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Environmental Assessment of Growing Industrial Crops on Marginal Lands in Europe

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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.

As part of the comprehensive integrated life cycle sustainability assessment within MAGIC, the life cycle environmental impacts associated with nine selected value chains (combinations of industrial crops and biomass conversion technologies) were analysed in this study. In order to cover the range of potential environmental impacts as completely as possible, the environmental assessment combined two methods: screening Life Cycle Assessment (LCA) and Life Cycle Environmental Impact Assessment (LC-EIA).

A large number of both general and specific results have been compiled in chapters 4 (LCA) and 5 (LC-EIA). The key findings from both analyses are summarised in section 6.1.

Key conclusions:

- 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.

- 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.
- **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'.
- **There is competition of biomass with other renewables** (e.g. ground-mounted photovoltaic (PV) systems) **for the same marginal land**. These alternatives uses can be much more environmentally friendly.

- 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, the 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.

Recommendations:

- 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, this possibility is given:
  - Support programmes should clearly define the criteria by which marginal land is identified. In addition to the much-discussed biophysical criteria, 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**. 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 so-called indirect land-use changes (iLUC) can be avoided. The focus should therefore be on abandoned agricultural land.
  - Support programmes should **exclude the transformation of land that is worthy of environmental protection**. 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).

  - Support programmes should **exclude the use of land for which payments under agri-environmental programmes have been made in the last ten years**.
  - 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 not only at the national and/or supranational level, but also at the regional level. 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' 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.
- For the sustainable establishment of industrial crops, **it is essential to build up the farmers' competencies regarding the selection of suitable crops and varieties.** This could be realised through external advisory services or the MAGIC Decision Support System (DSS).

Further specific conclusions and recommendations can be found in sections 6.2 and 6.3, respectively.

Our research 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 renewable energy sources such as solar energy. Social aspects such as rural development and job creation should be considered in addition to economic aspects. 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 environmental implications associated with selected bioenergy carriers and bio-based products from industrial crops grown on marginal land in Europe and to highlight optimisation potentials. The environmental assessment provides answers to the goal questions defined earlier in the project (see [Rettenmaier 2018] and section 2.1.1).

In order to cover the spectrum of all potential environmental impacts as completely as possible, the environmental assessment was carried out using a combination of two methods: screening Life Cycle Assessment (LCA) and Life Cycle Environmental Impact Assessment (LC-EIA). MAGIC partner IFEU was responsible for the screening LCA part while partner FCT NOVA performed the LC-EIA. Methodological details are summarised in chapter 2, followed by a brief description of the selected value chains in chapter 3. Results are presented in chapters 4 and 5 for screening LCA and LC-EIA, respectively. The report closes with conclusions and recommendations in chapter 6.

2 Methods

The sustainability assessment in MAGIC is based on common goal, scope, definitions and settings for the environmental, economic and social analyses. They are a prerequisite of an overall sustainability assessment and highly affect its. They are described in section 2.1. Specific definitions and settings that are only relevant for LCA and LC-EIA in the environmental assessment are described in sections 2.2 and 2.3, respectively.

2.1 Common definitions and settings

A well-founded sustainability assessment requires common definitions and settings on which the environmental, economic and social assessment are based. Thus, general definitions and settings lead to an efficient professional communication between the project partners in WP6 and ensure consistent data and results for the sustainability assessment. For an extensive description of the overall definitions and settings see Deliverable D 6.1 [Rettenmaier 2018]. 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 environmental assessment.

For additional *specific* definitions, settings and methodological aspects of the two approaches of the environmental assessment please refer to sections 2.2 (LCA) and 2.3 (LC-EIA), respectively.

2.1.1 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 Decision context
- IV 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 three 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 Decision-context

The decision-context is one key criterion for determining the most appropriate methods for the so-called life cycle inventory (LCI) model, i.e. the LCI modelling principle. The International Reference Life Cycle Data System (ILCD) handbook differentiates three decision-context situations (see Table 1). These situations differ regarding the question whether the LCA study is to be used to support a decision on the analysed system (e.g. product or strategy), and,

- if so: by the extent of changes that the decision implies in the background system and in other systems because of market mechanism. These can be “small” (small-scale, non-structural) or “big” (large-scale, structural).
- if not so: whether the study is interested in interactions of the depicted systems with other systems (e.g. recycling credits) or not.

Consequences are considered large scale if the annual additional demand or supply, triggered by the analysed decision, exceeds the capacity of the annual replaced installed capacity of the additionally demanded or supplied process, product, or broader function, as applicable.

Situation B is considered to apply for the MAGIC value chains, since its main application is policy information and development. It is assumed that the implementation of biomass production and use chains developed within the MAGIC project could have consequences that are so extensive that they overcome threshold – via market mechanism – result in additionally installed or additionally decommissioned equipment / capacity (e.g. production infrastructure) somewhere else.

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

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

IV 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.

2.1.2 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 2006b; a], 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 1. On the one hand more distinctions would exceed the scope of the analysis and on the other hand conditions vary strongly across Europe.

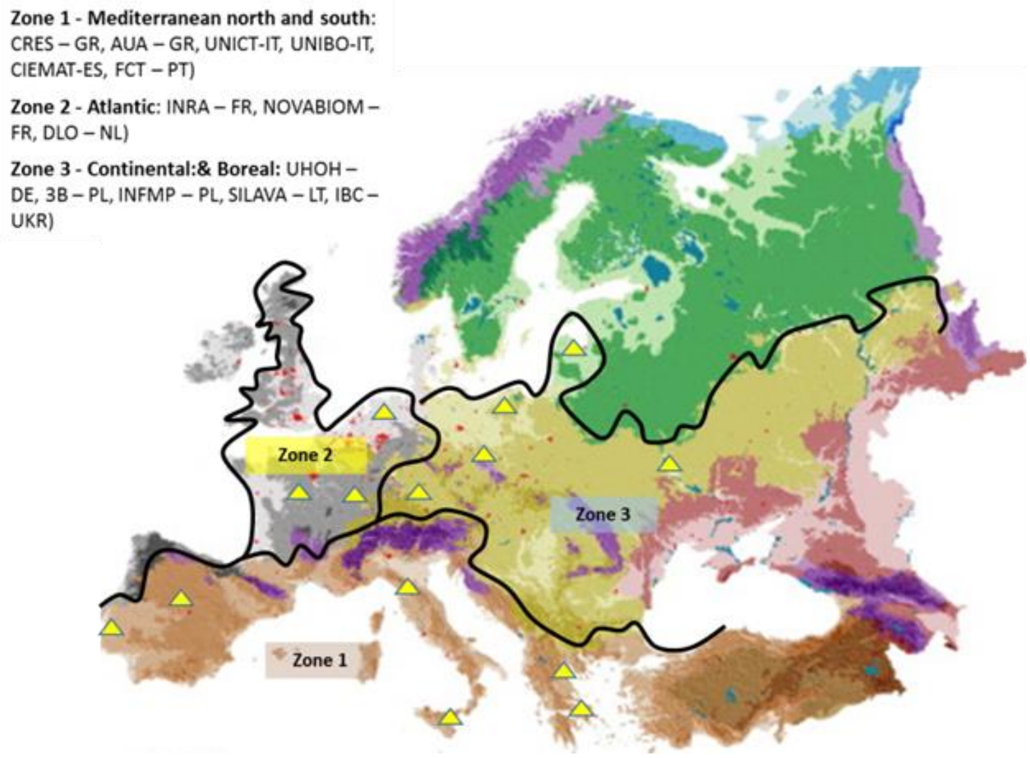

Figure 1: Major geographical/climatic zones in Europe; yellow spots indicate new and established field trials. Source: MAGIC Description of the Action (DoA)

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 2.1.2 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 2.1.1) 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 2):

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.

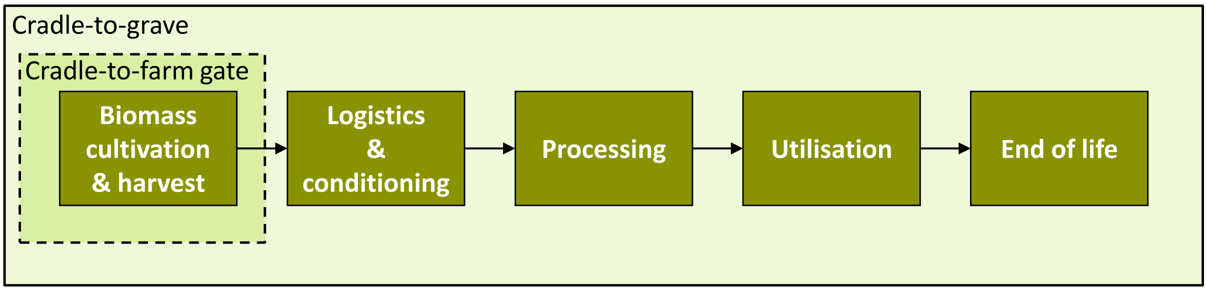

Figure 2: System boundaries from cradle-to-grave and from cradle-to-farm gate applied within the MAGIC project. Source: ifeu, own illustration

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 36).

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 (for more details on LULUC, see section 2.2.2 IV).

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 2.1.2 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 2:

Table 2: 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. As to the LCA-related data, see section 2.2.2 I.

2.2 Specific definitions and settings for LCA

The screening life cycle assessment (LCA) is based on international standards such as [ISO 2006a; b] and the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012]. In the following, specific settings and methodological choices are detailed.

2.2.1 Introduction to LCA methodology

Life cycle assessment (LCA) is structured, comprehensive and internationally standardised through ISO standards 14040:2006 and 14044:2006 [ISO 2006a; b]. The LCA within the MAGIC project is carried out largely following these standards on product life cycle assessment. According to the ISO standards, an LCA consists of four iterative phases (Figure 3):

- Goal and scope definition (see section 2.1),
- Inventory analysis (see section 2.2.2),
- Impact assessment (see section 2.2.3), and
- Interpretation (see chapter 4).

The ISO standards 14040 and 14044 provide the indispensable framework for life cycle assessment. This framework, however, leaves the individual LCA analysts with a range of choices, which can affect the legitimacy of the results of an LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance.

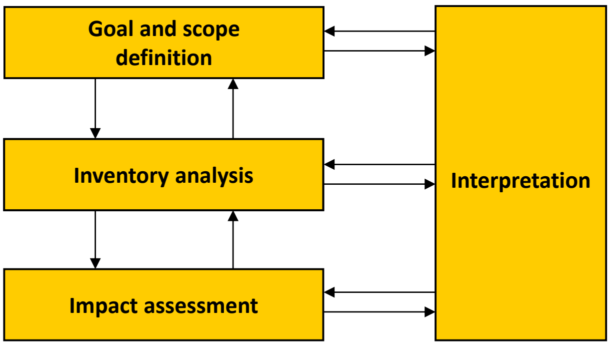

Figure 3: Phases of an LCA [ISO 2006a; b]

The International Reference Life Cycle Data System (ILCD) Handbook [JRC-IES 2012] has therefore been developed to provide guidance and specifications that go beyond the ISO standards 14040 and 14044, aiming at consistent and quality-assured life cycle assessment data and studies. The screening LCA study carried out within the MAGIC project takes into account the major requirements of the ILCD Handbook following these considerations of flexibility and strictness. The analyses in this study are so-called screening LCAs which follow the above mentioned ISO standards except for a) the level of detail of documentation, b) the quantity of sensitivity analyses and c) the mandatory critical review. Still, the results of these screening LCAs are suitable to answer the goal questions reliably due to the close conformity with the ISO standards.

2.2.2 Settings for Life Cycle Inventory (LCI)

Settings for Life Cycle Inventory include the following aspects:

- I Data sources
- II Attributional vs. consequential modelling
- III Co-products handling

- IV Land use and land use changes
- V Biogenic carbon
- VI Carbon storage in products and delayed emissions

I Data sources

In addition to the data sources outlined in section 2.1.2 VIII, further primary data as well as secondary data such as on background processes (provision of non-biomass material inputs such as fertilisers, and conventional reference products of the MAGIC products) were taken from IFEU's internal database [IFEU 2019], from the ecoinvent database [Ecoinvent 2018] and from literature data where necessary. A summary of this data can be found in section 9.1 in the annex.

II Attributional vs. consequential modelling

The sustainability assessment can follow a consequential or attributional approach, which has implications for the methodological approach for co-products, indirect effects, etc., especially in LCA. Consequential modelling is more extensive and “aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy” according to ILCD Handbook [JRC-IES 2010]. Consequential modelling is recommended for decision-contexts where influential impacts are expected on a meso/macro-level [JRC-IES 2010]. As pointed out in section 2.1.1 III, this is the case for the MAGIC systems. Hence, a consequential modelling approach is applied in this assessment.

There is only one exception to this: The accounting principles of the Renewable Energy Directive (RED II) stipulate that an attributional modelling approach is chosen. For the results shown in section 4.3.3 this methodological setting is applied accordingly.

III Co-products handling

As explained in section 2.1.2 V, the system boundary includes all products and co-products. For each usable co-product produced, the environmental burdens of the main product need to be reduced. The general alternatives concerning this procedure of co-product handling are exemplarily illustrated in Figure 4. For the main research questions defined in the MAGIC project, this is however less relevant, because the main aim is not to calculate environmental footprints of products but to find out how far environmental burdens can be mitigated by using a hectare of marginal land. In this case, it is less relevant if this mitigation is achieved by main products or co-products. Therefore, system expansion is applied, which according to ISO standards for LCA [ISO 2006a; b] is preferred over allocation: the impacts of a multi-output system are balanced with the avoided impacts of the reference products that are replaced by the products of the multi-output system.

Deviating from this general setting, the accounting principles of the Renewable Energy Directive (RED II) stipulate that multi-output processes are resolved by allocating the burdens among co-products according to their energy content. For the results shown in section 4.3.3, allocation is applied accordingly.

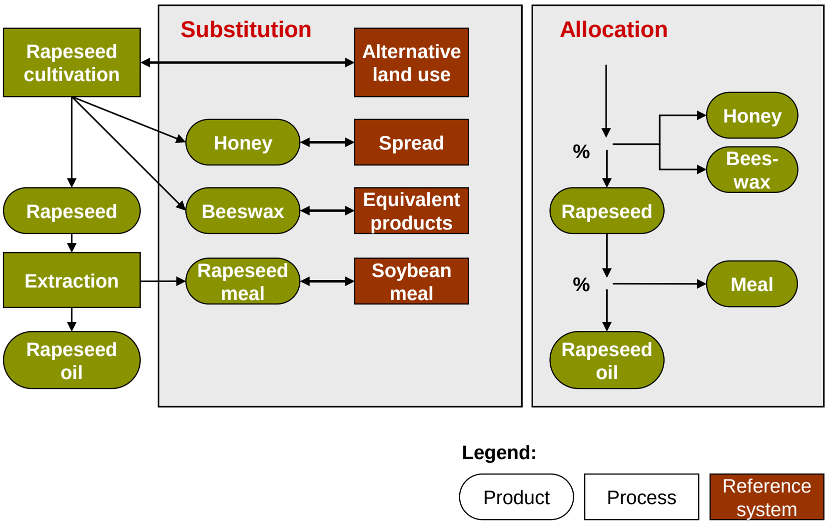

Figure 4: Exemplary illustration of methodological approaches for co-product accounting. Source: ifeu, own illustration

IV Land use and land use changes

Land use change (LUC) and land use (LU), in particular of organic soils, lead to emissions beyond those caused by cultivation as such. These have to be taken into account for any LCA of agricultural systems.

Assessment methods for LUC and LU effects of using marginal land

A multitude of LULUC assessment methodologies exist, which mainly consist of variants of the direct land use change (dLUC) and indirect land use change (iLUC) concepts. The use of previously unused land precludes iLUC, while dLUC can still be relevant as discussed above. The main question is to which land use and thus to which products direct LULUC effects should be attributed.

In other words, are burdens only attributed to the crop cultivated on marginal land or distributed via land use markets to e.g. all crops cultivated in the EU because limited land availability in general is the concern to be addressed. This depends on the study context. The reference system in this study is leaving the land unused and providing products from conventional (fossil) resources. This comparison is only valid and delivers useful answers if all LULUC effects are attributed to the crop cultivated on marginal land using the classical dLUC approach extended by LU (emissions from organic soils).

For standard agricultural land, the methodological approach abbreviated as ‘attributional land use and land use change (aLULUC)’ is applied for the inventory analysis. An elaborate explanation and discussion is reported in [Fehrenbach et al. 2020]. The main idea is to evenly allocate the burdens associated with both the use of agricultural land[1] and the land use changes that have taken place in one country to all agricultural land use of that country based on a land use market approach. Thus, for each country and class of agricultural land (e.g. annual cropland, grassland) one emission factor per hectare per year is obtained.

Marginal land is considered not to be part of the land use markets since the main idea of the MAGIC project is to avoid competition about standard agricultural land and thus LUC effects. Therefore, the aLULUC concept is not applied to marginal land. Instead, carbon stock changes from uncultivated marginal land (idle land) to cultivated land including carbon contained in biomass and soil are attributed to the use of marginal land. An amortisation time of 20 years is used for this purpose.

Expected and potential LUC and LU effects of using marginal land

The effect of taking marginal land into use crucially depends on the previous state this land is in. Very different types of land are often summarised as ‘marginal land’ and there is no clear definition of this term. According to its goal and scope, this study considers ‘marginal land’ to be unused for a while and therefore be covered by successional vegetation most appropriately described as grassland or woody grassland / shrubland (section 2.1.2).

This implies that successional vegetation has to be cleared and that carbon contained in it (above and below ground) will be released as CO_2. This can also affect the soil carbon content potentially leading to further CO_2 release. Both these one-time effects are summarised as LUC-induced emissions.

Additionally, the sites may consist of organic soils / peatland. This is mainly relevant in the Atlantic and Continental zone. In this case, additional greenhouse gases including CO_2, N_2O and CH_4 may be released if this land is drained for cultivation or if peatland re-wetting is prevented by this new use. These emissions can be considered continuous throughout the time of use because most organic soils contain so much carbon that it would take many decades to be released completely. Therefore, they are termed land use (LU)-induced emissions. Taken together, organic soils and peatlands contain twice as much carbon than all forests in this world [Parish et al. 2008].

The amount of released greenhouse gases can vary substantially especially depending of the former use, the humidity of the site and whether perennial or annual crops are planted. How the cultivation of marginal land could affect LUC and LU and how this could be assessed is analysed in detail in a dedicated section (section 4.3.1).

Deviating from this general setting, the accounting principles of the Renewable Energy Directive (RED II) stipulate the accounting of annualised emissions from carbon stock changes

[1] Mainly because of continuous emissions due to the agricultural use of organic soils.

caused by direct land-use change (dLUC) only. Continuous emissions from land use (LU) on drained organic soils / peatland are not accounted according to the calculation rules of the RED II. For the results shown in section 4.3.3, this is applied accordingly.

V Biogenic carbon

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

VI Carbon storage in products and delayed emissions

Carbon storage in products is expected to be much shorter than 100 years for all MAGIC products. Delayed emissions are therefore not taken into account in this study.

2.2.3 Settings for Life Cycle Impact Assessment (LCIA)

According to ISO standard 14040 [ISO 2006a], life cycle impact assessment (LCIA) includes the mandatory steps of classification and characterisation as well as the optional steps of normalisation and weighting. Classification and characterisation depend on the chosen impact categories and LCIA methods. Regarding the optional elements, only the normalisation step is applied within the MAGIC project. The corresponding specifications of these LCIA elements are described in the following sections including

- I Impact categories and LCIA methods
- II Special impact categories
- III Normalisation
- IV Weighting.

I Impact categories and LCIA methods

All main environmental issues related to the MAGIC value chains should be covered within the impact categories of the screening life cycle assessment in a comprehensive way. Furthermore, the impact categories must be consistent with the goal of the study and the intended applications of the results. This study addresses the midpoint indicators listed in Table 3.

Table 3: Overview on included midpoint impact categories. [Detzel et al. 2016]

Midpoint impact category	LCIA method
Non-renewable energy use (NREU)	[Borken et al. 1999; VDI (Association of German Engineers) 2012]
Climate change	[IPCC 2013]
Acidification	[CML 2016]
Eutrophication, terrestrial	[CML 2016]
Eutrophication, freshwater	[CML 2016]
Ozone depletion	[Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010]
Particulate matter	[de Leeuw 2002]
Summer smog (Photochemical ozone formation)	[van Zelm et al. 2008]
Phosphate rock use	[Reinhardt et al. 2019]
Land use	[Fehrenbach et al. 2019]
Water use	[Boulay et al. 2018]

Potential environmental impacts can be analysed at midpoint or at endpoint level. For the environmental assessment within the MAGIC project, the midpoint level is considered as more suitable than the endpoint level because the impacts are analysed in a more differentiated way and the results are more accurate. The specific impact categories at midpoint level are chosen according to the LCIA methods recommended by [Detzel et al. 2016].

This set of methods also includes three long-neglected impact categories covering environmental issues that are particularly affected by agricultural biomass production: phosphate rock footprint, land use footprint and water footprint:

- The phosphate rock use is mostly dominated by the crops' phosphorus requirements but other life cycle stages may also play an important role. The associated impacts on phosphorus resources are covered by the impact category "phosphate rock footprint" [Reinhardt et al. 2019].
- Impacts on natural land use are addressed by the hemeroby approach according to [Fehrenbach et al. 2015, 2019]. This approach includes both the degree of human influence on a natural area and the distance of that area to the undisturbed state.
- The water scarcity footprint is calculated based a water use midpoint indicator representing the relative Available WAter Remaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met [Boulay et al. 2018].

In this screening LCA, however, some impact categories are excluded for various reasons: Impact categories that are irrelevant for the MAGIC value chains are excluded from this study. This is the case for ionising radiation, for example. The reason behind this is that the selected impact categories should only cover the relevant environmental aspects of the MAGIC value chains to avoid an information overload.

Furthermore, impact categories are excluded (i) that are still under methodological development or (ii) that cannot ensure sufficient LCI data quality for the reference year 2030 (i.e.

impact categories on toxicity). Important ecotoxicity impacts on biodiversity and local impacts on water resources are analysed within the LC-EIA instead (see chapter 5). Specific issues on human health are nevertheless covered by the categories particulate matter formation and photochemical ozone formation.

II Normalisation

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

Within the MAGIC project, the value chains are characterised for Europe. Therefore, the resource demand and emissions per capita in the European region are chosen as reference for normalisation. Last available data from [Sala et al. 2015a] are taken. These values refer to the year 2010 and the EU 28 countries (see section 9.1 in the annex).

III Weighting

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

2.2.4 Greenhouse gas balances according to European legal requirements

In the light of a controversial discussion on the net benefit of biofuels and bioenergy and the share of renewable energy in the transport sector, the European Renewable Energy Directive (2009/28/EC, RED) on the promotion of the use of energy from renewable sources [European Parliament & Council of the European Union 2009] set out a mandatory share of 10% by the year 2020 and a number of sustainability criteria. These criteria had to be met by biofuels and bioliquids to be able to be counted towards this target of 10%.

The RED has been substantially amended several times and recast in 2018 [European Parliament & Council of the European Union 2018]. The sustainability criteria defined in the RED II are partly the same as in the original RED and partly new or reformulated. In particular, the RED II introduces sustainability criteria for forestry feedstocks as well as GHG criteria for solid and gaseous biomass fuels. These requirements influence the marketing opportunities of biofuels within Europe. Biofuels that comply with the defined criteria have better chances on the market. Therefore, biofuel producers are interested if their biofuels fulfil the criteria or not. However, these criteria are not crucial for political decision and strategies only.

Within the MAGIC project, the climate change-related criteria of the RED II are most important: the greenhouse gas (GHG) emission savings from the use of biomass fuels. In the transport sector, the emission saving shall be at least 60% (after October 2015), increasing to 65% after January 2021 – including emissions from direct land-use changes (dLUC) – compared to the defined emissions of the fossil fuel comparator. For electricity, heating and cooling, the emission saving shall be at least 70% after January 2021.

The rules for calculating the GHG impact are defined in two annexes to the RED II: Annex V for biofuels and bioliquids and Annex VI for biomass fuels, respectively. These rules follow a more pragmatic approach and differ considerably from the ISO standards 14040 and 14044 (see section 2.2.2). Therefore, the results of the alternative calculation of GHG emissions according to the European legal requirements for biofuels is presented as a special topic in section 4.3.3, using the example of (ligno-)cellulosic ethanol (see chapter 3).

2.3 Specific definitions and settings for LC-EIA

This part of the report addresses the local environmental impacts with a generic (life-cycle) approach, which are not yet being considered in state-of-the-art LCAs. It covers impacts such as on fauna and flora, on soil and on water and uses elements from an environmental impact assessment (EIA), a standardised methodology for analysing the potential environmental impact of proposed projects. This study was developed and applied on selected value chains linked with the cultivation of different industrial crops in marginal soils in Europe.

In this study, several categories directly related with local environmental impacts (e.g. biodiversity and landscape) were chosen. The influence of the crops traits and of the processing options, and the influence of the farming and of the processing unit location were also investigated. Overall interactions and similarities or equalities were pointed out. Environmental hot spots in the systems were detected and options for improvement were presented.

The assessment focuses on local environmental effects. Data are collected and evaluated on that level. The environmental impact analysis of a crop value chain requires good knowledge of the cultivation operations, the requirements and the productivity of the various crops in different climates, soil types and methods of cultivation, knowledge on its processing, use and disposal. There is not a general list of criteria to assess the environmental impact nor a general description of methods to be used. Fixing the environmental criteria is part of the EIA process. Usually criteria address emissions to soil, ground and surface waters and air, effects on living environment and health of people in the surroundings, effects on surrounding ecosystems, and effects on cultural assets. In this study we followed the approach suggested by [Biewinga & van der Bijl 1996] and adjusted by [Fernando et al. 2010]. The focus is on the impact of cultivation, processing, use and disposal on biotic and abiotic resources, through the analysis of the crop's value chain interaction with its environment and management practices. In the assessment of the local environmental impacts, the study was divided in 3 parts:

1) Evaluation of the impacts of the different cropping systems, EIA – Cultivation phase;
2) Evaluation of the impacts of the different processing technologies, EIA – processing;
3) Evaluation of the impacts of the selected value chains, EIA – value chains.

To determine the environmental impact of the cultivation of the selected industrial crops on marginal land and their use, different categories were studied: emissions to soil, ground and surface waters and air, effects on the quality of soil and on water resources, use of mineral resources and waste generation, and biological and landscape diversity. Each of these categories comprises different indicators (Table 4). The collection of data represents both literature review and our own experience which includes published and unpublished data associated with the MAGIC project and with previous projects.

Table 4: Environmental impact assessment methodological steps for each impact category

Category	Indicator	Assessment steps
Emissions to soil, water and air	Fertilizer emissions	An estimation of the amounts of minerals (N, P, K) used and their removal with the crop can show whether there is a mineral build-up in the soil or the reverse. Although high N, P and K content of the soil favours soil fertility, there is the risk that an excess of plant-available nutrients in the soil may be lost through future leaching or erosion, an important fact regarding the long-term fertility of the soil and the eutrophication of soil and water.
	Pesticide emissions	Concerning the quality of soil, ground and surface water and air, one of the most serious problems is pollution by pesticides. The amount of emission is affected by the amount of pesticides used and characteristics of the pesticide.
Biodiversity		Literature review and evaluation of generic effects of the systems regarding: i. biodiversity disturbance as related to management practices and intensity; ii. aggressiveness, nativeness and allelopathy; iii. reported increase or decrease of abundance and diversity of floral and faunal species.
Impact on soil	Nutrient status (NS)	Calculation of nutrient status (nitrogen (N), phosphorus (P), potassium (K)) in the soil: Balance = input – output (including gases emissions, for N) At each stage, transformation of the nutrient status for N, P and K in a score: results obtained for N, P and K were scored quantitatively from lower impact to higher impact. Soil nutrient status result in each stage or along the life cycle is an average of the three different scores (N, P and K).
	Erosion (E)	Calculation of harmful rainfall by evaluating: i. Biogenic system: soil cover along the crop development phases from start of growth, to closure of crop, to start of senescence and harvest.; soil disturbance during processing and use; ii. Conventional system: soil disturbance during extraction, processing and use; iii. Estimation of a soil cover ratio and level of disturbance (C-value) for each phase and system and of a regional amount of rainfall in each phase (R-value). iv. Assessment of an erosion control factor (P-value) reflecting the intensity of erosion control in each region v. Calculation of the harmful rainfall: Total harmful rainfall $= \sum(C \times R)_{stage\ and\ region} \times P_{region}$ vi. Transformation of the harmful rainfall in a score: results were scored quantitatively from lower impact or higher impact.
	Soil properties	Literature survey of the negative and/or positive impacts of each system on structure, organic matter and pH.

Landscape		Evaluation of the variation of systems scene in terms of structure (height, density, heterogeneity and openness) and colour. Variation was considered to be a benefit when gains in structure and/or colour were noticed. Variation implying loss of structure and/or colour debited the landscape values.
Waste production and utilisation		An inventory of waste products used and produced during biomass cropping will be performed. In this qualitative approach, each of them will be judge positively or negatively.
Impact on water and mineral resources	Groundwater depletion (G)	i. Quantification of system's water requirement. ii. Quantification of rainfall and water available to the system along the life cycle. iii. Calculation of soil water balance: *Groundwater balance = irrigation + rainfall – water requirement* iv. Transformation of the groundwater balance in a score: results were scored quantitatively from lower impact or higher impact.
	Effects on hydrology (H)	Effects on water flow and run-off and on refill of aquifers as influenced by: i. Biogenic system: crop permanence on soil, crop water needs; crop root system, harvesting, processing and use ii. Conventional system: extraction, processing and use iii. Transformation of the effects on hydrology in a score: results were scored quantitatively from lower impact or higher impact.
	Use of mineral resources	The use of mineral resources, i.e. withdrawal of materials from the environment, can lead to exhaustion. In this study, the use of phosphate and potash fertilizer, as a criterion for the exhaustion of fertilizer ores will be assessed.

Impacts of cultivation, conversion, use-phase and end of life of the biogenic systems were compared with the conventional reference system life cycle. In this assessment, analysis of the biogenic/conventional system interaction with its environment and management practices was executed. Issues related to the toxicity burden and time required to restore the land to its native condition, as well as the ability for it, were taken into account. The different cropping systems were compared with idle land and also with wheat and maize cultivation systems. The analysis made was a semi-quantitative one (some categories were analysed qualitatively by comparison the conventional ones, some other categories were analysed quantitatively, but after translated to a qualitative format).

3 Analysed systems

The environmental 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.

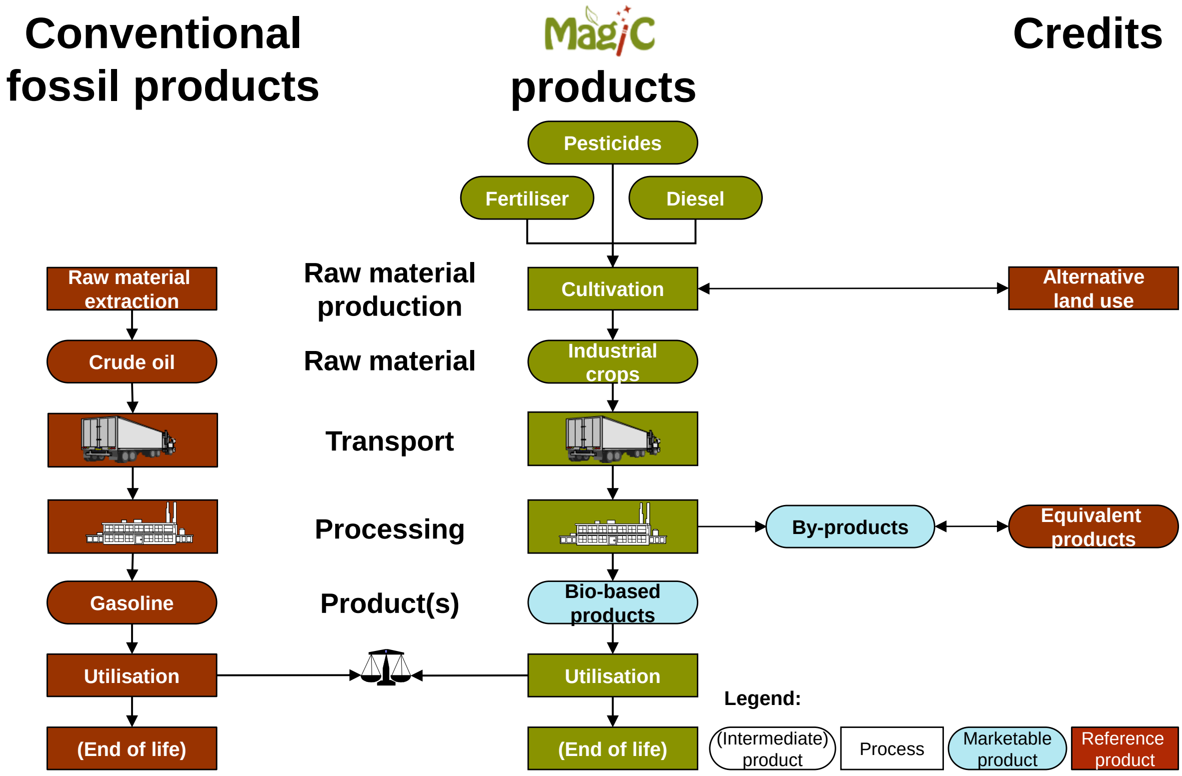

Figure 5: Sustainability assessment within the MAGIC project. The MAGIC bio-based products are compared to conventional reference products, both along the entire life cycle. Source: ifeu, own illustration

Ten value chains have been selected for in-depth analysis within the sustainability assessment in the framework of an internal project workshop on selection of value chains and interlinkages (MS6.2 / MS18).

An overview of the ten selected value chains is given in Table 5. It shows a good representation of:

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

Table 5: 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)	energy
Poplar	Gasification	Energy (SNG)	energy
Switchgrass	Fermentation	Ethanol	fuels
Willow	Pyrolysis	Biochemicals (biotumen)	materials
Safflower (high oleic)	Oxidative cleavage	Azelaic and pelargonic acid	chemicals
Camelina (high oleic)	Metathesis	Methyl decenoate	chemicals
Castor	Alkaline cleavage	Sebacic acid	chemicals
Industrial hemp	Mechanical processing	Insulation material	materials
Sorghum	Anaerobic digestion	a) heat & power b) biomethane	energy
Lupin	Extraction	Adhesives	chemicals / materials

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 2.1.2 VIII and in section 9.1 of the annex. 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 2.1.2 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 Results: Life Cycle Assessment

A screening life cycle assessment (LCA) was carried out for nine selected industrial crops grown on marginal land and used for different purposes (for details on the methods see sections 2.1 / 2.2). In the following, the results are presented. First, an overview is given in section 4.1. Second, each of the nine value chain is discussed individually in section 4.2. Third, the results for overarching special topics are presented in section 4.3.

4.1 Result Overview

In the following, we explain how the figures presented in the subsequent section 4.2 are generated, starting from stacked bar charts displaying results by contributions of life cycle steps, to charts showing ranges of net results for life cycle comparisons and to line charts.

Exemplary LCA results for industrial heat from Miscanthus compared to industrial heat from natural gas are presented in Figure 6. Greenhouse gas (GHG) emissions mainly arise due to fertilisation, land occupation, logistics and conversion. As these GHG emissions are outweighed by credits due to the substitution of natural gas, a net advantage is achieved on the bottom line. Regarding acidification, the emissions (especially from conversion) are higher than the credits for replacing natural gas which results in a net disadvantage for Miscanthus.

