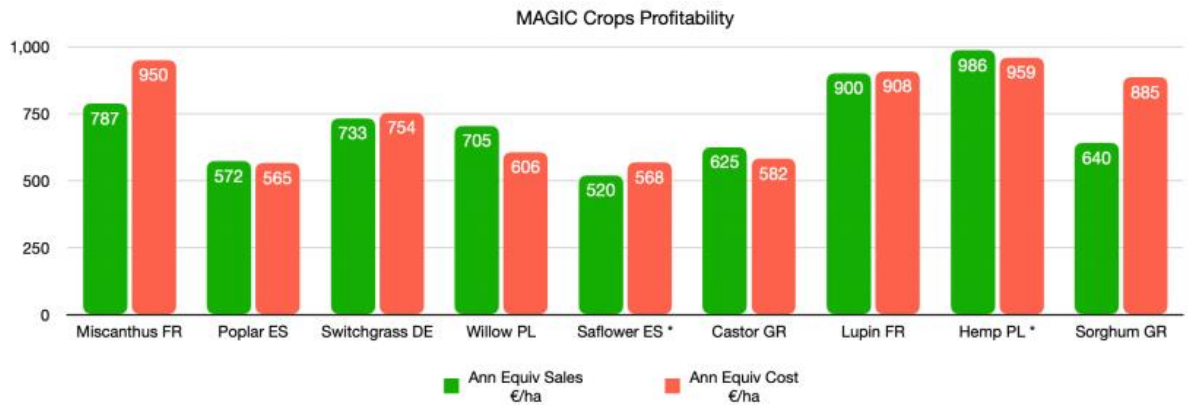

Figure 8: Annual equivalent sales and costs of MAGIC crops in selected EU climatic zones.

Table 5: Selection of economic results of MAGIC crops in different EU climatic zones.

	Avg annual Yield t/ha	Selling Price ** €/t	Ann Equiv Sales €/ha	Ann Equiv Cost €/ha	Ann Equiv Profit €/ha	Breakeven Price *** €/t
Miscanthus FR	9.60	80	787	950	-163	**97**
Poplar ES	6.32	100	572	565	7	**100**
Switchgrass DE	9.00	80	733	754	-21	**82**
Willow PL	7.50	100	705	606	99	**86**
Saflower ES *	1.10 / 4,00	400 / 20	520	568	-48	**444**
Castor GR	1.25	500	625	582	43	**466**
Lupin FR	3.00	300	900	908	-8	**303**
Hemp PL *	0.70 / 5.30	500 / 120	986	959	27	**181**
Sorghum GR	8.00	80	640	885	-245	**111**
	** Seeds / Stems*	*** Usually quoted*	**** Zero NPV for perennial crops. Zero profit for annual crops..*			

4.2.2 Conclusions

The economic assessment of the agricultural production has shown, that in general the ability of the selected MAGIC crops grown on marginal land with reduced inputs combined with a lower rent of marginal land, does not compensate for the loss in production volumes. The majority of MAGIC crops are close to economic viability (break-even point), but the return may not be sufficient to motivate farmers cultivating them on marginal lands.

Therefore, the role of the State as the initiator and supporter of investments in terms of subsidies is crucial. These subsidies could be in an order of magnitude as the gap between the selling price and the break-even price given in the last column of Table 5. Least affected lines would be the MAGIC value chains with the smallest share of biomass costs in the overall costs as for example, insulation material from hemp. Other economically promising MAGIC value chains with larger shares of biomass costs in the overall costs are more dependent upon subsidisation.

Finally, economic results of perennial crops should guarantee a return (IRR) higher than the cost of funds and cover the risk of the investment of establishing the crops. In comparison with perennial crops, annual crops are more flexible, generate income from the first year and require less initial capital investment. Thus, they are probably more appropriate in the early period of marginal land utilisation. Long term targeted financial incentives or quotas are imperative in order to attract investment in such new ventures with high beneficial environmental and social impact.

4.3 Summary: social life cycle assessment

The social life cycle assessment, performed by the project partner Imperial College London, United Kingdom, analysed the social impacts of the MAGIC scenarios described in chapter 3. The following section gives a summary on the key issues and findings from the original social life cycle assessment report [Panoutsou et al. 2021]. For details, further information on the method used and more results please refer to the original report.

4.3.1 Used methodology

There is no universally accepted methodology for conducting social sustainability assessment, although the guidelines developed by UNEP-SETAC [Andrews et al. 2009; Benoît Norris et al. 2013] highlight the appropriateness of employing a Life Cycle approach that incorporates social criteria, known as Social Life Cycle Assessment (SLCA). SLCA is defined as a "social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle" [Andrews et al. 2009]. Thus, SLCA is complementary to LCA and aims to assess the overall sustainability of a product chain. SLCA is still at a developmental stage and can be employed on its own or in combination with other techniques [Ciroth et al. 2011].

The method employed for social assessment of the impacts of the MAGIC value chains combines elements of SLCA and Value Chain Analysis (VCA). Value chain analysis has been introduced by Porter [Porter 1985] to represent internal activities involved with producing goods and services. The approach applies a systemic strategy to analyse value chain activities, understand challenges and identify competitive advantages and disadvantages. In the participatory VCA approach a series of interviews and surveys were used to "understand important challenges that restrict the development and implementation within and across the value chain stages, and agree on S-LCA impact categories that relate to the challenges and select indicators that are relevant to the social implications of the value chain's performance but can also be associated to the stakeholder groups (in the case of MAGIC: farmers, value chain actors and local community)" [Panoutsou et al. 2021]. This data collection via interviews and surveys was complemented with literature reviews. The work evaluated the positive impacts (handprints) (e.g., creation of jobs, rural development, income diversification, etc.) in addition to the negative ones (footprints) (e.g., land use, health and safety, etc.).

Within the VCA, several challenges have been identified for each of the four value chain stages land use (LU), biomass production (BP), conversion (C) and end use (EU). The challenges together with the defined stakeholder categories, impact categories, its category indicators and corresponding inventory indicators are presented in Table 6 .

Table 6: Stakeholder and impact categories, indicators, and relevance to challenges within and across the value chain stages.

Stakeholder category	Impact category	Category indicators	VC stage[10]	Inventory indicators	Relevant challenges
Farmers	Working conditions	Wages (diversification of income)	BP	Income and profitability per crop	Unemployment in rural areas Lack of crop diversification and job opportunities
		Social benefits	BP	Incentives at farm level	Social and economic resilience in rural areas
		Health and safety	BP	Compliance with health and safety regulations	Safe, low impact practices
Value chain actors	Innovation	Technology development	C	Technological Readiness Level (TRL)	Advanced and efficient technologies are not supported enough.
		System versatility	C	Scale & relationship to logistics	Lack of awareness in SMEs and industries
		Market size	EU	Market size and trends	Highly innovative technologies with slow commercialisation rate
Local community	Natural resources	Biodiversity	BP	Crop traits relevant to biodiversity	Safeguard planetary boundaries; monoculture, low variety of species, reduced numbers of pollinators, etc.
		Land acquisition, delocalisation and migration	LU	Land occupancy (annual/ perennial)	Marginal land with limited rehabilitation opportunities
		Access to natural resources	LU	Crop yields/ha	Limited land availability, low waterfall, etc.
	Rural development	Local employment	All	Jobs	Unemployment, Lack of job opportunities
		Contribution to rural economy	All	Gross Value Added (GVA)	Rural development
	Governance	Public commitment to sustainability	All	Policies	Low awareness of benefits and usability of biobased products

For the impact assessment within the SLCA a scoring system (see Figure 9) for social risks and opportunities has been introduced to grade each of the category indicators for each stage from “low risk/ high opportunity” to “very high risk/ very low opportunity”. The scoring system is using numbers as well as a colour code.

Low risk/ high opportunity	-3
Medium risk/ medium opportunity	-1
High risk/ Low opportunity	1
Very High risk/ Very Low opportunity	3

Figure 9: Scoring system for social risks and opportunities.

4.3.2 Results

For each of the analysed value chains, a spiderweb was developed, showing the scores of the social impact assessment (social risks and opportunities). Figure 10 exemplarily shows the social risks and opportunities of all category indicators for the value chain industrial heat from Miscanthus on marginal and standard land. The diagram depicts indicators with high risk and low opportunity on the outside and indicators with low risk and high opportunity on the inside.

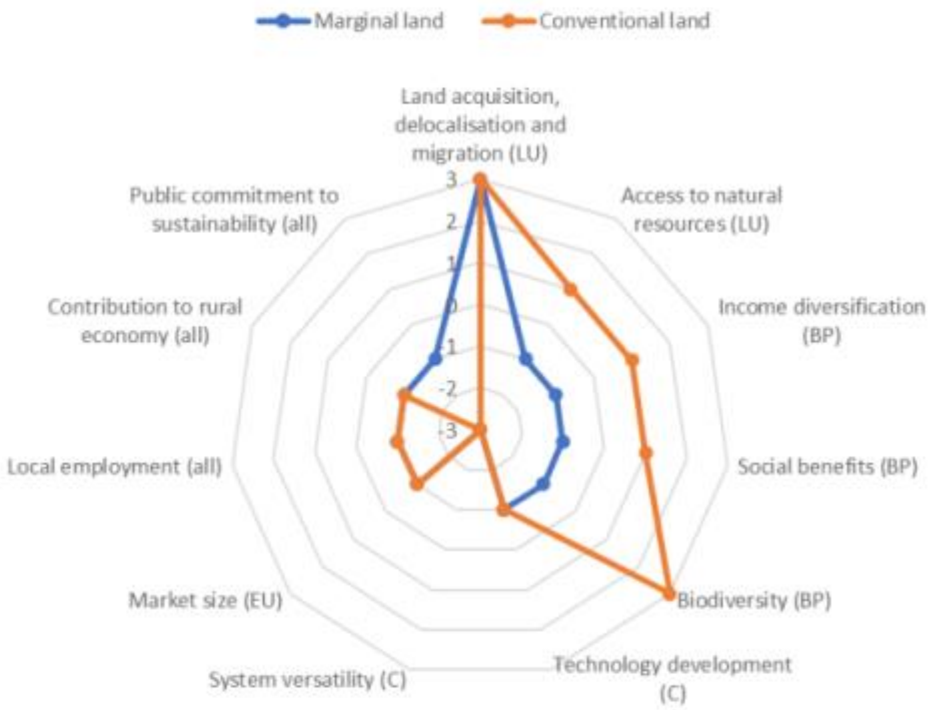

Figure 10: Comparison of social risks and opportunities of the analysed category indicators for the value chain industrial heat from Miscanthus from marginal and standard land.

In the case of industrial heat from Miscanthus, social risks for the access to natural resources, income diversification, social benefits and biodiversity are ranked higher in standard land than using marginal land. The cultivation of Miscanthus on standard land is considered a high social risk in terms of access to natural resources and income diversification. The reason for this is the competition with the production of food and feed crops. On the other hand, this risk is reduced when using marginal land. Thus, the sustainable implementation of this value chain on marginal land offers opportunities for income diversification, social benefits and rural development. The other indicators do not show any substantial differences between the use of standard land and marginal land. Therefore, from a social point of view, the cultivation of Miscanthus on marginal land is advantageous when compared to standard land.

The social impact assessments of the other value chains show comparable results with the value chain industrial heat from Miscanthus. For details see [Panoutsou et al. 2021].

4.3.3 Conclusions

The following conclusions apply to all analysed value chains and are not specific to the example of the value chain industrial heat from Miscanthus shown above.

- Farmers and local communities see high risks in the highly **innovative nature** of cultivating the analysed crops on marginal land. On the other hand, the cultivation of these crops is regarded as providing high opportunities for **rural development** and the restoration of marginal land
- **Perennial crops** cultivated on marginal land are ranked high in terms of **governance** (due to high priority in Renewable Energy Directive II). On the other hand stakeholders are also sceptical towards perennial crops because of long-term commitment for land use.
- **Annual crops** are seen by all stakeholder groups as providing **high or even very high opportunities** across all impact indicators. An essential factor is the possibility of smart and sustainable cropping options by using crop rotation, agroforestry as well as the possibility to react rapidly to price fluctuations and market developments.
- The majority of analysed conversion technologies are highly innovative and have rather low Technological Readiness Level (TRL). Thus, the stakeholders see medium opportunities, especially for a short term implementation. Nevertheless, some value chains, e.g. industrial heat from Miscanthus, biogas/biomethane from sorghum, ethanol from switchgrass or insulation material from hemp are regarded as having higher chances of being implemented at the short term and therefore display a higher opportunity.

5 Results: Integrated sustainability assessment

The integrated life cycle sustainability assessment (ILCSA) builds on the results of three separate assessments of individual sustainability aspects whose results are summarised in sections 4.1 - 4.3. This chapter combines, extends and jointly assesses these individual results in order to give an integrated view on the sustainability impacts of the MAGIC value chains. For methodological details, definitions and settings see chapter 2.

First, an overview of sustainability impacts of all analysed value chains is provided in section 5.1. Second, the results of the indicator selection are presented in section 5.2. Finally, section 5.3 shows the results for the integrated sustainability assessment for each of the analysed value chains.

5.1 Overview of all sustainability impacts of all analysed value chains

As described in chapter 3, nine exemplary value chains were selected for the integrated sustainability assessment, which were subsequently subjected to individual analyses of their impacts on the environment, the economy and society. The selection was based on four factors: technical feasibility, time to market, market potential, and data availability. Moreover, one aim of the selection was to arrive at an interesting mixture of crop categories (lignocellulosic crops, oil crops & carbohydrate/ multipurpose crops), conversion technologies and products categories (energy, fuels, chemicals & materials).

Various environmental, economic and social aspects relevant for sustainability have been studied in individual assessments, which form the basis of this integrated sustainability assessment (for summaries see sections 4.1 - 4.3). The performance of assessed MAGIC scenarios and conventional reference systems regarding all these aspects is quantified or qualitatively rated using various indicators.

The indicators include sustainability indicators in the strict sense, which depict impacts on objects of protection such as climate or human health. Further indicators depict barriers that may prevent the implementation of the scenario. Such barriers may lead to substantially worse actual sustainability impacts when trying to implement a scenario, for which low potential impacts were anticipated. Another type of indicators reflects risks that may lead to substantially worse sustainability impacts in case of accidents etc. This is needed because scenarios are only assessed under routine operation conditions, thus excluding such rare incidents by definition. The suitability and scientific validity of the indicators has been verified in the individual assessments.

Table 7 shows an overview of all sustainability impacts of the analysed value chains. While the result values are derived from the respective reports [Rettenmaier et al. 2021; Soldatos et al. 2021; Panoutsou et al. 2021], an assessment was carried out within the framework of the ILCSA on the basis of qualitative or significant quantitative differences and marked using a traffic light colour system (for details on the methodology, see section 2.3). Beyond the indicators already used in the three individual assessments, the additional social indicator "sustainable employment" was developed (for details see section 5.2).

The nine selected value chains and their respective target products are only comparable with each other to a limited extent, since they belong to very different product categories. Although a comparison makes sense for various questions, such as the greatest possible GHG emission savings per hectare (the value chains are comparable per se), it is not in the focus of the main question of the MAGIC project:

1. The main focus of the MAGIC project and this sustainability assessment is the cultivation of industrial crops on marginal land compared to cultivation on standard land, i.e. it is not a comparison of technologies or value chains.
2. The selection of nine value chains must be regarded as exemplary and incomplete due to the small number. For example, the selected crop-technology combinations (value chains) are missing out on direct combustion pathways which are already established today. Furthermore, in our view, potential alternative uses of the marginal land, e.g. for PV, should also be included in such a comparison.
3. In addition, but only after knowledge of the LCA results, large bandwidths become apparent (e.g. GHG emission savings of 0 - 11.5 t CO_2eq/ha/yr), which overlap between the value chains (see Figure 6, p. 31). This means that the individual performance of the value chain (yield) is sometimes more decisive than the selection of the value chain itself.

Therefore, no ranking of the value chains and no recommendations are derived on the basis of the comparison in Table 7, yet it may contribute to useful insights.

The following overarching results can be derived on the basis of Table 7:

Environment

With regard to non-renewable energy use (NREU) and climate change, all the value chains examined show slight to very clear advantages over the respective conventional reference system. The opposite picture emerges for the other environmental impacts examined: here, the conventional reference systems generally perform better.

The environmental impacts NREU and climate change correlate without exception in all the value chains examined. The same applies to the environmental impacts acidification, eutrophication, ozone depletion, particulate matter formation and summer smog.

The value chains that produce value added chemicals and use annual crops as a source of biomass (organic acids from safflower, sebacic acid from castor and adhesives from lupin) show slight advantages over the other value chains in terms of the environmental impacts eutrophication, acidification, ozone depletion, particulate matter formation and summer smog. However, when considering the local environmental impacts (LC-EIA), they show disadvantages compared to other value chains, especially if they include perennial plants.

While the value chains with the use of perennial crops are advantageous for the local environment compared to the respective reference systems, the value chains with the use of annual crops tend to show disadvantages for the local environment.

Table 7: Overview of sustainability impacts of all analysed value chains.

			MAGIC scenarios								
			Miscanthus → Industrial heat			Poplar → SNG			Switchgrass → Ethanol		
	Indicator	Unit	C1	C2	Std	C1	C2	Std	C1	C2	Std
Environment: LCA	Non-renewable energy use (NREU)	GJ / (ha·yr)	-114	-140	-204	-16	-32	-48	-34	-50	-67
	Climate change	t CO_2 eq / (ha·yr)	-5,5	-6,9	-10,5	-0,5	-1,9	-3,3	-1,2	-2,3	-3,4
	Acidification	kg SO_2 eq / (ha·yr)	10	13	18	12	25	37	11	17	23
	Eutrophication, terrestrial	kg PO_4 eq / (ha·yr)	2,4	2,9	4,3	2,0	4,2	6,4	2,1	3,2	4,3
	Eutrophication, freshwater	kg PO_4 eq / (ha·yr)	1,1	1,3	1,6	0,9	1,4	1,9	1,8	2,4	3,0
	Ozone depletion	g CFC-11 eq / (ha·yr)	41	50	74	11	24	37	41	62	83
	Particulate matter	kg PM2.5 eq / (ha·yr)	10	13	19	12	25	38	7	11	14
	Summer smog	kg NMVOC eq / (ha·yr)	11	14	20	12	25	38	5	7	10
	Phosphate rock use	kg phosphate rock eq / (ha·yr)	45	55	79	37	72	108	190	284	378
	Land use	m^2 aL-eq · a / (ha·yr)	3750	3750	3760	2580	2660	2730	3780	3790	3800
Environment: LC-EIA	Water	-	–	–	–	o	o	o	– –	– –	– –
	Soil	-	++	++	++	++	++	++	+	+	+
	Biodiversity & landscape	-	+	+	o	+	+	+	–	–	– –
	Wastes production	-	+	+	o	–	–	–	–	–	–
Economy	Feedstock costs	€ / t_{DM}	105	93	81	153	92	80	105	84	76
	Payback Period	years	18+	15+	13+	20+	20+	20+	20+	20+	20+
	NPV	million €	-13,2	-8,1	-3,3	-200,9	-147,5	-137,0	-238,1	-168,7	-142,2
	IRR	%	1%	2%	4%	<-40%	<-30%	-21%	<-40%	<-30%	-11%
	Profitability Index (PI)	-	0,6	0,8	0,9	-0,5	-0,1	0,0	-0,6	-0,1	0,1
	Return on Equity	%	2%	4%	6%	-146%	-16%	-12%	-105%	-11%	-5%
Society	Working conditions	-	–	–	++	– –	– –	+	–	–	++
	Innovation	-	++	++	+	++	++	+	++	++	+
	Natural resources	-	+	+	– –	–	–	– –	+	+	– –
	Rural development	-	++	++	o	++	++	o	++	++	o
	Governance	-	++	++	++	+	+	+	+	+	+
	Sustainable employment	-	+	+	–	++	++	– –	++	++	–

Table 7: (continued).