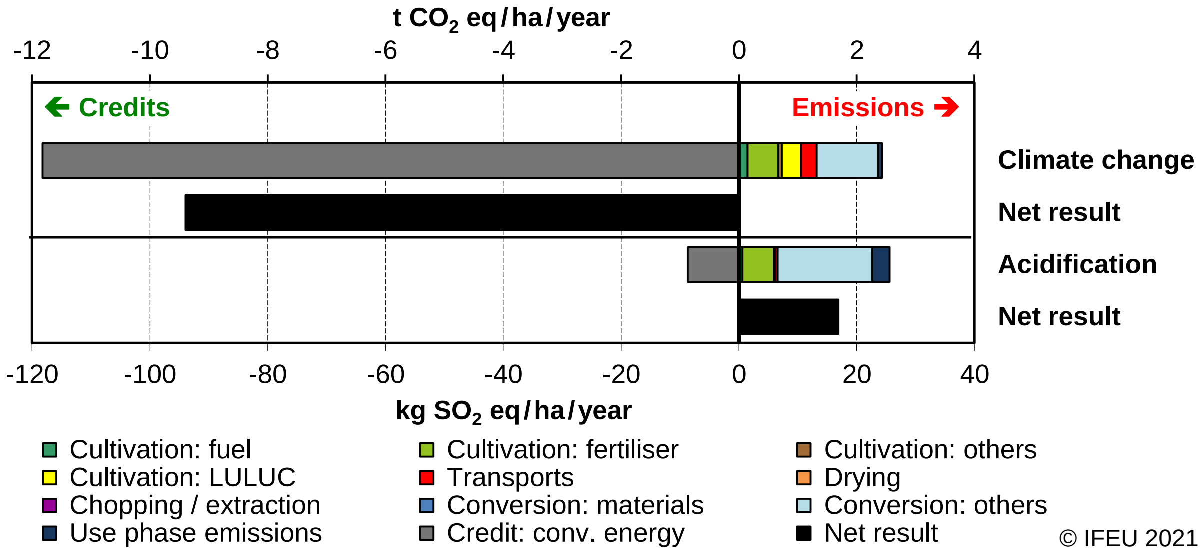

Figure 6: LCA results for industrial heat from Miscanthus compared to industrial heat from natural gas for the impact categories climate change and acidification at a yield of 12.5 t_{DM}/ha/yr.
How to read the figure: The 1st bar illustrates that industrial heat from Miscanthus grown on 1 ha of marginal land causes annual GHG emissions of about 2 t CO_2 eq. The substitution of industrial heat from natural gas can save almost 12 t CO_2 eq. In sum (2nd bar), GHG emissions of about 9.5 t CO_2 eq can be saved.

In Figure 6, the results for the impact category 'climate change' and 'acidification' are expressed in t CO_2 eq and kg SO_2 eq, respectively. To make impact categories comparable, the results are normalised to inhabitant equivalents in Figure 7 (see section 2.2.3 III).

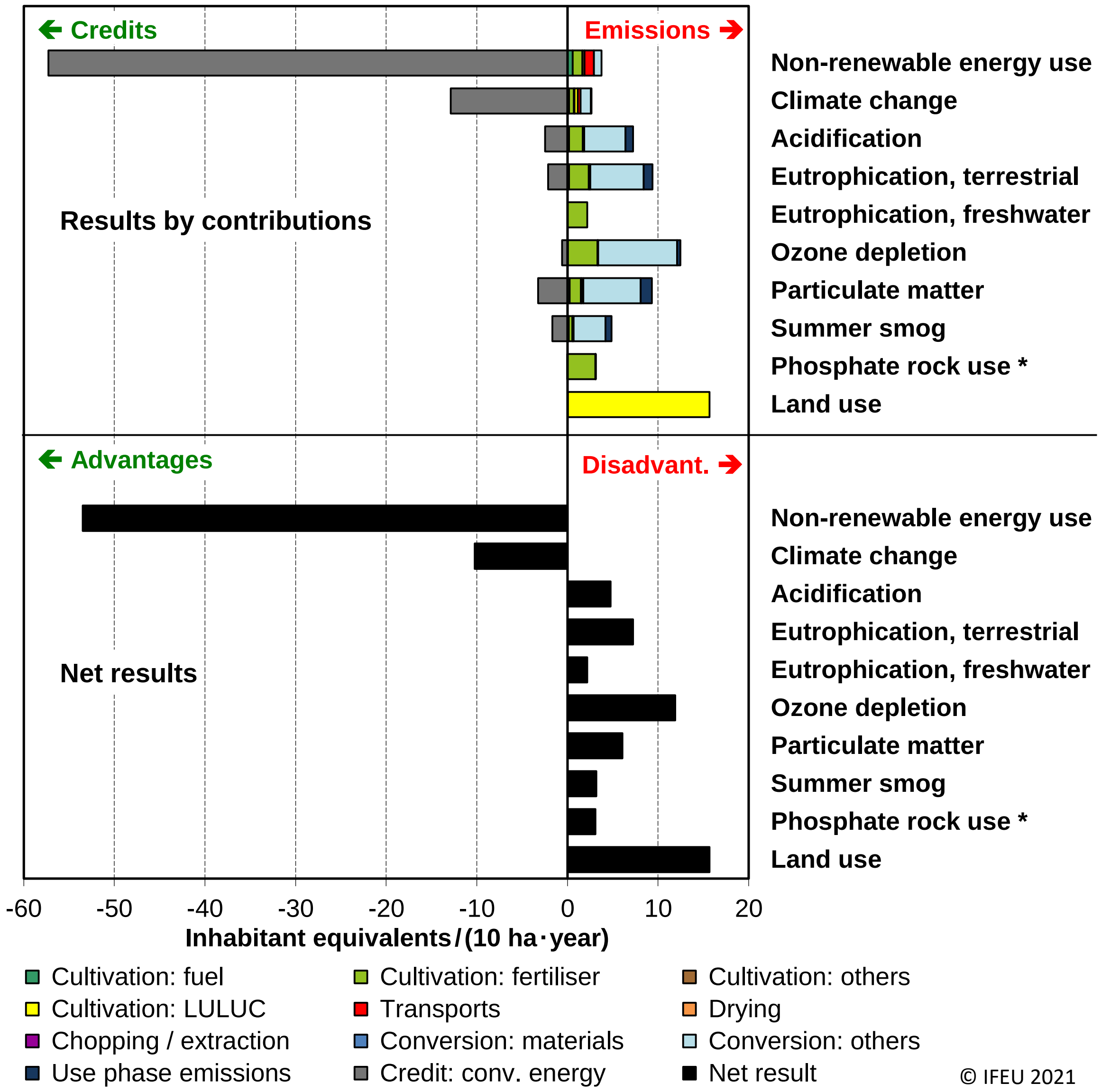

Figure 7: Normalised LCA results (given in inhabitant equivalents) for all impact categories for industrial heat from Miscanthus compared to industrial heat from natural gas at a yield of 12.5 t_{DM}/ha/yr. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results. * results for phosphate rock use: multiply by 10.

How to read the figure: The 2nd bar in the lower panel illustrates that industrial heat from Miscanthus grown on 10 ha of marginal land can save GHG emissions equal to the average annual GHG emissions of about 10 EU inhabitants (equal to 93.9 t CO_2 eq).

Key findings as illustrated in Figure 7:

- Top: the individual life stages contribute to the individual impact categories to a varying degree
- Bottom: a pattern of advantages and disadvantages becomes apparent in the net results

Figure 6 and Figure 7 show LCA results for only one specific yield level of Miscanthus. However, yield levels can vary significantly depending on the climatic and soil conditions for cultivation at different locations. Figure 8 presents the results of the life cycle GHG balance for very low to high yields. Every second bar (green colour) represents the net result. Different net results can be combined to a range, as it is done with the bar at the bottom. The yield level 'high' is not considered for the range bar since such high yields are rarely obtained on marginal land).

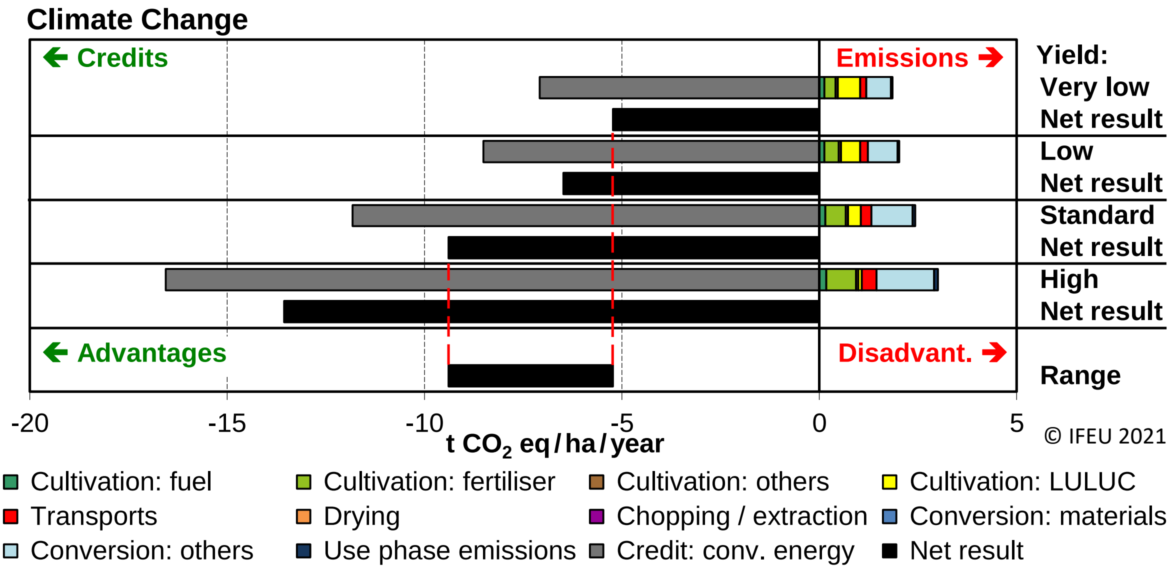

Figure 8: LCA results for industrial heat from Miscanthus (compared to industrial heat from fossil energy carriers) in the Mediterranean zone (AEZ 1) for the impact category climate change at yield levels ranging from "Very low" to "High".

How to read the figure: The bar at the bottom shows that industrial heat from Miscanthus grown on marginal land can save GHG emissions of about 5-14 t CO_2 eq per annum. It demonstrates how the ranges in the following Figure 9 are generated.

Key finding as illustrated in Figure 8:

- The quantitative results of the GHG balance strongly depend on the yield. The higher the yield, the greater the advantages associated with this environmental impact.

Similarly, ranges can also be obtained for the other impact categories, again mostly as a function of yield. This is shown in Figure 9, which provides an overview of the results for all value chains. In Figure 9 (and in section 4.2), the reader will notice that in contrast to most other impact categories, the results for the impact category 'land use' are within a relatively small range across all yield levels for most of the crops. This is because in most of the figures, the results are referred to 1 ha per year for which the quality-weighted land occupation is constant for all yield levels. Obvious exceptions are safflower and hemp, whose co-products replace other bio-based products and associated land use, with the credit increasing with increasing co-product yield.

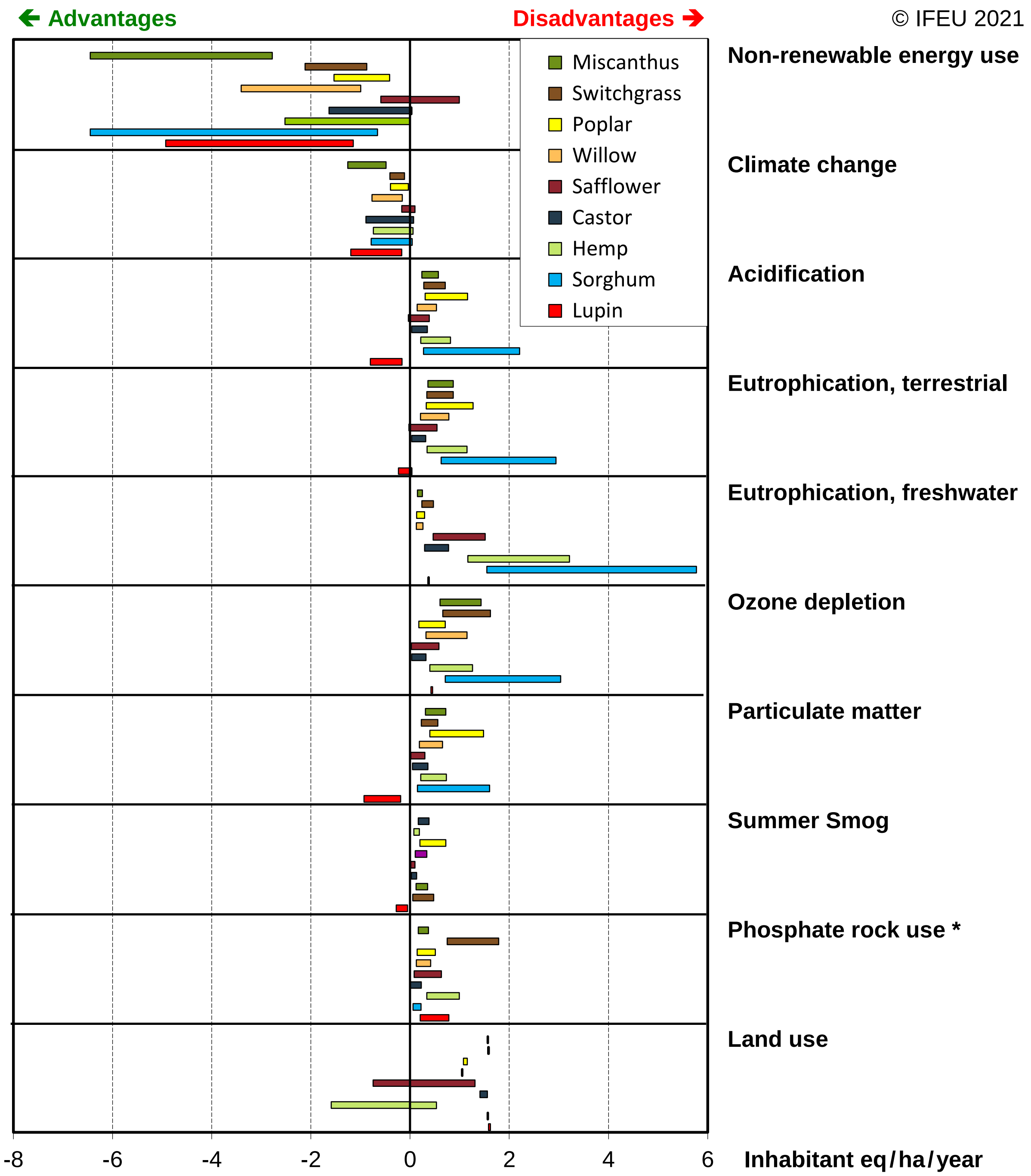

Figure 9: Ranges of LCA results for all bio-based value chains (compared to conventional reference products) and all impact categories across all yields and agro-ecological zones. * results for phosphate rock use: multiply by 10.

How to read the figure: The second bar from the top illustrates that replacing fossil gasoline with ethanol from switchgrass grown on 1 ha marginal land can save non-renewable energy equal to the average annual non-renewable energy demand of about 1 to 2 EU inhabitants.

Key findings as illustrated in Figure 9:

- The well-known pattern of environmental advantages in terms of fossil energy savings and global warming, and disadvantages in terms of some agriculture-dominated environmental impacts, also applies to cultivation on marginal land.
- The main difference between bio-based products from marginal land compared to standard land is the yield, which acts as a scaling factor for both environmental benefits and disadvantages.

In the following section 4.2, the net results for all impact categories will be presented as a function of yield using a line chart. Figure 10 presents how these line charts are generated by using the LCA results for very low to high yields. In contrast to the previous figures, the bars are vertical. Every second bar (green colour) represents the net result. These net results can be connected to a (mostly straight) line. In this way decreasing or increasing results as a function of yield can be displayed by ascending or sloping lines.

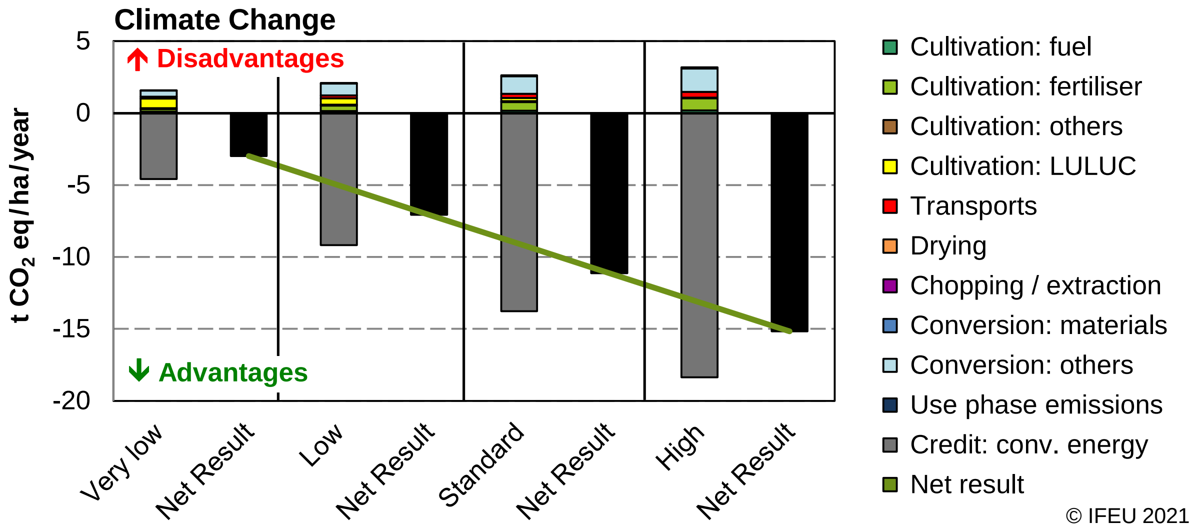

Figure 10: LCA results for industrial heat from Miscanthus (compared to industrial heat from natural gas) in the Mediterranean zone (AEZ 1) for the impact category climate change at yield levels ranging from “Very low” to “High”.

How to read the figure: The green line depicts the net results as a function of yield to demonstrate how the line graphs with the LCA results in the following section 4.2 are generated.

4.2 Crop-specific results

In this section, the results of the screening LCAs for the nine value chains are presented.

4.2.1 Miscanthus: industrial heat via pyrolysis

In this section, the results of the screening LCA for industrial heat from Miscanthus are presented, compared to industrial heat from fossil energy carriers. Details on the value chains and methods used are found in sections 9.1 and 2.1 / 2.2, respectively.

All impact categories

The LCA results for all environmental impact categories are shown in Figure 11.

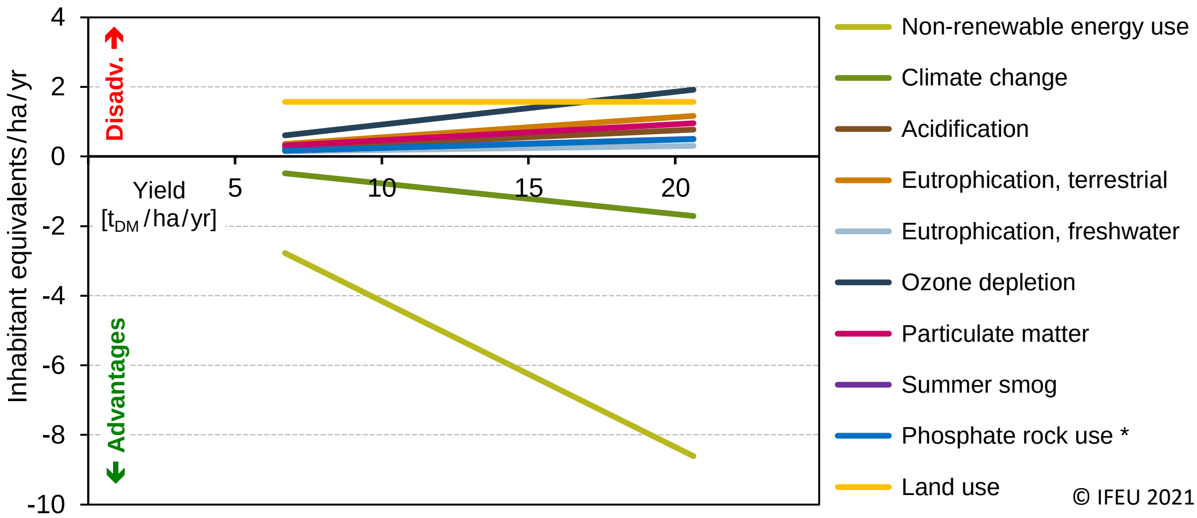

Figure 11: LCA results for industrial heat from Miscanthus (via pyrolysis) versus industrial heat from natural gas. * results for phosphate rock use: multiply by 10.

How to read the figure: The lowest straight illustrates that at a yield of 15 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of about 6 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as freshwater eutrophication and summer smog.
- An exception to this is the constant land use footprint: the quality-assessed land occupation by Miscanthus cultivation is the same for all yields and is not influenced by bio-based auxiliaries or reference products.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 12 illustrates the greenhouse gas emission savings that could be achieved by growing Miscanthus on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 11 and the results and conclusions listed in those sections apply qualitatively.

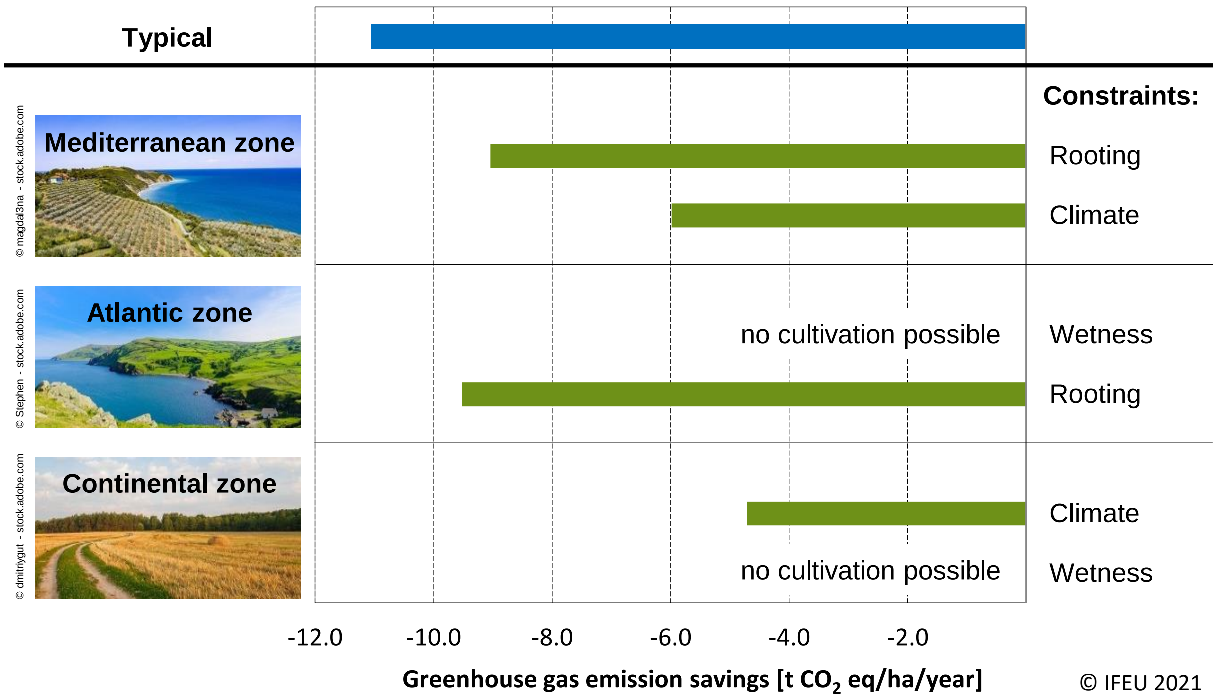

Figure 12: GHG emission savings for industrial heat from Miscanthus (via pyrolysis) versus industrial heat from natural gas for two biophysical constraints each in the three agro-ecological zones.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

Variation of reference products: substituted heat production

The chosen reference product has a great impact on LCA results. The previous results compare industrial heat from Miscanthus to industrial heat from natural gas. In this section, two additional fossil energy carriers are considered as reference products. Figure 13 shows the resulting effects for a yield level of 9.0 t_{DM}/ha/yr.

For example the substitution of light fuel oil is related to higher credits for industrial heat from Miscanthus, which means greater overall advantages and lower disadvantages than the substitution of natural gas. This is because heat from light fuel oil is related to larger CO_2, NO_x and SO_2 emissions per MJ than heat from natural gas. This is even more the case for industrial heat from coal. Altogether, this confirms the results of [Rettenmaier et al. 2015].

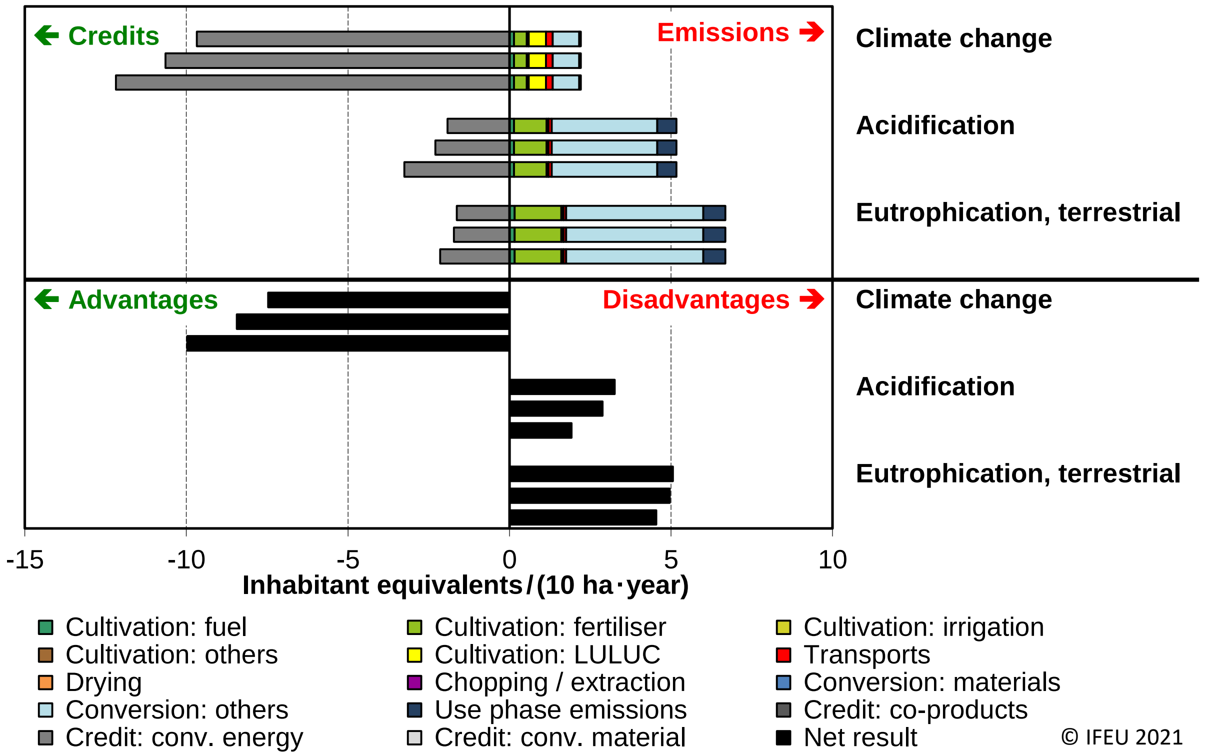

Figure 13: Impact of the energy carrier used for conventional heat production on the LCA results for industrial heat from Miscanthus versus industrial heat from natural gas (upper bars), from light fuel oil (middle bars) and from coal (lower bars) for selected impact categories.

Key findings:

- In addition to yield, there is a number of other factors that determine results. These include the substituted conventional product (also known as the reference product). Depending on this, a partly considerable range is obtained.
- In order to achieve the greatest possible environmental advantages, the energy use of Miscanthus for industrial heat should therefore first substitute those energy carriers that have a particularly large environmental footprint.

4.2.2 Poplar: synthetic natural gas via gasification

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The results of the screening LCA for synthetic natural gas from poplar are presented in this section, compared to natural gas. Details on the value chains and methods used are found in sections 9.2.2 and 2.1 / 2.2, respectively.

All impact categories

In Figure 14, the LCA results for all environmental impact categories are given.

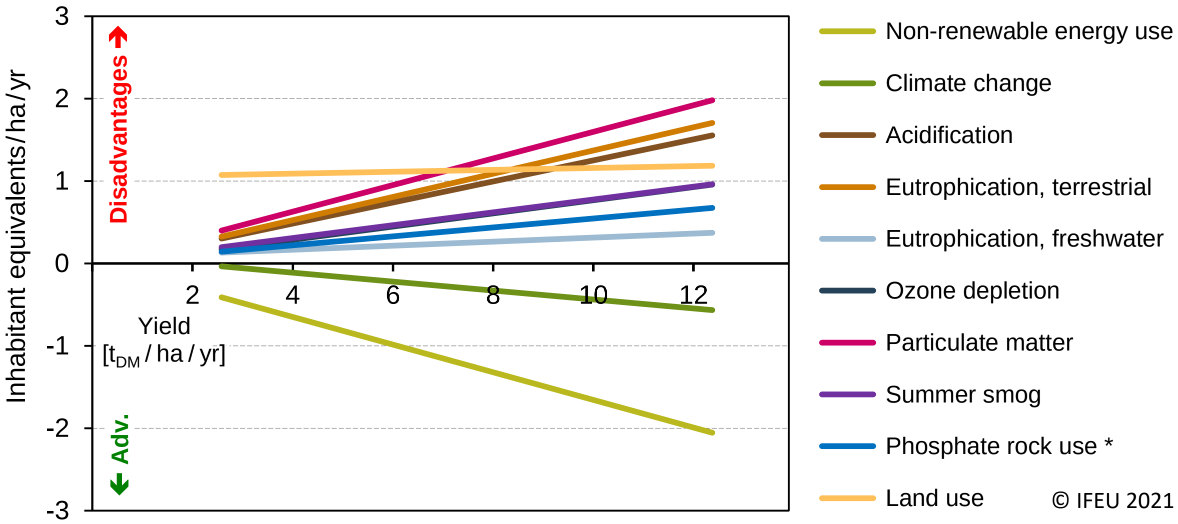

Figure 14: LCA results for synthetic natural gas from poplar (via gasification) versus natural gas. * results for phosphate rock use: multiply by 10.

How to read the figure: The lowest straight illustrates that at a yield of 12 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 2 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as freshwater eutrophication.
- Although the quality-assessed land occupation due to poplar cultivation is the same for all yields, the land use footprint increases slightly due to the use of bio-based auxiliaries which have their own land use footprint (here: RME) in the conversion process, of which larger quantities are required at higher poplar yields.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 15 illustrates the greenhouse gas emission savings that could be achieved by growing poplar on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 14 and the results and conclusions listed in those sections apply qualitatively.

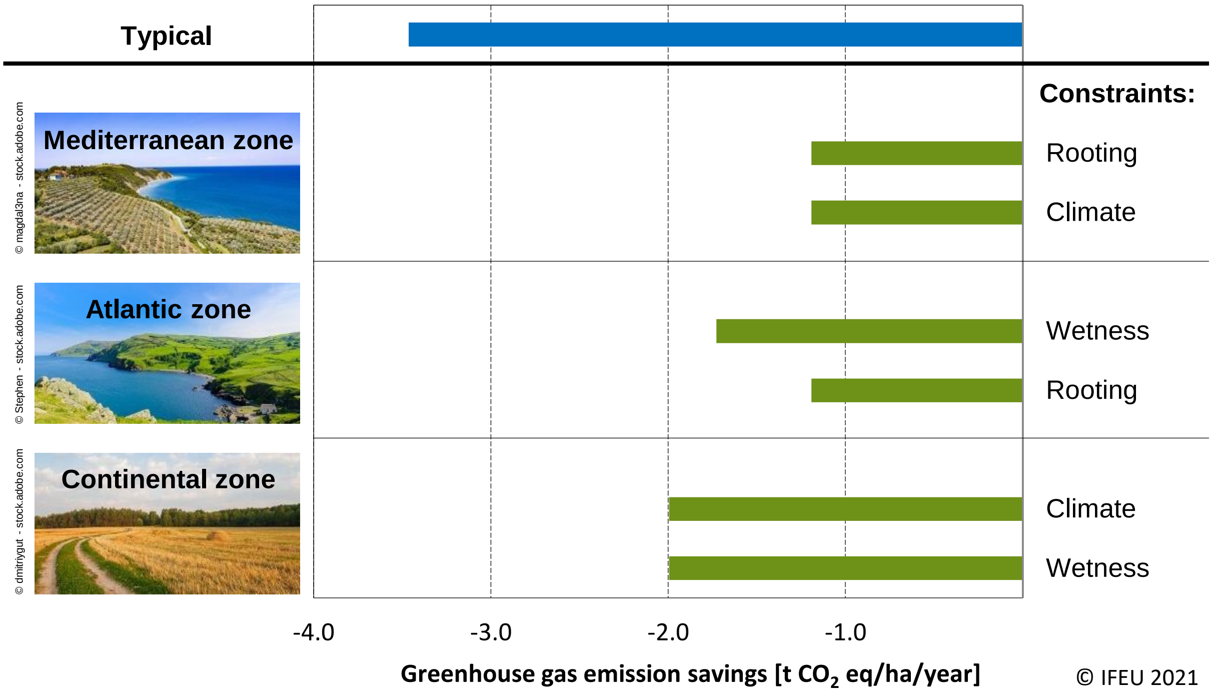

Figure 15: GHG emission savings for synthetic natural gas from poplar (via gasification) versus natural gas for two biophysical constraints each in the three agro-ecological zones.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

4.2.3 Switchgrass: Ethanol via hydrolysis and fermentation

In the following, the results of the screening LCA for ethanol from switchgrass are presented, compared to fossil gasoline. Details on the value chains and methods used are found in sections 9.2.3 and 2.1 / 2.2, respectively.

All impact categories

The LCA results for all environmental impact categories are given in Figure 16.