MAGIC scenarios																	
Willow → Biotumen			Safflower → Organic acids			Castor → Sebacic acid			Lupin → Adhesives			Hemp → Insulation material			Sorghum → Biogas		
C1	C2	Std	C1	C2	Std	C1	C2	Std	C1	C2	Std	C1	C2	Std	C1	C2	Std
-46	-79	-112	-5	-10	-18	-5	-28	-51	-61	-105	-148	-14	-22	-30	-38	-71	-132
-2,2	-4,4	-6,6	0,6	0,1	-0,5	-0,2	-3,9	-7,2	-3,1	-6,3	-9,4	-0,6	-1,5	-2,3	-0,3	-1,3	-3,3
7	12	18	4	7	12	2	3	5	-10	-17	-25	11	16	22	14	27	49
1,6	2,8	4,0	0,9	1,6	2,6	0,3	0,5	0,9	-0,1	-0,6	-1,0	2,5	3,8	5,1	3,7	7,5	13,2
1,0	1,4	1,7	3,8	6,2	9,2	2,1	3,3	4,9	2,6	2,6	2,6	9,8	14,2	18,6	10,6	20,3	34,9
25	43	61	9	18	28	3	5	8	24	25	25	28	43	58	41	83	146
7	12	18	3	5	7	2	3	4	-9	-16	-23	8	12	16	8	13	25
8	13	18	2	3	5	2	3	4	-5	-9	-14	8	12	16	5	9	16
39	65	90	70	123	190	11	2	1	69	114	158	97	144	191	14	26	44
2500	2500	2510	2960	2300	1470	3700	3550	3420	3800	3830	3870	630	-930	-2490	3750	3750	3760
–	–	–	–	–	–	–	–	–	– –	– –	– –	– –	– –	– –	–	–	–
++	++	++	– –	– –	– –	–	–	–	– –	– –	– –	o	o	o	o	o	o
+	+	+	–	–	–	– –	– –	– –	–	–	–	–	–	–	– –	– –	– –
+	+	o	– –	– –	– –	– –	– –	– –	–	–	– –	+	+	o	–	–	–
99	81	78	460	318	251	576	344	267	262	211	262	156	115	95	148	85	70
20+	20+	20+	6+	4+	4+	20+	10+	8+	13+	5+	5+	5+	4+	4+	20+	15+	11+
-4,7	-3,1	-2,7	156,7	249,8	293,5	-123,9	34,8	75,4	0,0	38,9	45,9	19,9	25,8	28,7	-2,6	-0,2	0,1
-7%	-2%	-1%	17%	23%	26%	<-35%	8%	11%	5%	19%	21%	20%	24%	26%	NA	2%	7%
0,2	0,5	0,5	2,5	3,4	3,8	-0,2	1,3	1,7	1,0	3,4	3,9	2,9	3,5	3,8	-2,1	0,7	1,2
-3%	0%	1%	23%	27%	28%	-8%	15%	18%	19%	23%	24%	18%	19%	19%	NA	8%	11%
– –	– –	+	+	+	++	–	+	+	–	+	++	+	+	++	+	+	++
++	++	++	++	++	++	++	++	++	++	++	++	+	+	+	++	++	++
–	–	– –	+	+	–	+	+	–	+	+	–	+	+	–	+	+	–
++	++	o	++	++	o	++	++	o	++	++	o	++	++	o	++	++	o
–	–	–	+	+	+	+	+	+	+	+	+	++	++	++	++	++	++
++	++	– –	++	++	o	++	++	– –	++	++	o	++	++	o	++	++	o

Economy

From an economic point of view, the energy products-related value chains cannot produce feasible results under the current fossil fuel prices. This could be solved by considering very large plant capacities along with special subsidy regimes. Expanding the already existing subsidy schemes also for marginal land and the potential bioenergy products could increase the chances for feasible local applications based on crops produced on marginal land.

Value added chemicals like organic acids from safflower, sebacic acid from castor and adhesives from lupin may produce promising results even under the current market conditions. However, it should be kept in mind that their current price levels are largely open to fluctuations, due to also highly probable change of supply/demand relationship. Additionally, these product categories are considered having better chances of success under an add-on plant approach to already existing chemical plants, rather than stand-alone plants.

From an economic point of view, producing insulation material from hemp seems to be a promising value chain. Relatively low capital investment needs, combined with easily applicable operations, the potential to use the whole mass of hemp straw and already existing market needs lead to high internal rates of return and short payback periods.

On the one hand, the net present value (NPV) indicator is a good measure of the economic performance a value chain could have. On the other hand, it is highly dependent on the products manufactured and the size of the biorefinery plant. The same applies to the feedstock costs, which can only be used to a limited extent to make a statement about the economic efficiency of the value chains.

Social

Regarding social indicators, perennial crops cultivated on marginal land rank rather high in terms of governance but are viewed sceptically by farmers when it comes to (i) a long term commitment for land use and (ii) biodiversity risks: on average perennial crops are rated worse than annual crops regarding the indicator natural resources. Annual crops on the other hand are perceived as opportunities by the majority of farmers. However, since land use and biodiversity impacts are already covered by the environmental assessment (which by the way provides objective information on these impacts that is challenging the interviewed farmers' subjective views), the indicator natural resources is not taken into account in the further analysis.

In terms of working conditions, the cultivation of crops on marginal land is associated with high risks for farmers, as they often have to use heavy machinery in sites that are difficult to access. In this regard, the perennial crops are also rated worse than annual crops.

Moreover, all crops (both perennial and annual) cultivated on marginal land can contribute to rural development and sustainable employment especially by facilitating income diversification. In addition, the cultivation of these crops offers smart sustainable cropping options through crop rotation, agroforestry and more.

5.2 Results of indicator selection including a SWOT analysis

As described in section 2.3, a condensation to a more easily interpretable number of indicators was carried out by means of an iterative process. The result of this condensation was subsequently subjected to a SWOT analysis.

Selection of indicators

Table 8 shows an overview and a short description of all indicators selected for the integrated sustainability assessment in MAGIC. For details on the iterative selection process, please see section 2.3.

Table 8: Overview of sustainability indicators selected for the integrated assessment.

Impact category	Description / Explanation
Environment	
GHG and energy balance	The environmental impacts non-renewable energy use (NREU) and climate change correlate without exception for all value chains and are therefore considered and evaluated together.
Resource use	The indicators phosphate rock use and land use are combined under the term 'resource use'. They are not correlated.
Airborne emissions	The environmental impacts acidification, eutrophication and ozone depletion contribute to 'human interference with the nitrogen cycle' and to the overshooting of other planetary boundaries and are combined with particulate matter and summer smog to form the indicator 'airborne emissions'.
Nature conservation	In addition to climate change, the loss of biodiversity is an important socially discussed issue, which is why biodiversity and landscape are included in the ILCSA by the indicator ‘nature conservation’.
Economy	
IRR	The internal rate of return (IRR) is the annual rate of growth that an investment is expected to generate.
Payback period	The payback period is the required number of years to recover initial investments.
Society	
Rural development	Creation of jobs in rural areas and contribution to rural development. For the evaluation of this impact category, the scores of the social assessment were used directly.
Sustainable employment	The impact category ‘sustainable employment’ is generated by combining the indicators ‘income diversification’ and ‘social benefits’ of the social assessment. Sustainable employment is a priority theme of the funding objectives of the European Regional Development Fund and the European Social Fund and therefore corresponds to the guidelines of the European Commission.

SWOT analysis

The following SWOT analysis examines the condensation of the large number of indicators collected into the eight indicators for the subsequent ILCSA. It provides a valid assessment of strengths, weaknesses, opportunities and threats and thus transparently shows the advantages and disadvantages of this condensation. The results of the SWOT analysis are presented in Table 9.

Table 9: Results of the SWOT analysis on the condensation of sustainability indicators for further application within the Integrated Sustainability Life Cycle Assessment.

Strengths	**Weaknesses**
Easier to communicate	Larger workload
Easier to understand	
Better overview of data	
Focus on the essentials	
Opportunities	**Threats**
Wider readership	Unconscious misinterpreration
Greater depth of impact	Deliberate misuse

The condensation of sustainability indicators for the ILCSA shows a number of advantages, such as easier communication, a better overview of the sustainability of the value chains and a potentially wider readership. This is associated with a potentially greater depth of impact of the results and conclusions. However, it should be noted that condensing the indicators to a significantly reduced number can lead to misinterpretation or even misuse of the results, as not all scores of the individual value chains presented in the assessments of environmental, economic and social sustainability are listed. Thus, certain aspects such as the impact of a particular MAGIC value chain on local aquatic environments or the absolute NPV can no longer be derived from the assessments.

Still, to avoid unconscious misunderstandings or deliberate misuse, the derivation of the conclusions and recommendations did not exclusively consider the condensed indicators; instead, it reflects the overall picture of the individual indicators.

5.3 Value chain-specific results of the integrated sustainability assessment

In this section, the results of the integrated sustainability assessment are presented. For each analysed value chain, results are provided for the selected set of indicators (see previous section 5.2). Details on the value chains can be found in the annex (sections 9.1 - 9.10) and the applied methodology is described in chapter 2.

- Industrial heat from Miscanthus (section 5.3.1)
- SNG from poplar (section 5.3.2)
- Ethanol from switchgrass (section 5.3.3)
- Biotumen from willow (section 5.3.4)
- Organic acids from safflower (section 5.3.5)
- Sebacic acid from castor (section 5.3.6)
- Insulation material from hemp (section 5.3.7)
- Biogas/biomethane from sorghum (section 5.3.8)
- Adhesives from lupin (section 5.3.9)

Table 10 below provides an example of the generated tables comprising the ILCSA results of the analysed value chains. In columns ① and ② 'Marginal land: MAGIC vs. conventional' the MAGIC value chains (bioenergy carriers and bio-based products from marginal land) are compared to their respective conventional reference system. In columns ③ and ④ 'Marginal land vs. standard land', the MAGIC value chains (on marginal land) are compared to the provision of the same bioenergy carriers and bio-based products from standard land. The results of both comparisons are referred to both hectares (per ha, columns ① and ③) and tonnes of biomass (per t_{DM}, columns ② and ④). The interpretation of results is mainly based on the comparisons in columns ③ and ④ because this is the main focus of the MAGIC project.

Table 10: Table of results showing exemplary results of the integrated sustainability assessment for biogas/biomethane from sorghum compared to heat and power from fossil energy carriers.

		①	②	③	④
		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	–	○
	Resource use	–	–	+	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	Internal rate of return (IRR)	○	○	–	–
	Payback period	–	–	–	–
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

* For details on the indicators, see Table 8 on p. 49

5.3.1 Miscanthus: industrial heat via pyrolysis

This section features the results of the ILCSA for industrial heat from Miscanthus cultivated on marginal land compared to industrial heat from fossil energy carriers. For details on the value chain see chapter 3 and section 9.1 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 11.

Table 11: Results of the integrated sustainability assessment for industrial heat from Miscanthus compared to industrial heat from fossil energy carriers. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	–	○
	Resource use	–	–	+	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	○	○	○	○
	Payback period	–	–	–	–
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results presented in Table 11 can be regarded as robust - at least with regard to the topics of environment and society: all sensitivity analyses carried out, such as varied yields (low or very low) or a variation in the fossil energy source replaced, do not lead to any qualitative changes in the results.
- The economic indicator IRR, on the other hand, reacts sensitively to biomass costs, plant size and, in particular, the bio-oil selling price, and could also turn out negative under slightly worse boundary conditions.
- The neutral results shown in yellow Table 11 show slight quantitative differences, but these are usually < 2%, so that they are not considered significant.

Key findings:

- Industrial heat from Miscanthus is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of Miscanthus for the provision of industrial heat is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.2 Poplar: SNG via gasification

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In the following, the results of the ILCSA for synthetic natural gas (SNG) from poplar cultivated on marginal land compared to natural gas are presented. For details on the value chain see chapter 3 and section 9.2 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 12.

Table 12: Results of the integrated sustainability assessment for SNG from poplar compared to natural gas. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	–	○
	Resource use	–	–	+	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	–	–	○	○
	Payback period	–	–	○	○
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results presented in Table 12 can be regarded as robust: all sensitivity analyses conducted, such as changed yields (low or very low) or different drying degrees, do not lead to any qualitative changes in results. Similarly, changes in biomass costs, labour costs and plant size do not have any effect on qualitative changes in results.
- The neutral results, shown in yellow in Table 12, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- SNG from poplar is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of poplar for the provision of SNG is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.3 Switchgrass: ethanol via hydrolysis & fermentation

The results of the ILCSA for ethanol from switchgrass cultivated on marginal land compared to fossil gasoline are presented in this section. For details on the value chain see chapter 3 and section 9.3 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 13.

Table 13: Results of the integrated sustainability assessment for ethanol from switchgrass compared to fossil gasoline. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	–	○
	Resource use	–	–	+	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	–	–	○	○
	Payback period	–	–	○	○
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results shown in Table 13 can be considered robust - at least with regard to environment and society: all sensitivity analyses performed, such as changed yields (low or very low), do not lead to any qualitative changes in results.
- The economic indicator IRR, on the other hand, reacts sensitively and could also be neutral with lower biomass costs and larger plants. However, a positive rating is unlikely.
- The neutral results, shown in yellow in Table 13, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Ethanol from switchgrass is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of switchgrass for the provision of ethanol is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.4 Willow: biotumen via pyrolysis

This section features the results of the ILCSA for biotumen from willow cultivated on marginal land compared to conventional bitumen. For details on the value chain see chapter 3 and section 9.4 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 14.

Table 14: Results of the integrated sustainability assessment for biotumen from willow compared to conventional bitumen. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	–	○
	Resource use	–	–	+	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	–	–	–	–
	Payback period	–	–	○	○
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results presented in Table 14 can be considered robust - at least with regard to environment and society: all sensitivity analyses performed, such as changed yields (low or very low) or different drying degrees, do not lead to any qualitative changes in results.
- On the other hand, the economic indicator IRR reacts sensitively to bio-oil costs, bio-tumen selling prices and technology cost reductions. Thus, it could also turn out positive under better boundary conditions.
- The neutral results, shown in yellow in Table 14, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Biotumen from willow is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of willow for the provision of biotumen is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.5 Safflower: organic acids via oxidative cleavage

In the following, the results of the ILCSA for organic acids from safflower cultivated on marginal land compared to conventional organic acids from biogenic sources. For details on the value chain see chapter 3 and section 9.5 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 15.

Table 15: Results of the integrated sustainability assessment for organic acids from safflower compared to conventional organic acids from animal fat. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	○	○	–	○
	Resource use	–	–	○	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	+	+	○	○
	Payback period	+	+	○	○
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results shown in Table 15 can only be considered robust from a social point of view. With regard to the environment, a variation of the substituted conventional organic acids may lead to qualitative changes in results. The scores in Table 15 are only valid if the conventional organic acids are produced from animal fat. The indicator 'GHG and energy balance' turns negative if palm oil or sunflower oil is used instead.
- Moreover, the economy indicator IRR reacts sensitively to biomass costs, plant sizes and product selling prices. Consequently, under slightly worse conditions, the assessment of the economy could also turn out negative.
- The neutral results, shown in yellow in Table 15, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Organic acids from safflower are mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of safflower for the provision of organic acids is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.6 Castor: sebacic acid via alkaline cleavage

The results of the ILCSA for sebacic acid from castor cultivated on marginal land compared to sebacic acid from paraffin are presented in this section. For details on the value chain see chapter 3 and section 9.6 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 16.

Table 16: Results of the integrated sustainability assessment for sebacic acid from castor compared to sebacic acid from paraffin. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	**per ha**	**per t_{DM}**	**per ha**	**per t_{DM}**
Environment	GHG and energy balance	○	○	–	○
	Resource use	–	–	○	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	–	–	–	–
	Payback period	–	–	–	–
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results presented in Table 16 can be considered robust - at least with regard to environment and society: all sensitivity analyses performed, such as changed yields (low or very low) or a variation of conversion efficiencies, do not lead to any qualitative changes in results.
- On the other hand, the economic indicator IRR reacts sensitively to biomass costs, plant size and sebacic acid selling price. Thus, it could also turn out positive under better boundary conditions.
- The neutral results, shown in yellow in Table 16, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Sebacic acid from castor is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of castor for the provision of sebacic acid is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.7 Hemp: insulation material

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This section features the results of the ILCSA for insulation material from hemp cultivated on marginal land compared to expanded polystyrene (EPS). For details on the value chain see chapter 3 and section 9.7 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 17.

Table 17: Results of the integrated sustainability assessment for insulation material from hemp compared to expanded polystyrene (EPS). * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	+	○
	Resource use	○	○	○	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	+	+	○	○
	Payback period	+	+	–	–
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results presented in Table 17 can be regarded as robust: all sensitivity analyses conducted, such as changed yields (low or very low) or a variation of the reference insulation material, do not lead to any qualitative changes in results. Similarly, changes in biomass costs, plant size and insulation material selling price do not have any effect on qualitative changes in results.
- The neutral results, shown in yellow in Table 17, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Insulation material from hemp is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of hemp for the provision of insulation material is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.8 Sorghum: biogas/biomethane

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In the following, the results of the ILCSA for heat and power (via biogas) from sorghum cultivated on marginal land compared to heat and power from fossil energy carriers. For details on the value chain see chapter 3 and section 9.8 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 18.

Table 18: Results of the integrated sustainability assessment for biogas/biomethane from sorghum compared to heat and power from fossil energy carriers. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	per ha	per t_{DM}	per ha	per t_{DM}
Environment	GHG and energy balance	+	+	–	○
	Resource use	–	–	+	–
	Airborne emissions	–	–	+	○
	Nature conservation	–	–	○	–
Economy	IRR	○	○	–	–
	Payback period	–	–	–	–
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results shown in Table 18 can be considered robust - at least with regard to environment and society: all sensitivity analyses performed, such as changed yields (low or very low) or a variation of the conversion route, do not lead to any qualitative changes in results.
- The economic indicator IRR, on the other hand, reacts sensitively to biomass costs, the chosen conversion route and the electricity conversion yield. Consequently, depending on the boundary conditions, the assessment of the economy could also turn out positive.
- The neutral results, shown in yellow in Table 18, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Biogas/biomethane from sorghum is mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of sorghum for the provision of biogas/biomethane is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

5.3.9 Lupin: adhesives

The results of the ILCSA for adhesives from Andean lupin cultivated on marginal land compared to polyurethane-based adhesives are presented in this section. For details on the value chain see chapter 3 and section 9.9 in the annex. The results for the indicators selected in section 5.2 are displayed in Table 19.

Table 19: Results of the integrated sustainability assessment for adhesives from Andean lupin compared to polyurethane-based adhesives. * see Table 8 on p. 49 for details

		Marginal land: MAGIC vs. conventional		Marginal land vs. standard land	
	Indicators*	**per ha**	**per t_{DM}**	**per ha**	**per t_{DM}**
Environment	GHG and energy balance	○	○	–	○
	Resource use	○	○	+	–
	Airborne emissions	–	–	–	○
	Nature conservation	–	–	○	–
Economy	IRR	+	+	–	–
	Payback period	–	–	–	–
Society	Rural development	+	+	+	+
	Sustainable employment	+	+	+	+

The following observations can be made from the comparison of marginal with standard land:

- The results presented in Table 19 can be considered robust - at least with regard to environment and society: all sensitivity analyses performed, such as changed yields (low or very low), do not lead to any qualitative changes in results.
- On the other hand, the economic indicator IRR reacts sensitively to biomass costs, plant size and product selling price. Thus, under slightly different boundary conditions the economic assessment could turn to one or the other.
- The neutral results, shown in yellow in Table 19, show slight quantitative differences. However, these are generally < 2%, so that they are not considered as significant.

Key findings:

- Adhesives from Andean lupin are mostly associated with the same environmental impacts whether the biomass is grown on marginal land or on standard land. However, lower yields lead to a higher demand for the resource land, which can have a negative impact on biodiversity. In terms of social consequences, however, the use of marginal land has considerable advantages.
- The crucial factor for the future use of marginal land for the cultivation of Andean lupin for the provision of adhesives is to compensate for the economic disadvantages compared to cultivation on standard land while at the same time optimising the social and environmental impacts.

6 Conclusions and recommendations

The aim of this study is to provide an integrated view on the sustainability impacts associated with nine selected value chains using biomass from marginal land in Europe. The main focus of the MAGIC project and this integrated sustainability assessment is the cultivation of industrial crops on marginal land compared to cultivation on standard land, i.e. it is not about a technology or value chain comparison. Based on the results in chapters 4 and 5, the following conclusions and recommendations can be drawn.

6.1 Conclusions

Within the MAGIC project, from a large number of feasible crop-technology combinations, almost 100 were identified as most promising. Of these, nine combinations of one crop with one conversion technology each were selected for the integrated sustainability assessment, so that the present study only covers a selection of all potentially possible combinations. Therefore, the focus of this study is not on a direct comparison of the results for the individual value chains or even a ranking of them, but on (i) an overview of sustainability impacts of all analysed value chains (section 5.1) and (ii) a consideration of the specific sustainability impacts of the individual value chains (section 5.3). This allows the following conclusions to be drawn:

- From an **environmental** point of view, the use of marginal land for the cultivation of industrial crops is mostly associated with the same environmental impacts as the use of standard land for the same purpose: the well-known pattern of environmental advantages and disadvantages for bioenergy and bio-based products from standard land also applies to marginal land. However, environmental benefits are only achieved by cultivation on unused, low carbon stock marginal land, which avoids so-called indirect land-use changes (iLUC) and associated negative environmental impacts. Due to the lower yields, however, cultivation on marginal land leads to higher land requirements, which can have an impact on both the conservation of biodiversity and the achievement of other sustainability goals that require land (see below).
- From a **social** perspective, the use of marginal land offers great opportunities in terms of rural development and sustainable employment, including the related indicators jobs, income diversification and social benefits.
- From an **economic** point of view, however, under current market conditions, only few of the feedstock production chains are able to reach break-even as independent activities, unless they are considered as complementary ventures to existing farm production lines, i.e. crop cultivation using marginal land patches and farm idle capacity. This also applies to the case where standard land is used (otherwise the value chains would already be realised to a greater extent), but the economic challenges are becoming increasingly more severe on marginal land. Compensating for the economic disadvantages compared to cultivation on standard land is therefore imperative and must be addressed as a matter of priority.

Likewise, it is rather unlikely to find in the EU very large concentrations of marginal land available for industrial crop cultivation, sufficient to feed single-feedstock, dedicated conversion plants. Thus, industrial conversion of biomass becomes economically feasible when supplementing the operation of similar, already existing large-scale conversion plants.

In summary, it can be concluded that the use of marginal land in Europe can help in achieving several sustainability goals. If done right, **cultivating industrial crops on marginal land can result in positive impacts** in terms of energy and greenhouse gas emission savings, for example, or with regard to social indicators. However, **economic viability of the investigated value chains is difficult to be achieved** without government commitment and a long term strategy, which encourages private investments in the agricultural and the industrial sector, respectively. This is the main bottleneck in the use of marginal land.

In order to develop marginal land in the future, corresponding support programmes would have to be set up by politics. This need for financial support opens up the possibility to **link the provision of financial support for marginal land to the fulfilment of environmental and social sustainability criteria**. Support programmes can be designed in such a way that they lead to an environmental and social optimisation of marginal land use. This requires.:

- first and foremost a **legally certain definition of marginal land** for use in funding programmes which not only considers positive (biophysical) criteria but also negative criteria (no-go areas, exclusion of use within the last 5 years)
- in case of designating a certain area of marginal land to the cultivation of industrial crops a **consideration of** both **alternative land uses** (e.g. for other renewables such as PV) **and other sustainability goals requiring land** (e.g. expansion of organic farming)
- a definition of **quantitative targets** such as the highest possible GHG emission savings combined with the greatest social benefits. However, GHG emission savings are lower priority than the protection of biodiversity.
- accompanying (or as part of) support programmes, differentiated **land use and land allocation plans** are needed both at the EU level and at the national, regional and local levels, which define the role of the future cultivation of industrial crops with regard to the essential but increasingly scarce resources of land, water and phosphate.

The latter points are particularly important because, besides combatting climate change, **one of the central challenges of our time is the conservation of biodiversity.** Since marginal land is often the ‘last retreat’ for many species which suffer from the intensive agricultural use of standard land, biodiversity in Europe will be affected, among others, by how much the pressure on marginal land will increase.

6.2 Recommendations

The following recommendations can be made to different stakeholders. Due to the need for a support programme outlined earlier, most of these are directed at policy makers.

To policy makers

- EU legislation should **link the provision of financial support for marginal land to the fulfilment of environmental sustainability criteria.** Since biomass production on marginal land is hardly viable without financial support [Soldatos et al. 2021], this possibility is given:
  - Support programmes should clearly define the criteria by which marginal land is identified. Bio-physical criteria, such as those applied in MAGIC, are basically suitable for this. However, in addition to those, the **fundamental condition** should be imposed **that financial support is only granted if the marginal land in question has not been used at all**, not even extensively, **in the last 5 years**. This is because environmental benefits only arise from a (renewed) use of previously unused (idle / abandoned) agricultural land. This is the only way by which indirect land-use changes (iLUC) can be avoided. The focus should therefore be on abandoned agricultural land.

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  - Support programmes should **exclude the transformation of land that is worthy of environmental protection**. This concerns the following types of land which are not necessarily congruent:
    - Land with high carbon stock and peatland
    - Land with high biodiversity value, e.g. highly biodiverse grasslands[1]
    - High nature value farmland (HNV)
  - Support programmes should **exclude the use of marginal agricultural land on which agricultural management has been extensified** in recent years, aiming at biodiversity conservation. The achievements made should not be jeopardised by creating a pull effect towards the cultivation of industrial crops.
    - Land for which payments under agri-environmental programmes[2] have been made in the last ten years should therefore not be eligible.

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

[2] 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.

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- In determining the level of financial support, **CO_2 abatement costs should be used as a guideline,** as these increase with the degree of marginality / more severe biophysical constraints. A lower threshold towards very marginal land needs to be defined, below which CO_2 abatement costs would rise to extreme levels (meagre yields and high risk of losing a plantation).

  In particular in water-scarce areas, alternative land uses such as ground-mounted photovoltaic (PV) systems should also be considered, some of which may offer greater environmental benefits than biomass production. However, nature conservation aspects in particular should also be given special consideration in these cases, e.g. only minimal soil sealing, e.g. by anchoring without foundations, no use of pesticides and a locally adapted ecological care concept.

- **Land use and land allocation plans should be prepared as part of publicly funded support programmes and concrete projects.** This is needed both at the supranational (EU) level and at the national, regional and local level: the more fine-grained the level, the more differentiated. It must be ensured that the respective subordinate level is taken into account, which is clearly illustrated at the example of the need for a supra-regional biotope network. Such plans can help to address and resolve trade-offs between nature conservation objectives, industrial crops cultivation and other alternative uses. Moreover, **stakeholder processes** for the integration of local and regional actors are highly recommended.
- **Guidelines for environmentally compatible cultivation of industrial crops on ecologically sensitive sites are necessary.** The so-called 'good farming practice' as defined in Council Regulation (EC) 1257/1999 [European Commission 1999] (and which is often referred to in the CAP) is not sufficient for the use of marginal land, at least not for ecologically sensitive sites. Therefore, guidelines need to go beyond the existing requirements.

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- **Capacity building**: For the sustainable establishment of industrial crops on marginal land, it is essential to build up competencies regarding the selection of suitable crops and varieties. This holds both for state agricultural advisers and for farmers. Both could benefit from the MAGIC Decision Support System (DSS) which is an excellent starting point for this.
- In order to allow further research on marginal land, **appropriate research funding should be provided**. The following points should be addressed with priority:
  - Research and development of varieties of industrial crops suitable for marginal areas should be further promoted. This is to ensure that total plantation failures can be largely avoided.

- Loss-reducing cultivation systems should be further investigated, such as the simultaneous cultivation of different plants on the same field (e.g. alley cropping with alternating rows of poplar and willow) or alternating harvesting cycles.
- Climate-resilient cultivation systems for perennial crops should be developed which also take into account possible future impacts of climate change in the respective growing region, for example decreasing precipitation in the Mediterranean region and the associated higher risk of droughts.
- The composition of biomass cultivated on marginal land should be elucidated since it may differ from biomass cultivated on standard land, e.g. in terms of ash or nitrogen content. This may limit potential use options both in the field of bioenergy and bio-based products and may also affect emissions which partly depend on these parameters.

To farmers and biomass users

- Farmers intending to cultivate industrial crops on marginal land should take advantage of information available, among others, through state agricultural advisory services, guidelines for environmentally compatible cultivation of industrial crops (see above) or the MAGIC Decision Support System (DSS). This holds for:
  - the **selection of crops** which must be done with utmost care. Crops must be adapted to the specific site. This is especially important for perennial crops, where a loss of the plantation in the early years would leave a high financial loss.
  - the **establishment of crops** which requires special care on ecologically sensitive sites
  - the **harvesting of crops**, the timing of which determines the water content of the biomass. A low water content is especially important the conversion of biomass from perennial crops.
- Farmers should also be aware of any **documentation and/or certification requirements** that they might be confronted with if they aim to market their products in certain sectors. For bioenergy carriers, the requirements laid down in the Renewable Energy Directive (RED II) apply.
- Biomass users should develop a **sustainable biomass supply concept** adapted to local availability of biomass that can be provided from agriculture without environmental damage. This should also take into account that some feedstocks may not be sustainably available in some years.

This study shows that action is needed to ensure the environmental compatibility of the use of marginal land for bioenergy and bio-based products, but also for other competing uses of the same land. In addition, social aspects such as rural development and sustainable employment should be considered. This will help to ensure the development of marginal land for the benefit of the environment and society.

7 Abbreviations

AEP	Aqueous extraction processing
AEZ	Agro-ecological zone
aLULUC	Attributional land use and land use change
ATL	Atlantic
BICO-PES	Bi-component polyester
BP	Biomass production
C	Conversion
CAP	Common agricultural policy
CBD	Cannabidiol
CHP	Combined heat and power
CON	Continental and boreal
D X.Y	Deliverable
DE	Germany
DFB	Dual fluidised bed
dLU	Direct land use
dLUC	Direct land use change
DM	Dry matter
DoA	Description of the Action
DSS	Decision Support System
EAEP	Enzyme-assisted AEP
EC	European Commission
EoL	End-of-life
EPS	Expanded polystyrene
ES	Spain
EU	End use
EU	European Union
FA	Fatty acid
FAME	Fatty acid methyl ester

FR	France
GHG	Greenhouse gas
GR	Greece
HMF	Hydroxymethylfurfural
HNV	High nature value
ILCD	International Reference Life Cycle Data System
ILCSA	Integrated life cycle sustainability assessment
iLUC	Indirect land use change
IRR	Internal rate of return
ISO	International Organization for Standardization
JRC-IES	Joint Research Centre - Institute for Environment and Sustainability
LCA	Life cycle assessment
LCC	Life cycle costing
LC-EIA	Life cycle environmental impact assessment
LCT	Life cycle thinking
LU	Land use
LULUC	Land use and land use change
MED	Mediterranean
MLP	Micellar lupin protein
MS X.Y	Milestone
NPV	Net present value
NREU	Non-renewable energy use
NREL	National Renewable Energy Laboratory
PET	Polyethylene terephthalate
PI	Profitability index
PL	Poland
PUR	Polyurethane
PV	Photovoltaic
R&D	Research and Development
RBD	Refined, Bleached, Deodorised
REA	Research Executive Agency
RED	Renewable Energy Directive

SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
SNG	Synthetic/substitute natural gas
SRC	Short rotation coppice
SWOT	Strengths, weaknesses, opportunities and threats
THC	Tetrahydrocannabinol
TRL	Technology readiness level
UNEP	United Nations Environment Programme
VC	Value chain
VCA	Value chain analysis
WGSR	Water gas shift reactor
WP	Work package
XPS	Extruded polystyrene

8 References

Alamia, A., Òsk Gardarsdòttir, S., Larsson, A., Normann, F., Thunman, H. (2017): Efficiency Comparison of Large-Scale Standalone, Centralized, and Distributed Thermochemical Biorefineries. *Energy Technology*, Vol. 5, No. 8, pp. 1435–1448. https://doi.org/10.1002/ente.201600719.

Alberts, G., Maria, A., Bauen, A., Boshell, F., Chudziak, C., Gebauer, J. P., German, L., Kaltschmitt, M., Nattrass, L., Ripken, R., Robson, P., Taylor, R., Wagner, H. (2016): Innovation outook advanced liquid biofuels. International Renewable Energy Agency IRENA.

Alexopoulou, E., Christou, M., Eleftheriadis, I. (2018): Handbook with fact sheets of the existing resource-efficient industrial crops (Deliverable D1.5). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. CRES, Athens, Greece. *http://magic-h2020.eu/documents-reports/*.

Alexopoulou, E., Monti, A. (2018): List of the most promising industrial crops (Deliverable D1.3). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. CRES, Athens, Greece. *http://magic-h2020.eu/documents-reports/*.

Alexopoulou, E., Rettenmaier, N., Wagner, T., Reinhardt, G., Vikla, K., Spekreijse, J., Piotrowski, S., Dubois, J.-L. (2020): Report on system description of selected value chains (Deliverable D6.2). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. CRES, Athens, Greece. *http://magic-h2020.eu/documents-reports/*.

Andrews, E. S., Barthel, L.-P., Beck, T., Benoît, C., Ciroth, A., Cucuzzella, C., Gensch, C.-O., Hébert, J., Lesage, P., Manhart, A., Mazeau, P., Mazijn, B., Methot, A.-L., Moberg, A., Norris, G., Parent, J., Prakash, Reveret, J.-P., Spillemaeckers, S., Ugaya, C. M. L., Valdivia, S., Weidema, B. (2009): Guidelines for Social Life Cycle Assessment of Products. UNEP, SETAC, Paris, France.

Benoît Norris, C., Traverso, M., Valdivia, S., Vickery-Niederman, G., Franze, J., Azuero, L., Aulision, D. (2013): The methodological sheets for sub-categories in social life cycle assessment (S-LCA). United Nations Environment Programme (UNEP) and Society for Environmental Toxicology and Chemiastry (SETAC).

van den Berg, D., Nair, P., Teo, J., Dubois, J.-L., Spekreijse, J., Vikla, K., Longhini, F., Porc, O., Carus, G. (2020): Report on technologies and market volumes of the selected value chains (Deliverable D6.3). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. BTG Biomass Technology Group BV, Enschede, The Netherlands. *http://magic-h2020.eu/documents-reports/*.

de Beus, N., Piotrowski, S. (2017): Final report on integrated sustainability assessment (Deliverable D7.3). In: *MultiHemp project reports*, supported by the EU's FP7 programme under GA No. 311849. nova Institute for Ecology and Innovation, Hürth, Germany. *http://multihemp.eu/media/2018/07/Deliverable_report_final_D7.3.pdf*.

Biertümpfel, A. (2014): Anbautelegramm: Zucker- / Futterhirse (Sorghum bicolor). Thüringer Zentrum Nachwachsende Rohstoffe der Thüringer Landesanstalt für Landwirtschaft, Jena, Germany. *http://www.tll.de/www/daten/publikationen/anbautelegramm/at_hirse.pdf*.

Bos, U. (2010): Aktualisierung der CO2-Bilanz des Dämmstoffes Thermo-Hanf mit PES- und PLA-Faser. Commissioned by Hock GmbH Co. KG, Nördlingen. Fraunhofer Institut für Bauphysik IBP, Echterdingen, Germany.

Ciroth, A., Finkbeier, M., Hildenbrand, J., Klöpffer, W., Mazijn, B., Prakash, S., Sonnemann, G., et al. (2011): Towards a Life Cycle Sustainability Assessment: Making informed choices on products. United Nations Environmental Program (UNEP), Paris, France. https://doi.org/DTI/1412/PA.

Corré, W. J., Conijn, J. G. (2016): Biogas production and digestate utilisation from agricultural residues. In: *Innovative Configuration for a Fully Renewable Hybrid CSP Plant (EC-GA n^o: 308912)*. SDLO-PRI.

von Cossel, M., Iqbal, Y., Scordia, D., Cosentino, S. L., Elbersen, B., Staritsky, I., van Eupen, M., Mantel, S., Prysiazhniuk, O., Maliarenko, O., Lewandowski, I. (2018): Low-input agricultural practices for industrial crops on marginal land (Deliverable D4.1). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. University of Hohenheim, Stuttgart (Hohenheim), Germany. *http://magic-h2020.eu/documents-reports/*.

Daniel-Gromke, J., Rensberg, N., Denysenko, V., Trommler, M., Reinholz, T., Völler, K., Beil, M., Beyrich, W. (2017): Anlagenbestand Biogas und Biomethan–Biogaserzeugung und-nutzung in Deutschland. In: *DBFZ report*,.

De Leon Izeppi, G. A., Dubois, J.-L., Balle, A., Soutelo-Maria, A. (2020): Economic risk assessment using Monte Carlo simulation for the production of azelaic acid and pelargonic acid from vegetable oils. *Industrial Crops and Products*, Vol. 150, p. 112411. https://doi.org/10.1016/J.INDCROP.2020.112411.

Dubrovskis, V., Adamovics, A., Plume, I., Kotelenecs, V., Zabarovskis, E. (2011): Biogas production from greater burdock, largeleaf lupin and sosnovsky cow parsnip. In: *Research for Rural Development*, pp. 388–392.

Eibl, I., von der Haar, D., Jesdinszki, M., Stäbler, A., Schmid, M., Langowski, H. (2018): Adhesive based on micellar lupin protein isolate exhibiting oxygen barrier properties. In: *Journal of Applied Polymer Science*, p. 46383.

European Commission (1999): Council Regulation (EC) No 1257/1999 of 17 May 1999 on support for rural development from the European Agricultural Guidance and Guarantee Fund (EAGGF) and amending and repealing certain Regulations. *Official Journal of the European Union*, Vol. L 160, pp. 80–102.

European Commission (2014): Commission Regulation (EU) No 1307/2014 of 8 December 2014 on defining the criteria and geographic ranges of highly biodiverse grassland. *Official Journal of the European Union*, No. L 351/3.

European Parliament, Council of the European Union (2018): Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). In: *Official Journal of the European Union*, L 328, pp. 82–209. *https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001*.

FNR (2016): Basisdaten Biobasierte Produkte. Gülzow, Germany.

Herrmann, C., Plogsties, V., Willms, M., Hengelhaupt, F., Eberl, V., Eckner, J., Strauß, C., Idler, C., Heiermann, M. (2016): Methanbildungspotenziale verschiedener Pflanzenarten aus Energiefruchtfolgen. In: *LANDTECHNIK*, pp. 194-209-194–209.

ISO (2006a): ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework. International Organization for Standardization.

ISO (2006b): ISO 14044:2006 Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization.

Jensen, J. H., Poulsen, J. M., Andersen, N. U. (2011): From Coal To Clean Energy. *Substitute Natural Gas*, No. April, pp. 1–5.

JRC-IES (2012): The International Reference Life Cycle Data System (ILCD) Handbook. Joint Research Centre - Institute for Environment and Sustainability (JRC-IES), Ispra, Italy. 72 p. *https://doi.org/10.2788/85727*.

Jung, S. (2009): Aqueous extraction of oil and protein from soybean and lupin: a comparative study. In: *Journal of food processing and preservation*, pp. 547–559. https://doi.org/10.1111/j.1745-4549.2009.00400.x.

Jungk, N. C., Reinhardt, G. A., Gärtner, S. O. (2002): Agricultural reference systems in life cycle assessments. In: van Ierland, E. V., Lansink, A. O. (eds.): *Economics of sustainable energy in agriculture*, *Economy & Environment*. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 105–119. https://doi.org/10.1007/0-306-48018-2_8.

Keller, H., Rettenmaier, N., Reinhardt, G. A. (2015): Integrated life cycle sustainability assessment – A practical approach applied to biorefineries. *Applied Energy*, Vol. 154, pp. 1072–1081. https://doi.org/10.1016/j.apenergy.2015.01.095.

Kintl, A., Vítěz, T., Elbl, J., Vítězová, M., Dokulilová, T., Nedělník, J., Skládanka, J., Brtnický, M. (2019): Mixed Culture of Corn and White Lupine as an Alternative to Silage Made from Corn Monoculture Intended for Biogas Production. In: *BioEnergy Research*, pp. 694–702.

Knoef, H. A. M. (2012): Handbook Biomass Gasification. BTG Biomass Technology Group BV.

Koponen, K., Soimakallio, S., Kline, K. L., Cowie, A., Brandão, M. (2018): Quantifying the climate effects of bioenergy – Choice of reference system. *Renewable and Sustainable Energy Reviews*, Vol. 81, pp. 2271–2280. https://doi.org/10.1016/j.rser.2017.05.292.

Lampart-Szczapa, E., Korczak, J., Nogala-Kalucka, M., Zawirska-Wojtasiak, R. (2003): Antioxidant properties of lupin seed products. In: *Food chemistry*, pp. 279–285.

Mergner, R., Janssen, R., Rutz, D., de Bari, I., Sissot, F. (2013): Lignocellulosic Ethanol Process and Demonstration.

Metzger, M., Bunce, R., Jongman, R., Mücher, C., Watkins, J. (2005): A climatic stratification of the environment of Europe. *Global Ecology and Biogeography*, Vol. 14, pp. 549–563.

Mursec, B., Vindis, P., Janzekovic, M., Brus, M., Cus, F. (2009): Analysis of different substrates for processing into biogas. In: *Journal of achievements in materials and manufacturing engineering*, pp. 652–659.

Padella, M., O'Connell, A., Prussi, M. (2019): What is still Limiting the Deployment of Cellulosic Ethanol? Analysis of the Current Status of the Sector. *Applied Sciences*, Vol. 9, No. 21, p. 4523. https://doi.org/10.3390/app9214523.

Panoutsou, C., Singh, A., Christensen, T., Areekul, O. (2021): Social Life Cycle Assessment (Deliverable D6.6). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. Imperial College London, London, UK.

Pari, L., Scarfone, A. (2018): Inventory on available harvesting technology for industrial crops on marginal lands (Deliverable D5.1). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Rome, Italy. *http://magic-h2020.eu/documents-reports/*.