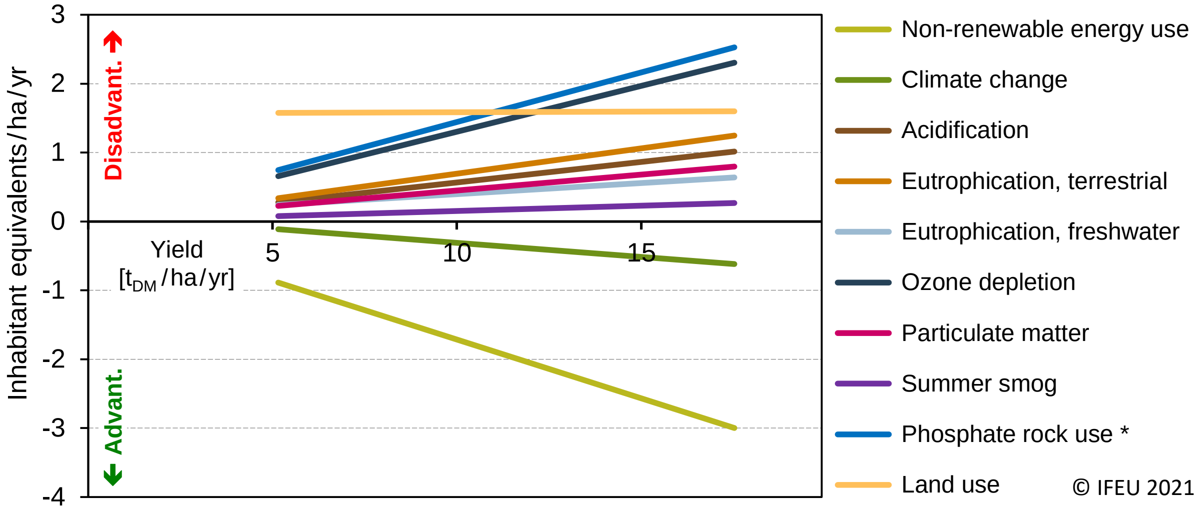

Figure 16: LCA results for ethanol from switchgrass (via hydrolysis and fermentation) versus fossil gasoline. * results for phosphate rock use: multiply by 10.
How to read the figure: The lowest straight illustrates that at a yield of 6 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 1 EU inhabitant can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as summer smog.
- An exception to this is the constant land use footprint: the quality-assessed land occupation by switchgrass cultivation is the same for all yields and is not influenced by bio-based auxiliaries or reference products.
- The phosphate footprint is dominated by conversion, which involves enzymes that use phosphate in their production. The share from agriculture (fertilisation), on the other hand, is about as small as for Miscanthus.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 17 illustrates the greenhouse gas emission savings that could be achieved by growing switchgrass on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 16 and the results and conclusions listed in those sections apply qualitatively.

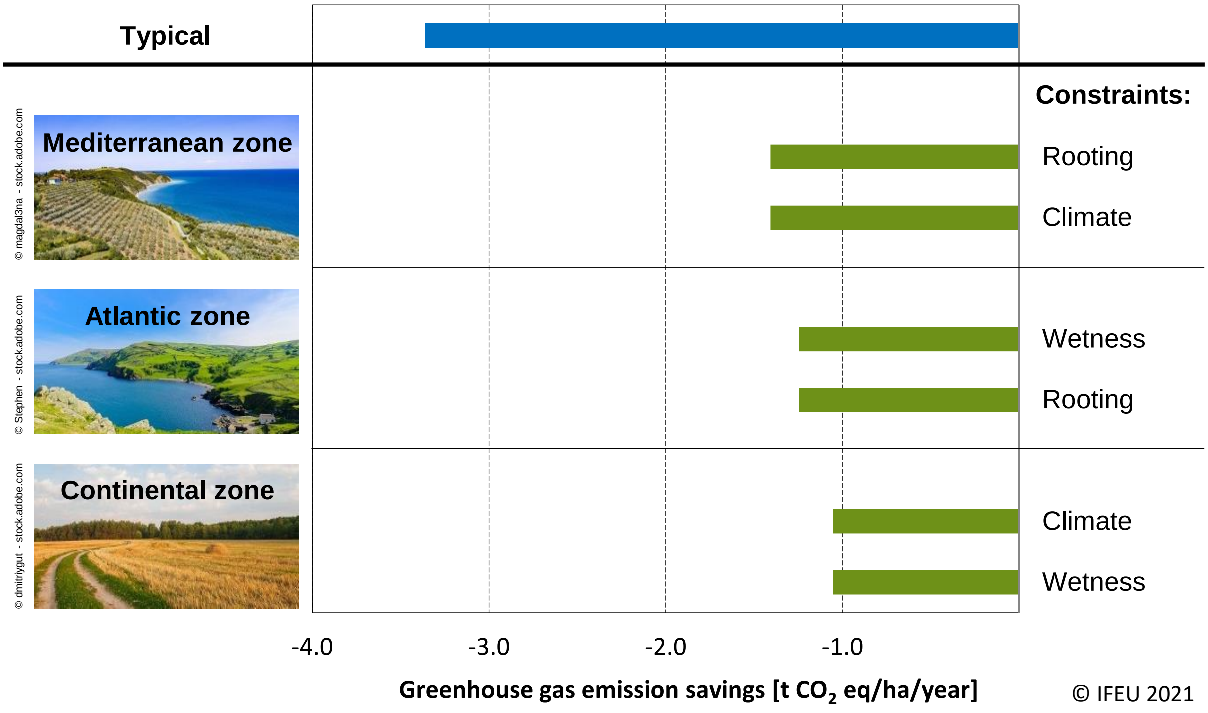

Figure 17: GHG emission savings for ethanol from switchgrass (via hydrolysis and fermentation) versus fossil gasoline for two biophysical constraints each in the three agro-ecological zones.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

Phosphate rock demand of the value chain

Compared to fossil gasoline, (ligno)cellulosic ethanol from switchgrass (via hydrolysis and fermentation) has a relatively high phosphate rock use, although it is based on a perennial grass. The phosphate rock demand of this value chain is at maximum five times as large as the corresponding value for Miscanthus, which is also a perennial grass.

The phosphate rock use broken down by processes is given in Figure 18. The bar with expenditures for fertiliser is only one quarter of the net result. In contrast, materials for the conversion make up the most important part of the result. This is caused especially by enzymes used for the hydrolysis. The result demonstrates that inputs into the conversion process can have a larger impact on certain environmental impacts than the agricultural expenditures. Therefore it is important to pay attention to the inputs of conversion and if necessary optimise the process. For more information on enzymes in the (ligno)cellulosic ethanol production, see [Kretschmer et al. 2013, section 4.1.6].

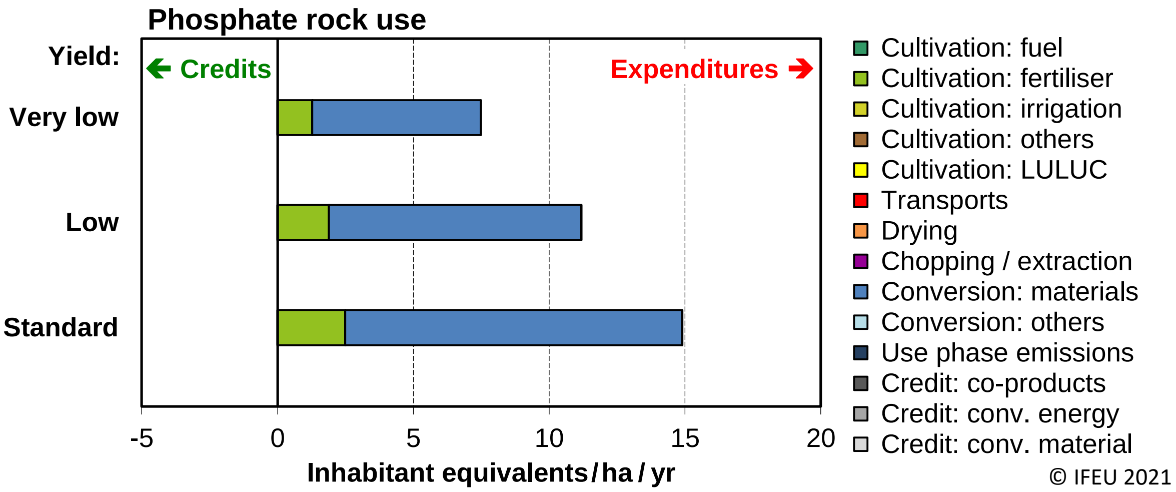

Figure 18: LCA results for ethanol from switchgrass (via hydrolysis and fermentation) versus fossil gasoline for the impact category phosphate rock use. Results are given for three yield levels in the Mediterranean zone.

Key finding:

- In addition to the cultivation of the biomass, expenditures (and associated emissions) for the materials and energy carriers used in the conversion process can also be decisive for the resulting environmental advantages and disadvantages.

4.2.4 Willow: Biotumen via pyrolysis

In this section, the LCA results for biotumen from willow are presented, compared to conventional bitumen. Details on the value chains and methods used are found in sections 9.2.4 and 2.1 / 2.2, respectively.

All impact categories

In Figure 19, the LCA results for all environmental impact categories are given.

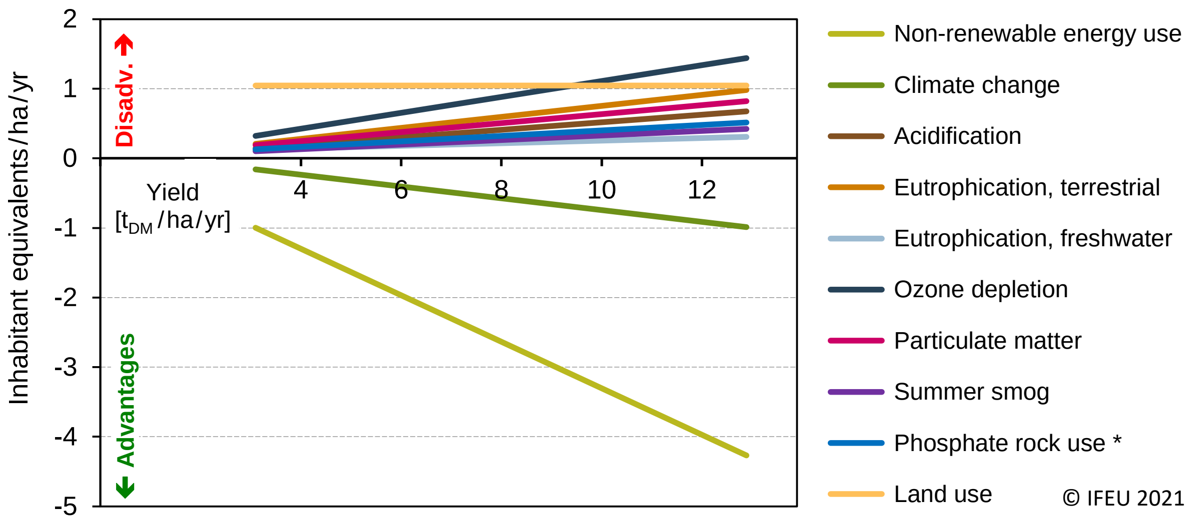

Figure 19: LCA results for biotumen from willow (via pyrolysis) versus conventional bitumen. * results for phosphate rock use: multiply by 10.

How to read the figure: The lowest straight illustrates that at a yield of 12 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 4 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as freshwater eutrophication and summer smog.
- An exception to this is the constant land use footprint: the quality-assessed land occupation by willow cultivation is the same for all yields and is not influenced by bio-based auxiliaries or reference products.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 20 illustrates the greenhouse gas emission savings that could be achieved by growing willow on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 19 and the results and conclusions listed in those sections apply qualitatively.

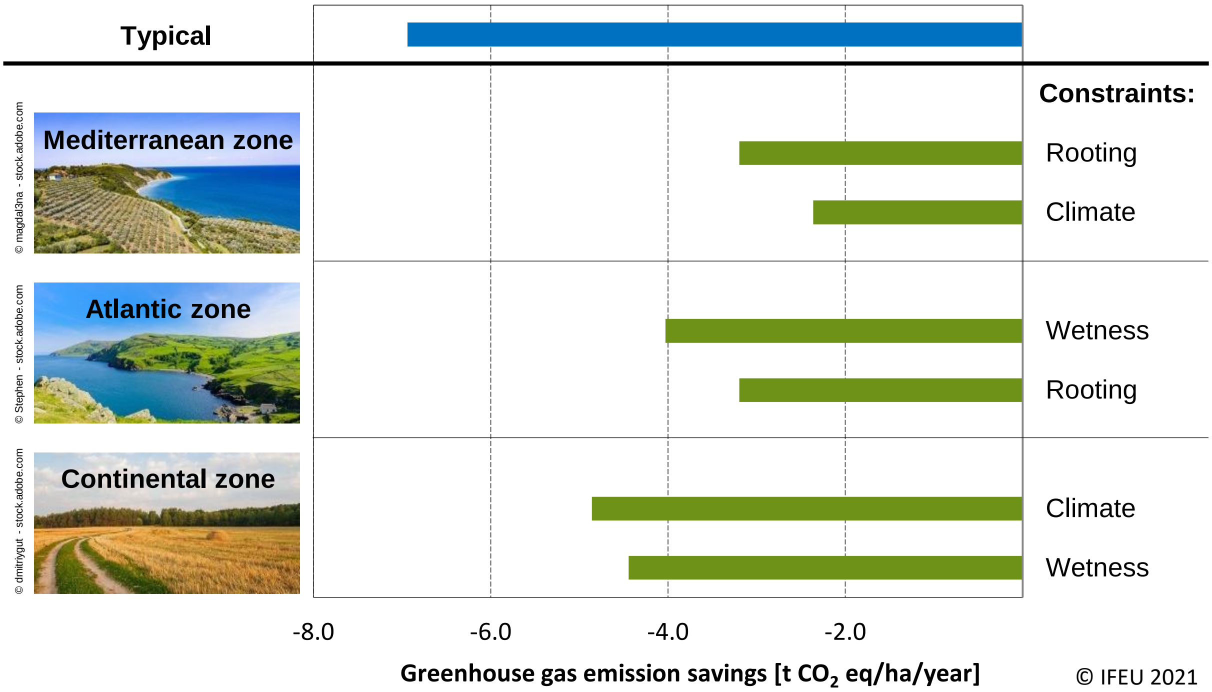

Figure 20: GHG emission savings for biotumen from willow (via pyrolysis) versus conventional bitumen for two biophysical constraints each in the three agro-ecological zones.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

4.2.5 Safflower: organic acids via oxidative cleavage


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In this section, the results of the screening LCA for organic acids from safflower are discussed, compared to conventional organic acids from biogenic sources. Details on the value chains and methods used are found in sections 9.2.5 and 2.1 / 2.2, respectively.

All impact categories

The LCA results for all environmental impact categories are depicted in Figure 21.

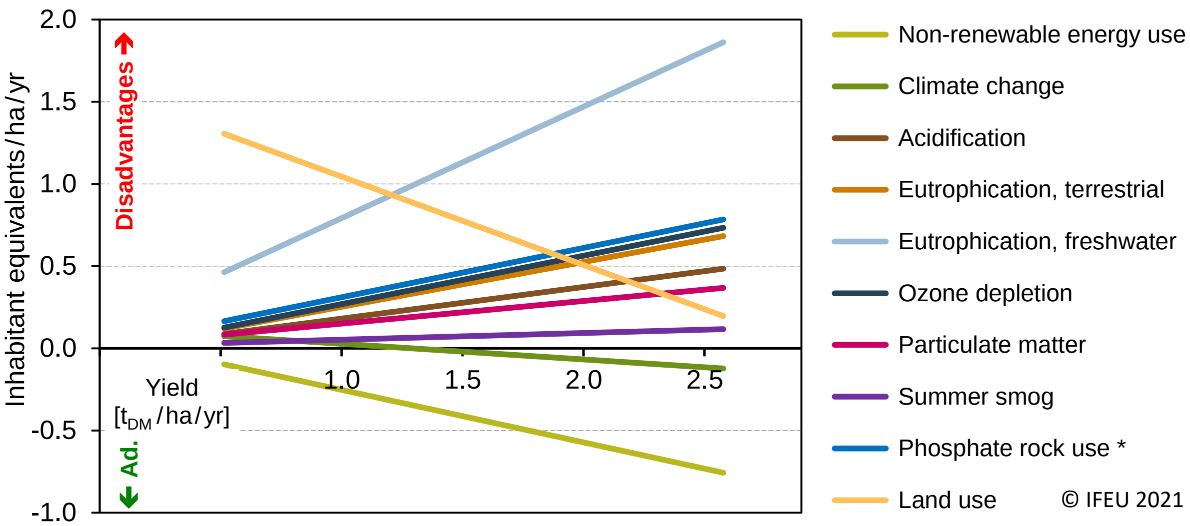

Figure 21: LCA results for organic acids from safflower (via oxidative cleavage) versus conventional organic acids from animal fat. * results for phosphate rock use: multiply by 10.
How to read the figure: The lowest straight illustrates that at a yield of 2 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 0.6 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as summer smog.
- Although the quality-assessed land occupation by safflower cultivation is the same for all yields, the land use footprint decreases significantly with increasing yield because more bio-based reference products (here: soy-based feed) which have a high land use footprint are substituted by the equally increasing yield of the co-product feed.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 22 illustrates the greenhouse gas emission savings that could be achieved by growing safflower on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 21 and the results and conclusions listed in those sections apply qualitatively.

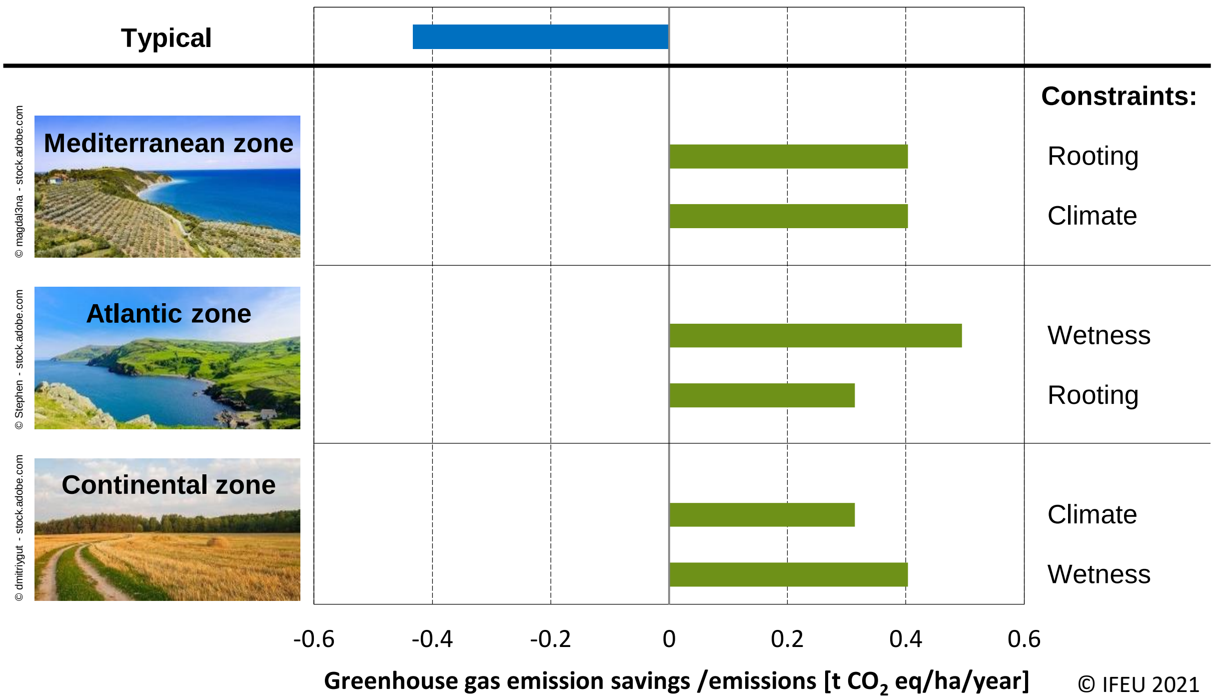

Figure 22: GHG emission savings for organic acids from safflower (via oxidative cleavage) versus organic acids from biogenic sources for two biophysical constraints each in the three AEZ.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

Variation of reference products: substituted conventional organic acids

Substitution of different reference products can lead to significant variations of LCA results (as shown for energy carriers in section 4.2.1). Here, organic acids from safflower are compared to conventional organic acids from animal fats, as discussed in the previous section, but also to organic acids from palm oil or sunflower oil. Ranges of LCA results for these comparisons are given for all yield levels in Figure 23.

Substitution of organic acids from animal fat with organic acids from safflower can achieve the highest savings of non-renewable energy. GHG savings can only be accomplished, if a certain yield level of safflower is reached. The same is true for replacing of organic acids from palm oil. Substitution of organic acids from sunflower oil has only small environmental advantages for terrestrial eutrophication and acidification. Concerning land use, an advantage can only be achieved, if a certain yield level of safflower is reached and if it replaces organic acids from palm oil or sunflower oil. The overall results, except for non-renewable energy use and climate change, are disadvantageous for safflower.

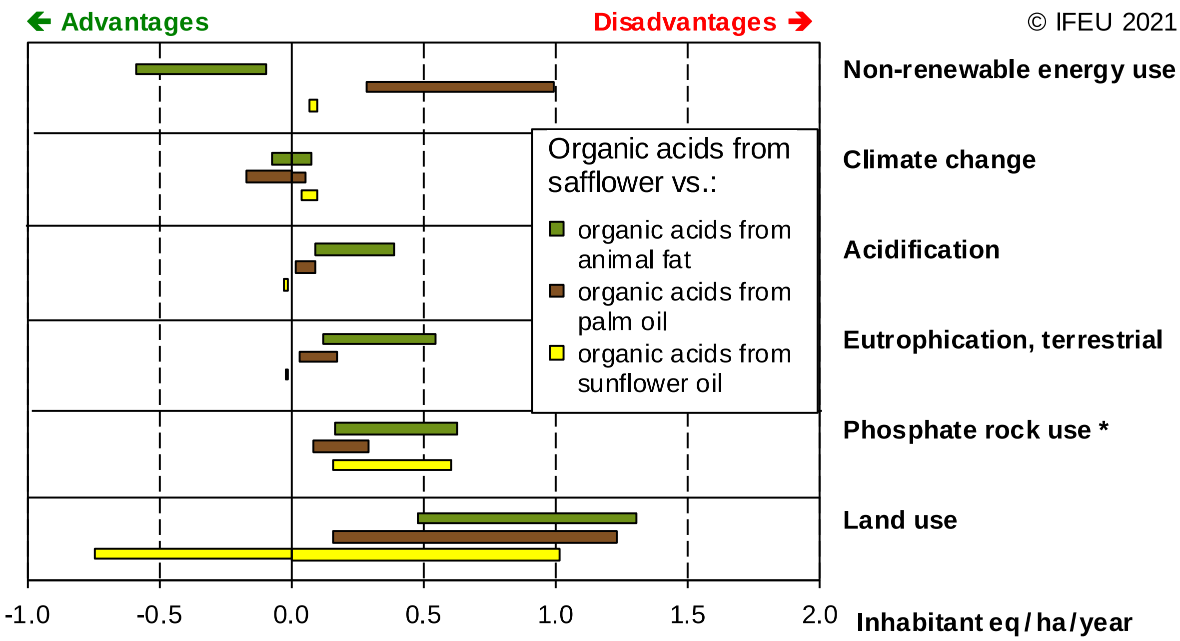

Figure 23: LCA results for organic acids from safflower versus conventional organic acids from animal fat, palm oil and sunflower oil for yield levels ranging from “Very low” to “Standard”. * results for phosphate rock use: multiply by 10.

Key findings:

- Only with a high yield of safflower can an advantage be achieved in some environmental impact categories. Otherwise, other bio-based reference products are more advantageous.
- In order to achieve the greatest possible environmental advantages, products with a particularly large environmental footprint should be substituted first.

4.2.6 Castor: sebacic acid via alkaline cleavage

The results of the screening LCA for sebacic acid from castor, compared to sebacic acid from paraffin, are presented in the following. Details on the value chains and methods used are found in sections 9.2.7 and 2.1 / 2.2, respectively.

All impact categories

In Figure 24 the LCA results for all environmental impact categories are given.

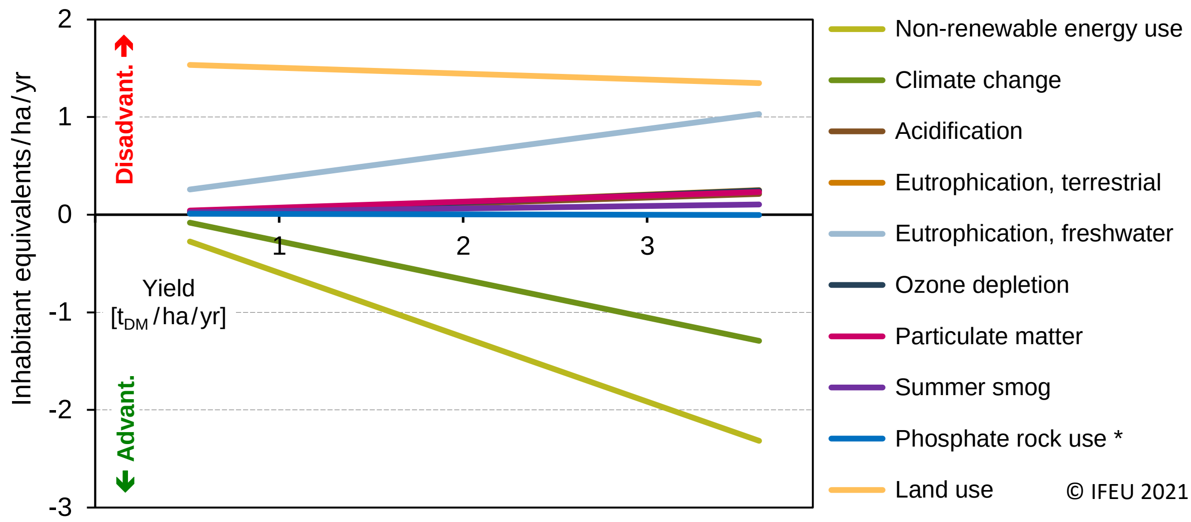

Figure 24: LCA results for sebacic acid from castor (via alkaline cleavage) versus sebacic acid from paraffin. * results for phosphate rock use: multiply by 10.
How to read the figure: The lowest straight illustrates that at a yield of 3 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of ~2 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as summer smog.
- An exception to this is the constant land use footprint: the quality-assessed land occupation by castor cultivation is the same for all yields and is not influenced by bio-based auxiliaries or reference products.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 25 illustrates the greenhouse gas emission savings that could be achieved by growing castor on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). In the Atlantic AEZ no castor cultivation is possible. The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 24 and the results and conclusions listed in those sections apply qualitatively.

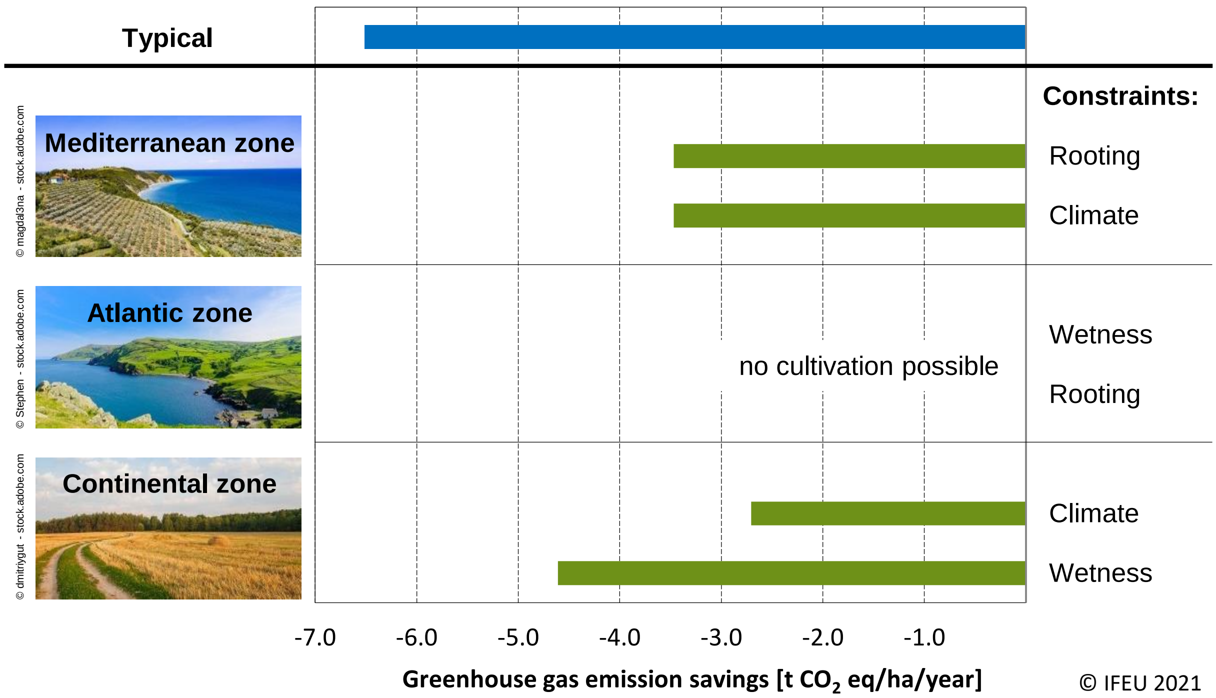

Figure 25: GHG emission savings for sebacic acid from castor (via alkaline cleavage) versus sebacic acid from paraffin for two biophysical constraints each in the three agro-ecological zones.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

Variation of conversion efficiencies

In the previous section, results are shown for the life cycle comparison between sebacic acid from castor oil and sebacic acid from paraffin. The results may vary depending on the conversion efficiency from castor to sebacic acid. The more efficiently power and chemicals are used, the lower the environmental footprint. On top of that, production efficiency of the reference product has a wide range as well. The lower the efficiency, the higher are the environmental burdens of the reference product, which means higher credits for the bio-based system.

In Figure 26, LCA results are shown for the best (upper bars) and the worst case (lower bars) scenarios. In the best case scenario, the reference product with the highest environmental burdens is replaced by the bio-based product with the highest conversion efficiency. Results in Figure 24 are based on this scenario. In the worst case, the reference product with low environmental burdens is replaced by a bio-based product with poor conversion efficiency.

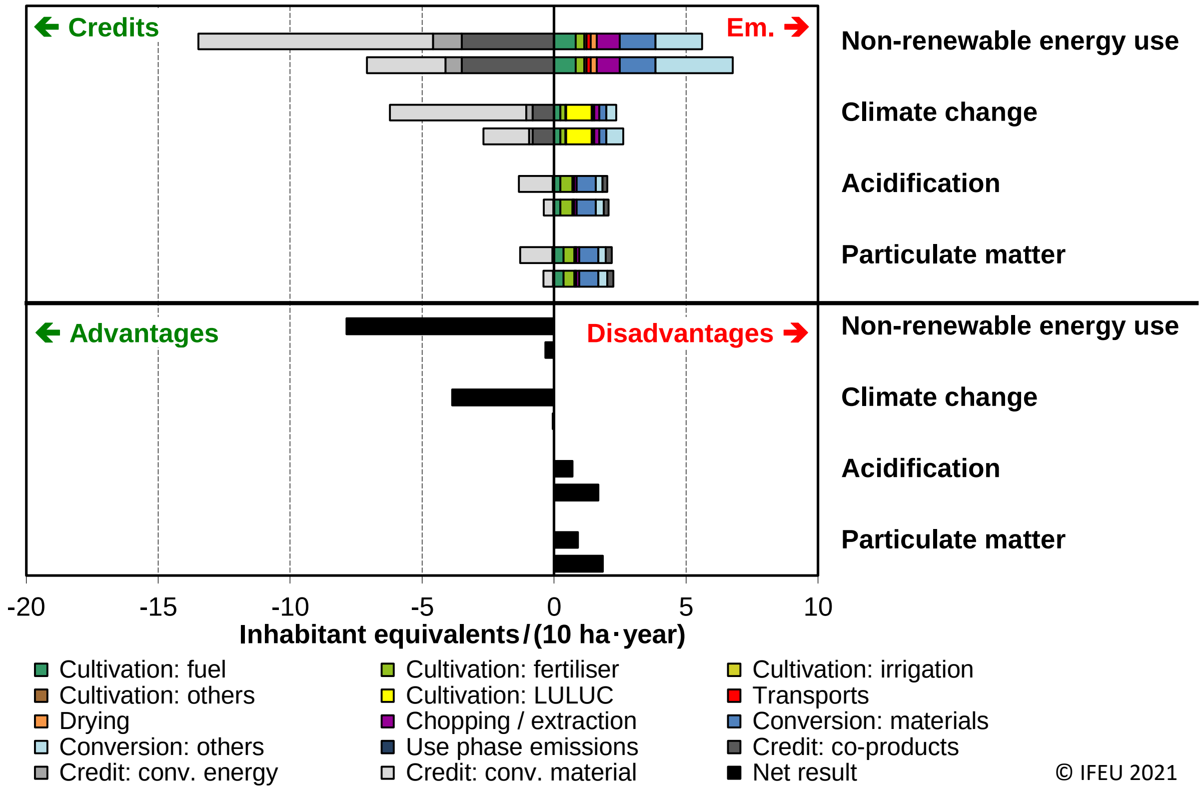

Figure 26: LCA results for sebacic acid from castor (via alkaline cleavage) versus sebacic acid from paraffin at a yield level of 1.3 t_{DM}/ha/yr. The best case and the worst case scenario, respectively upper and lower bars, are presented for each category.

Key finding:

- Environmental advantages can only be achieved by aiming for high conversion efficiency in the manufacturing of the bio-based products and by first replacing the reference products with the largest environmental footprint.

4.2.7 Hemp: insulation material

Results of the screening LCA for insulation material from hemp, compared to expanded polystyrene (EPS), are presented in this section. Details on the value chains and methods used are found in sections 9.2.8 and 2.1 / 2.2, respectively.

All impact categories

The LCA results for all environmental impact categories are given in Figure 27.

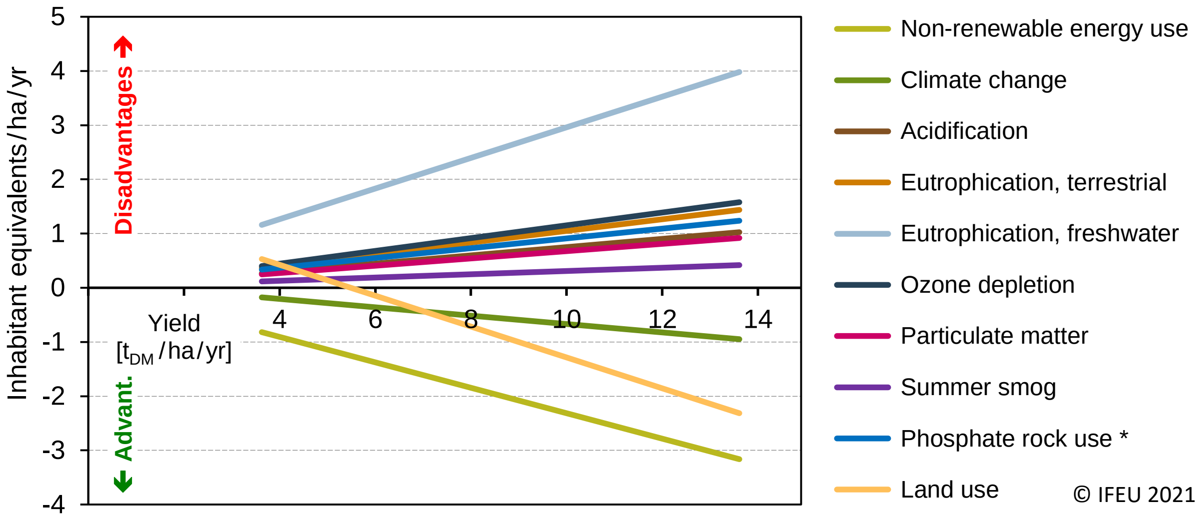

Figure 27: LCA results for insulation material from hemp versus conventional EPS. * results for phosphate rock use: multiply by 10.

How to read the figure: The lowest straight illustrates that at a yield of 13 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 3 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages.
- The land use footprint decreases with increasing yields and undergoes a change of sign towards environmental advantages. This is because the quality-assessed land occupation by hemp cultivation remains constant but with higher yields, the credits for the co-products increase. Hemp seeds can be used as food to replace edible seeds such as flaxseed, which have a low yield and thus occupy much more land.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 28 illustrates the greenhouse gas emission savings that could be achieved by growing hemp on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 27 and the results and conclusions listed in those sections apply qualitatively.

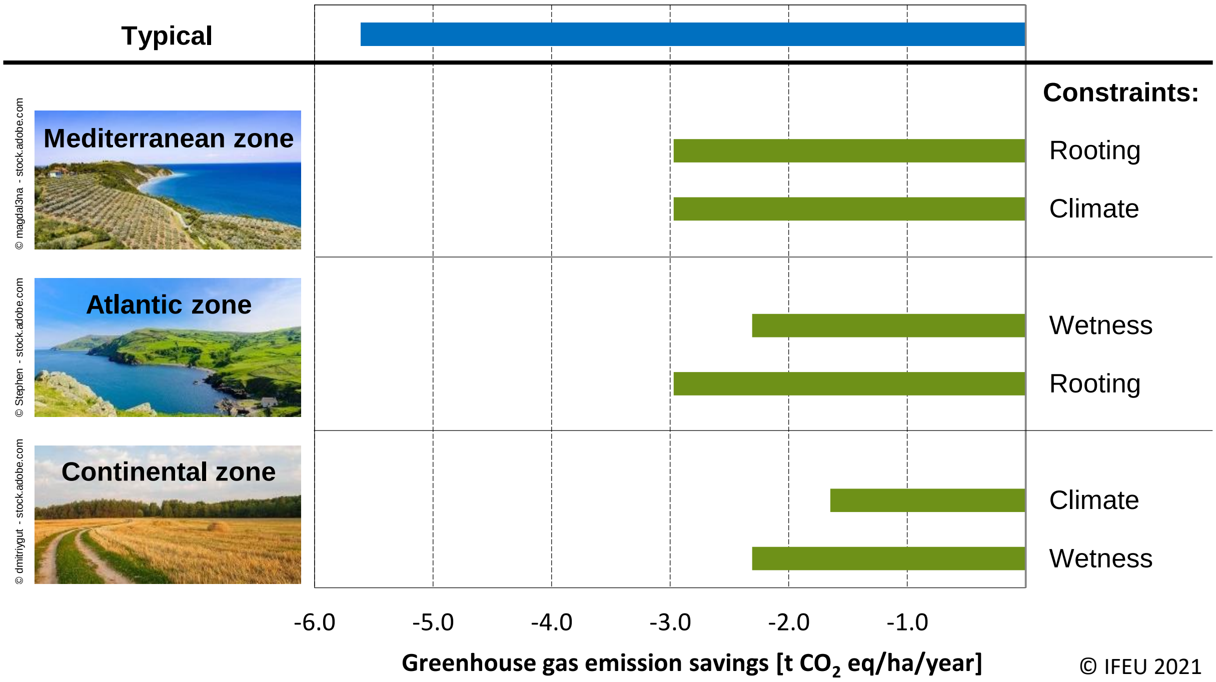

Figure 28: GHG emission savings for insulation material from hemp versus conventional EPS for two biophysical constraints each in the three agro-ecological zones.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

Variation of reference product: mineral wool insulation

As already discussed in sections 4.2.1 and 4.2.5, the overall outcome of an LCA is also dependent on the substituted reference product. Hemp-based insulation can replace EPS but also mineral wool. In Figure 29, LCA results (inhabitant equivalents) are given, broken down by processes and contributions to the life cycle.

Emissions in each category on the right side are the same for substitution of both types of insulation materials. Also credits for co-products are identical. The only differences are the credits for the reference product. Credits for the substitution of petroleum-based EPS are higher in most of the categories. In contrast, no significant savings of non-renewable energy and greenhouse gas emissions can be achieved if mineral wool is substituted by hemp.

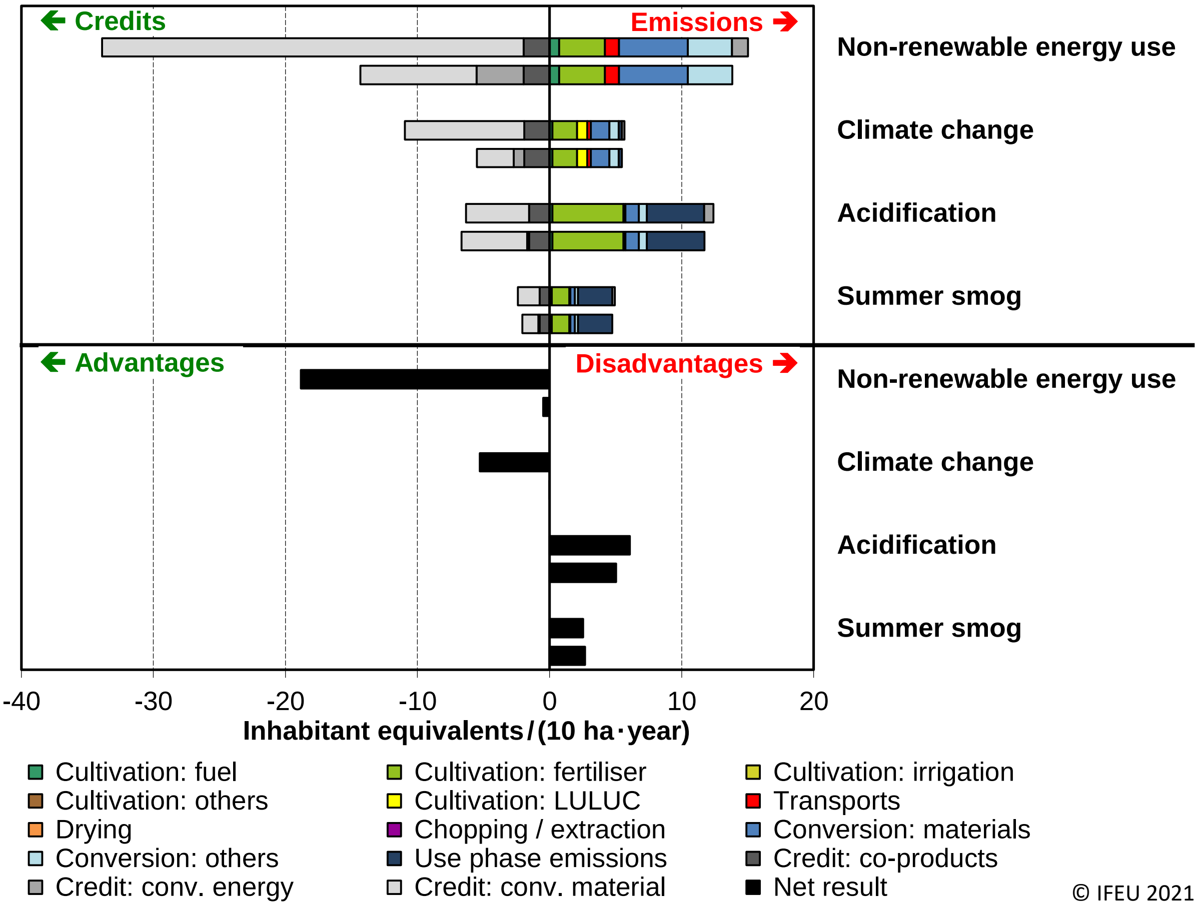

Figure 29: LCA results for hemp-based insulation versus conventional insulation from mineral wool (upper bars) and from EPS (lower bars), respectively, at a yield level of 8.0 t_{DM}/ha/yr.

Key finding:

- Depending on the substituted reference product, environmental advantages and disadvantages result for the value chain. To achieve the greatest environmental advantages, products with a particularly large environmental footprint should be substituted first.

4.2.8 Sorghum: biogas/biomethane

In the following, the results of the screening LCA for heat and power from sorghum biogas are presented, compared to heat and power from fossil energy carriers. Details on the value chains and methods used are found in sections 9.2.9 and 2.1 / 2.2, respectively.

All impact categories

The LCA results for all environmental impact categories are given in Figure 30.

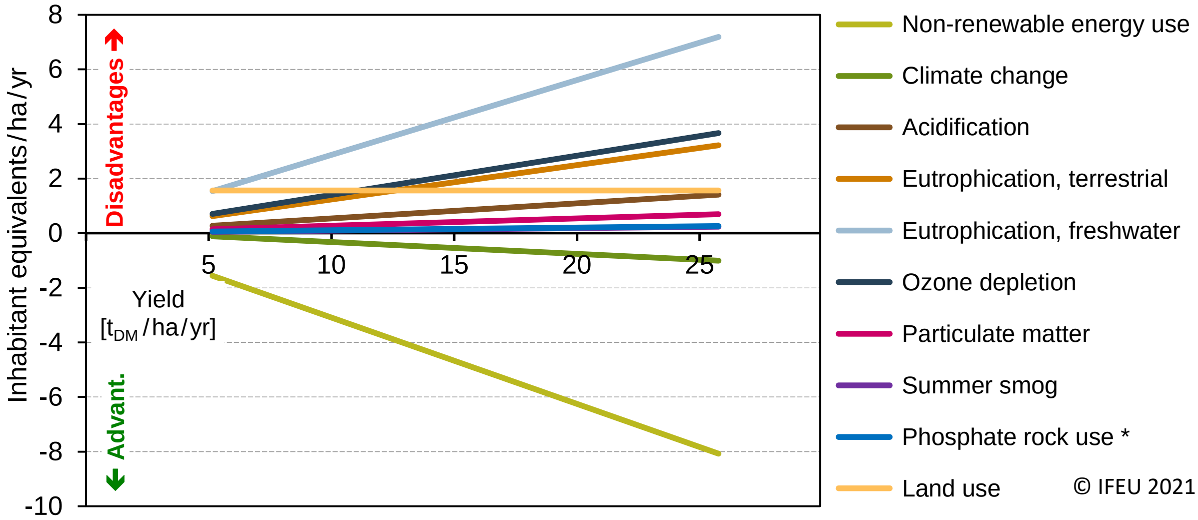

Figure 30: LCA results for heat and power from sorghum biogas versus heat and power mix from fossil energy carriers. * results for phosphate rock use: multiply by 10.
How to read the figure: The lowest straight illustrates that at a yield of 20 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of ~6 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as summer smog and particulate matter.
- An exception to this is the constant land use footprint: the quality-assessed land occupation by sorghum cultivation is the same for all yields and is not influenced by bio-based auxiliaries or reference products.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

Growing constraints and agro-ecological zones

As yields on marginal land are usually lower than on standard soils, this section presents LCA results for the agro-ecological zones (AEZ) defined in section 2.1.2 exemplified by the impact category climate change. For these three zones, Figure 31 illustrates the greenhouse gas emission savings that could be achieved by growing sorghum on marginal lands under two specific growing constraints that have a large impact in the respective zone (see section 2.1.2 II and VIII). The results show:

- Due to individual biophysical constraints, only significantly lower GHG emission savings can be achieved on marginal soils compared to standard soils.
- The reduction in GHG emission savings can be even more pronounced when constraints are combined (not shown in the figure, as self-explanatory).
- The differences in the results can depend significantly on the individual constraints. These, in turn, can be significantly different depending on the climate zone.
- Since the other LCA results are directly related to the yield per hectare (see section 4.1 and previous page), these can be taken quantitatively from Figure 30 and the results and conclusions listed in those sections apply qualitatively.

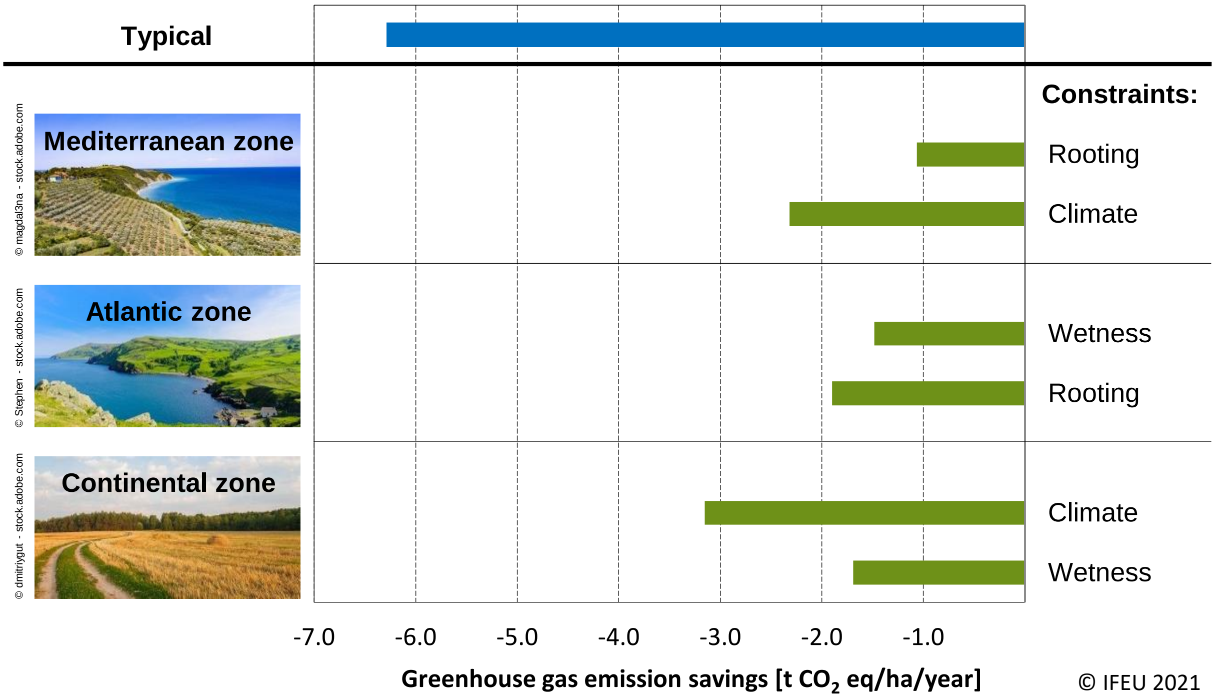

Figure 31: GHG emission savings for heat and power from sorghum biogas versus heat and power mix from fossil energy carriers for two biophysical constraints each in the three AEZ.

Key finding:

- If the focus is on GHG savings, the most important goal is to achieve the highest possible yields. This can be achieved by minimising the most important biophysical constraints in the respective agro-ecological zones, for example through sustainable irrigation or appropriate soil management.

Alternative conversion route: biomethane from Sorghum compared to natural gas

Biogas from the fermentation of sorghum can be used directly to produce power and heat, as shown in the previous section. Alternatively, it can be further purified to biomethane, which can be injected into the natural gas grid. This is useful, when consumers of heat and power are not close to the conversion site. But upgrading of biogas to biomethane requires a larger digester and thus larger areas for cultivation of biomass feedstock (see section 9.2.9.2).

In Figure 32, the LCA results for all impact categories for biomethane from sorghum compared to natural gas are given in inhabitant equivalents. Compared to biogas the disadvantages of acidification, terrestrial eutrophication and particulate matter become larger and advantages like climate change and non-renewable energy use get smaller. This is caused by a more energy intensive conversion and smaller credits due natural gas as reference product instead of a conventional heat and power mix (see section 4.2.1).

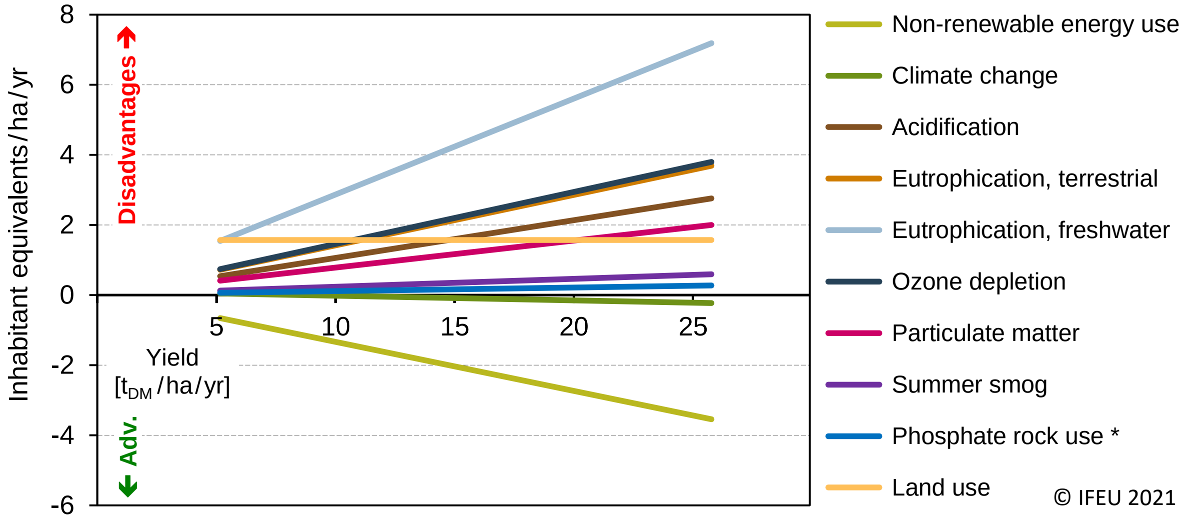

Figure 32: LCA results for biomethane from sorghum versus natural gas. * results for phosphate rock use: multiply by 10.

How to read the figure: The lowest straight illustrates that at a yield of 15 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 2 EU inhabitants can be saved.

Key findings:

- While the environmental disadvantages of conversion to biomethane from sorghum are about as great as those of conversion to biogas, the environmental advantages are only about half as great. In particular, there are virtually no GHG emission savings to report.
- Whether conversion to biomethane is worthwhile also depends on local conditions. If a connection to the natural gas grid is possible and sufficient land is available, the production of biomethane for injection into the natural gas grid may be a viable option.

4.2.9 Lupin: adhesives

In this section, the results of the screening LCA for adhesives from lupin are given, compared to polyurethane-based adhesives. Details on the value chains and methods used are found in sections 9.2.10 and 2.1 / 2.2, respectively. In contrast to the other crops, results for specific biophysical constraints cannot be presented for lupin, since cultivation trials for lupin have not been carried out in MAGIC and no data for the investigated AEZ was available.

All impact categories

In Figure 33, the LCA results for all environmental impact categories are given.

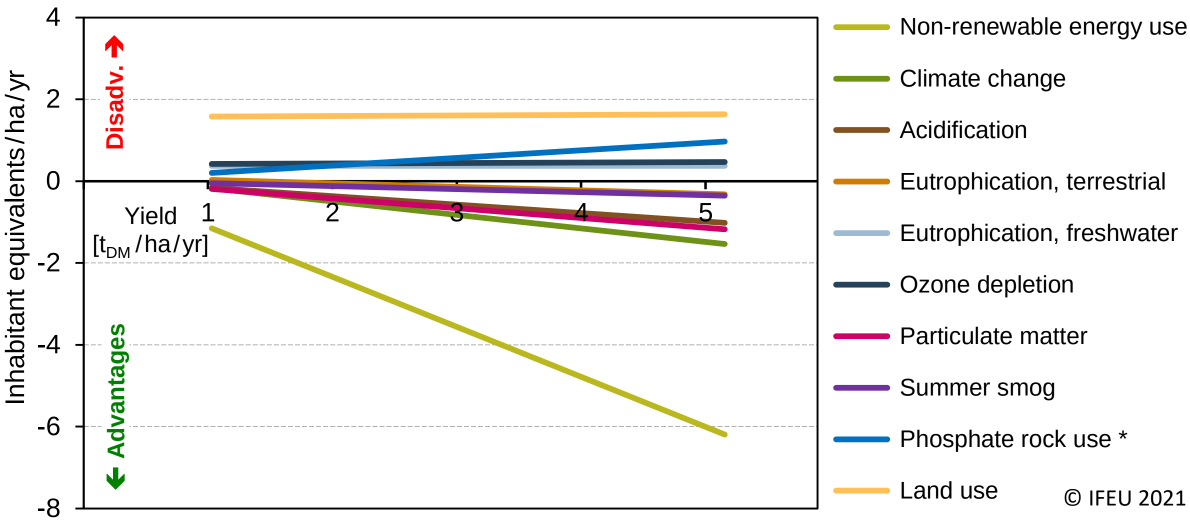

Figure 33: LCA results for adhesives from lupin versus polyurethane-based adhesives. Yields are on the horizontal axis. * results for phosphate rock use: multiply by 10.

How to read the figure: The lowest straight illustrates that at a yield of 5 t_{DM}/ha/yr an amount of non-renewable energy equal to the average annual demand of 6 EU inhabitants can be saved.

Key findings:

- The quantitative results of most environmental impacts are highly dependent on yield. The higher the yield, the greater the environmental advantages as well as the environmental disadvantages. This is also true for environmental impacts that show particularly low result values, such as freshwater eutrophication.
- Since lupine, as a nitrogen fixer, requires only a small initial fertilisation, the N_2O field emissions and thus the ozone depletion remain almost the same for all yields.
- The land use footprint increases slightly, as bio-based auxiliaries which have their own land use footprint (here: glucose) are used in the conversion process, and larger quantities of these are needed for higher lupine yields.
- Thus, a conclusive LCA result can be determined for any given yield, depending on soil marginality, climate, and other factors.

4.3 Special topics

This section focuses on a number of overarching special topics which are presented in the following.

4.3.1 Special topic: land use

The main idea of the MAGIC project is to avoid competition about standard agricultural land and thus iLUC effects (see sections 2.1.2 VI and 2.2.2 IV). Nevertheless, taking marginal land into use is a land use change[2], too. Furthermore, it may affect the use of organic soils and associated greenhouse gas emissions often summarised as emissions from land use (LU). These effects and their methodological coverage in this study are analysed in this section.

Figure 6 (p. 39) and Figure 8 (p. 41) show the impact of LULUC on the results under standard boundary conditions. These are a one-time loss of 5 t C/ha of marginal land, corresponding to 'sparse grassy vegetation', distributed over an amortisation period of 20 years and a one-time gain corresponding to the average carbon stock of the crop over the plantation period (LUC), which is e.g. 2.3 t C for Miscanthus at a yield of 9 t_{DM}/ha/year. Under these conditions, only mineral soils without LU-related emissions are considered. Taking into account the variability of marginal land, this can only be taken as a default setting with high variability between individual sites. This can have a significant influence on the carbon footprint of the product potentially leading to massive additional greenhouse gas emissions (Figure 34).

Even more important than the effects on climate change can be the effects on biodiversity. Land that is not well suited for agriculture because of biophysical constraints is often a perfect habitat for specialist organisms. If such land is left unused, very biodiverse ecosystems can emerge. These ecosystems will be destroyed or prevented from forming if this kind of marginal land was taken into use. Unfortunately, a quantitative assessment of biodiversity is still very immature and this particular case of successional vegetation on non-standard sites remains largely unquantified.

[2] Depending on the classification of marginal land as temporarily unused agricultural land, former agricultural land or other land, this change in usage may also be classified as land management change. This however does not affect the physical processes and their environmental impacts. For simplicity, we do not differentiate between the terms land use change and land management change.

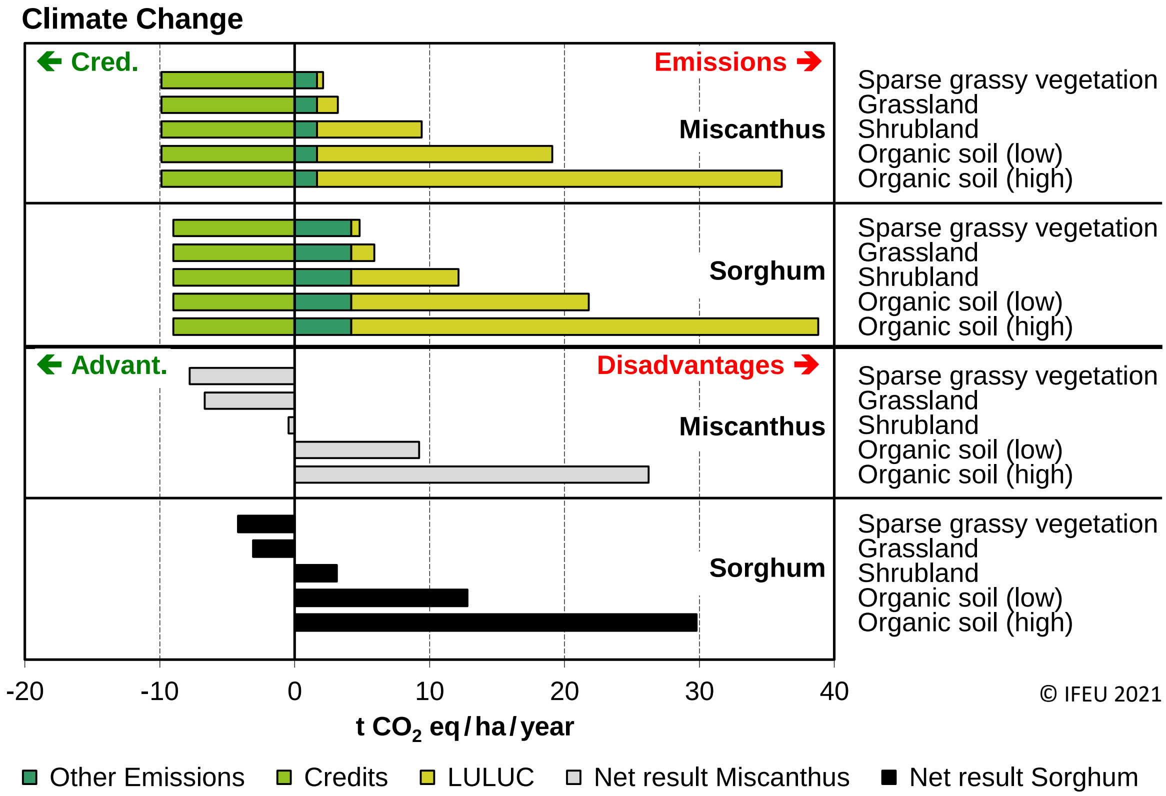

Figure 34: Influence of LULUC emissions on the carbon footprint of industrial heat from Miscanthus (via pyrolysis) and heat and power from sorghum biogas (both in the continental zone, at yields of 10.0 and 12.5 t_{DM}/ha/yr, respectively). In addition to the default coverage 'sparse grassy vegetation", grassland, shrubland and sparse grassy vegetation on organic soils is analysed. Lower number emissions from organic soils are taken from National Inventory Reports (NIR) to the Kyoto Protocol, high numbers from [IPCC 2014].

Key findings:

- The support of marginal land must under no circumstances lead directly or indirectly to the further or renewed use of organic soils.
- For all other areas, use, carbon loss and biodiversity loss must be weighed up on a case-by-case basis. This requires binding criteria catalogues as part of possible funding conditions.

4.3.2 Special topic: photovoltaics on marginal land

Apart from growing industrial crops, marginal land could also be used for other ways of providing renewable energy, e.g. by installing ground-mounted photovoltaic (PV) systems. The potential benefit of this type of land use depends very much on the local conditions. The exposition and thus the solar irradiation and sunshine hours are important. Also infrastructure like network connection and road access is required. PV systems need less maintenance than crops, but are not burden-free, e.g. in terms of impact on the landscape. In Figure 35, the environmental impacts of renewable electricity from a PV system are compared to those of bioenergy from four crops (discussed in section 4.2).

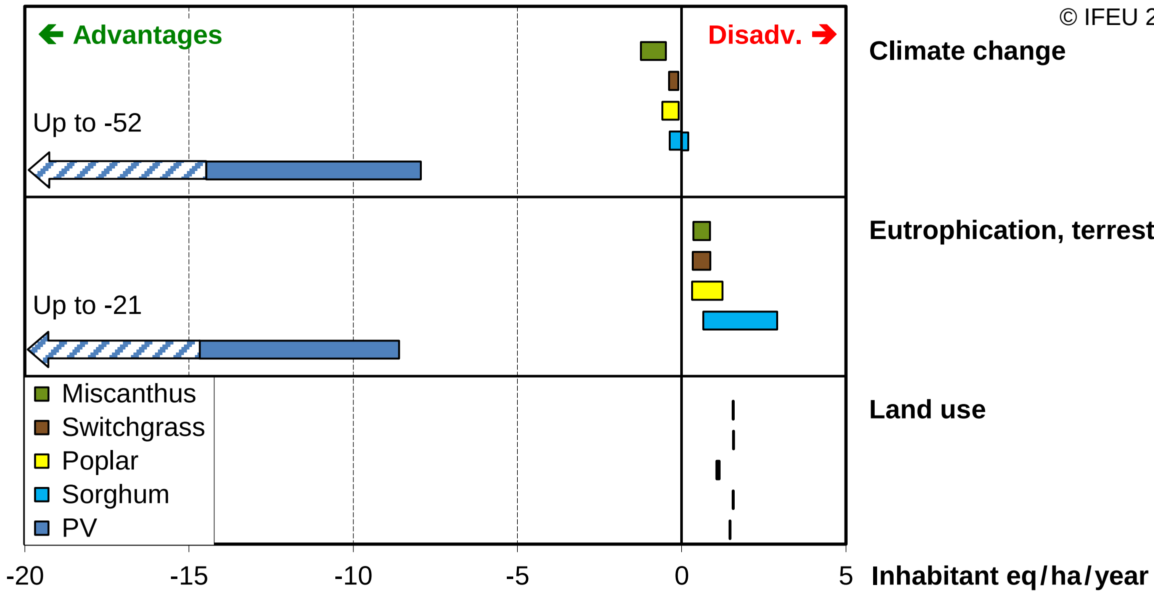

Figure 35: LCA results for renewable electricity from a PV system on marginal land compared to four exemplary bioenergy products: heat from Miscanthus, ethanol from switchgrass, synthetic natural gas from poplar and biogas/biomethane from sorghum (see results in section 4.2). The results for PV cover different intensities of solar irradiation from the MED to the CON zone.

Key finding:

- Compared to bioenergy, PV electricity can save more GHG emissions and reduce nutrient inputs. The overall environmental advantage is strongly dependent on the reference system, i.e. the substituted electricity mix.
- The land use footprint of all systems is similar - at least in relation to hectares and years. In relation to energy units (kWh or MJ), PV electricity would be clearly ahead.
- In water-scarce areas, where solar irradiation is also mostly intensive, a PV system on marginal land can present a better alternative than irrigated crops.
- Further aspects (advantages and disadvantages) in connection with the different types of renewable energy provision need to be considered, e.g. base load capability and storability.

4.3.3 Special topic: GHG emission savings according to the RED

This section investigates if the MAGIC value chains meet the sustainability criteria set out in the recast of the Renewable Energy Directive (RED II) [European Parliament & Council of the European Union 2018]. Details on calculation following the RED II are found in section 2.2.4. According to the calculation rules for biofuels laid down in Annex V of the RED II, GHG emission savings in the transport sector shall be at least 65% compared to the fossil fuel comparator (94 g CO_2 eq / MJ). Thus, to reach this threshold, life cycle GHG emissions of biofuels must be ≤ 33 g CO_2 eq / MJ.

The RED II calculation rules are applied to bioethanol from switchgrass, the only biofuel value chain in MAGIC. Results in Figure 36 illustrate that the analysed (ligno-)cellulosic ethanol pathway (see D6.3 [van den Berg et al. 2020]) on marginal land cannot fulfil the minimum GHG emission saving requirements of the RED II under most conditions, unless the process is substantially improved. Major burdens stem from the provision of glucose for enzyme production. Under favourable conditions, the 65% savings threshold could be reached even with this process, if the land used for switchgrass cultivation qualifies for a bonus (29 g CO_2 eq / MJ) that is awarded to 'severely degraded land' according to RED II. The results presented here cannot be transferred to other cellulosic ethanol pathways. The development is currently dynamic but data on advanced processes is not publicly available.

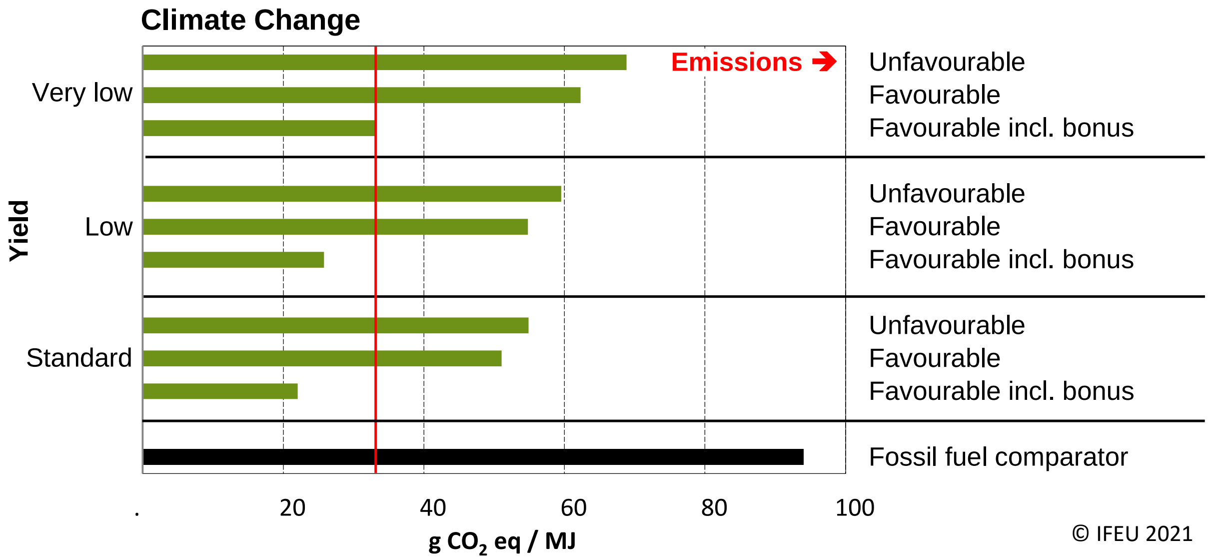

Figure 36: GHG emissions according to RED II for bioethanol from switchgrass (via hydrolysis and fermentation) compared to the fossil fuel comparator (black bar). The red line illustrates 65% GHG emisions savings threshold, that biofuels must not exceed.

Key finding:

- Ethanol from switchgrass cannot achieve the GHG emission saving of 65% without a significant improvement of the process considered here, where the glucose input leads to high environmental burdens. Only if the bonus for the use of severely degraded land can be awarded will the required GHG emission savings be achieved.

4.3.4 Special topic: Logistics / drying

Drying as part of the logistics is important to storage short rotation coppice (SRC) like poplar and willow but also perennial grasses like Miscanthus and switchgrass. Due to a lower water content at harvest of around 20 % (of fresh matter, FM), Miscanthus and switchgrass can be cut, air-dried on swath and baled. SRC are harvested with a self-propelled harvester (cut and chipped), forwarded to a place for air-drying and are then technically dried. In this sensitivity analysis also a scenario is shown with direct technically drying without air-drying. In section 9.1 to 9.2.4 alternative pathways with and without air-drying on the field are shown for perennial grasses and SRC.

Environmental impacts related to technical drying depend on the energy carrier used for drying, drying efficiency and the water content of biomass prior to drying. Drying is set to take place in central facilities. Further information to the energy carrier and drying efficiency can be found in [Rettenmaier et al. 2015, section 5.4.2.1]. In this section, solely the influence of the water content on expenditures for technical drying of poplar and willow is considered. As given in Table 6, poplar and willow has a water content of 50 % at harvest. The worst case is technical drying without air-drying before. If the biomass is air-dried, the water content can be reduced to 30 $\%_{FM}$ before technical drying in the best case.