Pelgrom, P. J. M., Berghout, J. A. M., van der Goot, A. J., Boom, R. M., Schutyser, M. A. I. (2014): Preparation of functional lupine protein fractions by dry separation. In: *LWT-Food Science and Technology*, pp. 680–688.

Porter, M. E. (1985): Competitive Advantage: Creating and Sustaining Superior Performance. Free Press, New York, USA.

Raja, I. A., Wazir, S. (2017): Biogas Production: The Fundamental Processes. In: *Universal Journal of Engineering Science*, pp. 29–37. https://doi.org/10.13189/ujes.2017.050202.

Raworth, K. (2012): A Safe and Just Space for Humanity - Can we live within the doghnut? In: *Oxfam Discussion Paper*. Oxfam. *https://www-cdn.oxfam.org/s3fs-public/file_attachments/dp-a-safe-and-just-space-for-humanity-130212-en_5.pdf*.

Raworth, K. (2017): A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*, Vol. 1, No. 2, pp. e48–e49. https://doi.org/10.1016/S2542-5196(17)30028-1.

Rettenmaier, N. (2018): Interim report on definitions and settings (Deliverable D6.1). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. IFEU - Institut für Energie- und Umweltforschung, Heidelberg, Germany. *http://magic-h2020.eu/documents-reports/*.

Rettenmaier, N., Spekreijse, J., van den Berg, D., Dubois, J.-L., Piotrowski, S. (2019): Selection of value chains and definition of interlinkages (Milestone MS 6.2). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. IFEU - Institut für Energie- und Umweltforschung, Heidelberg, Germany.

Rettenmaier, N., Zinke, C., Wagner, T., Reinhardt, G., Fernando, A. L., Costa, J., Barbosa, B., Duarte, M. P., Gonçalves, M. (2021): Report on Environmental Assessment: Environmental Assessment of Growing Industrial Crops on Marginal Lands (Deliverable D6.4). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. ifeu - Institut für Energie- und Umweltforschung Heidelberg, Heidelberg, Germany. *https://www.ifeu.de/en/project/en-magic*.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J. A. (2009): A safe operating space for humanity. *Nature*, Vol. 461, No. 7263, pp. 472–475. https://doi.org/10.1038/461472a.

Rødsrud, G. (2017): The World's most advanced biorefinery. p. 43.

Rüegsegger, M., Kast, M. (2019): Lessons Learned about Thermal Biomass Gasification - IEA Task 33 Thermal Gasification of Biomass and waste. IEA Bioenergy.

Soldatos, P., Karaoglanoglu, L., Kazaklari, G. (2021): Economic Analysis of selected Value Chains, Volume 1 & 2 (Deliverable D6.5). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. Agricultural University of Athens (AUA), Athens, Greece.

Spekreijse, J., Nair, P., Dubois, J. L., van den Berg, D., Raschka, A., zur Strassen, T., Geerken, S. (2018): Appropriate conversion technologies for the selected crops (Milestone MS 6.4). In: *MAGIC project reports*, supported by the EU's Horizon 2020 programme under GA No. 727698. BTG Biomass Technology Group BV, Enschede, The Netherlands.

Spirinchx, C., Peeters, K., Van de Moortel, E., Thoelen, P., De Troyer, F., Norton, A., Schmidt, V., Van Leemput, S. (2013): LCA: TIM project – LCA: Ten Insulation Materials. Project report. In: *TIM project reports*. D. Cuypers, Brussels, Belgium.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., Sörlin, S. (2015): Planetary boundaries: Guiding human development on a changing planet. *Science*, Vol. 347, No. 6223, p. 1259855. https://doi.org/10.1126/science.1259855.

Stolzenburg, K., Monkos, A. (2012): Sorghumhirsen zur Biogasnutzung als Alternative bzw. Ergänzung zum Energiemaisanbau. Landwirtschaftliches Technologiezentrum Augustenberg (LTZ), Karlsruhe, Germany.

Swarr, T. E., Hunkeler, D., Klöpffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. C., Pagan, R. (2011): Environmental Life Cycle Costing: A Code of Practice. SETAC.

Tao, L., Schell, D., Davis, R., Tan, E., Elander, R., Bratis, A. (2014): NREL 2012 Achievement of Ethanol Cost Targets : Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover NREL 2012 Achievement of Ethanol Cost Targets : Biochemical Ethanol Fermentation via Dilute-Acid Pretreat. *Nrel/Tp-5100-61563*, No. April, p. 43. https://doi.org/10.2172/1129271.

Thunman, H. (2018): GoBiGas demonstration – a vital step for a large-scale transition from fossil fuels to advanced biofuels and electrofuels.

United Nations (2015): Transforming our World: The 2030 Agenda for Sustainable Development. *https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf*.

Venderbosch, R. H. (2018): Fast Pyrolysis. In: Brown, R. C. (ed.): *Thermochemical Processing of Biomass*, John Wiley & Sons, Ltd. pp. 175–206. https://doi.org/10.1002/9781119417637.

Wang, J., Zhao, J., De Wit, M., Boom, R. M., Schutyser, M. A. I. (2016): Lupine protein enrichment by milling and electrostatic separation. In: *Innovative food science & emerging technologies*, pp. 596–602.

Yamamoto, M. (2018): Production and value chain upgrading St1 home market. pp. 1–8.

Zia, K. M., Bhatti, H. N., Bhatti, I. A. (2007): Methods for polyurethane and polyurethane composites, recycling and recovery: A review. In: *Reactive and functional polymers*, pp. 675–692.

9 Annex

Major parts of this section were originally published in D 6.2 [Alexopoulou et al. 2020] and in D 6.3 [van den Berg et al. 2020]. This quotation is not repeated in each sub-section. Only adaptations which were necessary to reflect most up-to-date design of the investigated value chains due to additional insights from research work were made for this report.

In the following, the nine selected value chains are presented one by one:

- Industrial heat from Miscanthus (section 9.1)
- SNG from poplar (section 9.2)
- Ethanol from switchgrass (section 9.3)
- Biotumen from willow (section 9.4)
- Organic acids from safflower (section 9.5)
- Sebacic acid from castor (section 9.6)
- Insulation material from hemp (section 9.7)
- Biogas/biomethane from sorghum (section 9.8)
- Adhesives from lupin (section 9.9)

Finally, section 9.10 presents more detailed process descriptions for the four value chains involving lignocellulosic crops (Miscanthus, poplar, switchgrass and willow) as well as for the two value chains involving oil crops (safflower and castor).

9.1 Industrial heat from Miscanthus (via pyrolysis)

This value chain describes the conversion of Miscanthus (*Miscanthus x giganteus* GREEF ET DEUTER EX HODKINSON ET RENVOIZE) to pyrolysis oil, which is then used for the production of industrial heat. This life cycle is compared to conventional ways of providing the same products or services (Figure 11). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

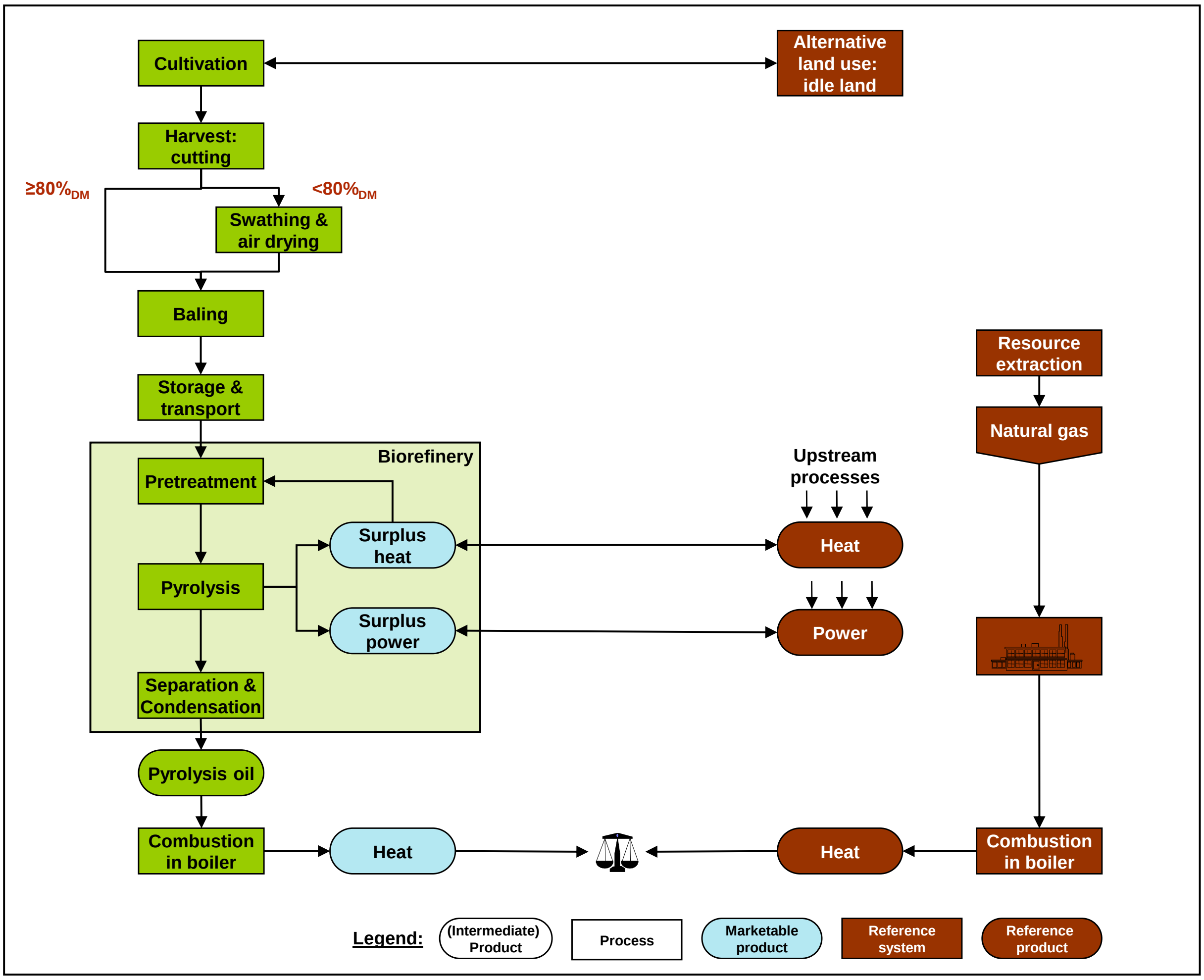

Figure 11: Simplified life cycle comparison for industrial heat from Miscanthus via pyrolysis versus industrial heat from fossil energy carriers.

9.1.1 Biomass provision

9.1.1.1 Cultivation

The life cycle phase "cultivation" in general (see Figure 11) can be subdivided into the following processes: field preparation, planting, maintenance including weed control, application of fertiliser, irrigation, harvest, and clearing after a plantation's life time. Miscanthus is a perennial C_4 grass[3], which originates from East Asia and grows up to 4 m tall. The herbaceous crop is incapable of producing fertile seeds, thus clones are used for planting. The amount of nitrogen and phosphorus removed at harvest (which needs to be replenished via fertilisation) is very low compared to the other crops.

9.1.1.2 Harvesting and logistics

It depends on the climate zone, whether harvesting can be done in one or two steps. If harvesting time is chosen appropriately, the water content of Miscanthus grown in the Mediterranean and Continental zone is lower than 20% (i.e. dry matter content exceeds 80%), so that Miscanthus can be baled directly after harvest. The water content is higher in the Atlantic zone. For that reason, Miscanthus is cut, then air-dried on swath and baled after drying. Thus, technical drying is not necessary in any of the climate zones. Prior to conversion and use, the baled biomass is set to undergo several logistic steps, which involve storage and transportation to a conversion unit.

9.1.2 Biomass conversion

Pyrolysis is selected for value chain 1 because of its large economic and environmental potentials. Also, a broad range of conversion technologies and products shall be assessed as part of the sustainability assessment in order to benefit from diverse insights. We are aware that direct combustion of Miscanthus (for heat and/or power generation) is state of the art technology with several benefits (extensively studied in the past; proven very favourable; easy to implement). Pyrolysis is currently only performed on woody biomass on commercial scale, but there is a large interest in expanding the feedstock range.

Before the value chain description, a general description of fast pyrolysis technologies is given. Next, the specific pyrolysis of Miscanthus is described together with an elaboration on the selected pyrolysis technology.

Fast pyrolysis is the action of rapidly heating a feedstock in the absence of oxygen in order to convert the feedstock to smaller parts. In the case of biomass fast pyrolysis, the biomass is heated to temperatures of 400-600 °C. This results in a breakdown of the biomass to form vapours. Condensation of the vapours results in a liquid called pyrolysis oil. Next to pyrolysis oil, char and some non-condensable gases are formed, which can be used to supply heat to the pyrolysis process. The only waste stream that remains are the minerals from the biomass in the form of ash.

[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.

Several different pyrolysis oil technologies for biomass conversion have been developed [Venderbosch 2018]. From these technologies, the rotating cone technology developed by BTG and marketed by BTG-BTL shows both the best promise on large scale application and has the best data availability. Therefore, this process was selected to model the pyrolysis conversion within the MAGIC project.

On large scale, the process has been proven to work reliably on woody biomass, for example in the commercial scale demo plant EMPYRO in Hengelo [Venderbosch 2018]. Data from this plant was used and adapted to Miscanthus using the in-house knowledge of BTG.

Figure 20 in section 9.10 (p. 102) shows a more detailed process description for industrial heat production from Miscanthus via pyrolysis. Before biomass can be converted to pyrolysis oil, a pre-treatment is required to make the biomass input suitable for pyrolysis. The pre-treatment consists of a sizing step (1) and a drying step (2). The drying step is required to get the moisture content below 5% right before the biomass enters the pyrolysis reactor to pre-vent reabsorption of moisture form the air. The energy obtained from combusting the char and non-condensable gases is more than sufficient to provide energy for the pyrolysis step (3). Rapid heat transfer is required in pyrolysis and often a heat carrier material, like sand, is used to improve the process. After pyrolysis, the sand and the formed char are separated from the pyrolysis vapours (5). Followed by condensation, the gases form pyrolysis oil, which can be used directly for combustion to heat. The non-condensable gases and the char are sent to a combustor (6) to provide energy for the pyrolysis process. Excess energy from flue gases can be converted to steam in a boiler (7) and is used for the drying of the biomass (2). The produced ash leaves the system at the boiler as well. The remaining steam can either be directly sold to nearby industry or (partially) converted to electricity in a steam turbine.

9.2 SNG from poplar (via gasification)

This value chain describes the production of synthetic natural gas (SNG) from poplar (*Populus spp.* L.) by gasification. This life cycle is compared to conventional ways of providing the same products or services (Figure 12). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

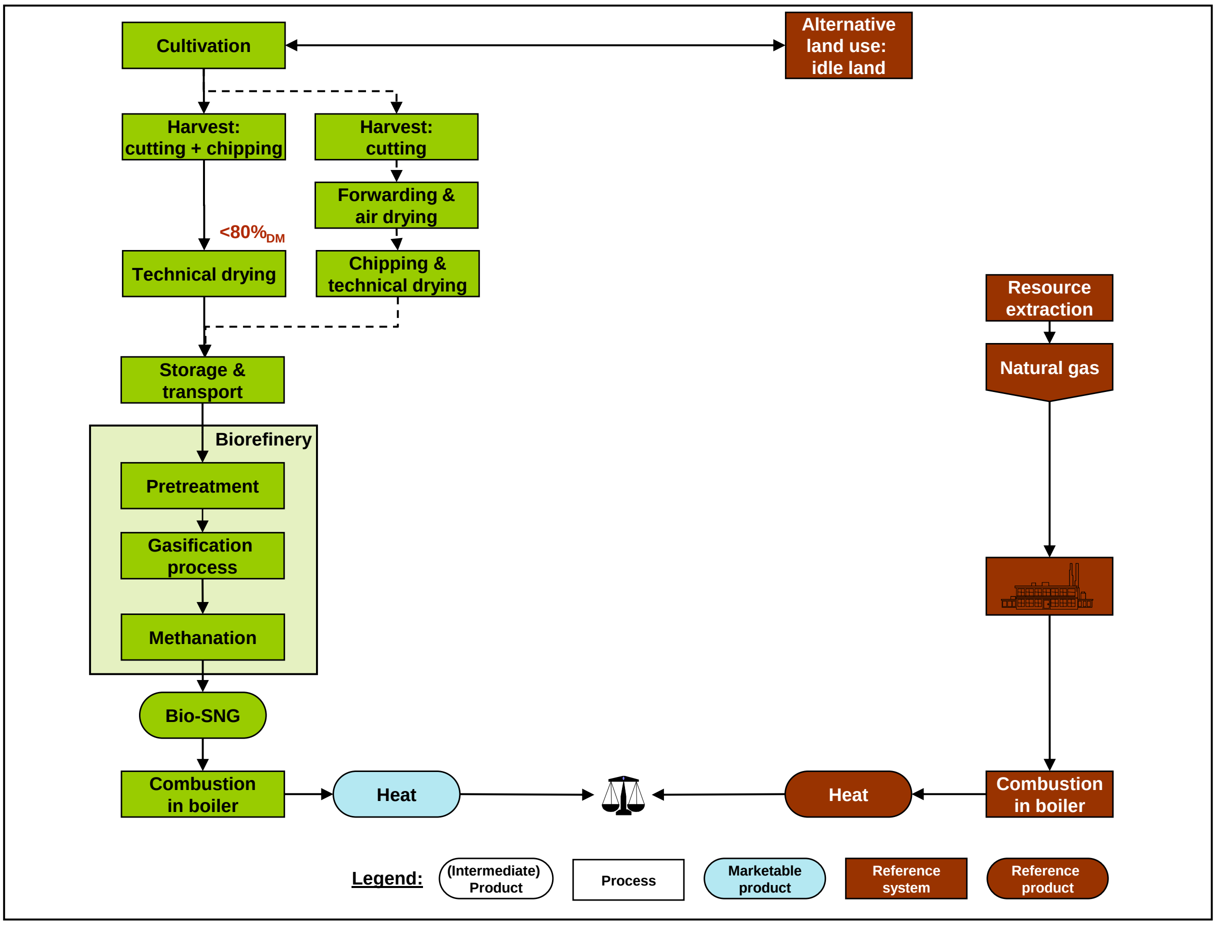

Figure 12: Simplified life cycle comparison for synthetic natural gas from poplar via gasification versus natural gas.

9.2.1 Biomass provision

9.2.1.1 Cultivation

Poplar is a perennial, woody crop, which is native to parts of North America and Eurasia. Its clones are used for planting and it has a relatively high demand for phosphorus, which needs to be replenished via fertilisation. In this study poplar is cultivated as short rotation coppice (SRC) with a plantation lifetime of 20 years.

9.2.1.2 Harvesting and logistics

The main harvesting strategy of short rotation coppice like poplar is cutting and chipping with a harvester in one step. Due to a high water content of more than 20%, technical drying is essential for the later use. Besides this strategy, another one with several steps is covered in a sensitivity analysis. This strategy includes cutting, forwarding the biomass to a place for air drying and in a second step chipping and technical drying (Figure 12). In both cases the woody biomass has to be stored and transported to the conversion unit.

9.2.2 Biomass conversion

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Gasification is a thermochemical process that can be used to convert solid biomass into a gas. It is performed at high temperatures and with controlled amounts of oxidising agents such as steam, air or oxygen to avoid full combustion of the feed. This produces a gas mixture (H_2 / CO) commonly called a syngas. The process is highly developed (TRL 9) and commonly used to produce heat and power [Knoef 2012]. Production of synthetic natural gas (SNG) via gasification means using the syngas as a raw material for the synthesis of SNG. The composition of SNG is mainly methane with small amount of hydrogen. Methane is readily available from natural gas, thus methanation in industrial scale has not been established. However, technology for methane production from syngas is well-known [Jensen et al. 2011] and commercial systems for methanation exist.

SNG production from solid biomass via gasification has so far only been demonstrated in the GoBiGas project at 20 MW_{SNG} scale in Gothenburg, Sweden. The 4-year project was technologically a success and showed that it is possible to produce SNG from woody biomass. The GoBiGas plant was shut down in 2018, due to economic reasons as the price of natural gas remained low compared to the price of SNG. It is expected that by 2030 this type of SNG production becomes more competitive with natural gas [Rüegsegger & Kast 2019]. As the technology used in the demonstration of GoBiGas proved to be successful for the purpose of producing SNG from biomass (TRL 6-7), it is reasonable to use similar process description for evaluating SNG production from poplar.

The process is divided into 2 parts, namely gasification and methanation. It should be noted that process flows like steam recycling or flue gas recycling are not shown to keep the scheme simplified. Figure 21 in section 9.10 (p. 103) shows a more detailed process description for SNG production from poplar via gasification. The main parts of the process are numbered and explained below.