Table 6: Water contents of biomass at harvest, before (after air drying) and after technical drying

Water content:	Poplar – min drying	Poplar – std drying	Poplar – max drying	Willow – min drying	Willow – std drying	Willow – max drying
At harvest	50 $\%_{FM}$	50 $\%_{FM}$	50 $\%_{FM}$	50 $\%_{FM}$	50 $\%_{FM}$	50 $\%_{FM}$
Before technical drying	30 $\%_{FM}$	35 $\%_{FM}$	50 $\%_{FM}$	30 $\%_{FM}$	35 $\%_{FM}$	50 $\%_{FM}$
After technical drying	20 $\%_{FM}$	20 $\%_{FM}$	20 $\%_{FM}$	20 $\%_{FM}$	20 $\%_{FM}$	20 $\%_{FM}$
Storage losses	3 $\%_{DM}$	3 $\%_{DM}$	3 $\%_{DM}$	3 $\%_{DM}$	3 $\%_{DM}$	3 $\%_{DM}$

In Figure 37, LCA results for synthetic natural gas from poplar (compared to natural gas) and biotumen from willow (compared to bitumen) are shown, whereby scenarios with minimal, standard and maximum drying effort are distinguished. As to willow, technical drying makes up more than half of all emissions. Emissions from drying of willow are also larger than corresponding emissions of poplar. For both, open air-drying can significantly improve the greenhouse gas balance and non-renewable energy use. All other investigated impact categories show a less significant or no improvement of the environmental performance (not shown).

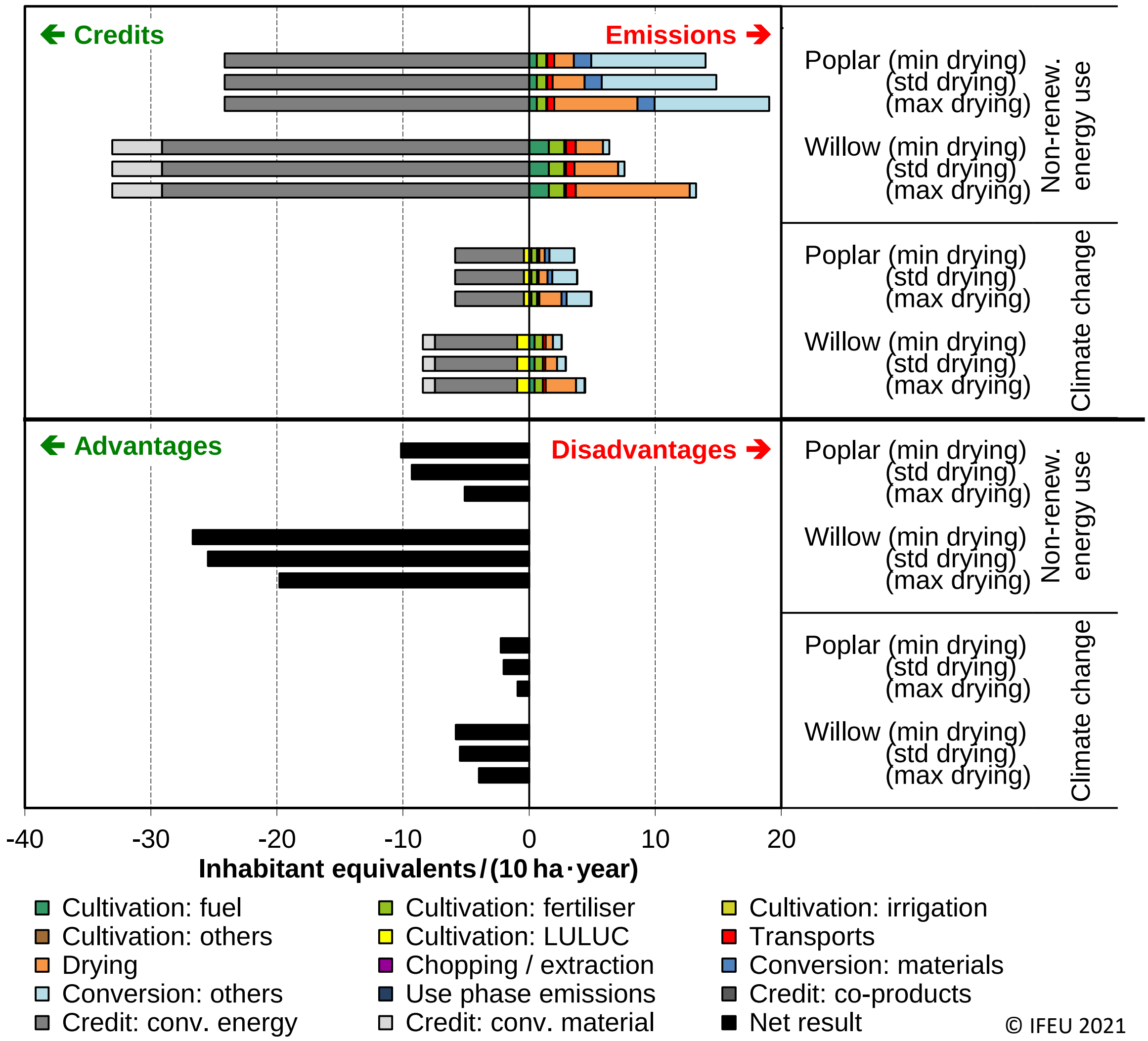

Figure 37: Normalised LCA results (inhabitant equivalents) of non-renewable energy use and climate change for natural gas from poplar (via gasification) versus natural gas and for biotumen from willow (via pyrolysis) versus conventional bitumen for yields of 5.5 t_{DM}/ha/yr (poplar) and 7.5 t_{DM}/ha/yr (willow), respectively.

Key findings:

- Expenses for technical drying should be kept as low as possible, as they can significantly deteriorate the LCA results.
- Air drying only makes sense if the disadvantages caused by storage losses do not exceed the environmental advantages gained.

5 Results: Life Cycle Environmental Impact Assessment

A life cycle environmental impact assessment (LC-EIA) was carried out for nine selected industrial crops grown on marginal land and used for different purposes (for details on the methods see section 2.3). In the following, the results are presented: first for biomass provision (5.1), followed by biomass conversion (0) and finally for the entire life cycle (5.3).

5.1 Impacts of the different cropping systems

Table 7 indicates the results of the EIA on the impact on the emissions to soil, air and water, namely emissions derived from the use of fertilizers and pesticides.

Table 7: Results of the EIA to the cultivation phase: impact on the emissions to soil, air and water

Crop	Emissions to soil, air and water	
	Fertiliser-related emission	Pesticide-related emission
Miscanthus	–	0
Switchgrass	–	–
Poplar	–	0
Willow	–	0
Safflower	– –	–
Castor	–	–
Hemp	–	0
Sorghum	– –	–
Lupin	+	–
Wheat	– –	– –
Maize	– – –	– – –

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

Minerals like nitrogen, phosphorus and potassium are largely applied on soils as fertilizers in order to achieve and maximize profitable yields. Consequently, soil, water and air can became polluted by these elements. But, if minerals applied to the soil are lower than the amount removed by the crop, than soil reserves can became depleted. Nitrogen applied to the soil can contribute to several environmental problems:

- Volatilisation of ammonia (NH_3) and oxides of N (NO_x) to the air; this contributes to the acidification.
- Leaching and runoff of ammonium (NH_4^+) and nitrate (NO_3^-) to ground and surface waters; this contributes to eutrophication and excess of nitrate in drinking water could be a threat to human health.
- Denitrification to nitrous oxide (N_2O); this contributes to the greenhouse effect and to ozone depletion. Some nitrous oxide can be produced during nitrification.

According to [IPCC 2006], 10% of the N input can be lost by volatilisation and 30% can be lost by leaching/runoff. The emissions of N_2O occur through both a direct pathway (i.e., directly from the N input, 1%), and through two indirect pathways: (i) following volatilisation of NH_3 and NO_x from managed soils (1%) and (ii) after leaching and runoff of nitrogen, mainly as NO_3^-, from managed soils (0,75%) [IPCC 2006]. So, for each crop, nitrogen losses can be estimated by using the IPCC emission factors. As N inputs we only considered fertilizers. Deposition from air was not considered once this input will be the same, for each region, for all the crops, including idle land. Symbiotic N-fixation was considered in the study, in the case of lupin. Concerning P and K emissions, while P from artificial fertilizer remains relatively inert in the soil, provoking no noteworthy effects, K may contribute to eutrophication of terrestrial ecosystems. This issue will be dealt with on the evaluation of the nutrient status of the soil. A range of N, P and K fertilizer application, for the three environmental zones studied, was observed, showing that fertilizer inputs are regionally specific. Yet, because similar variability within zones was also identified for the crops wheat and maize, N, P and K inputs and emissions were considered at an European level. Perennials, in addition to the annual crops castor and hemp, are the crops that show the lowest fertilizer emissions, thus showing only a small increased impact, when comparing with idle land. The annual crops safflower, sorghum, wheat and maize showed the higher emissions. Although an annual crop, lupin benefits from nitrogen fixation through symbiotic association with *Bradyrhizobium lupini*, which can yield around 21 kg N per ton of shoot dry weight [del Pozo & Mera 2021].

In terms of pesticides emissions, they contribute to ensure the supply of agricultural products, but they present shortcomings, namely noxious human health effects, damage to flora and fauna, contamination of soil and groundwater and imbalance of pests and diseases [Wilson & Tisdell 2001]. For the risk assessment, a pesticide score was determined for each crop resulting from pesticide application. This score was attained through the quantification of active substances applied in each crop; and on the effects on the environment, fauna and human health of each active substance. Table 7 shows that the crops studied present lower pesticide impact, which reflects their apparently low susceptibility to pests and diseases. Best results were found on hemp, Miscanthus, willow and poplar, which showed a score similar to idle land. Maize and wheat showed a higher pesticide risk. Lupin and sorghum, although needing high amounts of pesticides, according to the literature and some surveys consulted, the chosen pesticides applied present low toxicity and therefore results presented are similar to the score attributed to safflower, castor and switchgrass. Pesticides application and emissions were also considered at an European level.

Concerning effects of the marginality of the soils, in terms of the fertilizer related emissions, there is a trend for a lesser need of fertilizers with increasing marginality, once crop yields are lower, and the uptake of NP and K by the crop will be lower. Therefore, it would be expected a lower impact associated with fertilizer related emissions. Yet, the lower densification of the biomass may increase the impacts associated with NP and K run-off and leaching. In terms of the pesticides related emissions, it was considered that with increasing marginality, the same amount of pesticides would be applied on the same area of land. Therefore, the expected impact associated with pesticides application may increase, due to the lower densification of the biomass, which allows a higher run-off, leaching and dissemination of the applied pesticides. This is particularly relevant in the case of pesticides with active ingredients that are highly soluble and persistent in water (solubility > 1mg/l and > 28 days to degrade 70%), and that represent an acute toxicity to water organisms (LC_{50} ≤ 10 mg/l) [Fernando et al. 2010]. Nevertheless, since the crops studied present no impact or low pesticide impact, the marginality effect does not imply a higher risk linked with the pesticides related emissions.

Table 8 indicates the results of the EIA on the impact of the different cropping systems on soil. Indeed, common cropping management activities and crop characteristics affect soil quality through the change of nutrient, organic matter (SOM), structural and acidic statuses and erosion potentials.

Table 8: Results of the EIA to the cultivation phase: impact on soil

Crop	Impact on soil		
	Nutrient status	Erosion	Soil properties
Miscanthus	0	++	+++
Switchgrass	0	++	+++
Poplar	0	++	++
Willow	0	++	++
Safflower	–	–	0
Castor	–	0	+
Hemp	0	–	+
Sorghum	0	–	+
Lupin	0	– –	–
Wheat	– –	– – –	– – –
Maize	– – –	– –	– –

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

The nutrient status occurring in idle land (the reference system) was considered to be neutral, under the assumption that the uptake during vegetation growth, return to the soil during senescence and decomposition. Hence, when comparing with idle land, all crops, more or less, may disturb the soil's nutrient status. Fertilizer application should be as balanced as possible in order to avoid excessive deficit or surplus, which can be accomplished through inputs management. Although surplus may enrich the soil nutrient pool, excessive N, P and K, will be detrimental regarding eutrophication and resources exploitation (to name a few impact categories). Reversely, excessive deficit may cause plant malnutrition and soil depletion. According to Table 8, when comparing with idle land, the perennials, hemp, sorghum, and lupin showed a balanced approach regarding nutrient status of the soil. Safflower and castor may be less balanced in terms of the nutrient status, but this impact can be reduced if crop residues are incorporated in the soil. The same is valid for maize (that present the higher risk in terms of nutrient status). As already referred in the results presented in Table 7, fertiliser inputs were considered at an European level. But crop uptake was determined at each environmental region due to differences in productivity and biomass composition among regions. Yet, the range of fertilizers applied in Europe, on the studied cropping systems, followed the uptake by the crops, and therefore, in the different regions, the balanced approach reflected in Table 8, was also observed for each region. The same applies to the marginality effect. Once the application of fertilizers should follow the amount being uptaken by the crop, nutrient status on soils with increased marginality, for the studied cropping systems, should also follow the pattern observed in Table 8.

Soil conservation through soil erosion prevention is crucial for maintaining productivity. Erosion leads to the loss of fertile soil and structurally damage crops. Moreover, displacement of materials, such as nutrients and contaminants, through wind and water can affect nearby terrestrial and aquatic ecosystems. In this study, water erosion was assessed by crossing the potential damage caused by rainfall with the soil cover characteristics of the crops during their cultivation cycles. Crop growth was divided into different phases (start of growth, closure of crop, start of senescence, harvest) and a crop management factor was defined for each phase, crop, and environmental zone, reflecting the soil cover rate of the crop (considering canopy development, remaining and buried crop residues and tillage). For each crop and region, the different soil cover factors (C) are multiplied by the accumulated precipitation on that growth phase (R). The sum obtained in a year is than multiplied by a factor (P) that indicates the control of erosion and soil conservation carried out in each region, providing the total harmful rainfall:

$$\text{Total harmful rainfall}_{\text{crop and region}} = \sum (C \times R)_{stage\ and\ region} \times P_{region}$$

It was assumed that erosion control takes place in all climatic zones. Hence, for all regions it was decided to use a P value of 0.8 [Fernando et al. 2018]. Results show that lignocellulosic and woody crops exhibit average lower erodibility potential owing to greater interception of rainfall and more surface cover for a longer time period (Table 8). The continuous presence of an underground biomass in the soil also contributes to these findings. Results obtained indicate that impact is even lower than what is observed with idle land, and the results are in line with the work presented by [Cosentino et al. 2015] obtained in a sloppy area in Sicily. In contrast, annual crops pose higher erosion risks, particularly wheat, maize and lupin, due to the lower permanence in the soil. Castor, hemp, safflower and sorghum, benefit from the extension of the root system. Nevertheless, in this erosion impact analysis it was only considered the exposure of the soil to rainfall. Other important factors that might contribute to the erosion potential of each crop, such as wind, SOM and soil structure, which also influence the soils integrity, were not considered in this study. Moreover, when annual crops can be sown in autumn and survive to over-wintering, the impact on erosion will be reduced, due to the longer permanence in the soil. Intercropping options or the implementation of intermediate crops may also be envisaged to reduce the erosion potential of these industrial crops. In the work of [Samarappuli & Berti 2018], forage sorghum-maize intercropping proved to have a lower environmental impact compared with maize in all evaluated categories. This was largely because forage sorghum has several agronomic advantages over maize such as having a higher efficiency in utilising P and K, and requiring less water, and N fertilizer. But, these strategies pose some challenges, e.g. the selection of the appropriate crop species and the need of extra labour in preparing and planting the seed mixture and during crop management practices including harvest.

Assessment of the erosion risk is highly site specific, naturally owing to the weight of pluviosity. Mediterranean region is drier than Atlantic and Continental lies in between. Hence, the average erosion risk increases with the increment of the annual precipitation. The marginality effect reduces the gap of idle land to the crops with higher impact (e.g. wheat) and increases the gap positively to the crops with lower impact. When marginality increases, there will be a lower densification of the biomass, which will enhance the erosion risk. But, in idle land, the biomass densification will also decrease.

Evaluating the impact of crops on soil organic matter content, structure and pH is highly dependent on local conditions. Nonetheless, there are generic trends documented in literature that allow a comparison between trees, perennial grasses and annual crops. Concerning soil properties, annual cropping systems are the most damaging in terms of SOM content and structure due to high soil revolving, short permanence and litter removal (e.g. lupin, maize, wheat)(Table 2). Intensive soil amendment in annual systems may lead to sharp pH variations from the native status of the soil. Crops presenting deep roots (castor, hemp, sorghum and safflower) [Bhattarai et al. 2020; Fernando et al. 2010; Severino & Auld 2013] or if litter is left in the field, minimize the impact. Poplar and willow are reported to accumulate higher SOM than annuals but regarding soil pH, woody crops significantly increase soil acidity [Cannell 1999], which limits nutrient availability to crop growth [Bona et al. 2008]. When compared to trees and annuals, herbaceous perennials provide higher organic matter accumulation and structural enhancement related to permanence, high inputs of residues and vigorous root development [Fernando et al. 2018]. A less intensive soil amendment (by comparison with annuals) also contributes to minimize the impact of woody and herbaceous perennials.

As it was observed on the analysis of the impact of these crops on soil erosion, the marginality effect reduces the gap of idle land to the crops with higher impact (e.g. wheat) and increases the gap positively to the crops with lower impact. Biomass densification reduction in idle land is higher than what can be observed in an industrial crop field. Yet, since the marginality reduces the yields, a higher land area is needed to get the same amount of feedstock, which can hinder the use of marginal soils on the cultivation of these industrial crops.

Table 9 indicates the results of the EIA on mineral and water resources.

Crops can either be irrigated or suppress their water needs by accessing aquifers and precipitation water. Whichever way, unless rainfall tops requirements, freshwater must be extracted from surface or groundwater, which depletes natural stocks. Hence, depletion of groundwater resources was determined by comparing the available water provided by rainfall and the water requirements of the crop [Fernando et al. 2010]. According to these results, hemp, wheat and maize may lead to depletion of groundwater resources (Table 9). Safflower, sorghum and lupin may also contribute to deplete groundwater resources. Herbaceous and woody crops and castor do not inflict a depletion of groundwater resources. Even so, in regions with less precipitation, balances results can be lower, such as with switchgrass in the

Mediterranean. In fact, the impact on groundwater is highly site specific. Regions with lower rainfall (Mediterranean) record higher deficits. Opposed to this, high water demanding crops can present a balanced amount in regions with higher precipitation, like hemp in Atlantic. Increased marginal soil conditions, usually reduces the water use efficiency, due to the lower biomass densification, but, on the other hand, the lower biomass production also contributes to reduce the amount of groundwater demand.

Table 9: Results of the EIA to the cultivation phase: impact on mineral and water resources

Crop	Impact on mineral and water resources		
	Groundwater balance	Effects on hydrology	Mineral ore depletion
Miscanthus	0	–	–
Switchgrass	0	–	–
Poplar	0	–	0
Willow	0	–	0
Safflower	–	0	–
Castor	0	–	0
Hemp	– –	–	0
Sorghum	–	–	– –
Lupin	–	0	–
Wheat	– –	– –	– –
Maize	– – –	– – –	– – –

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

Hydrology effects of industrial crops cultivation can go beyond their water demand, focusing also on the crops cultivation effects on the flow of ground water, stream water, run-off, etc. Although these aspects are highly site specific, they are also related to crop traits. Soil covering minimize surface run-off and sediment and nutrient losses. So, the longer the crops permanence in the soil (e.g. herbaceous and woody crops) the better the beneficial effect due to minimisation of surface run-off. On the opposite, crops with shorter permanence in the soil have a higher impact on hydrology (e.g. wheat). But, negative impacts should be expected from species combining higher growth rates and transpiration rates, longer seasonal growth and deeper and more complex root system. Deep rooting slows down rainfall refill of aquifers, especially when associated with high evapotranspiration losses. Shortcomings concerning aquifer refilling were credited to crops with higher water needs (e.g., maize, hemp, switchgrass, poplar and willow) and deeper root systems (e.g., perennials, hemp and sorghum). Safflower and lupin present an impact on hydrology that is similar to the one that is observed with idle land. Among regions, the lower precipitation observed in the Mediterranean region accentuate the impact on aquifer refilling when high water demanding crops are being established. Increased marginal soil conditions, lowers biomass densification and allows the refill of the aquifers, but maximises surface run-off.

It can be claimed that the impact on water resources may be reduced if wastewaters are used to irrigate the fields and to cover the water deficit that may be reached in regions with low precipitation (Mediterranean). This is in fact a valuable environmental alternative: water stocks will be retained and aquifers will be filled up. Moreover, industrial crops fields constitute a promising option for the remediation of wastewaters, once excessive nutrients and pollutants will be intercepted by the underground system, improving the quality characteristics of the released effluents [Barbosa et al. 2015; Costa et al. 2016].

Agricultural systems rely on a supply of artificial fertilizers that in turn depend on the input of mineral resources. Hence, fertilizers use influence the depletion of mineral ores. In this respect, phosphate and potassium fertilizers were taken into account, once they are mined as mineral ores, with limited resources.

Results show that woody crops, hemp and castor are less P and K demanding, thus showing lower impact regarding mineral resources exploitation. Miscanthus, switchgrass, lupin and safflower show some impact, compared to idle land. In the case of Miscanthus and switchgrass, the impact is especially due to the K demand. Lupin benefits from roots release of carboxylic acids (malic and citric) and acid phosphatase which increases the soil P availability [del Pozo & Mera 2021]. The remaining annuals present a higher risk concerning mineral resources depletion. However, if the amount of K added to the soil will be less, those impacts will be reduced. Moreover, the reduction in the K added will not pose a problem since the soils are usually rich in this mineral and this will not create a soil deficit. In the case of P, the impact could be reduced if wastewaters rich in phosphates would be applied. Yet, the administration of those waters rich in phosphates should have to be done appropriately so that ground water would not be contaminated with those phosphates, that could after cause eutrophication problems [Barbosa et al. 2015]. Again, there is some variability among regions, but not significant, and therefore this parameter was analysed at an European level. The increased marginality of the soils also contributed to reduce the amount of mineral resources needed, and therefore, the gap to idle land was reduced, especially in the case of sorghum and maize, but not in the case of wheat.

Table 10 indicates the results of the EIA on waste (generation/use) and on biodiversity and landscape.

Regarding waste generation and waste use, the assessment consisted on scoring the crops relatively to their ability to take up contaminants and nutrients from sludge, slurry, landfills, wastewaters and soils and to their propensity to produce undesired waste during cultivation. These industrial crops have been thoroughly documented as apt remediators of heavy metal contaminated soils and landfill leachates, even wheat and maize. Irrigation with wastewaters and soil amendment with sewage sludge is reported as well. Thus all crops studied scored the same as idle land, or even with a lower impact when it was identified that phytoremediation and application of wastewaters and manure is an interesting option (e.g. in the case of herbaceous and woody crops and hemp [Barbosa et al. 2019; Barbosa & Fernando 2018; Fernando et al. 2010].

Regarding the generation of waste during cultivation, it was assumed that all crops produce it in the form of pesticide and fertilizer disposed packages and old machinery, thus scoring higher impact than idle land. Being less management intensive, perennial grasses and trees generate less waste than annual crops, thus presenting lower impact. Regarding castor, the ricin found naturally in castor beans and present in the waste material left over from processing castor beans, increases its impact of this crop. The differences among regions are linked with the variability in the yields. The same is true when analysing the effects of the marginality of the soils. But, the lower the yields, the lower the beneficial impact on the use of wastes but it also reduces the impact related with wastes generation.

Table 10: Results of the EIA to the cultivation phase: impact on waste, biodiversity and landscape

Crop	Waste (generation/use)	Biodiversity	Landscape
Miscanthus	+	0	0
Switchgrass	+	0	0
Poplar	0	+	0
Willow	0	+	0
Safflower	–	0	**+**
Castor	– –	–	0
Hemp	0	–	0
Sorghum	–	– –	0
Lupin	0	–	+
Wheat	– –	– – –	– – –
Maize	– – –	– –	– –

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

Biodiversity impact assessment is highly site-specific since it analyses the effect of the introduction of a crop and its cultivation system on the structure of ecological units and the sustainable development and use of an existing population. Landscape configuration and habitat richness have an impact on its community's diversity. It is agreed that more complex structure and heterogeneity of a vegetation system have a positive influence on its cover value for wildlife. So, establishment of a monoculture as a replacement of natural diversified vegetation is a violation against biodiversity. By definition, any natural vegetation type has the best performance concerning the ecosystem services and, consequently, biodiversity. Hence, compared to a natural system even if idle land, any industrial crop will have negative effects and they will be more severe the farther the system shifts from the native conditions. These effects vary, nonetheless, with the traits inherent to the crop, plantation siting and its management system.

Facing the lack of local onset data and extensive and systematic reference studies for each crop species, a generic approach was implemented. Crops and crop-types were benchmarked towards idle land and towards each other in a qualitative fashion. In general terms, establishment of a monoculture (all crops studied) and aggressiveness of species (none of the studied crops with this character) result in a higher impact. On the other hand, native species and colourful blossomed crops (safflower, castor and lupin) contribute to the biodiversity value. Globally, trees were considered richer in terms of biodiversity value and annual crops poorer. Perennial grasses were scored in between. Literature asserts that perennial grass and tree plantations support more microfauna, soil fauna and bird species [Fernando et al. 2018]. By opposition, annual crops have been reported as source of biodiversity loss due to short permanence on soil and thorough management, including high agrochemical inputs, ploughing and tillage and removal of litter soil cover (Fernando et al., 2010). The remaining variations in scoring are due to characteristics of the plants or of their cultivation practices and also to documented negative or positive impacts (Table 10).

Landscape impact assessment was performed by comparing the crops with idle land. Lacking onset data, the analysis was performed based on a subjective analysis of known crop traits. Structure and colour were chosen as criteria to evaluate landscape quality and greater variation earned positive evaluation. Idle land was considered a standard and variation was assumed to be a deviation in landscape characteristics of the crop towards idle land. The evaluation of structure included height, density, heterogeneity and openness of the crop. Assessment of variation of colour considered significant variation of colour of the crop along its life cycle and/or presence of structures, such as inflorescences, with distinct coloration. Variation was considered to be a benefit when it embraced gains in structure and/or colour and variation implying loss of structure and/or colour debited the landscape values [Fernando et al. 2010]. Hence, positive scoring yielded from increases in height, heterogeneity, density, openness and colour. Negative scoring resulted from the opposite. Non-variation was considered to be neutral. The impact on landscape values in even among crops (Table 10). The exception is wheat and maize, which represented a downgrade to landscape when comparing with idle land. Blossoming crops presented lower impact than idle land, except castor that loses in aesthetics, hence being evaluated in line with idle land.

Results presented, and following the generic approach described to evaluate impacts on biodiversity and landscape, don't variate among the different regions. Regarding the effects of the marginality on biodiversity and landscape, as seen on the impact to soil quality, the negative gap to idle land is reduced and the positive gap to idle land is increased. Yet, marginal land can harbour high levels of biodiversity or very unique valuable components of biodiversity (such as food and medicinal resources for locals) and therefore this aspect has to be taken in consideration before the land use change [Dauber et al. 2012].

5.2 Impacts of the different processing technologies

Table 11 shows the results of the EIA related with the local impacts of the different processing technologies. In this assessment, comparison was made only among the different processing technologies and with idle land.

Although all the processing options may cause disturbance on the idle land, taking into consideration the area occupied by the different processing units, it was considered that the disturbance to the native system in terms of biodiversity and landscape would not be high enough to be marked up for most of the processing options. Concerning soil quality, the same pattern was applied, and no major disturbance was foreseen, considering the area occupied by most of the processing units. Yet, fermentation, oxidative cleavage and fatty acids production units were marked with a negative status, in comparison with idle land, because these processes induced a higher disturbance of the native systems (Table 11). In fact, these processes were moderately penalised due to a higher extension (in area) needed for the processing compared with the other processing techniques. Because of this, a higher gap from native conditions is shown when the installations are settled. Fermentation is further penalised, regarding biodiversity and landscape, due to the possible presence of microorganisms in the waste streams that are potentially pathogenic, toxic and infective, causing potential concern for affecting native microbial populations. Indeed, the numbers of cellulolytic bacteria and mould are extensive. Use of these microorganisms in large-scale production substantially increases the potential for their release into the environment, either through unintentional releases or potentially as a constituent of cellulosic ethanol waste. Additionally, genetically designed varieties of microorganisms have been developed to improve or combine stages of the ethanol production process. These modified microorganisms may bring risks locally. If leaked to the environment, may change its ecology, posing a risk to the ecosystems [Menetrez 2010]. It is uncertain how introducing large quantities of foreign microbes with specialised capabilities in the breakdown of plant structures might alter the natural balance of flora and fauna. In the anaerobic digestion process, the same risks associated with the presence of microorganisms in the waste streams, may also affect native microbial populations, but in this case, the disturbance to the native systems was not so significant as the one recorded with the fermentation process.

The need for raw materials besides biomass feedstock may also increase the impact on biodiversity and landscape, if we consider the disturbance on the native systems linked with the obtainance of those raw materials. In the gasification process, this is linked with olivine, calcine and K_2CO_3 needed. Moreover, the need of active carbon to adsorb tar may also provide a higher impact on the value chain and process. But, if this active carbon is being produced from agricultural wastes (e.g. olive pomace, [Fernando et al. 2009]), or other lignocellulosic residues, than a bonus can be attributed to the system. Fermentation, oxidative cleavage and fatty acids production units, have also been penalised in terms of biodiversity and landscape due to the need of raw materials (sulphuric acid, sodium hydroxide, lime, cobalt acetate, to name a few). The biorefinery associated with lupin and the production of hemp insulation maths, are processes also penalised due to the disturbance that they may cause in terms of biodiversity and landscape, once several raw materials are needed: fire retardants, NaCl, polyester binder, etc. But the amount needed does not significantly disturb the native systems.

Compared to the conventional processes, all the biogenic processes behave better, mostly because the conventional processes occupy a large area. The only process where the conventional and the studied process present similar impact is the oxidative cleavage, where the conventional process also uses a biogenic raw material. In terms of effect of the marginality of the soil, the impacts can be higher, mostly because the use of biomass from marginal soils may present different characteristics and higher amount of wastes can be produced. Therefore, if the amount of wastes will increase due to the effect of soil marginality, then a higher pressure will occur on the disposal phase either on the biodiversity and also on the landscape and on soil. Yet, literature is still limited on the effect of the characteristics of the biomass obtained from marginal soils on the processing waste streams. Most of the existing information is linked with commercial processing units, such as combustion and less or non-existing on the processes studied in this project. The obtained information in this project, especially in WP4, will be important to provide highlights on the mass flows of the different value chains studied, when the biomass being used is harvested from marginal soils. It would be interesting, in the future, to evaluate how a biomass, such as sorghum and switchgrass, from marginal soils, with different characteristics and composition (e.g. higher lignin content, less sugars, higher ash content) can affect the biological processing of the biomass. Is the fermentation process or the anaerobic process affected by the composition of the biomass? Does the composition of the biomass change the microbial populations responsible for the biological processes? Those are some questions that still need an answer.

Table 11: Results of the EIA of the different processing technologies: impact on biodiversity, landscape, soil quality, water use and wastes production

Technology	Biodiversity & Landscape	Wastes production	Soil Quality	Water Use
Pyrolysis	0	–	0	**–**
Gasification	0	– –	0	**0**
Fermentation	–	– –	–	– –
Thermochemical fractionation (TCF)	0	–	0	**–**
Oxidative cleavage	–	– –	–	**0**
Fatty acids	–	–	–	**0**
Biorefinery / extraction	0	– –	0	– –
Fibre production	0	0	0	0
Anaerobic digestion	0	–	0	0

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

Processing impacts on water use penalises the more water demanding technologies, namely fermentation, and the biorefinery associated with lupin. [Murphy & Kendall 2015], indicate in their study that the impact on water use associated with cellulosic ethanol production can be reduced if water is recycled through the process where possible. The same applies for the lupin biorefinery. Other processing options do not represent an impact on the water use, namely, gasification, oxidative cleavage, fatty acids production, insulation maths production and anaerobic digestion, because in the process, minimal or very limited amount of water is needed. Pyrolysis and thermochemical fractionation stay in between, due to the amount of water needed to process the biomass (please see Deliverable 6.3 for more details on the water balance).

The conventional systems, especially those linked with the petrochemical based processes, present also a high impact in terms of water use [Sun et al. 2018]. Most of the biogenic systems present a higher impact than the conventional-fossil ones. The exceptions are the oxidative cleavage and the fatty acids production units, the gasification process and the hemp insulation math production, which show similar or lower water use than the conventional processes. In this case, the marginality effect does not affect (at least directly) the water use need by the processing units, which provides a bonus to the use of biomass from marginal land in those biogenic systems.

Gasification (due to the tar production), fermentation, and oxidative cleavage represent a higher impact in terms of wastes production and also wastewater production. [Chidikofan et al. 2017], in their study, indicate that gasification, although presenting many positive effects, can also affect environmental and human health. Indeed, during the process of biomass gasification, tars are produced and generally discharged in the local environment. The study also indicated that when tars are dumped into water comparatively to their discharge on soil, the impact levels are higher. The disposal of tars is in fact problematic due to the presence of chemical substances known to be carcinogenic, mutagenic and /or toxic. However, the impact associated with the tars is also linked with the type of biomass and with the operational conditions of the gasification process. Moreover, as stated before, the tar can be adsorbed to active carbon (which can be produced through agricultural wastes, a bonus n the system). Waste streams from fermentation, oxidative cleavage and the biorefinery approach on the use of lupin, as also the conventional based systems, which can contain a variety of chemicals that have potential environmental consequences to biodiversity, soil quality and that may limit water use are penalised. Regarding the fermentation process, the waste streams produced contain a variety of components that change according to the ethanol generation process used and the feedstock, and those components can be potentially harmful to the environment if adequate care is not taken to manage those risks [Menetrez 2010]. Waste stream management and utilisation of the cellulosic ethanol process is mandatory for the process implementation development. Indeed, the cellulosic ethanol waste materials can contain a variety of chemicals, viable biological microorganisms, and biologically derived proteins and toxins that can have potential environmental consequences. Wastewaters present a high biochemical oxygen demand, which can cause hypoxia, and suffocate aquatic animals, if discharge in water streams without treatment. Interestingly, it was mentioned in the study of [Menetrez 2010], that the water quality can also be changed when the cellulosic ethanol waste is added to the diet of cattle. Cows that are fed a diet of 40% distillers' grain (the maximum limit) produced faecal material with 41% more phosphorous and 33% more nitrogen than cows fed conventional feedlot diets. To accommodate this for land disposal, in excess of 40% more land will be needed to treat the waste of cows consuming distillers' grain if it is disposed of by the currently used practice of spreading it over fields. Additionally, water quality around feedlots will likely worsen by the load of more nitrogen and phosphorous in streams and rivers. However, all those wastes produced in the fermentation process can also be dried and combusted to provide energy for the plant (please see Deliverable 6.3). The production of wastes rich in chemicals in the oxidative cleavage and the production of a high number of wastewaters in the biorefinery approach on the use of lupin, also penalises these processes.