Biomass acquired in the upstream processes is fed to the process (1). For gasification the raw material should be relatively fine and dry. Typically, suitable size is approximately 7-10 cm in diameter and moisture content around 10% [Thunman 2018]. If the wood is fed as chips with typical moisture content of 40%, a dryer is necessary to reach suitable plant efficiencies at a commercial scale (*e.g.* 100 $MW_{biomass}$) [Alamia et al. 2017].

Gasification (2) is done in a dual fluidised bed gasifier (DFB) operated in 2 zones, respectively a gasifier and a combustor (not shown separately). Combustion fuelled by natural gas and the by-products from the process creates the required heat for the gasification. For oxidising the feed to syngas in the gasification, steam is introduced.

Gasification of biomass produces many more products than just gas, like ash, char and tars, which have to be removed prior to methanation. (3) Ash is removed in a cyclone and partly recycled back to the process. Subsequently, tars are removed (4). The by-products are then recycled back to combustion in order to improve the efficiency of the process.

Methanation is preferred at high pressures and for process optimisation compression of the product gas is carried out prior to methanation (5). Further, conditioning of the gas is required prior to methanation, where the gas composition is optimised for methanation in a Water Gas Shift Reactor (WGSR, 6).

After the WGSR, methanation (7) is carried out over a catalyst. This is carried out in series and can require 3-4 steps. Commercial well-defined methanation systems are available, e.g. Haldor Topsoe TREMP [Jensen et al. 2011]. Followed by methanation, the feed is cleaned up from CO_2 and the synthetic natural gas is dried (8). Further, compression of the SNG may be necessary to provide it to the grid.

Since gasification of woody biomass remains challenging and since direct combustion of poplar is state of the art technology, the latter might be added and covered in a sensitivity analysis.

9.3 Ethanol from switchgrass (via hydrolysis & fermentation)

This value chain describes the conversion of switchgrass (*Panicum virgatum* L.) to ethanol via hydrolysis and fermentation. This life cycle is compared to conventional ways of providing the same products or services (Figure 13). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

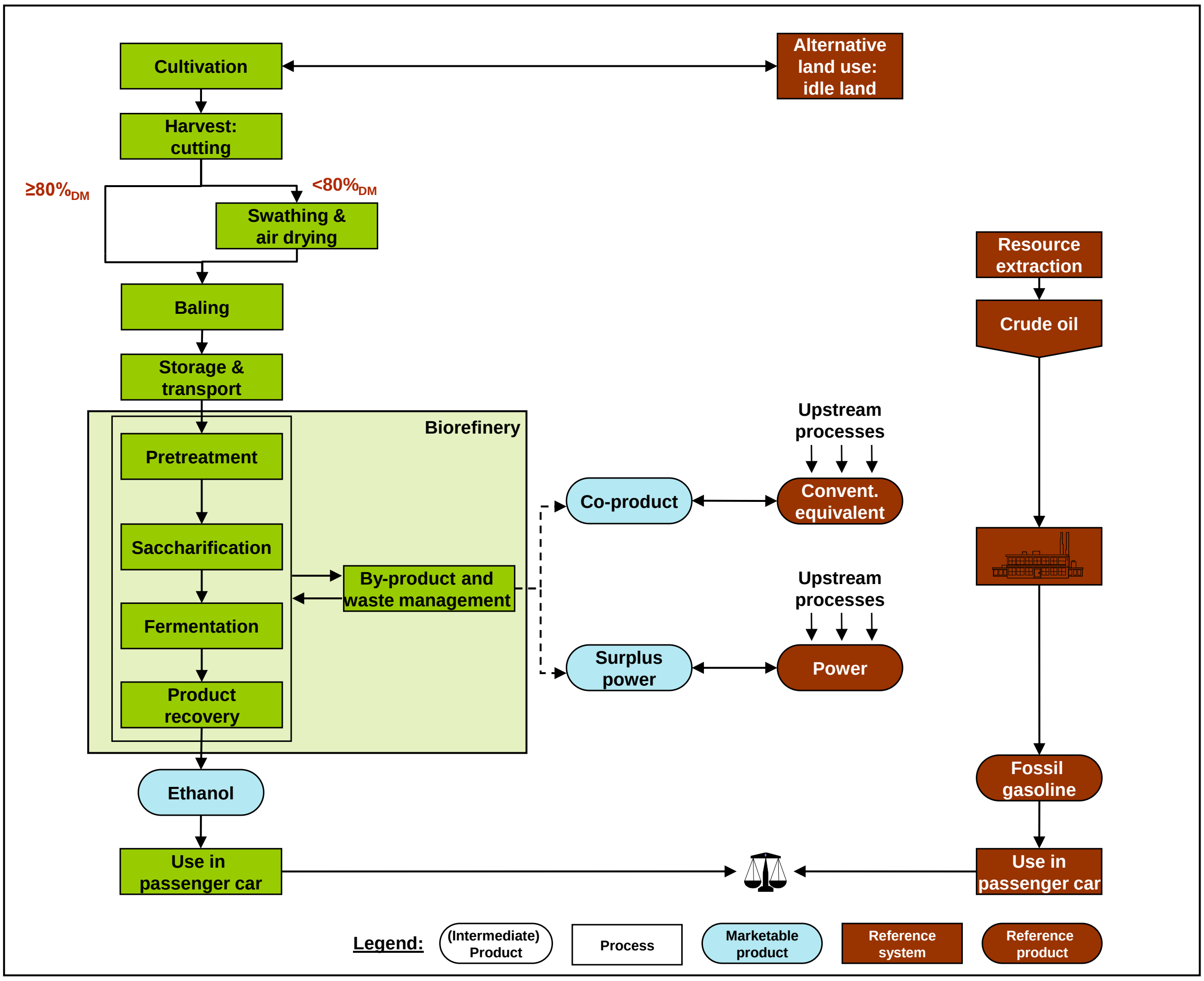

Figure 13: Simplified life cycle comparison for ethanol from switchgrass via hydrolysis and fermentation versus fossil gasoline.

9.3.1 Biomass provision

9.3.1.1 Cultivation

Switchgrass is a perennial C_4 grass, which originates from North America and grows up to 3 m tall. Switchgrass and Miscanthus have been in the centre of scientific attention during the past twenty years due to their favourable characteristics, including yield, nutrient demand, water use efficiency, adaptability to competitive environmental conditions, etc. Unlike Miscanthus, switchgrass can be seeded and its yields are lower than those of Miscanthus. Its demand for potassium is very low compared to other crops. In contrast, its demand for nitrogen is high.

9.3.1.2 Harvesting and logistics

Like Miscanthus, switchgrass has a very low water content of less than 20% at harvest. It is cut and baled directly after harvest. If the water content is too high at harvest, Switchgrass is cut, dried on swath and then baled. Therefore no technical drying is necessary. Before use, the baled herbaceous crop has to be processed and transported to the conversion unit.

9.3.2 Biomass conversion


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Hydrolysis is a method that converts the starch of the biomass to sugars, which are then converted by microorganisms to ethanol in the fermentation process. Ethanol produced this way from lignocellulosic biomass is called 2nd generation ethanol whereas 1st generation ethanol production utilises biomass with high sugar and starch content absent of (ligno)cellulosic material. The most challenging part for the 2nd generation ethanol production is the efficient hydrolysis of the cellulosic part of the biomass to fermentable sugars. Lignin part of the biomass will not be converted in this process. Many efforts have been made in the field of cellulosic ethanol production resulting in development of various technologies and process configurations. Currently in Europe (November 2019), the only operational commercial 2nd generation ethanol plant is the Borregaard Industries AS plant in Norway producing 16 kton ethanol per year [Padella et al. 2019]. In the years 2013 – 2017, Beta Renewables in Crescentino, Italy produced 40 kton ethanol per year from giant reed (*Arundo donax* L.), but due to ownerships change the plant has been idle. The new owner (Versalis) is planning to restart the production at the plant. In addition, St1 in Finland is planning to commission 40 kton ethanol (Cellunolix®) plant in 2020 [Padella et al. 2019].

Figure 22 in section 9.10 (p. 104) shows a detailed schematic presentation of ethanol production from switchgrass. This system description adapts the known designs of Borregaard, St1 and Versalis as well as information acquired from the US National Renewable Energy Laboratory (NREL) report [Knoef 2012; Mergner et al. 2013; Tao et al. 2014]. The main parts of the process are each marked with a number and are part of the cellulosic ethanol biorefinery.

Biomass acquired in the upstream processes arrives in bales at the site. The bales will be broken down at the plant (de-baling) followed by a clean-up of the biomass from stones and possible other foreign particles. As lignocellulosic biomass is very stable towards decomposition by micro-organisms, a pre-treatment (1) of the material is required. Pre-treatment is a process that reduces the crystallinity of the cellulose and its polymerisation. Furthermore, it increases the surface area of the biomass, removes hemicellulose and breaks the lignin seal. These changes will make it possible to harvest the sugars in the hydrolysis. There are several pre-treatment methods available, but the most advanced are steam explosion (TRL 6-8), acid or alkali-pre-treatment (TRL 5-7) and hydrothermal pre-treatment (TRL 4-6) [Alberts et al. 2016]. Each pre-treatment method has its advantages and disadvantages depending on the feedstock used and the further process steps combined. From the ones mentioned above, steam explosion and acid hydrolysis are the most suitable candidates for a material such as switchgrass [Alberts et al. 2016]. Pre-treatment produces solid and liquid streams; hemicellulose is degraded to a C5 sugars solution and the solid part remaining is cellulose and lignin.

Followed by the pre-treatment, saccharification and fermentation takes place (2). The produced liquid and solid streams might need conditioning, for instance removal of acids formed in the pre-treatment to prevent inhibition of microorganisms in hydrolysis and fermentation. Cellulosic material will undergo saccharification in hydrolysis to release the sugars (C6) for fermentation. This is done with enzymes, which is also one of the major cost factors of the whole process. The enzymes can cost 30-50% of the whole ethanol production [Mergner et al. 2013]. Benefits of enzyme usage are operational as corrosion-durable materials are not needed and difficult separation steps can be avoided (*e.g.* acidic hydrolysis). In enzymatic hydrolysis the target is to produce as high concentration of sugars as possible without compromising the hydrolysis process. Enzyme inhibition is a challenge in the hydrolysis as side products can be formed that prevent further conversion of cellulose to sugars. Recycling of enzymes is necessary, and it should be considered to produce the enzymes at the plant itself to lower the costs.

Degradation of hemicellulose and cellulose material results in C5 and C6 sugars, pentoses and hexoses respectively. These sugars can be fermented to ethanol. However, one of the main factors in cellulosic ethanol production is that pentose fermenting microorganism are scarce. A second important factor is that the stream produced in earlier process parts contains also compounds that are inhibitory for the fermentation. Therefore, multiple options for fermentation exist depending on the previous process steps chosen. Some of them combine hydrolysis with fermentation, or have separate units for both, some ferment hexoses and pentoses separately or combine the both saccharification and fermentation. Fermentation sugar to alcohol produces also heat and CO_2. Furthermore, in this process part, yeast propagation is carried out for fast production of the yeast. Part of the sugars produced in hydrolysis can be used for this step.

The by-product streams formed are wastewater and lignin with other products that can be extractable from the stream (by-product and waste management, 4). The amount of lignin recovered depends on the composition of the biomass. Lignin is a high energy value product that can be burned for steam to be used in the plant itself and/or for electricity production. Other options for lignin utilisation are gasification for syngas production or pyrolysis for pyrolysis oil production. Both these intermediary energy carries can be further refined to value-added products like hydrocarbons. Wastewater contains organics from the process, such as acetic acid, furfural, HMF, and residual sugars. It can be purified in multiple ways, *e.g.* anaerobic digestion to produce biogas (CH_4).

By-products could also be utilised further to marketable chemicals (5). A part of these chemicals originates from the cellulose/hemicellulose part of the biomass and some are lignin derived chemicals. Naturally, the quantities are dependent on the original biomass composition and process conditions applied. Borregaard is producing vanillin as a by-product in the ethanol biorefinery and mannose on a pilot scale [Rødsrud 2017]. St1 can produce vinasse, furfural and turpentine as by-products from ethanol from pine saw dust [Yamamoto 2018]. Possible future products that could be marketed are, for instance, higher alcohols, diols, acids and furthermore from lignin, aromatics and phenols extracted from lignin [Mergner et al. 2013].

In conclusion the pre-treatment of biomass is challenging and most demonstration and commercial plants are struggling with this step. Some of them even had to shut down. Due to economies of scale, this value chain needs to be established at fairly large scale, corresponding to 250,000 tonnes dry matter biomass input.

9.4 Biotumen from willow (via pyrolysis)

This value chain describes the conversion of willow (*Salix spp.* L.) by pyrolysis to form biotumen, which can replace fossil-based bitumen in roofing material. This life cycle is compared to conventional ways of providing the same products or services (Figure 14). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

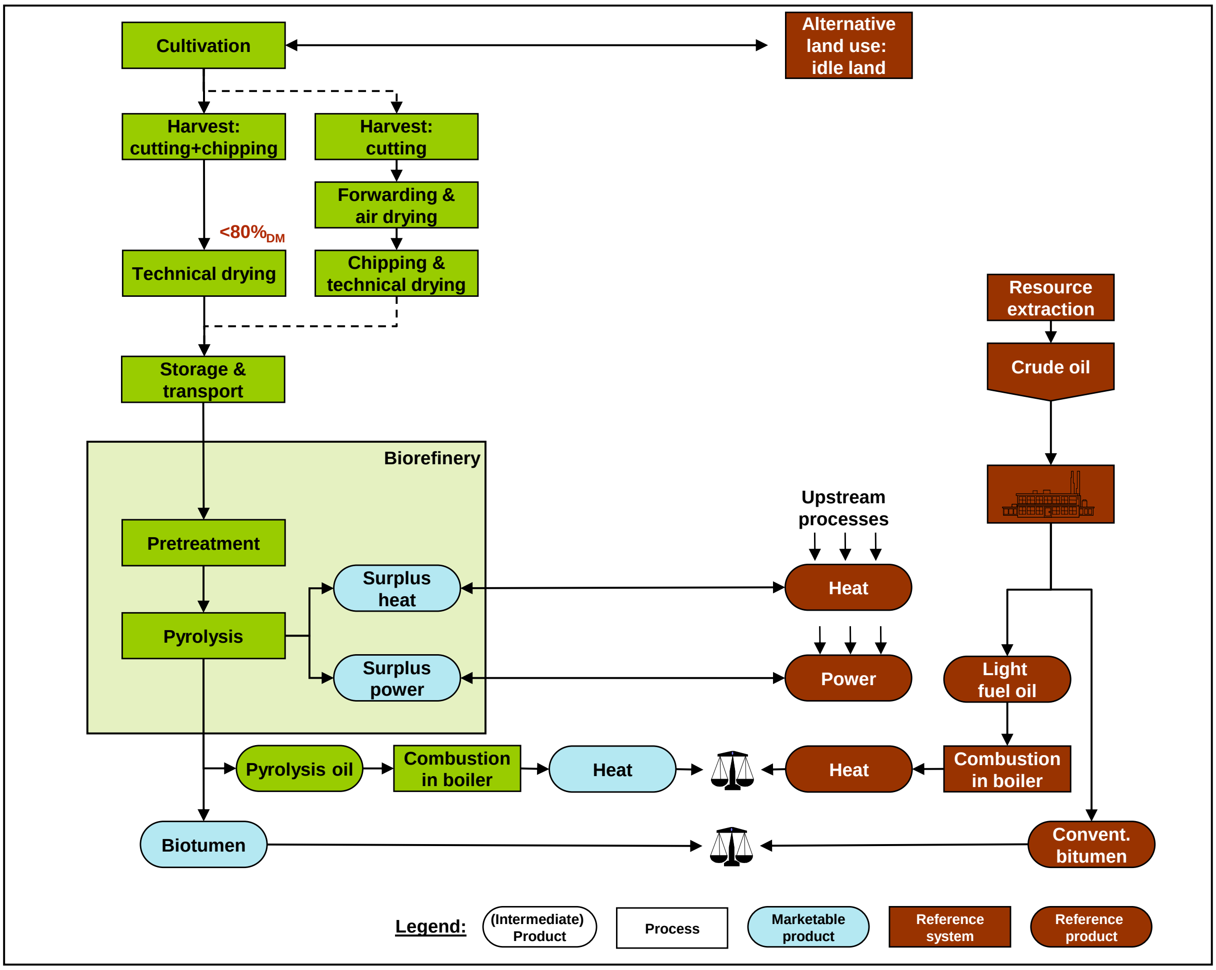

Figure 14: Simplified life cycle comparison for biotumen from willow via pyrolysis versus bitumen from fossil resources.

9.4.1 Biomass provision

9.4.1.1 Cultivation

Willow is a perennial, woody crop native to Europe, Western Asia and the Himalayas. Like poplar it is reproduced via cuttings and has a relatively high demand for phosphorus, which needs to be replenished via fertilisation. Willow is also set to be cultivated as short rotation coppice with a plantation lifetime of 20 years.

9.4.1.2 Harvesting and logistics

Willow as short rotation coppice is harvested similar to poplar, whereby the main harvesting strategy is cutting and chipping with a harvester in one step. Due to a high water content of more than 20%, technical drying is essential for the later use. Besides this strategy, just as with poplar, another less common strategy is covered in a sensitivity analysis (Figure 14). This strategy includes cutting, forwarding the biomass to a place for air drying and in a second step chipping and technical drying. In both cases the woody biomass has to be stored and transported to the conversion unit.**Biomass conversion**

In order to obtain biotumen, the willow undergoes pyrolysis, identical to the value chain described in section 9.1 The produced pyrolysis oil is then partly separated into 2 fractions, sugars and lignin fraction. The lignin fraction can then be used in the roofing application and the sugar fraction can be mixed with the remaining oil.

Figure 23 in section 9.10 (p. 105) shows a detailed schematic presentation of biotumen production from willow. As can be seen in Figure 23, willow undergoes a pre-treatment before the pyrolysis similar to Miscanthus in value chain 1. Here, a sizing (1) and drying (2) step is required as well, which can be powered from the energy obtained from the pyrolysis step (3). However, after the pyrolysis process the value chain changes from the process shown in Figure 11 (p. 79). Rather than having the pyrolysis oil as a final output, the pyrolysis oil is separated into fractions. This fractionation (4) results in two main fractions, a pyrolytic sugar fraction and a pyrolytic lignin fraction. Since the pyrolytic sugars will be mixed back with the pyrolysis oil (5), the fractionation is performed at the pyrolysis factory.

The pyrolytic sugar fraction contains the products from the cellulosic material of the biomass and could be applied as wood preservative treatment or as a foundry resin. However, in order to focus the value chain on a single product, the pyrolytic sugar fraction is mixed back with the pyrolysis oil, which is then used for the production of industrial heat.

The pyrolytic lignin contains the lignin parts of the biomass. This fraction contains a lot of water, which needs to be removed in a drying step before the final product is obtained. The structure of the lignin, compared to lignin obtained from for example the Kraft process, is different due to the pyrolysis step. This makes the material more suitable in an application such as a roofing material. The lignin can be mixed with standard roofing material ingredients, replacing part of the fossil-based bitumen.

9.5 Organic acids from safflower (via oxidative cleavage)

This value chain describes the conversion of a high-oleic safflower variety (*Carthamus tinctorius* L.) by oxidative cleavage to form organic acids. This life cycle is compared to conventional ways of providing the same products or services (Figure 15). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

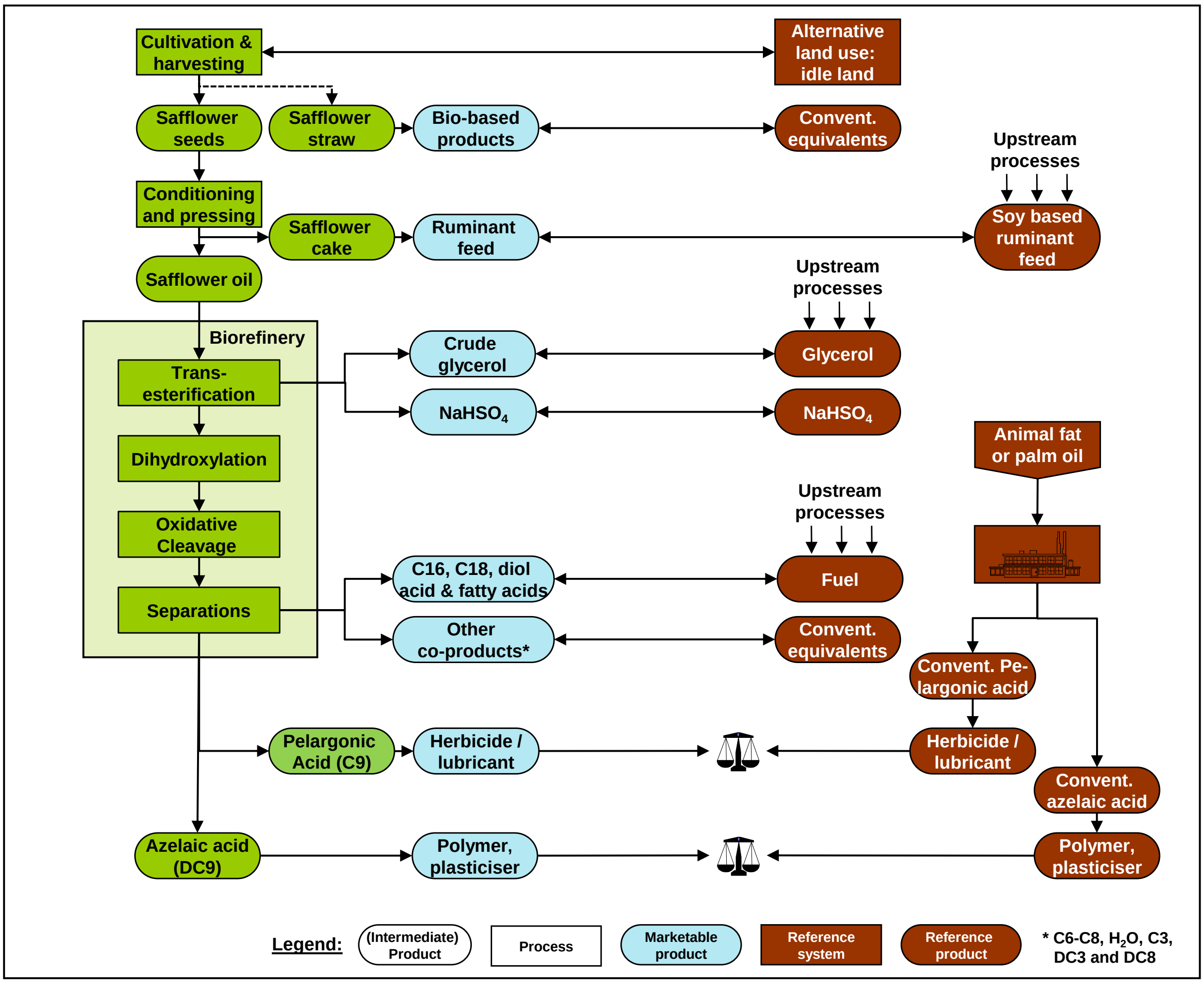

Figure 15: Simplified life cycle comparison for organic acids from safflower via oxidative cleavage versus organic acids from fossil resources.

9.5.1 Biomass provision

9.5.1.1 Cultivation

Safflower belongs to the aster family (Asteraceae) and is a branching thistle-like herbaceous annual (spring or winter) plant, with numerous spines on leaves and bracts. The growing period is 110 to 150 days. The safflower plant, 0.6 - 1.5 m high, produces many branches with heads at its ends. Each head can produce up to 20-100 seeds. Safflower seed generally contains 33-60% hull and 40-67% of kernel.

The crop is grown for local use as an oilseed or a food colorant. Two safflower varieties are distinguished: a high-oleic acid variety (74 – 80%) and a more conventional high-linoleic acid variety (70 – 80%). The crop is adapted to semiarid regions and marginal conditions. However, it cannot survive on soils with standing water even for few hours when the air temperature is above 20ºC. During the rosette stage, the young plants can survive low temperatures (-7°C) but during elongation period the plant is sensitive to cold [Alexopoulou et al. 2018].

9.5.1.2 Harvesting

Safflower can be harvested with conventional combines equipped with a standard header (grain platform). Preferably, the moisture content at harvest should be <10%; if higher, the crop can be windrowed and threshed after the seeds are dry enough [Pari & Scarfone 2018]. Appropriate measures (such as small-meshed screen enclosures and blowing out radiators with air once or twice daily) should be taken to prevent overheating of the combine (fire hazard) due to fuzz from the seed heads which may clog radiators and air intakes.

9.5.1.3 Logistics, pre-treatment, oil extraction and refining

The oil content of the seeds is 34 – 36% and the moisture content should be < 8% for safe long-term storage, i.e. technical drying might be necessary. The seed meal has 24% protein content and a high fibre content. Meal from decorticated seeds (most of hulls removed) has about 40% protein content with a reduced fibre content. Safflower meal is used as a protein supplement for livestock.

Safflower seeds look like pistachios, that means the hull is thick and hard, hence represents a lot of weight. It is a lignocellulosic material therefore it is beneficial to remove it before pressing. Dehulling improves crushing efficiency, but the hardness of the seed coat and the extreme softness of the kernel make the operation costly and only economically viable if there is a market for the hulls. In a previous EU project (EuroBioRef), Arkema worked on valorisation of the hull, and there would be a potential market for it. In addition, if it is left during the pressing stage, some lignin is extracted, which contributes to some aromatic residues in downstream glycerine and/or oil. So, it is suggested to remove the hull at the conditioning stage of the seeds. The hull could be valued separately for example for its energy content. In addition, the by-product, safflower meal is mostly used as a protein ingredient for animal feeding.

9.5.2 Biomass conversion

In order to convert safflower oil to organic acids, a process of oxidative cleavage is proposed. It is the cleavage of alkenes double bonds to generate carbon-oxygen bonds of aldehydes and then to acids. The high oleic safflower oil used in this process is rich in oleic acid (C18:1) - about 82%, 3.5% of palmitic acid (C16:0), 5% of stearic acid (C18:0), 7.5% of linoleic acid (C18:2), 0.5% of arachidic acid (C20:0) and 1.2% of behenic acid (C22:0). The process of oxidative cleavage of high oleic safflower oil covers 4 main steps. Figure 24 in section 9.10 (p. 106) shows a detailed schematic presentation of the process.

In step 1, the transesterification of the triglycerides from the RBD safflower oil with methanol and an inorganic base (sodium hydroxide or sodium methylate) occurs to obtain the fatty acids methyl esters (FAME) and glycerol. Crude glycerol is then extracted from the reaction medium. As it has a commercial value, we do not investigate further purification. In addition, the amount of glycerol produced is usually about 10 wt % of the oil, so it is often a small amount for a specialty oil and does not justify having an on-site purification. Some companies are collecting the crude glycerine and refine it on another larger site. As the remaining methanol is then recycled for transesterification process [De Leon Izeppi et al. 2020].

Step 2, dihydroxylation, comprises the oxidation of the double bond with concentrated hydrogen peroxide and catalyst for the formation of methyl dihydroxy-stearate intermediates and other fatty acids. As an alternative to ozonolysis, oxidative cleavage using hydrogen peroxide has been proposed. Hydrogen peroxide is a clean strong oxidising agent because its decomposition produces only oxygen and water, however, the decomposition is quite exothermic ($\Delta H^\circ = -100.4$ kJ/mole). In addition, a tungsten-based catalyst is often also used in this reaction together with hydrogen peroxide. Saturated fatty acids such as palmitic acid (C16:0) and stearic acid (C18:0), are not expected to react during the process, therefore they are recovered at the end of the process [De Leon Izeppi et al. 2020]. In the reference process, using animal fat or palm oil, the saturated fatty acids do not react either.

Step 3 involves the C-C oxidative cleavage of the intermediate diol formed in step 2. Currently the cleavage of unsaturated fatty acids is mostly accomplished by ozonolysis. Oxidation of the olefins by ozone (O_3) has been used as a clean and efficient reaction for use in the production of bio-based aldehydes (reductive ozonolysis) and acid/diacids (oxidative ozonolysis). However, this oxidative cleavage process presents some disadvantages, such as high-energy (high electricity) consumption and the need for a special technology for the production of ozone (ozone generator).

In the process considered, this step 3 corresponds to the oxidative cleavage with molecular oxygen, under pressure, of the intermediate diol, in the presence of the in situ-formed catalyst, obtained by the reaction between the remaining tungsten catalyst of the first step and the metastable form of cobalt acetate added before the beginning of this step. The reaction is performed with addition of oxygen, under moderate pressure of 20 bars of industrial air (containing about 21 % oxygen). This reaction could also be done at lower pressure with oxygen enriched air, or high concentration oxygen. Lower pressure reduces the capital cost, but higher oxygen concentration can generate safety risks which have to be analysed. In this reaction, in the presence of oxygen (absence of hydrogen peroxide), the tungstic acid was not active without the addition of cobalt acetate, and cobalt acetate was not active alone (note that in this case, there is not enough hydrogen peroxide to continue the oxidation and that the sole source of the oxidant is oxygen, which then must interact with the cobalt moiety) [De Leon Izeppi et al. 2020].

Finally, step 4 constitutes the purification process. After oxidative cleavage, the products are being separated into 2 phases. The aqueous phase contains C3, DC3, pelargonic acid (C9) and lighter monocarboxylic acids (C6-C8) that can be separated with a distillation column. The light monoacids C6-C8 obtained is a mixture that can be valorised whose value depend on their mix composition and their market prices. As for pelargonic acid (C9), it has a potential application as herbicides and lubricants. Whereas the heavy organic phase contains mono and dicarboxylic acids, the esters of the fatty acids present initially in step 2 such as methyl stearate, palmitate and still the remaining diol intermediate, and in addition some heavy products generated during the reaction such as acetals and esters. This phase is then fed into a distillation column where the light monoacids can be recovered at the top of the column. The monomethyl azelate, methyl palmitate, methyl stearate and the esters of methyl dihydroxy-stearate recovered from the bottom of the distillation column are continuously fed into a reactor with an emulsifier and then hydrolysed into three consecutive columns filled with acid ion exchange resin with methanol being eliminated in the process (and recycled at the first step).

The azelaic acid (and other diacids) is separated by crystallisation from the heavier saturated fatty acids palmitic and stearic. Azelaic acid has a potential application as plasticisers and polymers. Products obtained with one carbon less such as acid C8 (octanoic acid) and dicarboxylic acid DC8 (suberic acid) are the result of the decarboxylation of pelargonic acid and azelaic acid intermediates (reaction takes place during the oxidative cleavage), a side-reaction (loss of selectivity) of the process [De Leon Izeppi et al. 2020].

9.6 Sebacic acid from castor oil (via alkaline cleavage)

This value chain describes the conversion of castor (*Ricinus communis* L.) to decanedioic acid (sebacic acid) via several oleochemical processes (among others alkaline cleavage). This life cycle is compared to an alternative way of providing the same products or services through fermentation of petroleum-derived paraffins (Figure 16). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

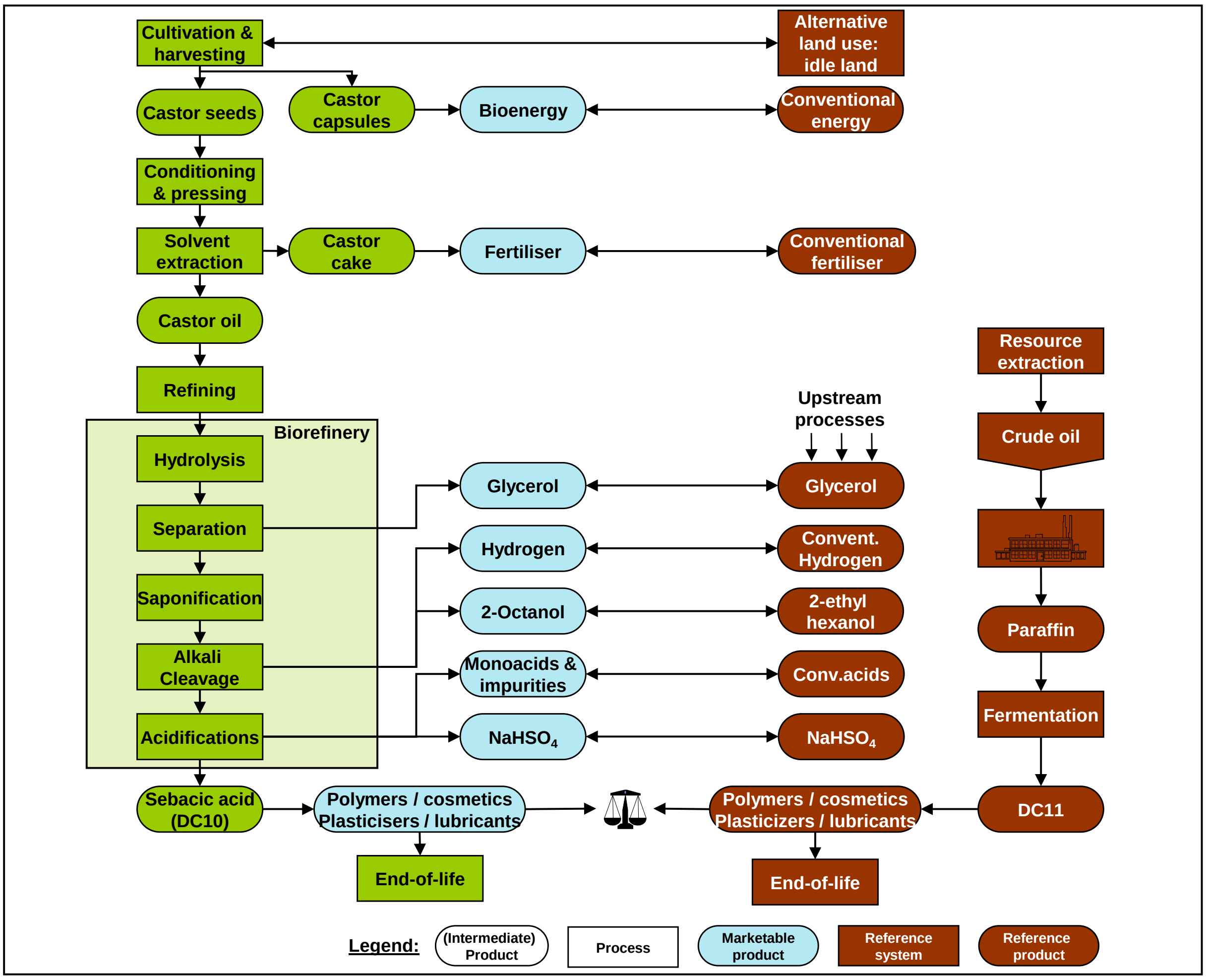

Figure 16: Simplified life cycle comparison for products derived from sebacic acid from castor oil versus the same products from paraffins derived through fermentation of petroleum[4].

[4] The benchmark is the fermentation of petroleum-derived paraffins as it is practiced in China (and previously also in Japan). Several diacids are obtained and commercialised with such a process from DC10 to DC18).

9.6.1 Biomass provision

9.6.1.1 Cultivation

Castor belongs to the spurge family (Euphorbiaceae) that is cultivated both as an annual and perennial crop. The crop varies greatly in its growth (80 cm to 3 m high) and appearance (shape, colour). The annual growing cycle depends on the cultivation site and can be up to 180 days when it is grown in India and between 120 and 150 days in the Mediterranean region. The crop is quit tolerant to marginal conditions, both in terms of climate (it is quite drought-tolerant) and soil (moderately fertile soils are preferred). However, a frost free climate is mandatory for the crop [Alexopoulou et al. 2018].

9.6.1.2 Harvesting

The harvesting mechanisation of castor oil is still an unresolved problem. The problem is mainly related to the fact that the traditional varieties are very tall, have several racemes, and capsules ripening over a period of 2 months, which makes 2-3 manual harvesting per season necessary. Breeders worldwide are developing new varieties with characteristics that permit the introduction of harvesting mechanisation. Once this is achieved, either conventional combines equipped with a modified maize header (to prevent seed losses) or purpose-built castor headers (as announced by Evofuel Ltd. in 2018) could be used. However, since castor beans are very susceptible to cracking and splitting during harvest, adjustment of the combine (e.g. cylinder speed and cylinder-concave clearance) is very important [Pari & Scarfone 2018].

9.6.1.3 Logistics, pre-treatment, oil extraction and refining

Castor beans are transported to a processing/storage facility. In case of manual harvest, a de-hulling step is necessary. The empty capsules (~1/3 of the harvested biomass) are briquetted and used for bioenergy purposes. In case of mechanical harvest (using a combine), the empty capsules remain on the field and are ploughed in. They maintain soil fertility and thus substitute for conventional mineral fertilisers. The seeds are crushed by either cold or hot pressing. The oil produced then has a better quality. Mechanical oil extraction is conducted and yields 30% of oil. The protein-rich press cake cannot be used as animal feed since it contains several toxic compounds.

Since the oil is expensive, the cake, which still contains a lot of oil, is recovered through extraction with n-hexane solvent. Hexane is chosen to be a suitable solvent because of its properties like boiling point, high volatility and low sensible heat. Its boiling point is 69°C and so it can be easily separated from other via distillation process. It has high volatility and low sensible to heat (335 kJ/kg) so it is easy to remove from seed and oil with low energy requirement. The hexane is then recycled, and the castor meal, which is rich in nitrogen content, can be used as organic fertiliser. The castor seeds contain ricin, which is a toxic protein, but it is inactivated due to heating process during extraction. The oil has to be more chemically refined as it contains more free fatty acids and other impurities.

9.6.2 Biomass conversion

Figure 25 in section 9.10 (p. 107) shows a detailed schematic presentation of the process. The processing of castor oil is done in multiple steps. At the biorefinery, castor oil is first hydrolysed with the addition of catalyst to achieve different fatty acids: 87% of ricinoleic acid (C18:1,OH), 5% of oleic acid (C18:1), 4% of linoleic acid (C18:2), 2% of palmitic acid (C16:0), 2% of stearic acid (C18:0) and glycerol. Glycerol is separated and commercialised and water is recycled back to the hydrolysis step. Ricinoleic acid was determined as the main fatty acid component of castor oil and hence, after saponification with sodium hydroxide, sodium ricinoleate was determined as the main content of saponified castor oil. This sodium ricinoleate then undergoes alkali cleavage with sodium hydroxide to form two new compounds, in a sequence of reactions taking place simultaneously in the same reactor.

The dehydrogenation of sodium ricinoleate as the first step of alkali cleavage resulting in the formation of unsaturated keto acid which isomerises to α,β-keto acid in the presence of alkali. This keto acid undergoes a retro aldol fission to yield 2-octanone and the aldehyde of sodium sebacate in the presence of water. The 2-octanone takes up hydrogen either from the first step of dehydrogenation or from the oxidation of the aldehyde sodium sebacate to form 2-octanol. On the other hand, the aldehyde of sodium sebacate will undergo oxidation to form disodium sebacate in the presence of alkali, while releasing hydrogen. All these reactions occur simultaneously in a single reactor/step.

Other than disodium sebacate, 2-octanone and 2-octanol, the products also contain unreacted fatty acids sodium salts and side products such as 10-hydroxydecanoic acid salt (there is more octanone and 10-hydroxydecanoic acid when the reaction temperature is low). The next step consists of acidification process to pH 6 with concentrated sulfuric acid to produce monosodium sebacate with monosodium salt of fatty acid and unreacted fatty acids being eliminated in the process. After separation, the monosodium sebacate was then acidified to pH 4 using concentrated sulfuric acid to yield sebacic acid. A final purification step enables to obtain a higher yield of end-products. These oleochemicals are precursors for industrially important plasticisers, surface coatings and perfumery chemicals.

The reference product can be also produced through fermentation of petroleum derived paraffin. Sebacid acid is produced this way by a limited number of suppliers, one of them is Cathay Industrial Biotech, others are Hilead, or Corvay. Very few data is available on this reference route.

Alternatively, sebacic acid will compete with dodecanedioic acid (DC12) which can be produced also by fermentation of paraffins, or of lauric acid (Verdezyne had plans for it), and it can be produced by oxidation of cyclododecane. Cyclododecane is produced by cyclotrimerisation of butadiene followed by hydrogenation. Some data is available on this process.

9.7 Insulation material from hemp

This value chain describes the production of an insulation material from industrial hemp (*Cannabis sativa* L.). This life cycle is compared to conventional ways of providing the same products or services (Figure 17).

Industrial hemp (*Cannabis sativa* L.) is an interesting multipurpose crop with a multitude of applications for the fibres, the by-products shives and dust as well as the seeds (for food or bird feed) and pharmaceuticals (CBD and THC).