The pyrolysis process, the thermochemical fractionation, the fatty acids production unit and the anaerobic digestion also produce wastes and wastewaters but their biogenic characteristics renders them benefits. In the pyrolysis unit, and also in the thermochemical fractionation unit, the ash being produced can be given a value, either by incorporation in cement or by deposition in soil. Adding value to the ash being produced in the processing units can be also a bonus in the gasification and fermentation processes. Application of ash (from pyrolysis plants) in soil can contribute to achieve a balanced nutrient status which provides bonus to this system. In fact, there are extensive concerns regarding biomass ash handling and management such as ash disposal, ash storage, ash usage, and transportation and the ash produced from biomass is much more in quantity as compared to a conventional system. The ash can be stored in dumping grounds that causes serious harmful effects to the environment as the utmost origin of inert pollution as well as the aesthetic of the place where the processing unit is based. Biomass ash contains trace elements like Ag, Hg, Ba, As, Cd, Mn, Cl, Ni Cr, Cu, Pb, S, Zn and V that are risky for plant growth and soil quality as the biomass ash consist of soluble salts and it can also increase the salinity of the soil. These ashes may also represent a danger to aquatic life when they fall into rivers and streams, or when salts are leached. The air quality can also be significantly affected by the ashes and dust associated, affecting locally the region [Munawar et al. 2021]. Which means that there is a need for a silo to handle this waste. Conventional utilisation of ash can be categorised in the following (i) in the construction industry (ii) used as a recycling fuel and (iii) agriculture usage, but there are also novel applications (nanotechnology and energy storage systems) for the ash that can be obtained from these processing units. The benefits of a reuse of the ash, in a circular economy approach, will render the process environmental advantages, as mentioned. The use of biomass ash desires to be assessed on a case to case basis which needs to be carefully analysed due to the presence of toxic metals or water-soluble dangerous compounds. Yet, ash derived from cleaner biomass feedstock is usually not problematic, and it consist of minerals, trace elements and may be used as soil amendments in forests or agglomerating substances in cement etc., but the composition has to be quantified and the impacts of these materials need to be studied in detail before application. Interestingly, when considering biomass from heavy metals contaminated soils, this issue may represent a problem, if the ash composition is rich in heavy metals [Barbosa et al. 2019]. Moreover, biomass from marginal soils may increase the amount of ash per year produced in the processing unit once the biomass feedstock may be richer in ash content. When used as fertilizer and nutrient supplement in the agriculture industry, several benefits (but also some constraints) can be signalised: the cations, increases the pH, improving the acid neutralizing potential. This will reduce the acidic behaviour of risky elements from soil to water resulting in less mobilisation and bioavailability. It increases biotic activities and provides a healthier environment to microorganisms. And it helps to refine surface, airing and water capacity [Alavéz-Ramírez et al. 2012]. But also salinity can be increased which is not favourable in many conditions. It was mentioned in a study that the application of ash can enhance the availability of soil nutrients to plants, with an increase in the value of chlorophyll and carotenoid pigments that are utilised in the photosynthesis process further, which can increase the number and size of fruits and flowers of the plant, which, indirectly, will help boosting biodiversity indexes. Reference studies highlight that some ash may present good properties for its reuse in the manufacturing of construction material. In the construction industry, ash is being used in brick kilns for the manufacturing of bricks, in the cement industry, road construction and mine filling [Maschio et al. 2011]. In addition, ash can also be used as an adsorbent in environmental applications, due to its alkaline nature. The negative charge on its surface provides the ash with ability to have electrostatic adsorption and precipitation to remove the metal ions from aqueous solutions.

Concerning the anaerobic digestion process, the production of the sludge and the disposal of the final digestate may also increase the environmental impact of the process. The use of digestate as biofertiliser is a common practice related to biogas production. Application of digestate as a biofertiliser and as soil improver is indeed a sustainable approach, allowing to reduce the production, transport and use of synthetic chemicals. However, spreading the digestate on soils may also imply the release into the ecosystems of high amounts of ammonia and nitrate, which may penalize the system [Paolini et al. 2018]. Yet, a study from [Möller 2015] indicates that direct effects of anaerobic digestion on long-term sustainability in terms of soil fertility and environmental impact at the field level are of minor relevance; The authors indicate that the most relevant issue (with regard to both emissions to atmosphere and in soil fertility) is related to possible changes in cropping systems. According to this study, the main direct problems of anaerobic digestion are short-term effects on soil microbial activity and changes in the soil microbial community. Considering soil quality, digestate is considered almost inert which results into a lower degradation rate of the organic matter. In fact, labile fractions of original biomass such as carbohydrates are rapidly degraded, causing the enrichment of more persistent molecules such as lignin and non-hydrolysable lipids [Tambone et al. 2009]. In terms of nitrate leaching and release into the atmosphere of ammonia and nitrous oxide, the current state of knowledges needs to be improved once the review work by [Möller 2015] indicates that the impact can be either negligible or at least ambiguous, depending on the type of soil. A significant impact of soil moisture-soil mineral-N interactions on N_2O emissions was also observed by [Senbayram et al. 2014]. As for nitrous oxide, digested products are more recalcitrant than fresh biomass [Paolini et al. 2018]. Therefore, the main critical issue in final use of digestate is nitrogen release into the environment, which can be reduced by applying the best practices for preserving soil quality. Yet, the management of nitrogen dosage is sometimes difficult because of the feedstock variability. Hemp insulation maths production unit show limited impacts concerning wastes. The most problematic issue related with this processing option is the dust being released during the process that can impact on the workers' health. But, good practices installed can reduce the impact associated with.

As mentioned, the marginality of the soils may affect the amount of wastes being produced in the processing units and also on the characteristics of the wastes. This is particularly critical in the case of the ash production, as discussed. Also, the type of feedstock may affect the fermentation and the anaerobic digestion processes, once the microbial community responsible for the processing may be affected by the feedstock composition. The feedstock composition may also negatively affect the other thermochemical, chemical and mechanical processes, and the quality of the products being produced, along with the amount of wastes and wastes characteristics. Interestingly, the biogenic systems present a lower impact in terms of wastes than the conventional-fossil ones.

5.3 Impacts of the selected value chains

Table 12 shows the results of the EIA related with the local impacts of the different cropping systems and the different 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 12: 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

In this assessment, analysis of the biogenic/conventional system interaction with its environment and management practices was executed. In the value chain different parameters were integrated: land use, aggressiveness (emissions, noise, smell, effects beyond the 10 ha), nativeness (habitat loss, effects beyond the 10 ha), colour, land disturbance (carbon stock loss), shelter provision, and impervious surface were scored qualitatively in the comparison with idle land, that was scored “0”. In the analysis made, the different scores attributed to the crops and to the processing options were taken into consideration, as also the amount of biomass needed to feed the processing units. The time required to restore the land to its native condition was also a parameter that was accounted when comparing the biogenic and the conventional systems. In terms of local impacts on biodiversity and landscape, industrial heat from Miscanthus, SNG from poplar and biotumen from willow, benefit either from the crops cultivation beneficial effects and also from the low impacts associated with the processing options. Organic acids from safflower and adhesives from lupin, although presenting benefits in the cultivation phase, the amount of land area needed to provide feedstock and also the impacts associated with the processing (production of organic acids), nullify those benefits. Regarding the production of insulation maths from hemp and production of biogas/biomethane from sorghum, the score assessed resulted more from the impacts associated with the cultivation phase. In the case of ethanol production from switchgrass, although the cultivation of this perennial presented null impacts, the impacts associated with the processing option, and the amount of biomass needed to feed the unit, render this value chain a negative value. Concerning biodiversity and landscape, sebacic acid from castor oil presents a high impact that is associated with the cultivation, the processing and the amount of land needed to provide feedstock. Results also indicate that the biogenic system is penalized when compared with the conventional-fossil one. In the case of the value chain associated with safflower, the impacts will be similar to the conventional value chain. In terms of the marginal conditions, the benefits in terms of biodiversity and landscape associated with the cultivation in marginal soils are somehow hindered by the negative aspects associated with the use of a biomass that will produce more disturbance in the processing stage. But, overall, the entire value chain benefits slightly from the use of marginal soils.

In terms of local impacts due to wastes, the production of insulation maths from hemp benefits either from the low impacts associated with the cultivation phase and also from the low impacts associated with the processing unit. The value chain associated with Miscanthus and willow presents also low impact, because the benefits associated with the cultivation phase nullifies the negative impacts associated with the processing units. SNG from poplar benefit from the cultivation phase, but the impacts associated with the processing nullifies those benefits strongly. The same applies to ethanol from switchgrass and adhesives from lupin, which are even more penalized due to the land area needed to provide feedstock. Regarding the production of biogas/biomethane from sorghum, the negative score associated resulted either from the impacts associated with the cultivation phase and the processing stage. Organic acids from safflower and sebacic acid from castor oil presents a high impact that is associated with the cultivation, the processing and the amount of land needed to provide feedstock. As per biodiversity and landscape, the biogenic systems present a higher impact in terms of wastes than the conventional-fossil ones. In the case of the value chain associated with safflower, the impacts will be similar to the conventional value chain. In terms of the impacts on the value chains due to the wastes, induced by the marginality effect of the soils, the negative gap to idle land is slightly increased, mostly due to the impact of the biomass characteristics on the processing stage that will also increase the amount of wastes.

In terms of impacts on soil, industrial heat from Miscanthus, SNG from poplar and biotumen from willow benefit highly from the crops cultivation positive effects, although there are also low impacts associated with the processing options. Ethanol production from switchgrass value chain also presents a positive score, mostly due to the cultivation phase that cover the negative aspects associated with the processing stage and the amount of land area needed to produce feedstock. Regarding the production of insulation maths from hemp and production of biogas/biomethane from sorghum, the score assessed is linked with the null impacts on the soil either from the cultivation phase and from the processing stage. Sebacic acid from castor oil is penalized by the processing stage and the amount of land area needed to produce feedstock although the cultivation phase presents limited impacts. Adhesives from lupin presents low impact in the processing stage but high impact on the cultivation phase. Organic acids from safflower, presents impacts either in the cultivation and the processing stages. Moreover, the amount of land area needed to provide feedstock also renders those value chains a negative score. In terms of the impact on soil, again, the biogenic systems present a higher impact than the conventional-fossil ones. The safflower value chain presents an impact similar to the conventional value chain. In terms of the marginal conditions, the benefits in terms of soil associated with the cultivation in marginal soils are also somehow hindered by the negative aspects associated with the use of a biomass that will produce more disturbance in the processing stage. But, overall, the entire value chain benefits slightly from the use of marginal soils. This is particularly important if a higher bonus is given to the ability of the crop to help remediate the marginal conditions of the soil, which is particularly relevant in the case of the woody and herbaceous crops. The positive score is also of relevance in the Mediterranean and the Atlantic regions, once adverse rooting conditions is an important biophysical constraint associated with these regions.

Perennial crops cultivation can cause an impact in terms of the water use due to the deep rooting that slows down rainfall refill of aquifers. Yet, the value chain linked with poplar presented no impact because the benefits of the processing stage in terms of water use nullify the negative impact of the cultivation stage. In the case of Miscanthus and willow value chains, the negative score is linked with the cultivation phase but also with the processing stage. The same applies to the switchgrass value chain, but in this case, the score is more negative due to the negative impact of the processing stage. The value chains of safflower and castor, present also a negative score that is attributed to the cultivation phase and to the large land area needed to provide feedstock. In the case of the sorghum value chain, the negative score is linked with the cultivation phase. The same applies to the hemp value chain, but in this case, the more negative value is associated with the more negative impact associated with the water use on the cultivation phase. Lupin value chain presented the highest impact in terms of water use, due to the cultivation phase, to the processing stage and also due to the amount of land area needed to provide feedstock. In terms of the impact on water use, the biogenic systems present a higher impact than the conventional-fossil ones. The safflower value chain presents an impact similar to the conventional value chain.

In terms of the effects of the marginality of the soil on the impact assessment of the value chains, the status will be similar to what is scored for standard soils even in the Mediterranean area where water resources are a constraint. In this region, the crops that showed a higher impact on water use add a penalising score to the value chains (case of hemp).

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. Miscanthus, poplar and willow also take advantage of the processing stage that presents less local impacts when comparing the different technologies. In the case of switchgrass, the benefits of the cultivation phase are highly offset by impacts linked to the processing unit. Also, 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. The hemp and sorghum value chains received some negative impacts due to the cultivation stage and less to the processing stage.

6 Synopsis, conclusions and recommendations

In this chapter, a synopsis of the key findings from the environmental assessment is presented (section 6.1). On this basis, conclusions have been drawn (section 6.2) and recommendations made to different stakeholders (section 6.3), which are listed below.

6.1 Synopsis of the key findings of the environmental assessment

In this study, the environmental impacts of nine selected value chains comprising the cultivation and use of industrial crops on marginal land were assessed. In order to cover the spectrum of potential environmental impacts associated with bioenergy and bio-based products from marginal land as completely as possible, the environmental assessment was carried out using a combination of two methods: screening Life Cycle Assessment (LCA) and Life Cycle Environmental Impact Assessment (LC-EIA). Their key findings are summarised below.

6.1.1 Key findings from LCA

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 eleven environmental impact categories were evaluated in the screening LCA. The analysis (for details see chapter 4) 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.

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 biomass-based energy carriers and 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 (successional vegetation).
- 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 much more environmentally friendly than bioenergy: Bioenergy competes with other renewable energies, e.g. ground-mounted photovoltaic (PV) systems, for marginal land. The environmental advantages of PV electricity per unit of energy are significantly greater than those of bioenergy. In particular, the energy and GHG emission savings are several times higher than when the land is used to provide bioenergy.

6.1.2 Key findings from LC-EIA

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 (for details see chapter 5) 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 constrains 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 offers several environmental advantages and provides 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.

6.2 Conclusions

On the basis of the results in chapters 4 and 5 as well as the key findings in section 6.1, 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).


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- 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.

- **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'.
- **There is competition of biomass with other renewables** (e.g. ground-mounted photovoltaic (PV) systems) **for the same marginal land**. These alternatives uses can be much more environmentally friendly, in particular in terms of energy and greenhouse gas emission savings.
- 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.

6.3 Recommendations

On the basis of the conclusions in section 6.2, the following recommendations can be made.

- 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. Biophysical 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.
  - 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[3]
    - High nature value farmland (HNV)


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

- 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. The following type of land should therefore not be eligible for this purpose:
  - Land for which payments under agri-environmental programmes[4] have been made in the last ten years
- 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 offer several times greater environmental benefits than biomass production. However, nature conservation aspects in particular should also be given special consideration in these cases.


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- **Land use and land allocation plans should be prepared as part of publicly funded support programmes and concrete projects.** This is needed not only at the national and / or supranational level, but also at the regional level. 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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- For the sustainable establishment of industrial crops, **it is essential to build up the farmers' competencies regarding the selection of suitable crops and varieties.**
  - High priority should be given to ensuring that total plantation failures can be largely avoided.

[4] 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.

- The optimal choice of harvest time is also of great importance, especially with regard to the lowest possible water content of the biomass.

  This could be realised, for example, through external advisory services for farmers or the MAGIC Decision Support System (DSS) which is a good starting point for this.

Our research 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 renewable energy sources such as solar energy. Social aspects such as rural development and job creation should be considered in addition to economic aspects. 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
CBD	Cannabidiol
CHP	Combined heat and power
CON	Continental and boreal
D X.Y	Deliverable
DFB	Dual fluidised bed
dLU	Direct land use
dLUC	Direct land use change
DM	Dry matter
DSS	Decision support system
EC	European Commission
EoL	End-of-life
EPS	Expanded polystyrene
FAME	Fatty acid methyl ester
FM	Fresh matter
GHG	Greenhouse gas
HMF	Hydroxymethylfurfural
HNV	High nature value
ILCD	International Reference Life Cycle Data System
iLUC	Indirect land use change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle costing
LCIA	Life cycle impact assessment
LC-EIA	Life cycle environmental impact assessment
LCI	Life cycle inventory

LCT	Life cycle thinking
LU	Land use
LULUC	Land use and land use change
MED	Mediterranean
MLP	Micellar lupin protein
MS X.Y	Milestone
MUFA	Monounsaturated fatty acid
NREU	Non-renewable energy use
NREL	National Renewable Energy Laboratory
NUAA	Unutilised agricultural area
PAO	Poly-alpha-olefins
PET	Polyethylene terephthalate
PV	Photovoltaic
PUFA	Poly-unsaturated fatty acid
PUR	Polyurethane
RBD	Refined, Bleached, Deodorised
RED	Renewable Energy Directive
RME	Rapeseed oil methyl ester
SETAC	Society of Environmental Toxicology and Chemistry
SNG	Synthetic/substitute natural gas
SRC	Short rotation coppice
THC	Tetrahydrocannabinol
TRL	Technology readiness level
UNEP	United Nations Environment Programme
VC	Value chain
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.

Alavéz-Ramírez, R., Montes-García, P., Martínez-Reyes, J., Altamirano-Juárez, D. C., Gochi-Ponce, Y. (2012): The use of sugarcane bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks. *Construction and Building Materials*, Vol. 34, pp. 296–305.

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., 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. (2009): Guidelines for Social Life Cycle Assessment of Products. UNEP, SETAC, Paris, France.

Barbosa, B., Costa, J., Fernando, A. L. (2019): Production of Energy Crops in Heavy Metals Contaminated Land: Opportunities and Risks. In: R. Li, A. Monti: *Land Allocation for Biomass*, Springer International Publishing AG.

Barbosa, B., Costa, J., Fernando, A. L., Papazoglou, E. G. (2015): Wastewater reuse for fiber crops cultivation as a strategy to mitigate desertification. *Industrial Crops and Products*, Vol. 68, pp. 17–23.

Barbosa, B., Fernando, A. L. (2018): Aided phytostabilization of mine waste. In: *Bio-Geotechnologies for Mine Site Rehabilitation*, pp. 147–157.

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, Hürth, Germany. *http://multihemp.eu/media/2018/07/Deliverable_report_final_D7.3.pdf*.

Bhattarai, B., Singh, S., Angadi, S. V, Begna, S., Saini, R., Auld, D. (2020): Spring safflower water use patterns in response to preseason and in-season irrigation applications. *Agricultural Water Management*, Vol. 228, p. 105876.

Biertümpfel, A. (2014): Anbautelegramm: Zucker- / Futterhirse (Sorghum bicolor). Jena, Germany. *http://www.tll.de/www/daten/publikationen/anbautelegramm/at_hirse.pdf*.

Biewinga, E., van der Bijl, G. (1996): Sustainability of energy crops in Europe. A methodology developed and applied, Centre for Agriculture and Environment, Utrecht, February, CLM 234, (1996), 209 pp. Centre for Agriculture and Environment, Ultrecht.

Bona, K. A., Burgess, M. S., Fyles, J. W., Camiré, C., Dutilleul, P. (2008): Weed cover in hybrid poplar (Populus) plantations on Quebec forest soils under different lime treatments. *Forest Ecology and Management*, Vol. 255, No.7, pp. 2761–2770.

Borken, J., Patyk, A., Reinhardt, G. A. (1999): Basisdaten für ökologische Bilanzierungen [Basic data for environmental balances]. Vieweg, Braunschweig/Wiesbaden, Germany.

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.

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S. (2018): The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, Vol. 23, No.2, pp. 368–378.

Cannell, M. G. R. (1999): Environmental impacts of forest monocultures: water use, acidification, wildlife conservation, and carbon storage. In: *New Forests*,.

Chidikofan, G., Benoist, A., Sawadogo, M., Volle, G., Valette, J., Coulibaly, Y., Pailhes, J., Pinta, F. (2017): Assessment of Environmental Impacts of Tar Releases from a Biomass Gasifier Power Plant for Decentralized Electricity Generation. *Energy Procedia*, Vol. 118, pp. 158–163.

CML (2016): CML Impact Assessment V4.8. Institute of Environmental Sciences (CML), Leiden, The Netherlands.

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

Cosentino, S. L., Copani, V., Scalici, G., Scordia, D., Testa, G. (2015): Soil Erosion Mitigation by Perennial Species Under Mediterranean Environment. *Bioenergy Research*, Vol. 8, No.4, pp. 1538–1547.

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/*.

Costa, J., Barbosa, B., Fernando, A. L. (2016): Wastewaters Reuse for Energy Crops Cultivation. In: *Technological Innovation for Cyber-Physical Systems*,.

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. *DBFZ report*, No.30.

Dauber, J., Brown, C., Fernando, A. L., Finnan, J., Krasuska, E., Ponitka, J., Styles, D., Thrän, D., Van Groenigen, K. J., Weih, M., Zah, R. (2012): Bioenergy from "surplus" land: Environmental and socio-economic implications. *BioRisk*, No.7, pp. 5–50.

Detzel, A., Kauertz, B., Grahl, B., Heinisch, J. (2016): Prüfung und Aktualisierung der Ökobilanzen für Getränkeverpackungen. In: *UBA-Texte 19/2016*, Im Auftrag des Umweltbundesamtes, Institut für Energie- und Umweltforschung Heidelberg (ifeu), Heidelberg, Germany.

Dubrovskis, V., Adamovics, A., Plume, I., Kotelenecs, V., Zabarovskis, E. (2011): Biogas production from greater burdock, largeleaf lupin and sosnovsky cow parsnip. *Research for Rural Development*, Vol. 17, pp. 388–392.

Ecoinvent (2018): Ecoinvent database V3.5. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

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. *Journal of Applied Polymer Science*, Vol. 135, No.25, 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 (2009): Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. *Official Journal of the European Union*, No.L 140/16.

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). *Official Journal of the European Union*, No.L 328, pp. 82–209.

Fehrenbach, H., Grahl, B., Giegrich, J., Busch, M. (2015): Hemeroby as an impact category indicator for the integration of land use into life cycle (impact) assessment. *International Journal of Life Cycle Assessment*, Vol. 20, No.11, pp. 1511–1527.

Fehrenbach, H., Keller, H., Abdalla, N., Rettenmaier, N. (2020): Attributional land use (aLU) and attributional land use change (aLUC) - A new method to address land use and land use change in life cycle assessments, version 2.1 of ifeu paper 03/2018. In: *ifeu papers 03/2018*, ifeu - Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany. *www.ifeu.de/en/ifeu-papers/*.

Fehrenbach, H., Rettenmaier, N., Reinhardt, G., Busch, M. (2019): Festlegung des Indikators für die Bilanzierung der Ressource Fläche bzw. Naturraum in Ökobilanzen [Land use in life cycle assessment: proposal for an indicator and application guidelines]. In: *ifeu papers 02/2019*, ifeu - Institut für Energie- und Umweltforschung Heidelberg, Heidelberg, Germany. *www.ifeu.de/ifeu-papers/*.

Fernando, A. L., Costa, J., Barbosa, B., Monti, A., Rettenmaier, N. (2018): Environmental impact assessment of perennial crops cultivation on marginal soils in the Mediterranean Region. *Biomass and Bioenergy*, Vol. 111, pp. 174–186.

Fernando, A. L., Duarte, M. P., Almeida, J., Boléo, S., Mendes, B. (2010): Environmental impact assessment of energy crops cultivation in Europe. *Biofuels, Bioproducts and Biorefining*, Vol. 4, No.6, pp. 594–604.

Fernando, A., Monteiro, S., Pinto, F., Mendes, B. (2009): Production of biosorbents from waste olive cake and its adsorption characteristics for Zn2+ ion. *Sustainability*,.

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. *LANDTECHNIK*, Vol. 71, No.6, pp. 194–209–194–209.

IFEU (2019): Continuously updated internal IFEU database. IFEU - Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany.

IPCC (2006): 2006 Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programm. Institute for Global Environmental Strategies, Japan.

IPCC (2013): Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014): 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Methodological Guidance on Lands with Wet and Drained Soils, and Constructed Wetlands for Wastewater Treatment. In: *Task Force on National Greenhouse Gas Inventories*,.

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 (2010): International Reference Life Cycle Data System (ILCD) Handbook: General guide for Life Cycle Assessment - Detailed guidance. Joint Research Centre - Institute for Environment and Sustainability (JRC-IES), Ispra, Italy.

JRC-IES (2012): The International Reference Life Cycle Data System (ILCD) Handbook. Joint Research Centre - Institute for Environment and Sustainability (JRC-IES), Ispra, Italy.

Jung, S. (2009): Aqueous extraction of oil and protein from soybean and lupin: a comparative study. *Journal of food processing and preservation*, Vol. 33, No.4, pp. 547–559.

Jungk, N. C., Reinhardt, G. A., Gärtner, S. O. (2002): Agricultural reference systems in life cycle assessments. In: E. V. van Ierland, A. O. Lansink: *Economics of sustainable energy in agriculture*, Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 105–119.

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. *BioEnergy Research*, Vol. 12, No.3, 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, No.February 2017, pp. 2271–2280.

Kretschmer, W., Capaccioli, S., Chiaramonti, D., De Bari, I., Frattini, A., Giovannini, A., Janssen, R., Keller, H., Langer, M., Líden, G., Liuzzi, F., Masoni, P., Mergner, R., Müller-Lindenlauf, M., Notarfonso, M., Palmqvist, B., Passerini, G., Pescarolo, S., Reinhardt, G., Riva, A., Rossi, F., Rutz, D., Sissot, F., Weibel, U., Wolf, J. (2013): Integrated sustainability assessment of BIOLYFE second generation bioethanol. In: *BIOLYFE project reports*, supported by the EC's Seventh Framework programme under grant agreement number 239204, Institut für Umweltstudien (IUS), Heidelberg, Germany. *http://www.biolyfe.eu/images/stories/downloads/BIOLYFE-Integrated sustainability assessment.pdf*.

Lampart-Szczapa, E., Korczak, J., Nogala-Kalucka, M., Zawirska-Wojtasiak, R. (2003): Antioxidant properties of lupin seed products. *Food chemistry*, Vol. 83, No.2, pp. 279–285.

de Leeuw, F. A. A. M. (2002): A set of emission indicators for long-range transboundary air pollution. *Environmental Science & Policy*, Vol. 5, No.2, pp. 135–145.

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.

Maschio, S., Tonello, G., Piani, L., Furlani, E. (2011): Fly and bottom ashes from biomass combustion as cement replacing components in mortars production: Rheological behaviour of the pastes and materials compression strength. *Chemosphere*, Vol. 85, No.4, pp. 666–671.

Menetrez, M. Y. (2010): The potential environmental impact of waste from cellulosic ethanol production. *Journal of the Air and Waste Management Association*, Vol. 60, No.2, pp. 245–250.

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.
Möller, K. (2015): Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agronomy for Sustainable Development*, Vol. 35, No.3, pp. 1021–1041.
Müller-Lindenlauf, M., Gärtner, S., Reinhardt, G. (2014): Nährstoffbilanzen und Nährstoffemissionsfaktoren für Ökobilanzen landwirtschaftlicher Produkte [Nutrient balances and emission factors for life cycle assessment of agricultural products]. ifeu - Institute for Energy and Environmental Research, Heidelberg, Germany.
Munawar, M. A., Khoja, A. H., Naqvi, S. R., Mehran, M. T., Hassan, M., Liaquat, R., Dawood, U. F. (2021): Challenges and opportunities in biomass ash management and its utilization in novel applications. *Renewable and Sustainable Energy Reviews*, Vol. 150, No.January, p. 111451.
Murphy, C. W., Kendall, A. (2015): Life cycle analysis of biochemical cellulosic ethanol under multiple scenarios. In: *GCB Bioenergy*, pp. 1019–1033.
Mursec, B., Vindis, P., Janzekovic, M., Brus, M., Cus, F. (2009): Analysis of different substrates for processing into biogas. *Journal of achievements in materials and manufacturing engineering*, Vol. 37, No.2, 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.
Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., Cecinato, A. (2018): Environmental impact of biogas: A short review of current knowledge. *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, Vol. 53, No.10, pp. 899–906.
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/*.
Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M., Stringer, L. (2008): Assessment on Peatlands, Biodiversity and Climate Change: Main Report. Global Environment Centre, Wetlands International, Petaling Jaya, Wageningen.
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. *LWT-Food Science and Technology*, Vol. 59, No.2, pp. 680–688.
del Pozo, A., Mera, M. (2021): Lupin. *Crop Physiology Case Histories for Major Crops*, pp. 430–450.
Raja, I. A., Wazir, S. (2017): Biogas Production: The Fundamental Processes. *Universal Journal of Engineering Science*, Vol. 5, No.2, pp. 29–37.
Ravishankara, A. R., Daniel, J. S., Portmann, R. W. (2009): Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century. *Science (New York)*, Vol. 326, No.5949, pp. 123–5.
Reinhardt, G., Rettenmaier, N., Vogt, R. (2019): Festlegung des Indikators für die Bilanzierung der Ressource Phosphat in Umweltbewertungen [Establishment of the indicator for the accounting the resource "phosphate" in environmental assessments]. In: *ifeu papers 01/2019*, ifeu - Institut für Energie- und Umweltforschung Heidelberg, Heidelberg, Germany. *www.ifeu.de/ifeu-papers/*.
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., Gärtner, S., Keller, H., Müller-Lindenlauf, M., Reinhardt, G., Schmidt, T., Schorb, A. (2015): Life cycle assessment of bioenergy and bio-based products from

perennial grasses cultivated on marginal land. In: *OPTIMA project reports*, supported by the EU's FP7 under GA No. 289642, ifeu - Institute for Energy and Environmental Research, Heidelberg, Germany. *https://www.ifeu.de/landwirtschaft/pdf/IFEU_2015_LCA bioproducts marginal land.pdf*.

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.

Sala, S., Benini, L., Mancini, L., Pant, R. (2015a): Integrated assessment of environmental impact of Europe in 2010: data sources and extrapolation strategies for calculating normalisation factors. *The International Journal of Life Cycle Assessment*, Vol. 20, No.11, pp. 1568–1585.

Sala, S., Benini, L., Mancini, L., Pant, R. (2015b): Integrated assessment of environmental impact of {Europe} in 2010: data sources and extrapolation strategies for calculating normalisation factors. *The International Journal of Life Cycle Assessment*, Vol. 20, No.11, pp. 1568–1585.

Samarappuli, D., Berti, M. T. (2018): Intercropping forage sorghum with maize is a promising alternative to maize silage for biogas production. *Journal of Cleaner Production*, Vol. 194, pp. 515–524.

Senbayram, M., Chen, R., Wienforth, B., Herrmann, A., Kage, H., Mühling, K. H., Dittert, K. (2014): Emission of N2O from Biogas Crop Production Systems in Northern Germany. *Bioenergy Research*, Vol. 7, No.4, pp. 1223–1236.

Severino, L. S., Auld, D. L. (2013): A framework for the study of the growth and development of castor plant. *Industrial Crops and Products*, Vol. 46, pp. 25–38.

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. *http://magic-h2020.eu/documents-reports/*.

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.

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

Sun, P., Elgowainy, A., Wang, M., Han, J., Henderson, R. J. (2018): Estimation of U.S. refinery water consumption and allocation to refinery products. *Fuel*, Vol. 221, No.July 2017, pp. 542–557.

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.

Tambone, F., Genevini, P., D'Imporzano, G., Adani, F. (2009): Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. *Bioresource Technology*, Vol. 100, No.12, pp. 3140–3142.

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.

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

VDI (Association of German Engineers) (2012): VDI Standard 4600: Cumulative energy demand - Terms, definitions, methods of calculation. VDI (Association of German Engineers) e.V. / Beuth Verlag GmbH, Düsseldorf / Berlin, Germany. *http://www.vdi.eu/nc/guidelines/vdi_4600-*

kumulierter_energieaufwand_kea_begriffe_berechnungsmethoden/.

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

Wang, J., Zhao, J., De Wit, M., Boom, R. M., Schutyser, M. A. I. (2016): Lupine protein enrichment by milling and electrostatic separation. *Innovative food science & emerging technologies*, Vol. 33, pp. 596–602.

Wilson, C., Tisdell, C. (2001): Why farmers continue to use pesticides despite environmental, health and sustainability costs. *Ecological Economics*, Vol. 39, No.3, pp. 449–462.

WMO (World Meteorological Organization) (2010): Scientific Assessment of Ozone Depletion: 2010. Global Ozone Research and Monitoring Project - Report No. 52. World Meteorological Organization, Geneva, Switzerland.

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

van Zelm, R., Huijbregts, M. A. J., den Hollander, H. A., van Jaarsveld, H. A., Sauter, F. J., Struijs, J., van Wijnen, H. J., van de Meent, D. (2008): European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. *Atmospheric Environment*, Vol. 42, No.3, pp. 441–453.

Zia, K. M., Bhatti, H. N., Bhatti, I. A. (2007): Methods for polyurethane and polyurethane composites, recycling and recovery: A review. *Reactive and functional polymers*, Vol. 67, No.8, pp. 675–692.

9 Annex

9.1 Supplements to LCA

Normalisation

Table 13: Overview on normalisation factors per person and year of the EU28 states in the reference year 2010 [Sala et al. 2015b]

Midpoint impact category	Inhabitant equivalent values per person and year (EU28)	
Non-renewable energy use (NREU)	34	GJ cumul. primary energy
Climate change	9	t CO_2 equivalents
Acidification	35	kg SO_2 equivalents
Eutrophication, terrestrial	5	kg PO_4 equivalents
Eutrophication, freshwater	7	kg PO_4 equivalents
Ozone depletion	0,06	kg CFC-11 equivalents
Particulate matter	28	kg $PM_{2.5}$ equivalents
Summer smog (Photochemical ozone formation)	57	kg NMVOC equivalents
Phosphate rock use	23	kg phosphate rock std.
Land use	0,24	m^2·yr artificial land equivalents

Parameters on agricultural systems of the generic scenarios

This section summarises important agricultural data for the life cycle assessment (see Table 14). All data stem from IFEU's internal database [IFEU 2019] and are partially based on expert judgments by MAGIC partners and external experts. The cultivation of biomass is assessed in the way that full expenditures of crop cultivation are ascribed to the harvested crop based on a sustainable cultivation practise. This includes that nutrients replaced by fertilisation compensate the amount removed by harvest as well as emission to air and water. They exceed the deposition of nutrients from the atmosphere (in case of nitrogen) [Müller-Lindenlauf et al. 2014].

Table 14: LCA input data on cultivation of the crops [IFEU 2019]

Parameter	Unit	Mis-can-thus	Switch-grass	Pop-lar	Wil-low	Saf-flow-er *	Cas-tor **	Hemp ***	Sor-ghum	Lupin ****
Cultivation lifetime	years	20	20	20	25	1	1	1	1	1
Seedlings / Seeds	kg FM / ha / yr	23	0.13	125	150	28	15	45	8	25
Nitrogen fertiliser	kg N / t DM	2.7	9.4	6.2	4.6	35.4	9.5	17.1	17.1	2.0
Phosphorus fertiliser	kg P_2O_5 / t DM	1.6	1.6	2.6	2.6	16.1	5.7	8.3	5.2	12.7
Potassium fertiliser	kg K_2O / t DM	7.5	19.6	4.0	15.5	10.1	24.7	23.4	18.6	12.4
Calcium fertiliser	kg CaO / t DM	2.3	2.3	7.6	30.9	3.4	4.1	22.5	2.3	3.1
Pesticides	kg active subs-tance / ha / yr	0.8	0.8	0.7	1.2	1.0	1.0	0.0	5.0	2.0
Diesel for field work	l diesel / t DM	5	2	10	18	61	49	9	6	25
Water irrigated (MED)	m^3 / ha / yr	300	200	0	0	0	0	0	0	0
Diesel for irrigation	l diesel / ha / yr	15	10	0	0	0	0	0	0	0
Water content in removed biomass	% of FM	20	20	35	35	13	15	15	70	12
Diesel for transportation	l diesel / t DM	1	1	2	2	1	1	1	3	1
Storage losses	% of DM	3	3	3	3	3	3	3	3	3
Water content in delivered biomass	% of FM	20	20	20	20	8	6	15	70	12
Oil content seeds	% of FM	n.a.	n.a.	n.a.	n.a.	35	55	n.a.	n.a.	n.a.
Meal	t DM / t FM	n.a.	n.a.	n.a.	n.a.	0.6	0.4	n.a.	n.a.	n.a.