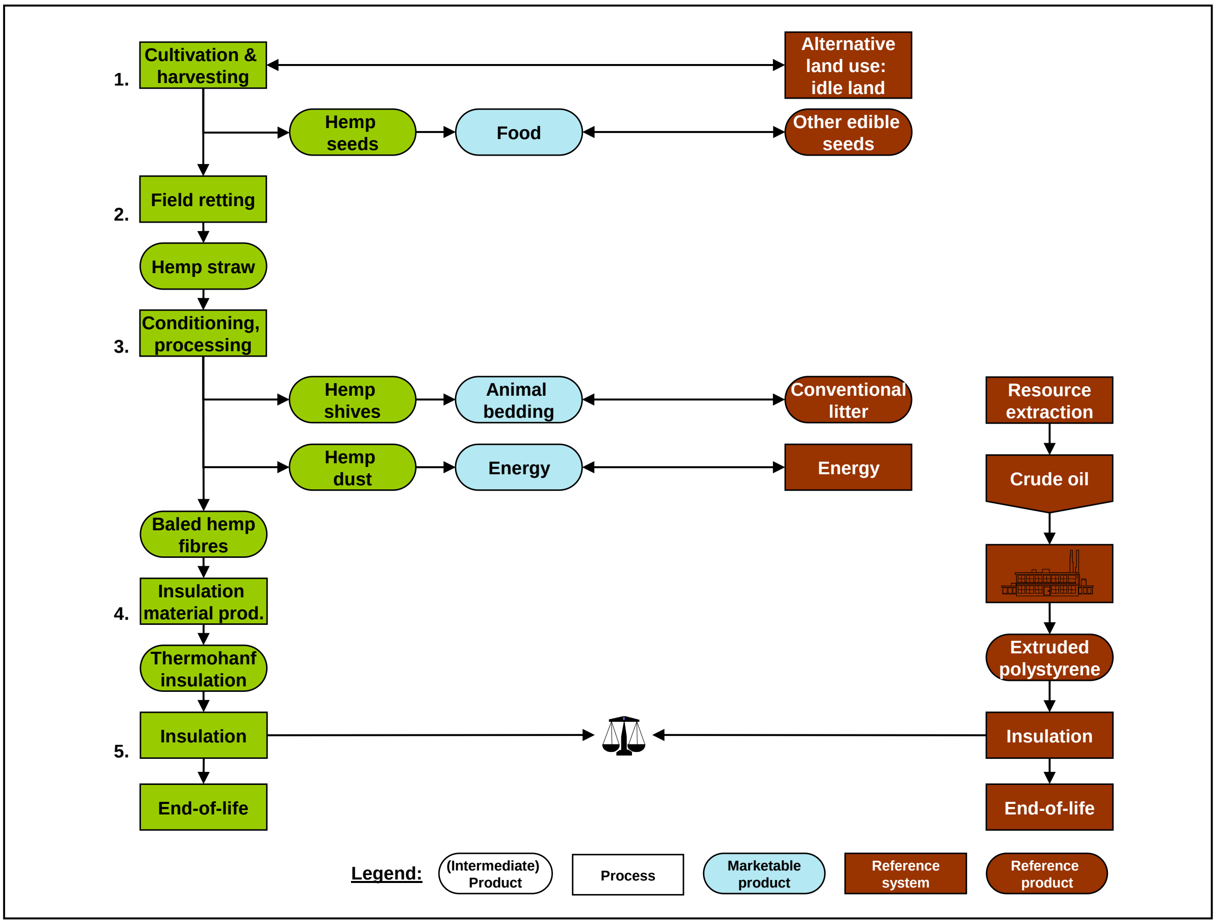

Figure 17: Life cycle comparison for insulation material from industrial hemp versus insulation material from fossil resources (e.g. extruded polystyrene).

9.7.1 Biomass provision

9.7.1.1 Cultivation

Hemp is an annual spring crop that is traditionally cultivated for its fibres and grows 2 to 4 m high. It is grown from seeds. Originally hemp came from Central Asia and migrated to China, from where it was spread all over the world. If it is cultivated for fibre, special attention should be given on potassium and calcium, and on phosphorus, if it is harvested for the seeds. In Europe no irrigation is used in commercial production. Naturally hemp is a dioecious crop with female and male plants, which differ in fibres content, number of seeds and need different amounts of time to mature. Nowadays a number of monoecious varieties is cultivated with similar properties of all plants and can thus be harvested more efficiently.

9.7.1.2 Harvesting and logistics

For the sustainability assessment, hemp is set to be grown for fibre and seeds. It is thus harvested at full maturity phase, when seeds in the middle part of panicles are mature. With a Double Cut Combine harvester (or corn kemper) seeds and stems can be cut and harvested in one step. The upper part with the seeds is cut, threshed and collected in a hopper of the harvester. The lower stem part, which has a water content of 20-30%, is also cut but left on the field. Depending on the weather, the stems need 14 days or more for retting and to loosen the fibres. After retting, when the water content is lower than 15%, the straw can be baled and transported to a storage or the conversion unit.

9.7.2 Biomass conversion

Insulation accounts for about 25% of fibre applications. One of the major commercially available hemp insulation materials is THERMO HANF®, produced by the company Thermo Natur, in Nördlingen, Germany. This product is a commercially available hemp-based insulation roll which provides thermal, acoustic, impact and fire resistance (www.thermo-natur.de). Production volumes amounted to 100,000 m^3 in 2007.

This specific type of insulation material is most suitable for the project because a lot of data exists from different studies, including LCA inventory data [Bos 2010; Spirinchx et al. 2013]. In the frame of the MultiHemp project (FP7-311849), nova-Institute performed an environmental hotspot analysis between THERMO HANF® and an innovative hemp blow-in insulation material [de Beus & Piotrowski 2017].

The life cycle comparison for the hemp value chain is displayed in Figure 17. It is assumed that hemp is cultivated for the dual use of the straw for fibres and the seeds for food. In addition, separated harvest of the leaves for extraction of pharmaceuticals or selling as tea is feasible but not representative for hemp cultivation in Europe and thus not assessed as part of this sustainability assessment.

After the hemp cultivation and harvest (1), the hemp straw is left on the field for retting (2), which separates the bast fibres from the shives. This step is essential and unique in the hemp value chain. The processing of hemp straw to obtain hemp fibres (3) is typically done in Europe in the so-called Total Fibre Line, which produces as by-products hemp shives and dust.

The shives as a by-product of the fibre production can be utilised for several purposes like bedding for animals (horses and rodents) or growing substrate for plants. They also can be used for the production of low-weight particle boards or as a solid fuel for energy production. Since animal bedding is still the largest market for the shives with more than 60%, this application is assessed as part of this sustainability assessment. The remaining fine particles (dust) after the separation of fibres and shives are set to be pressed into briquettes and incinerated for local heat.

The hemp fibres are then baled and transported to the insulation material production site. The production process for THERMO HANF® (4) consists of mixing long hemp fibres with BICO-PES fibres, layering this mix in a carding and cross-laying machine and bonding it in a thermobonding oven.

The conventional reference product for this product could be glass or rock wool insulation material or alternatively an insulation material from Expanded polystyrene (EPS), Extruded polystyrene (XPS) or Polyurethane (PUR).

9.8 Biogas/biomethane from sorghum

This value chain describes the production of biogas from sorghum (*Sorghum bicolor* (L.) MOENCH) as a substrate. This life cycle is compared to conventional ways of providing the same products or services (Figure 18).

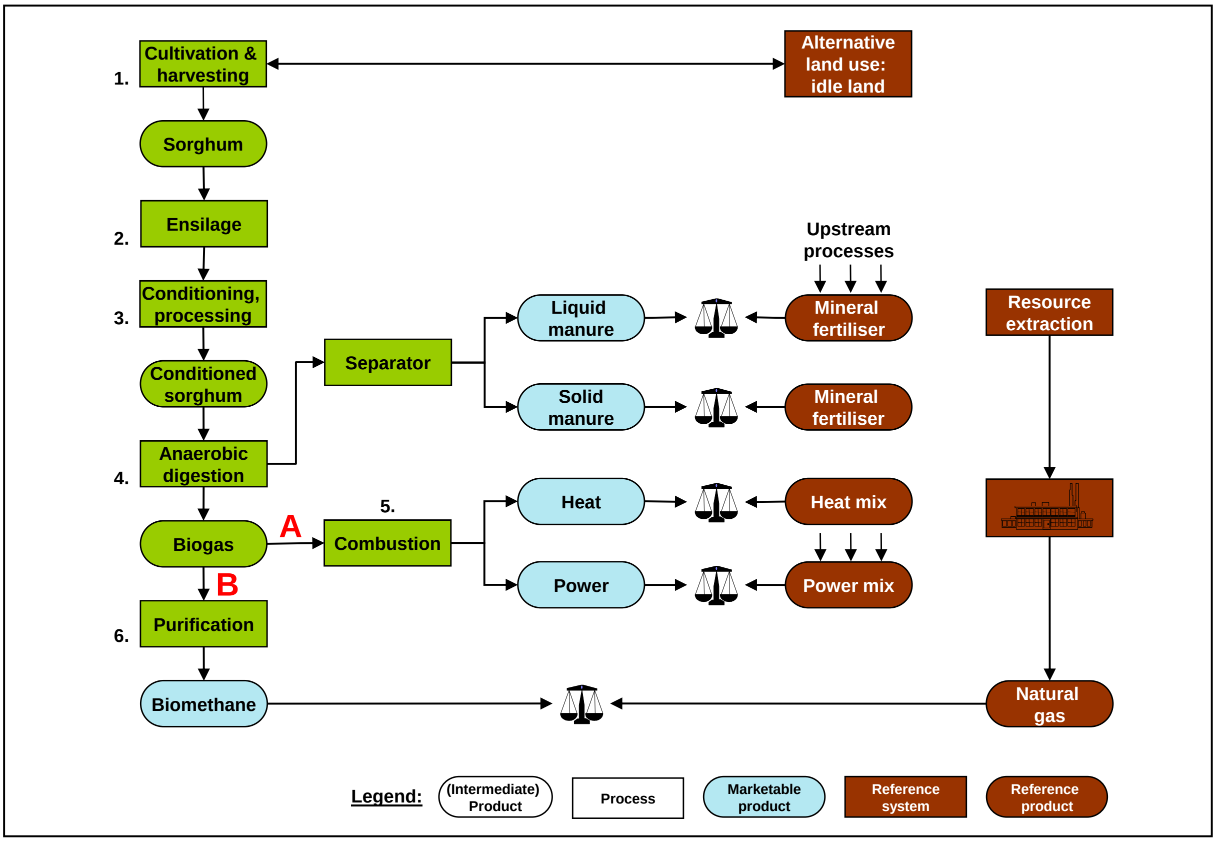

Figure 18: Life cycle comparison for biogas/biomethane from sorghum versus natural gas.

9.8.1 Biomass provision

9.8.1.1 Cultivation

Sorghum bicolor, also known as great millet, durra or milo, but commonly called sorghum is a grass species, which is native to Africa. Sorghum is an annual herbaceous spring C_4 crop, which can grow up to 5 m high. It is common in the drier, warm and temperate climates of Africa, America, Asia and Europe. Sorghum has a deep and large root system and therefore doesn't need irrigation. Because of its small seeds, the seedbed needs to be adequately prepared before sowing. There are several types of sorghum, mainly grain, sweet, forage and biomass sorghum varieties. For this value chain, biomass sorghum is set to be cultivated.

9.8.1.2 Harvesting and logistics

Most commonly sorghum is grown for its grains, which are used for food, animal feed and ethanol production. As a whole crop it can be used as substrate for biogas/methane production and achieves comparable yields to the conventional substrates e.g. maize [Herrmann et al. 2016; Mursec et al. 2009; Stolzenburg & Monkos 2012]. Crops such as maize, wheat and sorghum are excellent raw materials for the production of biogas and valuable by-products.

Sorghum is harvested, when the dry matter content is between 28% and 35% [Biertümpfel 2014], which is usually the case in late September or October. The crop can be harvested with a standard forage harvester with maize headers, which makes it easy to include it into an existing maize production system. The transportation from field to plant (see 1. in Figure 18) does therefore not pose a problem due to the available machines [Stolzenburg & Monkos 2012]. The harvester cuts the crops as a whole and loads them onto a trailer. The chopped sorghum needs to be ensiled or rapidly transported to the processing facility, because the fine fractions start fermenting immediately after chopping.

9.8.2 Biomass conversion

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After harvesting and chopping, the biomass is set to be ensiled (2.), because immediate use is not possible in remote areas. Subsequent pre-treatment is conducted with water and beneficial microorganisms (3.). The whole mixture is then pumped into the fermenter where the anaerobic digestion (4.) takes place. In the fermenter a great number of bacteria decompose the organic matter. The process happens at the absence of oxygen and in temperature-controlled environment to achieve the optimal activity of the microorganisms resulting in maximum output. Products of the process are biogas, waste heat (dissipated unused in air), and digestate as natural fertiliser.

Anaerobic digestion is a complex process that takes place in four biological and chemical stages i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis. The individual degradation steps are carried out by different consortia of microorganisms, which partly stand in syntrophic interrelation and place different requirements on the environment. Most of the bacteria are strict anaerobes [Raja & Wazir 2017]. Anaerobic digestion is most commonly used to convert organic material into biogas and is carried out all over the world. The environment of the fermenter needs to be strictly controlled to result in maximum gas output. Mostly, it is dependent on oxygen, temperature, pH level, nutrients and toxic materials [FNR 2016; Raja & Wazir 2017].

After releasing the gas out of the fermenter, it can either be used directly to produce electricity and heat (5.) or be further purified to biomethane (6.), which resembles conventional natural gas and can thus be fed into the natural gas grid. Due to the high investments, upgrading of biogas to methane only becomes profitable at a methane production of 2-4 mln m^3 annually [Daniel-Gromke et al. 2017]. Based on a crop yield of 15 t/ha dry matter, as stated in most studies, around 670 ha of sorghum would be required to gain a profitable methane yield of 3 mln m^3. Higher yields due to an accurate choice of the cultivar and the optimal adaption to the location are possible and already documented [Stolzenburg & Monkos 2012].

9.9 Adhesives from lupin

This value chain describes the conversion of Andean lupin (*Lupinus mutabilis* SWEET) to micellar lupin protein (MLP), which can be used as a food packaging adhesive. This life cycle is compared to conventional ways of providing the same products or services (Figure 19).

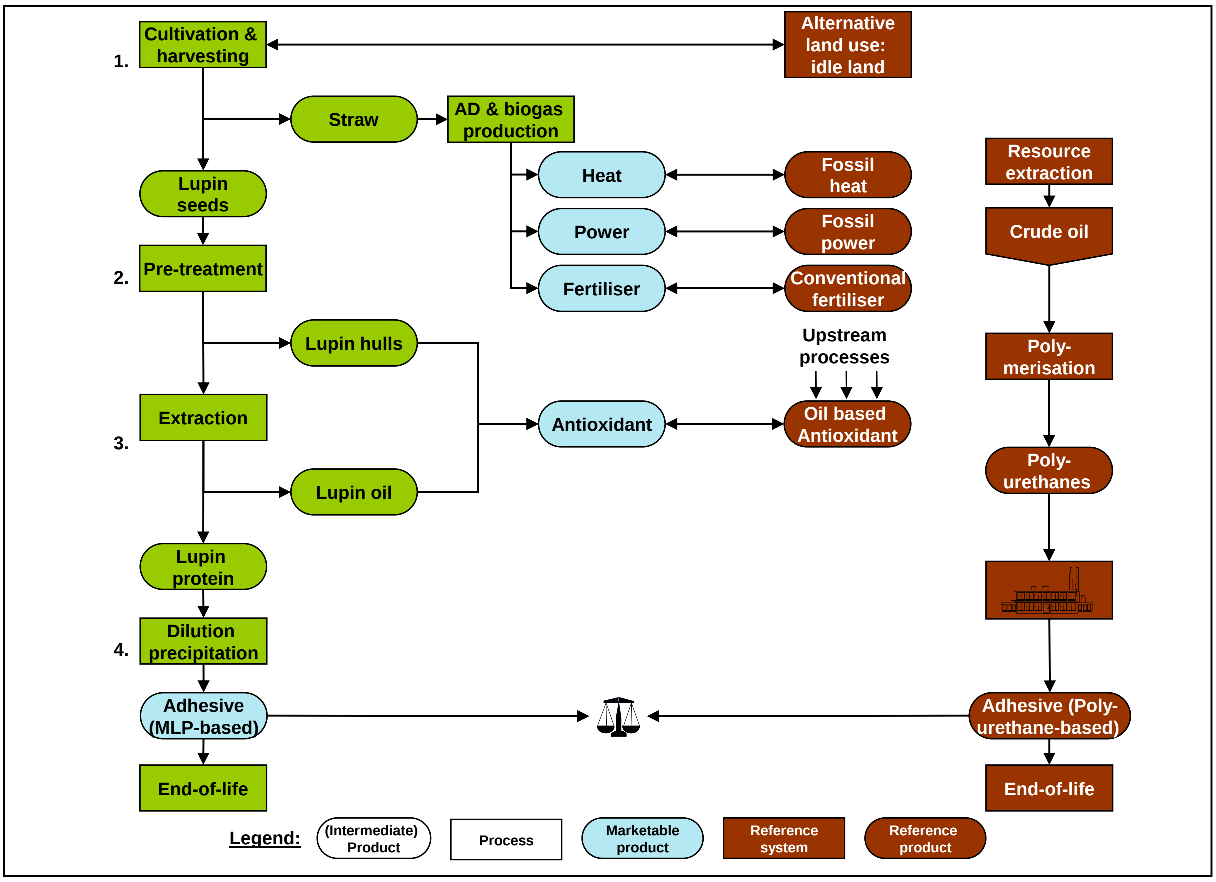

Figure 19: Life cycle comparison for adhesives from lupin versus adhesives from fossil resources.

9.9.1 Biomass provision

9.9.1.1 Cultivation

The Andean Lupin is an annual crop, which belongs to the legume family. It originates from the Andean region of Ecuador, Peru and Bolivia and can grow on a large diversity of soil types. Its beans are sown in 3 to 5 cm depth. Lupine can be cultivated either as summer crop in northern Europe or as winter crop in Mediterranean climate.

9.9.1.2 Harvesting and logistics

Harvest of the seeds is done in mid-summer, when the whole plant is yellow. A delayed harvest can lead to a loss of yield due to lodging, pod shattering and pod drop. It is performed with a combine equipped with a header for wheat. The rotor speed of the combine should be set to a minimum and the concave opened wide. To reduce harvesting losses the use of air reels is suggested, which blast air into the front. After harvest the seeds can be transported to a storage or to the conversion unit, while the straw is laid on swath and needs to be collected separately. Lupin straw could be used as a valuable source for anaerobic digestion and therefore power and heat (from CHP) and fertiliser (from digestate) production [Corré & Conijn 2016; Dubrovskis et al. 2011; Kintl et al. 2019].

9.9.2 Biomass conversion

The lupin adhesive stands out as a promising alternative to petrol-based adhesives [Eibl et al. 2018]. In fact, micellar lupin protein (MLP) showed a great potential as functional laminating adhesive due to its high adhesion and oxygen-barrier features. Formulations of MLP are used as laminating adhesive between various elements (e.g. high-density polyethylene foil and paper, coating for PET foil), being a valid alternative to the commonly used polyurethane-based adhesives [Eibl et al. 2018], whose raw materials are in most of the cases petroleum-based [Zia et al. 2007]. A detailed value chain description is shown in Figure 19.

Prior to the protein extraction step (3.), lupin seeds have to be pre-treated (2.). The pre-treatment phase is crucial to remove lupin hulls, via cracking, and to create extruded flakes, via extrusion. According to [Lampart-Szczapa et al. 2003], lupin hulls showed interesting antioxidant properties, that might qualify this by-products as high value side stream components. Similar antioxidant properties have also been found for lupin oils, by-product of the protein extraction step (3.).

Various techniques can be carried out in the extraction phase (3,), such as solvent, aqueous and dry extraction. However, because of the low oil content in the seed (e.g. compared to soybean), solvent extraction of lupin is not economically advantageous. Thus, aqueous extraction processing (AEP), allowing simultaneous extraction of the oil and protein from oilseeds, could be an appropriate alternative [Jung 2009]. According to the same study, the adoption of enzyme-assisted AEP (EAEP) yields considerable amounts of oil, protein and cream + free oil yields. Alternatively, dry extraction can be implemented. This technique involves dry fractionation by combining milling and air classification [Pelgrom et al. 2014] or electrostatic separation [Wang et al. 2016], consuming no water and low energy and producing functional protein enriched fractions.

Last, micellar lupin protein (MLP) isolate, the laminating adhesive, is obtained by dilution precipitation (4.). Dissociation reactions occur after abrupt dilution, leading to the orientation of hydrophilic groups to the protein surface. This change in protein structure results in globular, micelle-like protein with a smooth and fat like, but very sticky texture. As mentioned, due to their polarity, proteins in general exhibit excellent barrier properties against oxygen [Eibl et al. 2018].