* Yields include only seeds; seeds contain 45 % hull and 55 % kernel

** Yields include only seeds but inputs for husks are included in overall inputs (0.5 t husks DM / t seeds DM); husks are used as fertiliser because husks are toxic and no use as feed is possible

*** DM of whole plant incl. straw and seeds, straw to seed ratio is 88:12

**** only start fertilisation with 5 kg N / ha / yr

9.2 Supplements to system description

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]. Only adaptations which were necessary to reflect most recent changes in the design of the investigated value chains due to additional insights from research work were made for this report. A quotation in each of the following sections is not included.

9.2.1 VC 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 38). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

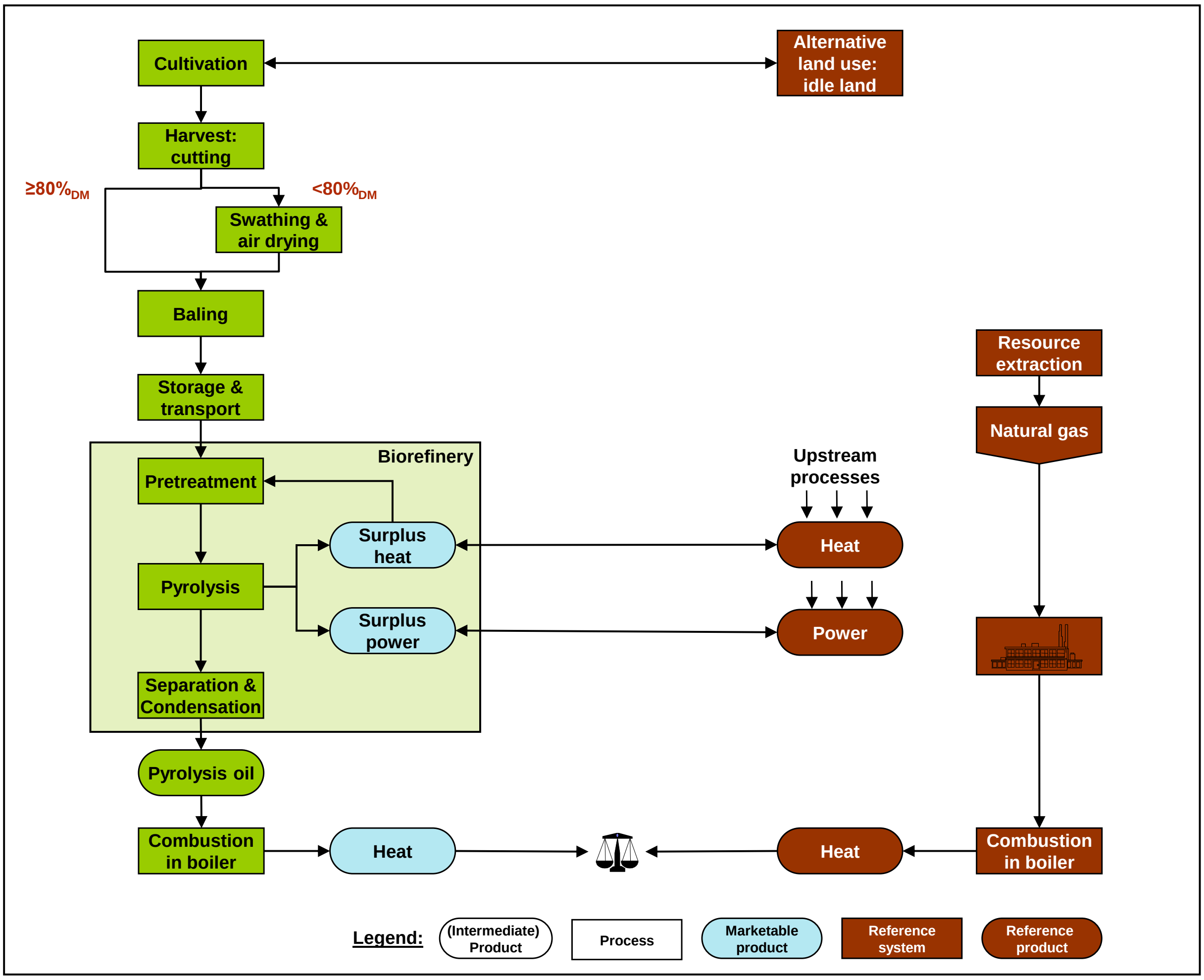

Figure 38: Simplified life cycle comparison for VC 1: industrial heat from Miscanthus via pyrolysis versus industrial heat from fossil energy carriers.

9.2.1.1 Biomass provision

Cultivation

The life cycle phase “cultivation” in general (see Figure 38) 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[5], 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.

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.

9.2.1.2 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

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[5] “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.

the pyrolysis process. The only waste stream that remains are the minerals from the biomass in the form of ash.

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 48 in section 9.2.11 (p. 138) 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 prevent 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.

9.2.2 VC 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 39). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

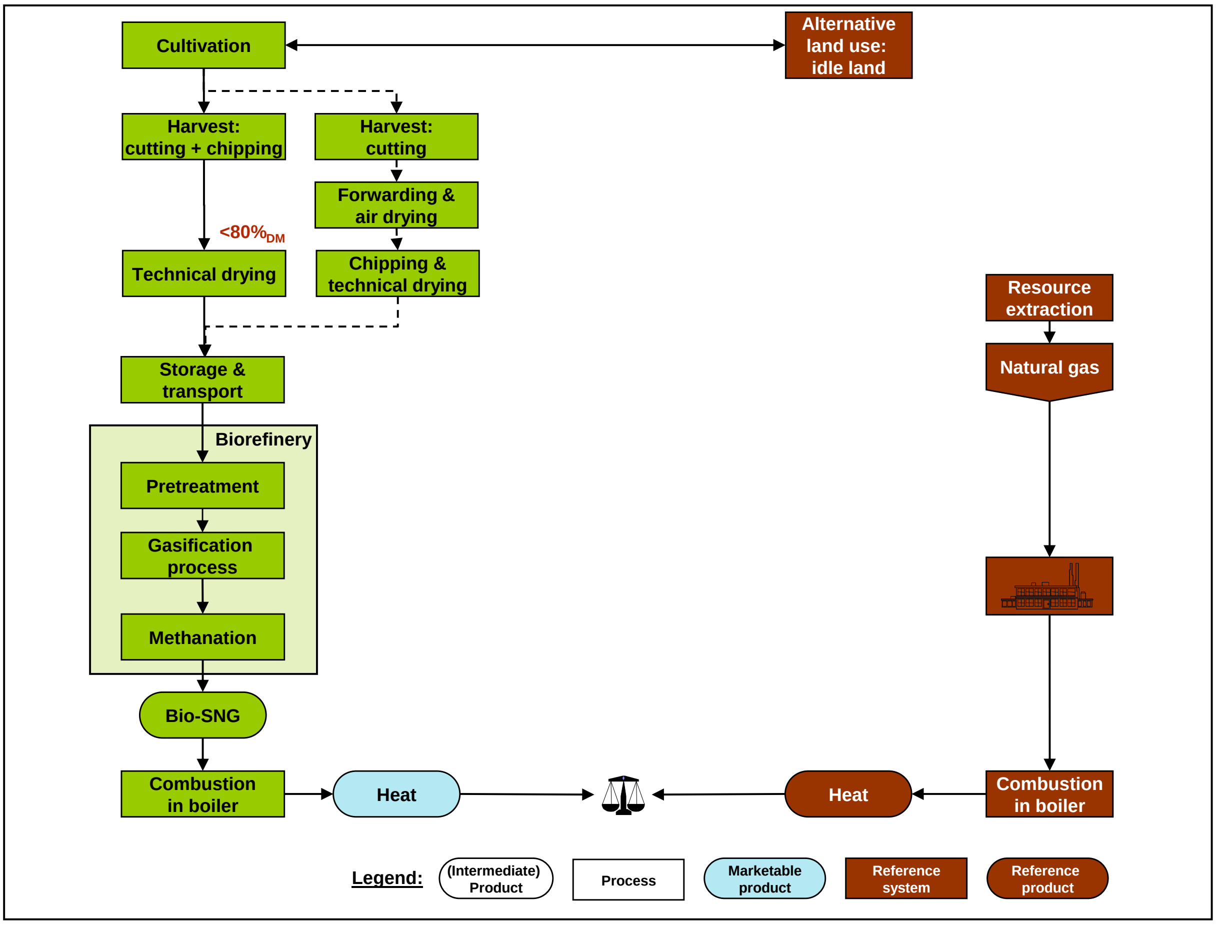

Figure 39: Simplified life cycle comparison for VC 2: synthetic natural gas from poplar via gasification versus natural gas.

9.2.2.1 Biomass provision

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.

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 39). In both cases the woody biomass has to be stored and transported to the conversion unit.

9.2.2.2 Biomass conversion

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.


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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 49 in section 9.2.11 (p. 139) 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.

9.2.3 VC 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 40). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

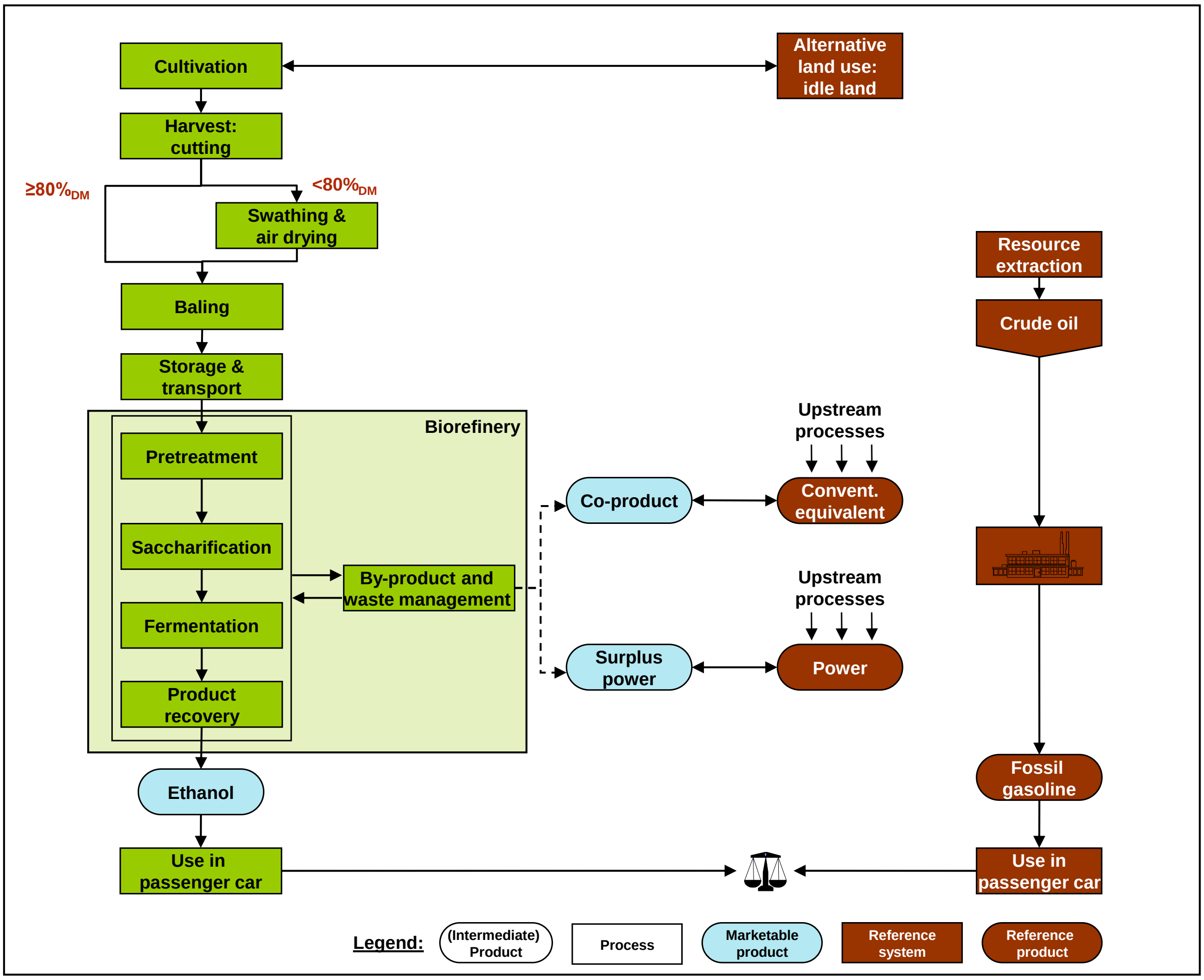

Figure 40: Simplified life cycle comparison for VC 3: ethanol from switchgrass via hydrolysis and fermentation versus fossil gasoline.

9.2.3.1 Biomass provision

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.

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.

9.2.3.2 Biomass conversion

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 2^{nd} generation ethanol whereas 1^{st} generation ethanol production utilises biomass with high sugar and starch content absent of (ligno)cellulosic material. The most challenging part for the 2^{nd} 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 2^{nd} 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 50 in section 9.2.11 (p. 140) 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 [Mergner et al. 2013; Rødsrud 2017; 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.

9.2.4 VC 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 41). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

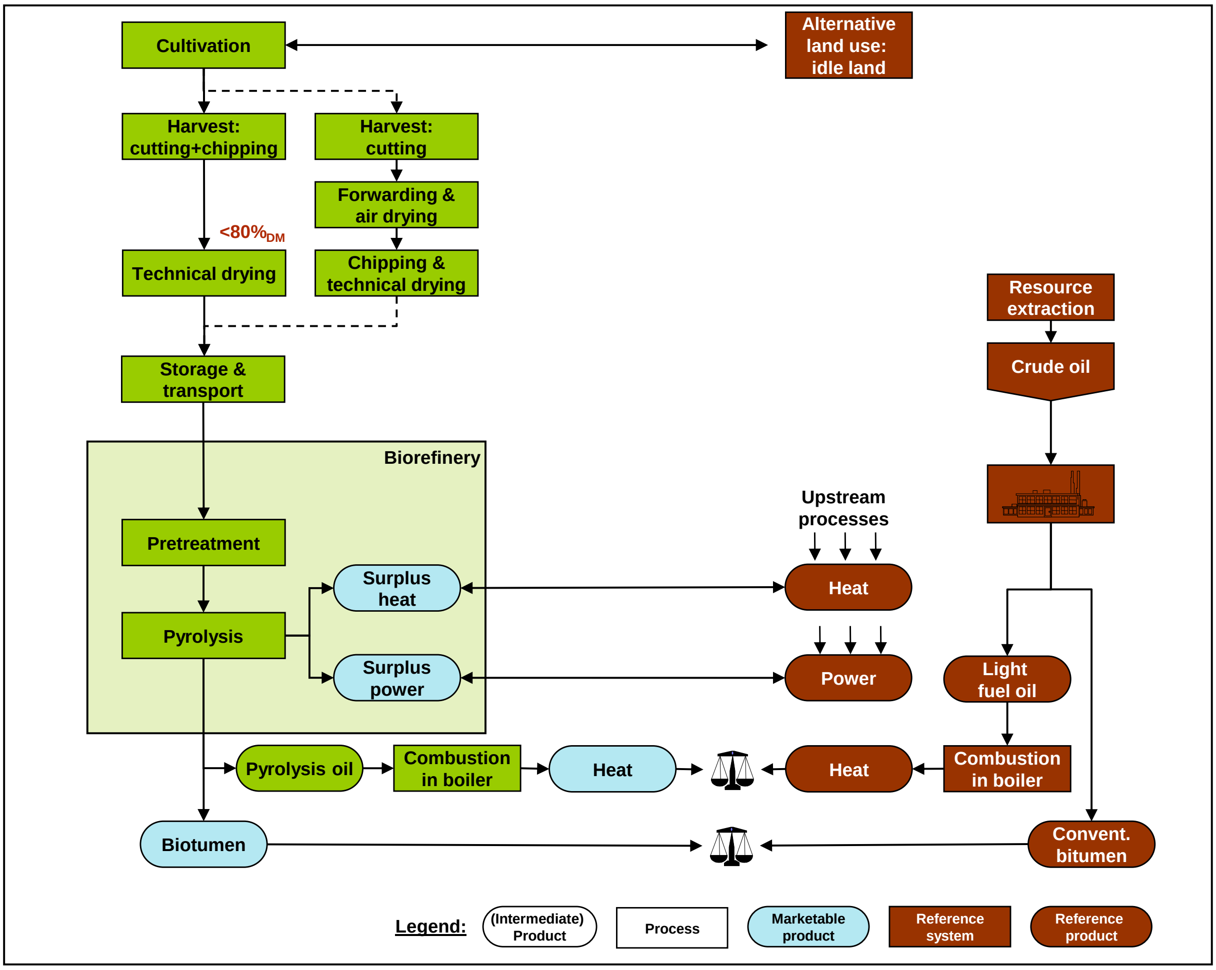

Figure 41: Simplified life cycle comparison for VC 4: biotumen from willow via pyrolysis versus bitumen from fossil resources.

9.2.4.1 Biomass provision

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 25 years.

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 41). 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 51 in section 9.2.11 (p. 141) shows a detailed schematic presentation of biotumen production from willow. As can be seen in Figure 51, 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 38 (p. 112). 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.

9.2.5 VC 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 42). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

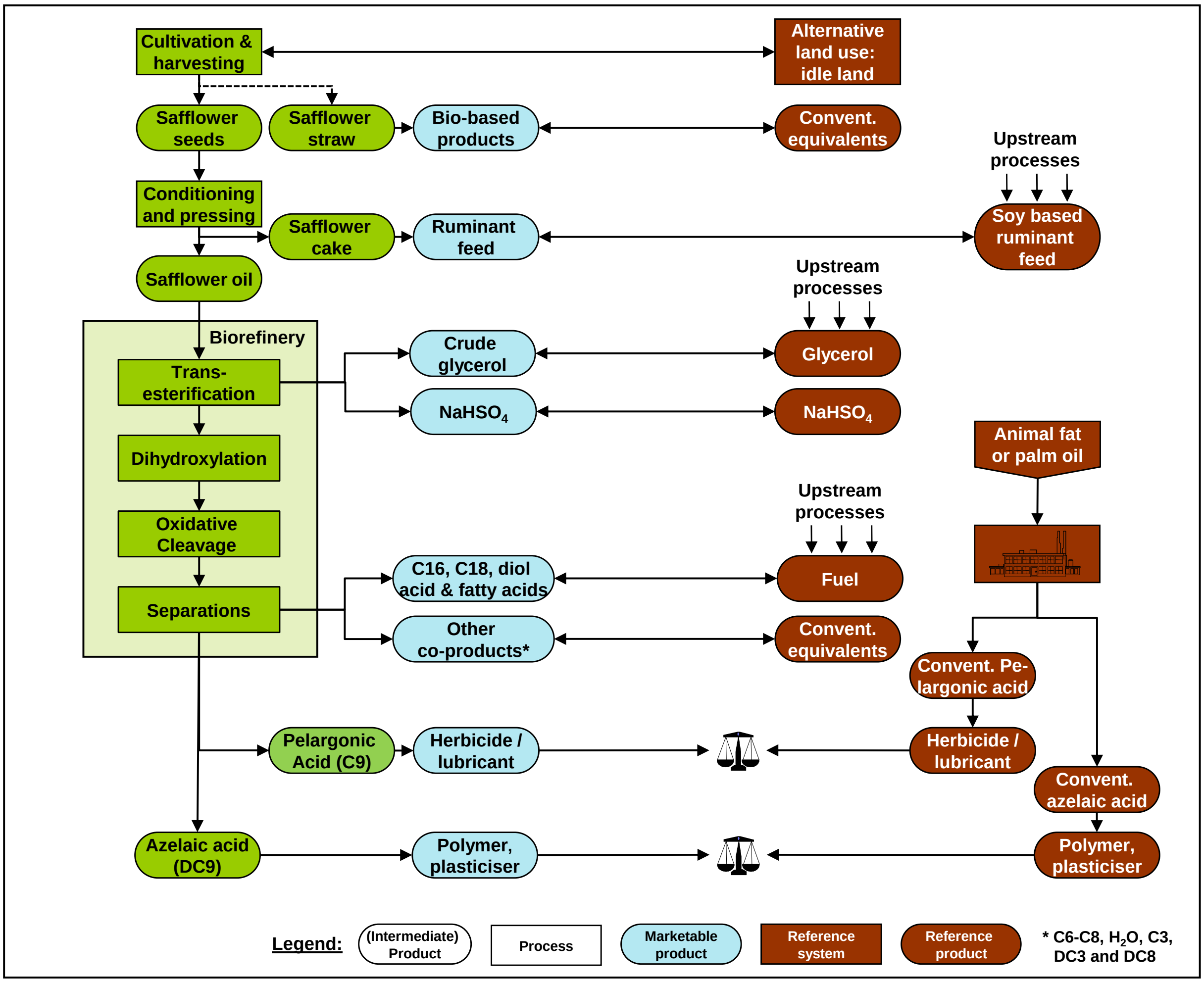

Figure 42: Simplified life cycle comparison for VC 5: organic acids from safflower via oxidative cleavage versus organic acids from fossil resources.

9.2.5.1 Biomass provision

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].

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.

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.

9.2.5.2 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 52 in section 9.2.11 (p. 142) 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].

9.2.6 VC 6: Methyl decenoate from camelina (via metathesis)

This value chain describes the conversion of a high-oleic ("improved") camelina variety (*Camelina sativa* (L.) CRANTZ) to methyl decenoate via metathesis. This life cycle is compared to conventional ways of providing the same products or services (Figure 43).

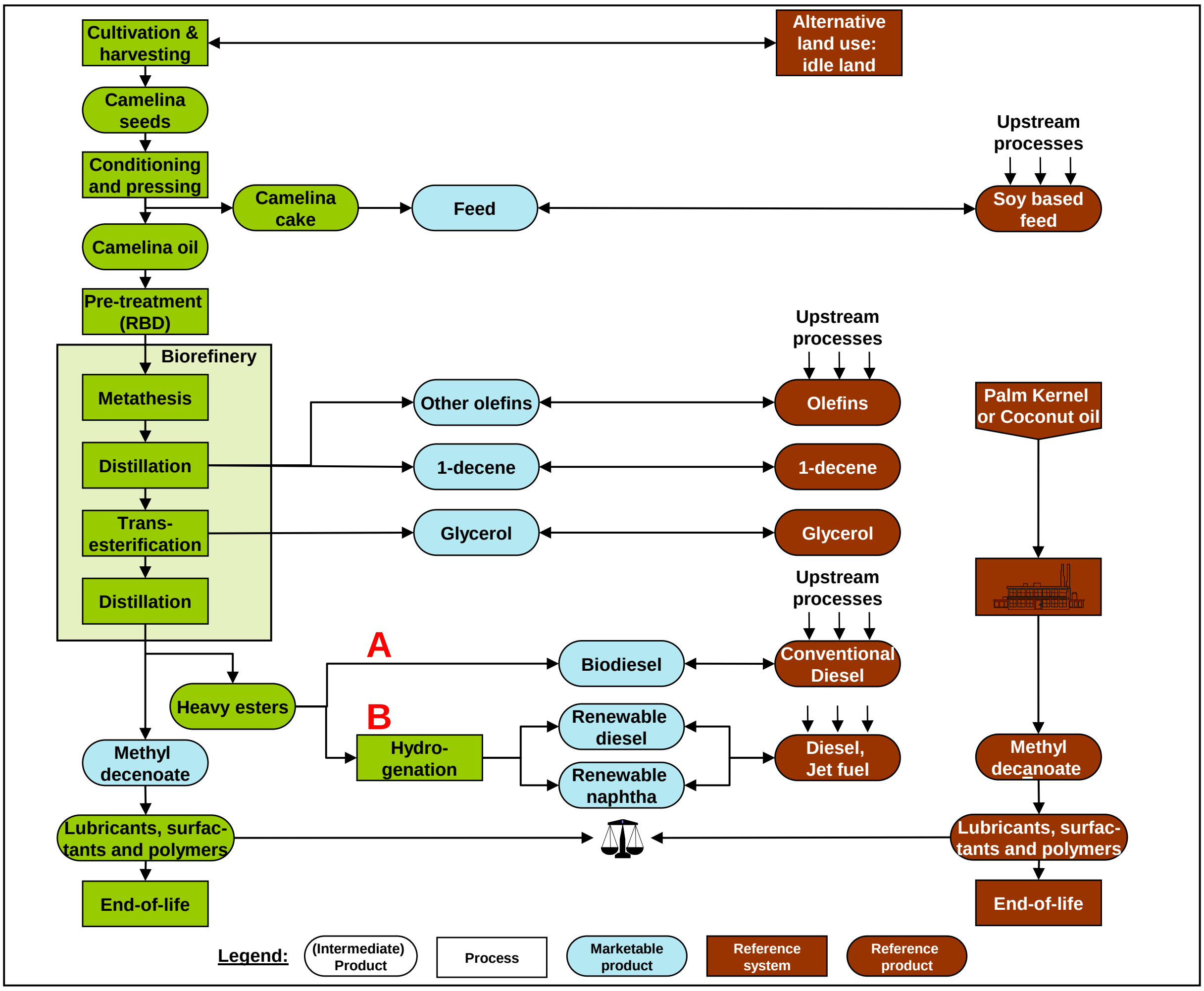

Figure 43: Simplified life cycle comparison for VC 6: methyl decenoate from camelina via metathesis versus methyl decanoate from biogenic resources[6].

9.2.6.1 Biomass provision

Cultivation

Camelina is an annual oil crop which can be grown as a winter crop but in mild climates such as the Mediterranean area also as a spring crop. It belongs to the crucifer family (Brassicaceae), has a short vegetation period (90-120 days) and is very tolerant to dry soils.

[6] Note that the reference product methyl decanoate is saturated while methyl decenoate is unsaturated.

Camelina cultivation is similar to rapeseed cultivation. Minor establishment efforts are required (little seedbed preparation, low sowing depth, no herbicide application). Also, camelina shows comparatively low nutritional requirements. Due to its drought and heat tolerance, little/no irrigation water has to be applied [Alexopoulou et al. 2018].

Due to its specifically short rotation period, camelina is suitable for double cropping, i.e. it can be integrated into a crop rotation without displacement of other crops or decreases in production volumes thereof. To maintain comparability among investigated value chains, this scenario will be assessed as part of an excursus only.

Harvesting

Camelina can be harvested with conventional combines and is usually direct-combined standing but can be swathed and then combined with similar seed yields. The harvesting should start when 50-75% of the pods are dried [Pari & Scarfone 2018]. The harvested seeds have a moisture content of approximately 13%. Straw including leaves and camelina pods remain on the field and are ploughed in. They maintain soil fertility and thus substitute for conventional mineral fertilisers. Seed yields range from 1-3 t/ha. A detailed table including all data used for the sustainability assessment will be given in MS6.3.

Logistics, pre-treatment, oil extraction and refining

Camelina seeds are transported to a processing/storage facility. There, a cleaning step is necessary to remove stalks, leaves and pods which are unintendedly among the seeds. The residues are set to be reapplied to agricultural fields to maintain soil fertility. In addition, pre-treatment encompasses technical drying of the seeds until they have a moisture content of approximately 9%.

Oil extraction is conducted by means of pressing, i.e. solvent extraction is not applied. Cake is obtained as a co-product from pressing. It is set to be used as animal feed, e.g. for cattle. Due to the anti-nutritional compounds, camelina cake should represent only a minor fraction of the diet. It is set to substitute for soy-based conventional feed. After pressing, the oil is refined. It can then be stored or directly be transported to the conversion unit.

9.2.6.2 Biomass conversion

The camelina oil used in this process originates from improved varieties that are genetically modified and/or selected and its composition is based on data from the COSMOS project. It consists of about 60% of oleic acid (C18:1), 20% of gondoic acid (C20:1, delta-11), 7% of linolenic acid (C18:3), 5% of palmitic acid (C16:0), 4% of linoleic acid, 3% of stearic acid (C18:0) and 1% of arachidic acid (C20:0).

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The cross metathesis of natural derived fatty acid esters with ethylene is one of the most attractive methods for the production of high value chemical intermediates that have various industrial applications. There are various reports on the use of ruthenium-based Grubbs-type metathesis catalysts for the ethenolysis of the methyl fatty acids. It is well established that these ruthenium complexes catalyse the ethenolysis of methyl fatty acids under homogeneous conditions are highly selective for the formation of 1-decene and methyl 9-decenoate from methyl-oleate. Metathesis is a chemical reaction in which two unsaturated hydrocarbons are converted to two new hydrocarbons by the exchange of carbon double bonds. In order to minimise the catalyst cost, and other variable cost, but also to maximise the products values, it is necessary to use a high monounsaturated fatty acid content (high MUFA).

As shown in Figure 43 (a more detailed process scheme can be found in section 9.2.11 [Figure 53 on p. 143] and in the Annex to D 6.2 [Alexopoulou et al. 2020]), after the pre-treatment step, the oil is reacted with ethylene and catalysed by a Ruthenium- based Grubbs' catalyst. After the olefin cross-metathesis step, products such as 1-decene, 9-decenoic acid glyceride and other olefins are formed. Since the metathesis is an equilibrium limited reaction, many other products are generated, the number of which increases drastically with the Poly-Unsaturated Fatty Acid content (PUFA) in the oil. These products are then fed into a distillation unit where 1-decene is recovered at the top together with other light olefins. 1-Decene is used mainly in the production of plasticiser alcohols and poly-alpha-olefins (PAO). At the bottom of the column, 9-decenoic acid containing triglyceride was converted into methyl 9-decenoate, together with the other fatty acids, by transesterification process in the presence of methanol and glycerol was eliminated in the process. The methyl 9-decenoate can be further isolated by distillation. In the biorefinery modelled here, the other FAMEs and coproducts are directed to a renewable diesel unit where the esters undergo full hydrogenation to iso paraffins. The light fraction (light fatty acids and olefins products) is going to be used as renewable naphtha, which can be used to produce renewable olefins (ethylene, propylene, butenes…). The slightly heavier fraction could be used as renewable jet fuel (if sufficiently isomerised to branched molecules). The metathesis route is then a way to extract methyl 9-decenoate which has a potential market to compete with the methyl decanoate from coconut and palm kernel, but also for new applications in polymers and surfactants. Depending on market conditions, the conversion could be increased or reduced to produce more or less 1-decene and methyl decenoate.

The final product in this process is methyl 9-decenoate. In order to directly compare it with the methyl decanoate, a hydrogenation step could be added as an option in order to have the same chemical compound. This option is possible since the producer could consider that he would always have the option to sell either product. But we prefer to consider the option where the producer could extract the amount of methyl 9-decenoate he needs for his market. And that the rest of products will be merged with the other products and directed to the hydrogenation unit producing more renewable naphtha (instead of petrochemicals). The renewable naphtha/jet/diesel would then be separated, and the naphtha cut would be used in a steam cracker to produce olefins. The producer could be interested to tune the composition in order to maximise the naphtha fraction (which is making most of the money in a classical refinery) and the jet fuel. The ideal chain length for these streams is about 6 to 10 for naphtha, and 8 to 16 for jet fuel. Similarly, the olefins produced in the process, which cannot be isolated easily, can be merged in the naphtha stream (before or after hydrogenation).

9.2.7 VC 7: 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 44). A more detailed process scheme can be found in the Annex to D 6.2 [Alexopoulou et al. 2020].

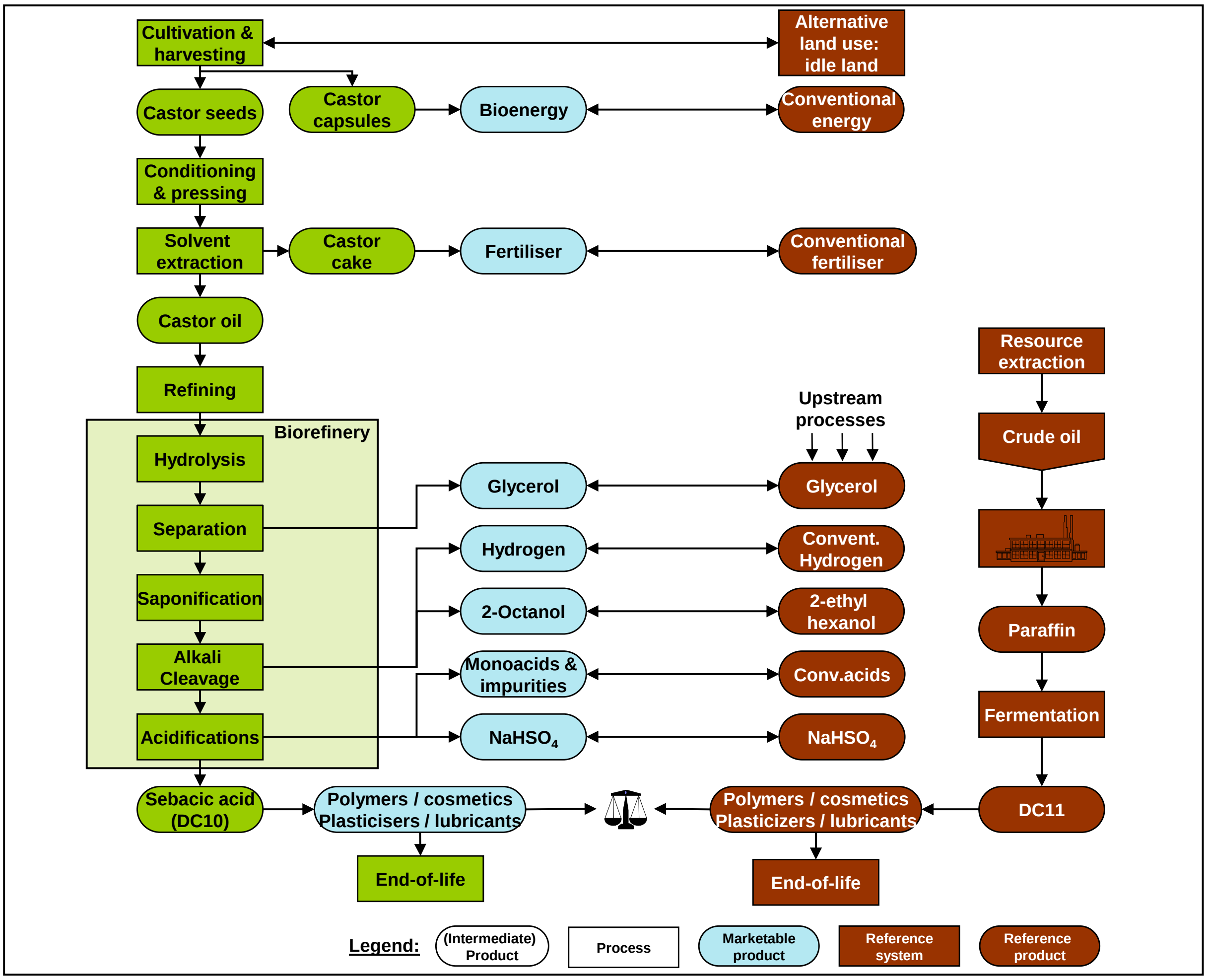

Figure 44: Simplified life cycle comparison for VC 7: products derived from sebacic acid from castor oil versus the same products from paraffins derived through fermentation of petroleum[7].

[7] 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).

9.2.7.1 Biomass provision

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].

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].

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.

9.2.7.2 Biomass conversion

Figure 54 in section 9.2.11 (p. 144) 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.

9.2.8 VC 8: 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 45).

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).