9.10 Details on biomass conversion

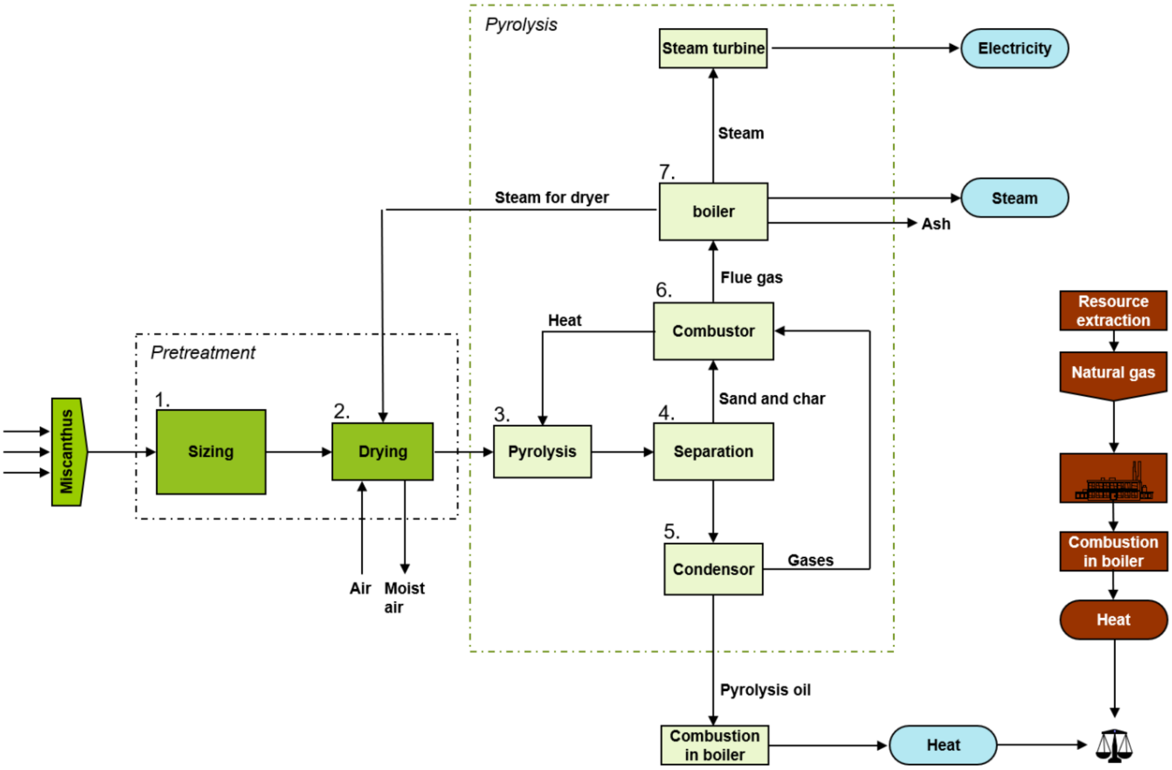

Figure 20: Detailed life cycle comparison for industrial heat from Miscanthus via pyrolysis versus industrial heat from fossil energy carriers.

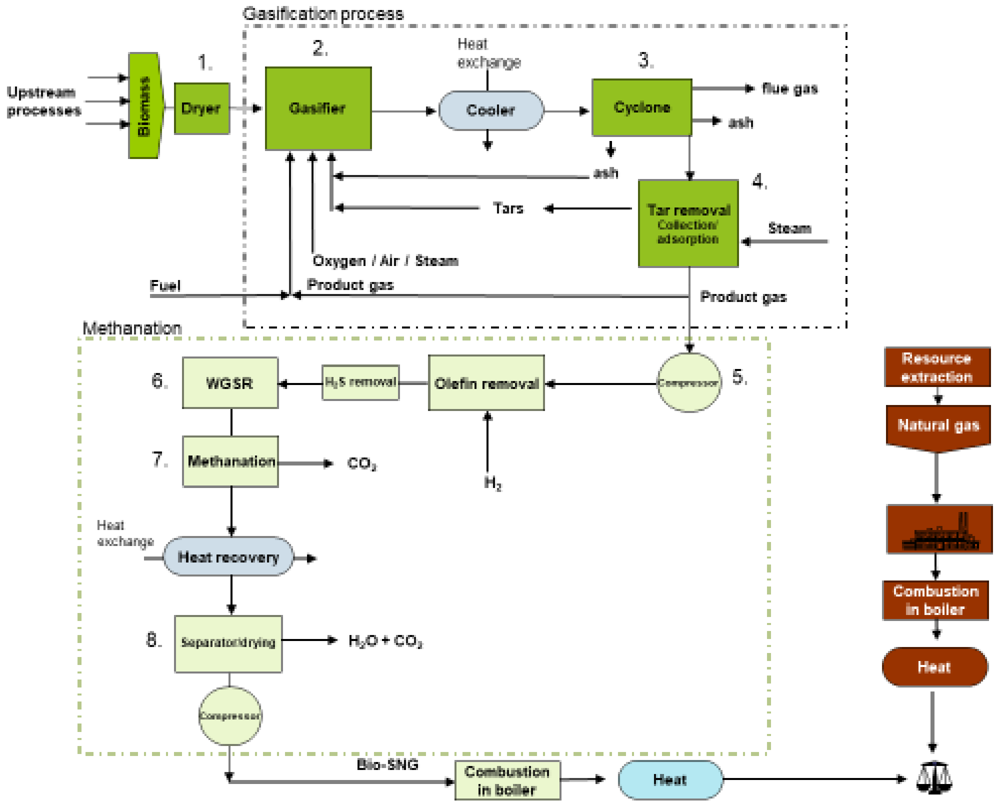

Figure 21: Detailed life cycle comparison for synthetic natural gas from poplar via gasification versus natural gas.

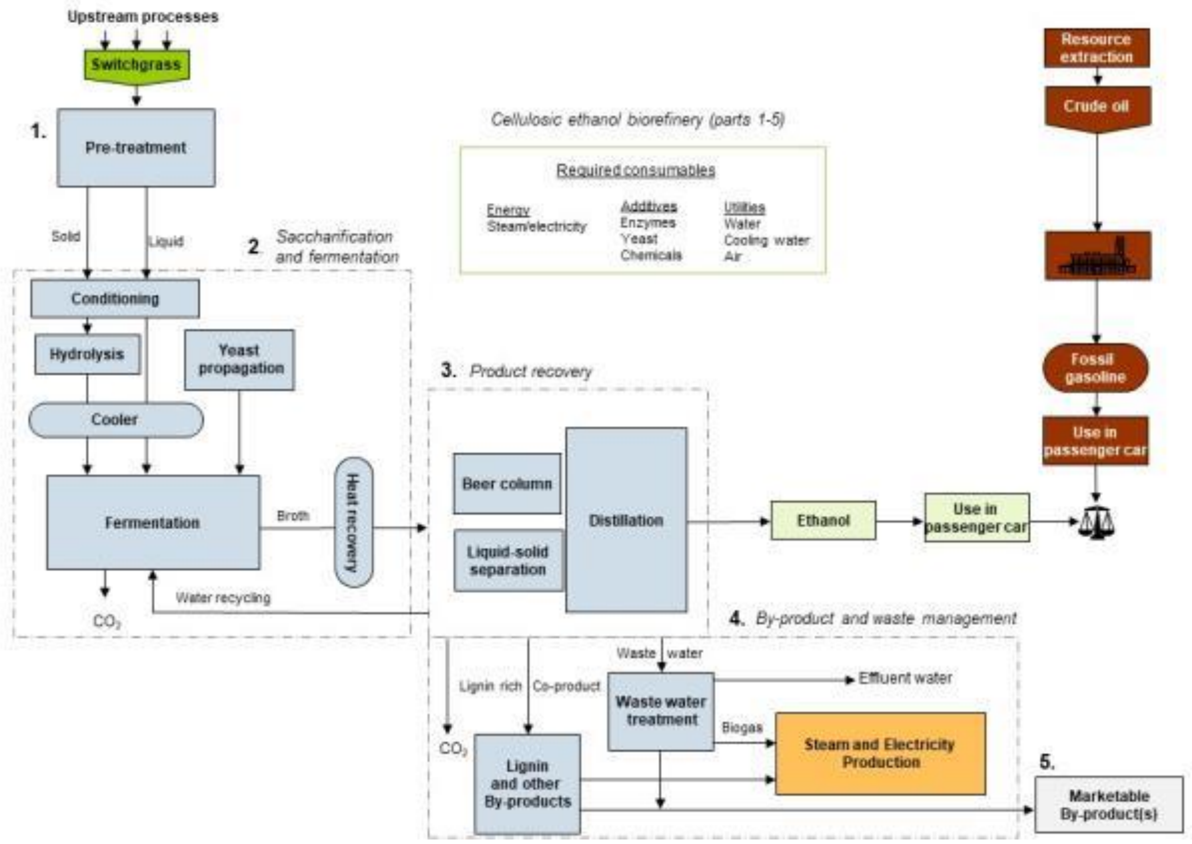

Figure 22: Detailed life cycle comparison for ethanol from switchgrass via hydrolysis & fermentation versus fossil gasoline.

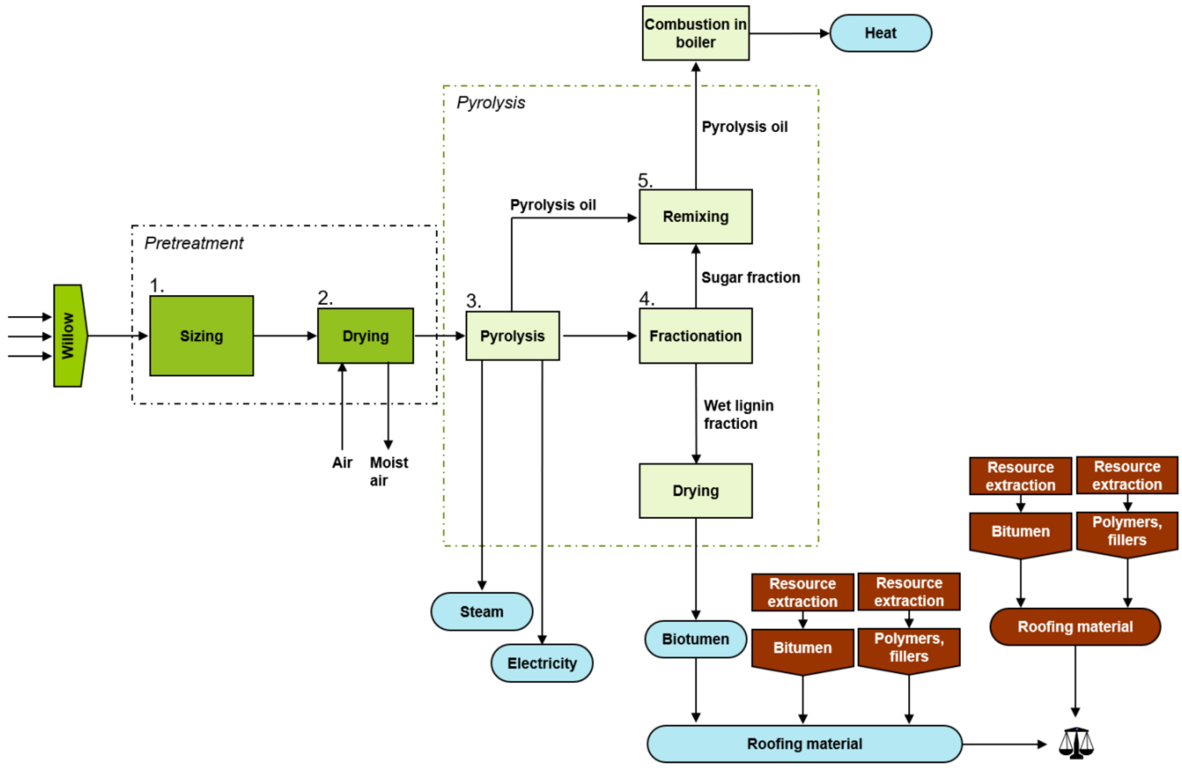

Figure 23: Detailed life cycle comparison for biotumen from willow via pyrolysis versus bitumen from fossil resources. A more detailed scheme for the pyrolysis section can be found in Figure 20.

Table 20: List of acronyms of chemicals used in Figure 24 and Figure 25.

Acronym	Full name	Acronym	Full name
C3	Propionic acid	FA	Fatty acid
C6	Caproic acid	FAME	Fatty acid methyl ester
C7	Heptanoic acid	H_2O	Water
C8	Octanoic acid	H_2O_2	Hydrogen Peroxide
C9	Pelargonic acid	H_2SO_4	Sulfuric acid
C16	Palmitic acid	H_2WO_4	Tungstic Acid
C18	Stearic acid	MeOH	Methanol
$Co(Ac)_2$	Cobalt Acetate	$NaHSO_4$	Sodium Bisulfate
CO_2	Carbon Dioxide	NaOH	Sodium Hydroxide
DC3	Malonic acid	O_2: Oxygen	Oxygen
DC8	Suberic acid		
DC9	Azelaic acid		
DC10	Sebacic acid		

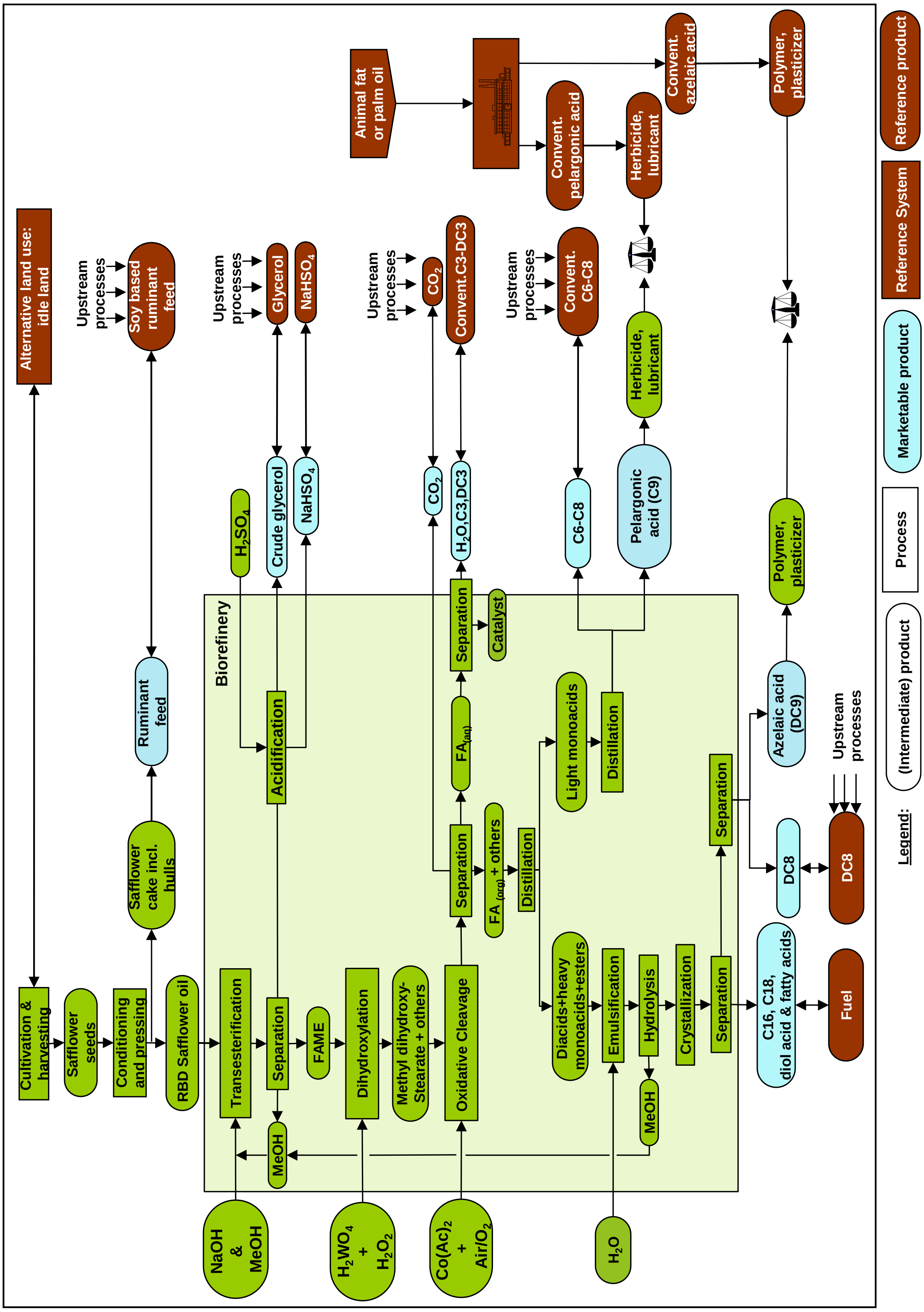

Figure 24: Detailed life cycle comparison for organic acids from safflower via oxidative cleavage versus organic acids from fossil resources. For acronyms please see Table 20 on p. 105.

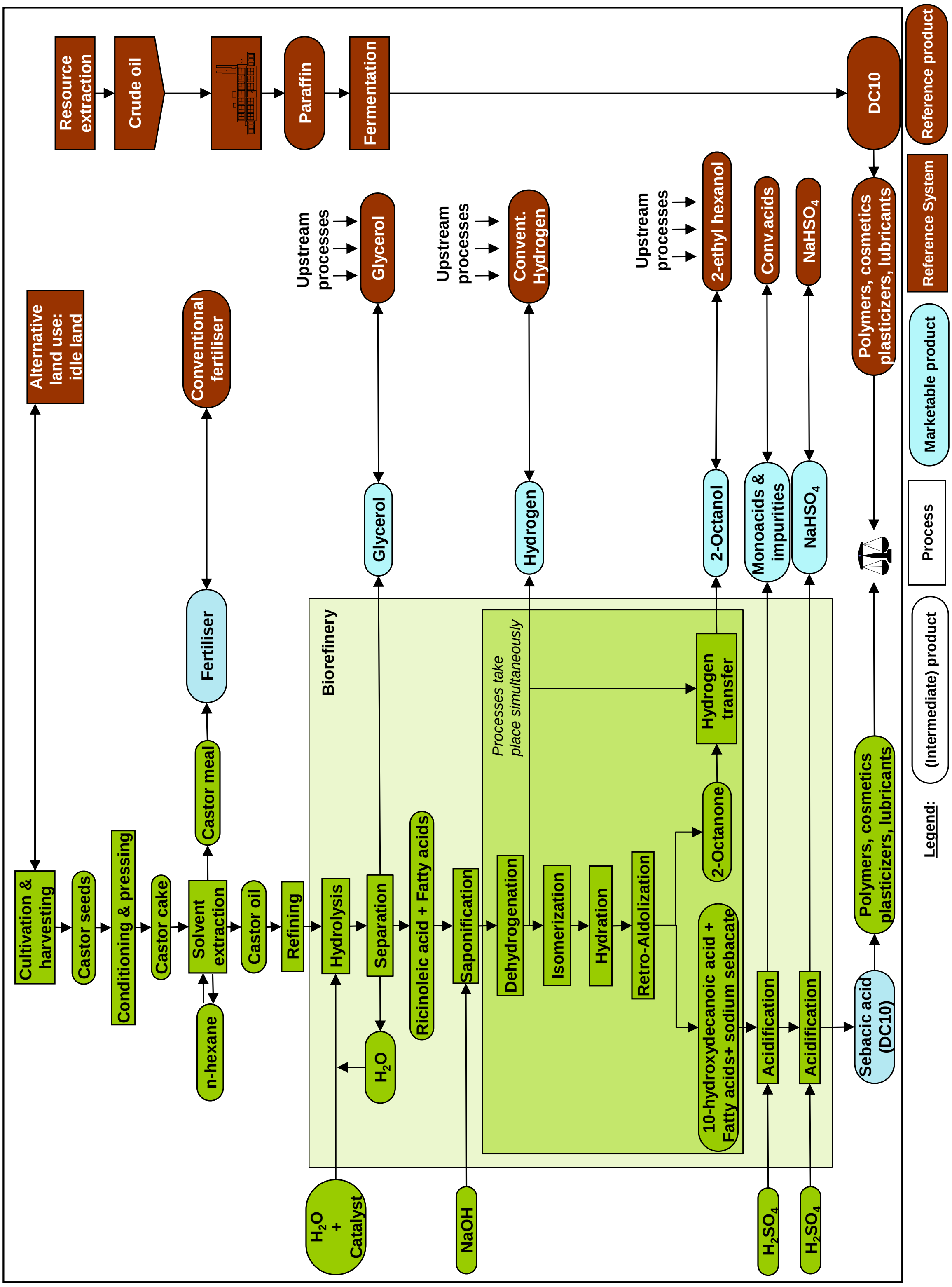

Figure 25: Detailed life cycle comparison for products derived from sebacic acid from castor oil (via alkaline cleavage) versus the same products from paraffins derived through fermentation of petroleum. For acronyms please see Table 20 on p. 105.

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