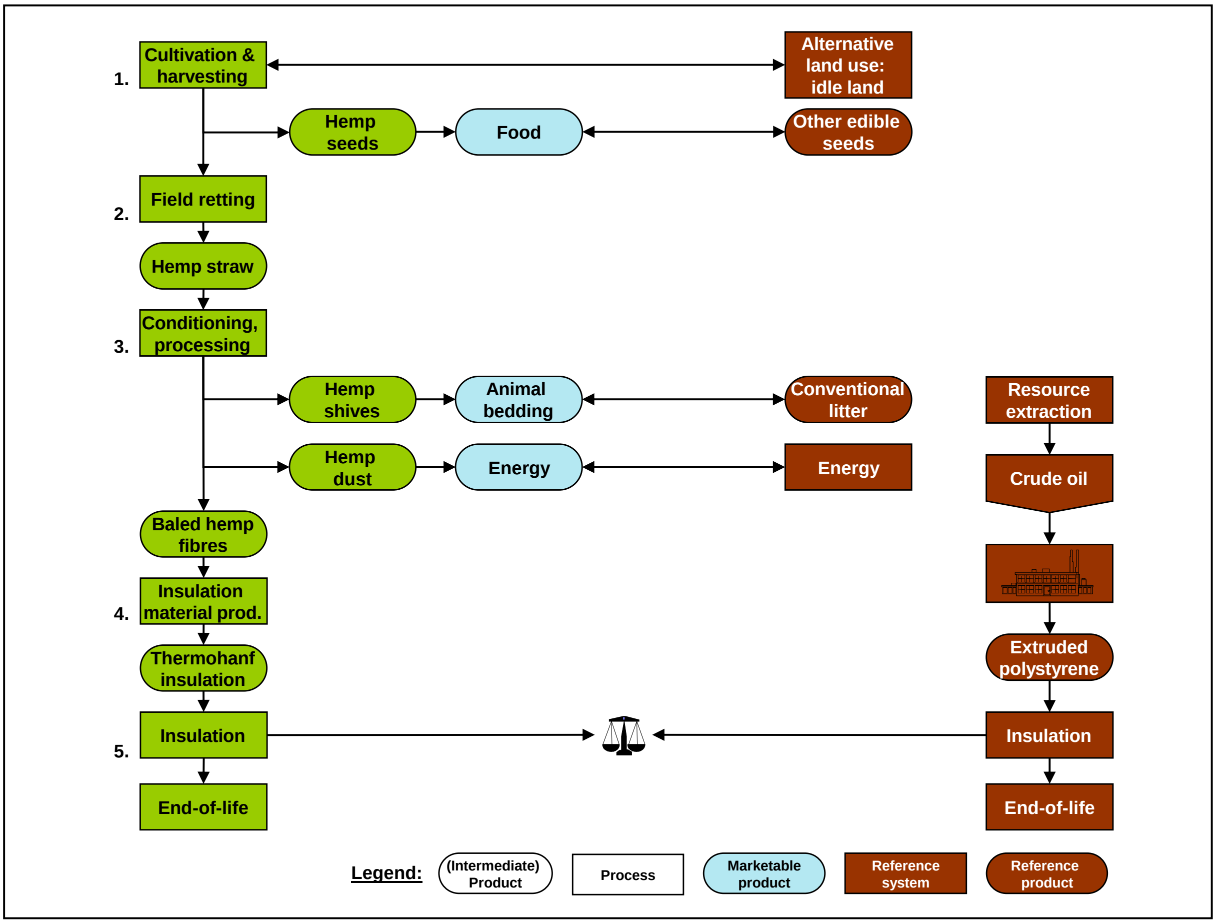

Figure 45: Life cycle comparison for VC 8: insulation material from industrial hemp versus insulation material from fossil resources (e.g. extruded polystyrene).

9.2.8.1 Biomass provision

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.

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.

9.2.8.2 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.

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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 45. 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).

9.2.9 VC 9: 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 46).

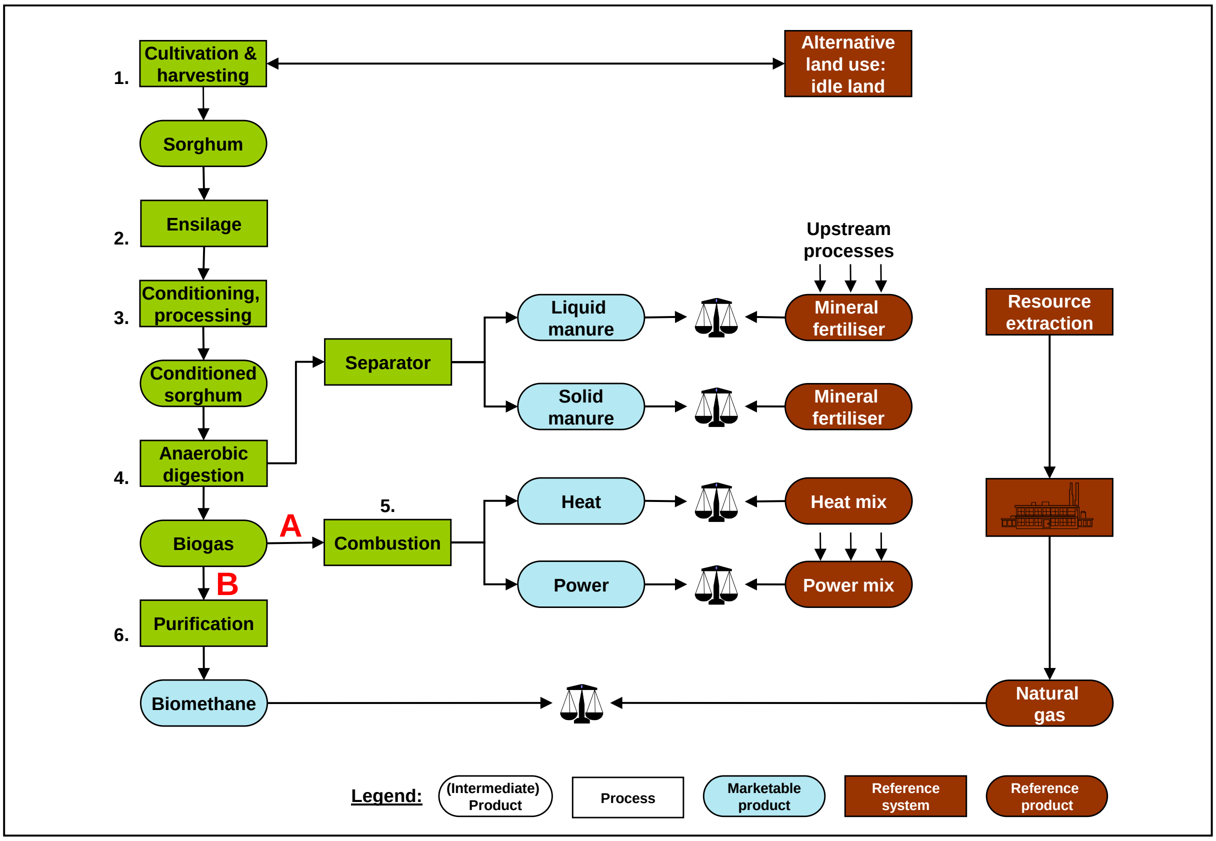

Figure 46: Life cycle comparison for VC 9: biogas/biomethane from sorghum versus natural gas.

9.2.9.1 Biomass provision

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 VC 9, biomass sorghum is set to be cultivated.

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 46) 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.

9.2.9.2 Biomass conversion

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.

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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 [own calculation based on 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].

9.2.10 VC 10: 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 47).

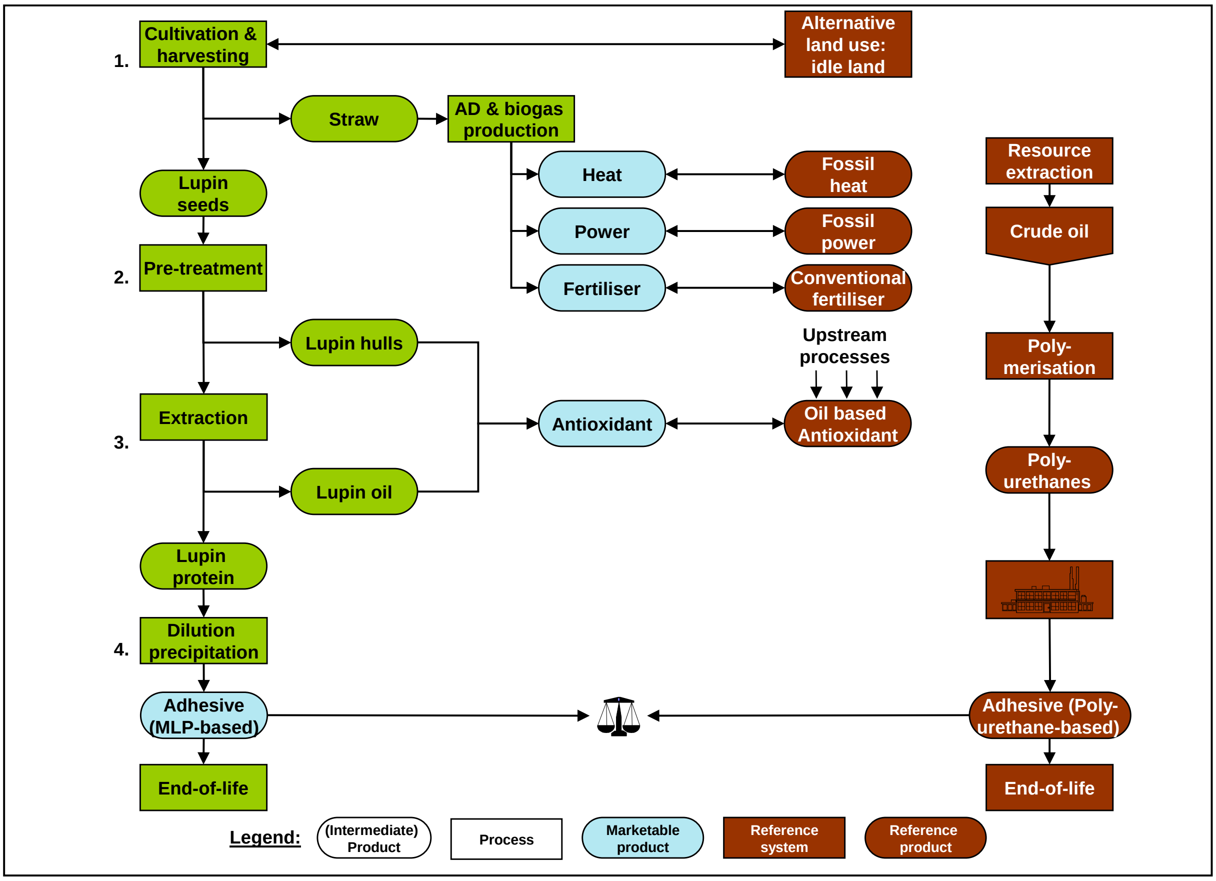

Figure 47: Life cycle comparison for VC 10: adhesives from lupin versus adhesives from fossil resources.

9.2.10.1 Biomass provision

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.

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].

9.2.10.2 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 47.

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].

9.2.11 Details on biomass conversion

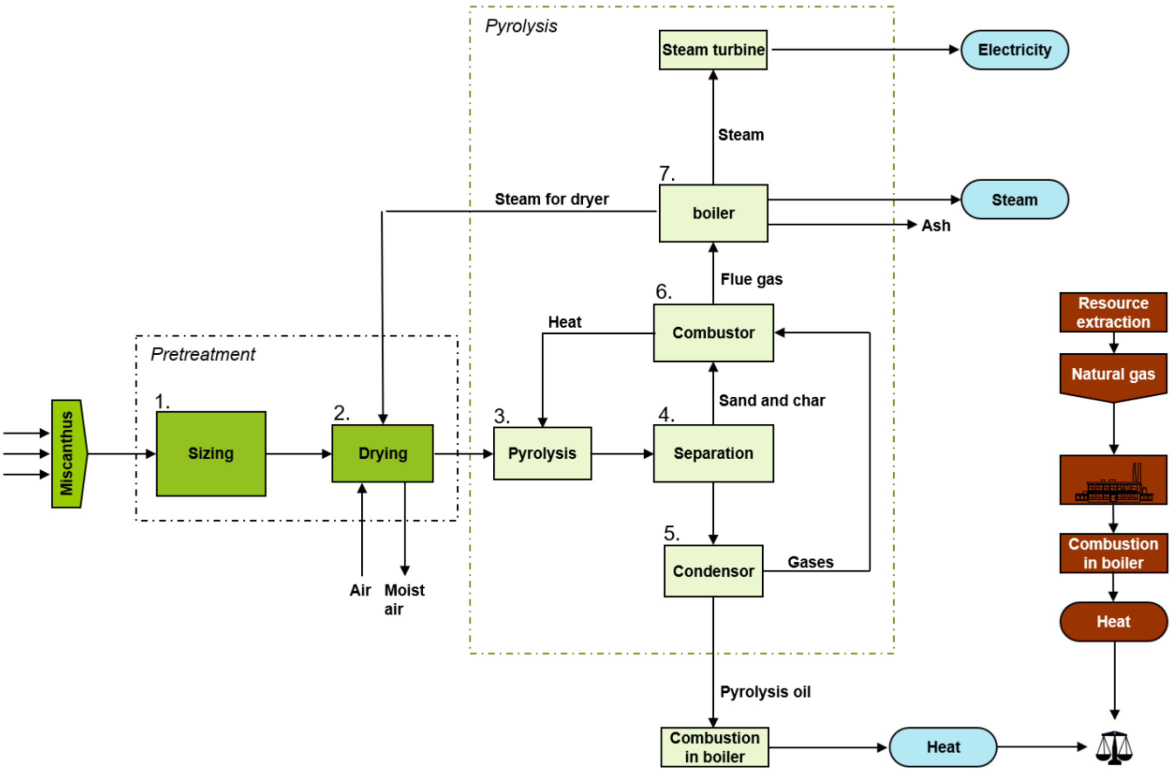

Figure 48: Detailed life cycle comparison for VC 1: industrial heat from Miscanthus via pyrolysis versus industrial heat from fossil energy carriers.

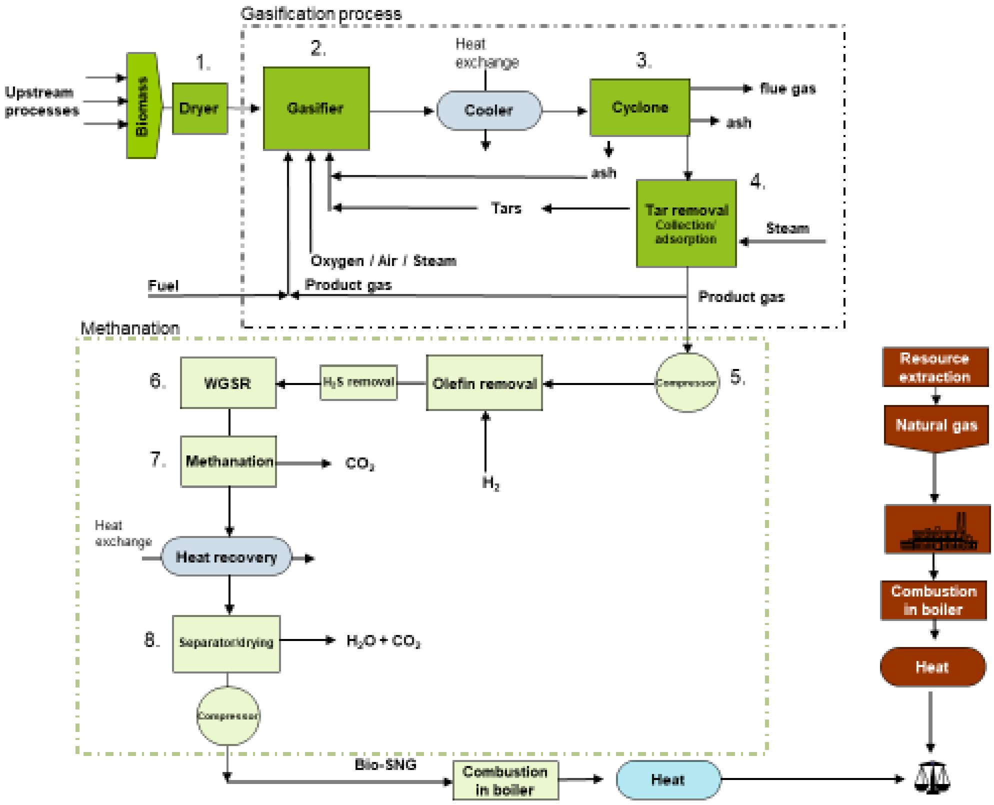

Figure 49: Detailed life cycle comparison for VC 2: Synthetic natural gas from poplar via gasification versus natural gas.

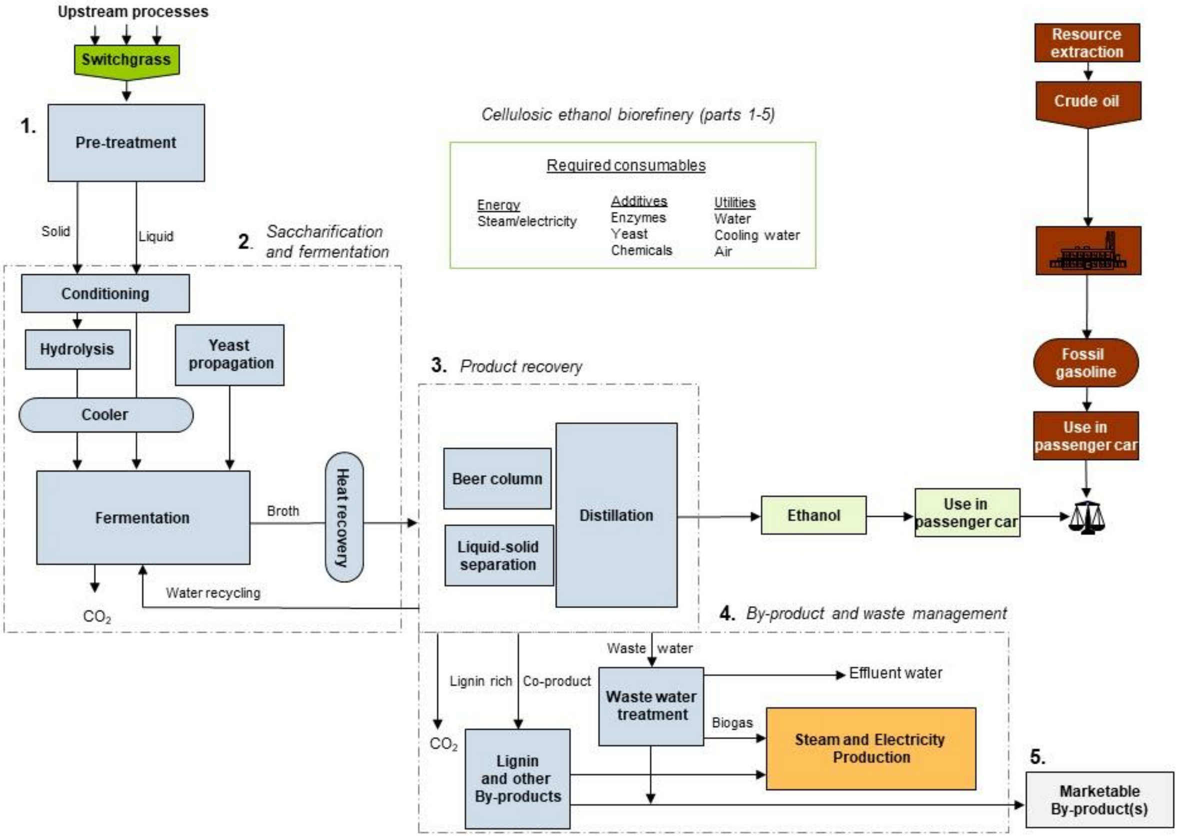

Figure 50: Detailed life cycle comparison for VC 3: ethanol from switchgrass via hydrolysis & fermentation versus fossil gasoline.

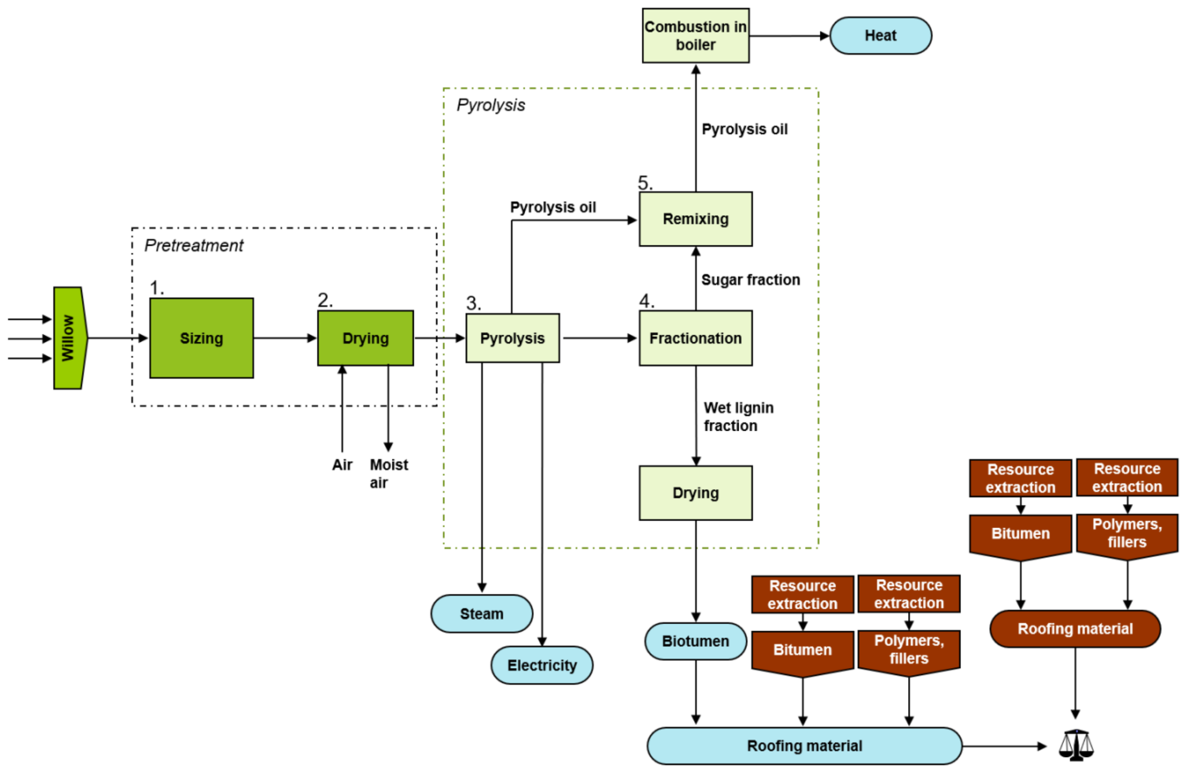

Figure 51: Detailed life cycle comparison for VC 4: biotumen from willow via pyrolysis versus bitumen from fossil resources. A more detailed scheme for the pyrolysis section can be found in Figure 48.

Table 15: List of acronyms of chemicals used in Figure 52 - Figure 54 (on the following 3 pages).

NaOH: Sodium Hydroxide	MeOH: Methanol	H_2SO_4: Sulfuric acid
NaHSO4: Sodium Bisulfate	H_2O_2: Hydrogen Peroxide	H_2WO_4: Tungstic Acid
$Co(Ac)_2$: Cobalt Acetate	O_2: Oxygen	CO_2: Carbon Dioxide
H_2O: Water	C3: Propionic acid	DC3: Malonic acid
C6: Caproic acid	C7: Heptanoic acid	C8: Octanoic acid
C9: Pelargonic acid	C16: Palmitic acid	C18: Stearic acid
DC8: Suberic acid	DC9: Azelaic acid	

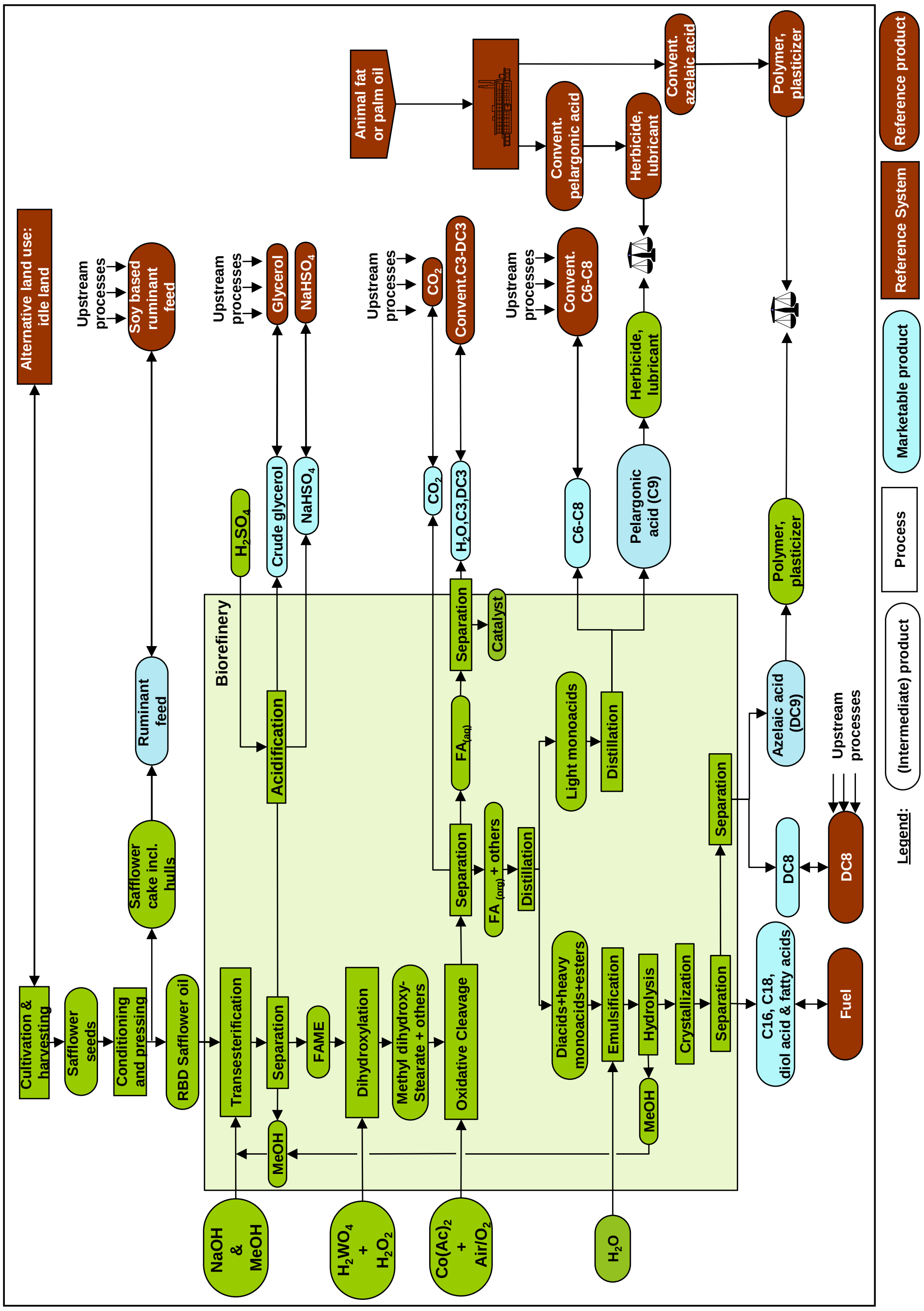

Figure 52: Detailed life cycle comparison for VC 5: organic acids from safflower via oxidative cleavage versus organic acids from fossil resources.

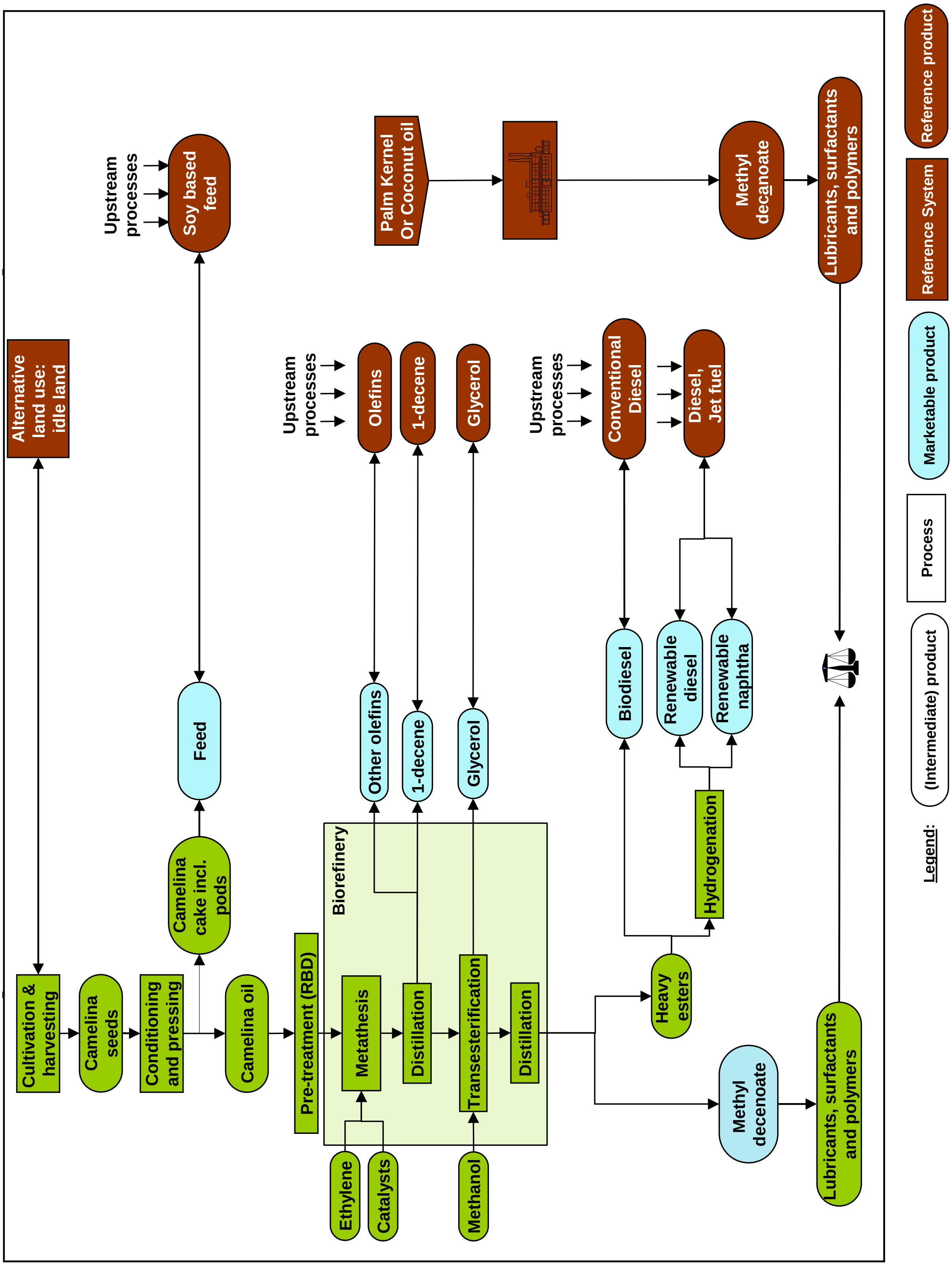

Figure 53: Detailed life cycle comparison for VC 6: methyl decenoate from camelina via metathesis versus methyl decanoate from biogenic resources.

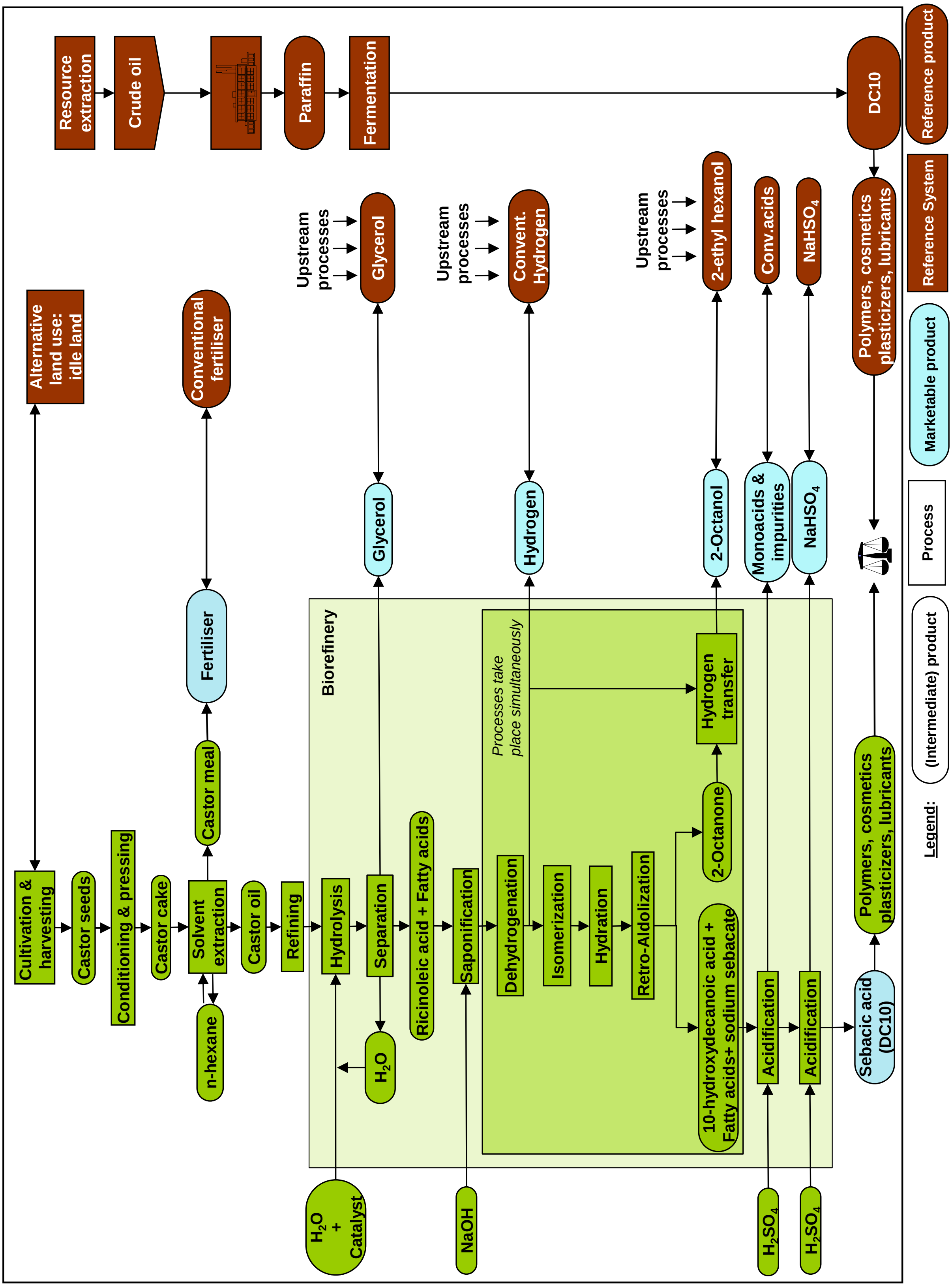

Figure 54: Detailed life cycle comparison for VC 7: products derived from sebacic acid from castor oil (via alkaline cleavage) versus the same products from paraffins derived through fermentation of petroleum.

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