Environmental assessment of an innovative lignocellulose biorefinery concept based on the acetone organosolv process

(Final report on environmental assessment)

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Executive Summary


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Large quantities of lignocellulosic residues are generated in agriculture and forestry, which have so far mainly been used for energy provision, if at all. In order to strive for a higher-value use in the future, various processes have been developed to break down lignocellulose into its components and facilitate efficient conversion into chemicals and building materials. One of these is the so-called organosolv process, in which the lignocellulose is treated with organic solvents such as ethanol, formic acid or acetone. In order to investigate the technical feasibility and overall sustainability, the EU and the Bio Based Industries Consortium co-funded the project "UNRAVEL: A Unique Refinery Approach to Valorise European Lignocellulosics". It researches and develops acetone organosolv fractionation to boost delignification, recovery yields and purity of the main constituents from lignocellulosic biomass.

The project is accompanied by an integrated life cycle sustainability assessment covering environmental, economic and social sustainability aspects using a common set of scenarios based on mass and energy balances from detailed process models. The scenarios comprise several valorisations of the lignocellulose fractions lignin, C5 sugars from hemicellulose and C6 sugars from cellulose. They include polyols from lignin for PUR/PIR (poly–urethane/polyisocyanurate) foams and fermentation of the sugar streams to chemicals (C5 to xylonate and C6 to acetone). This report covers the environmental assessment, which has been contributed by IFEU as deliverable D6.4. It is based on consequential screening life cycle assessments supplemented by life cycle environmental impact assessments.

Results

The project could achieve important steps towards the environmental sustainability of potential future biorefineries by introducing several successful innovations:

- A **new approach to pre-extraction** of biomass before organosolv fractionation can make previously not usable underutilised biomass residues such as roadside grass or mixed lignocellulosic residues available for lignocellulosic biorefineries. Although this requires additional energy, net effects can be positive if competition for feedstocks, possible pressure to resort to unsustainably sourced feedstocks in case of shortages and resulting environmental disadvantages can be mitigated.

- Additionally, much has been achieved through the **improvement of the core process** based on acetone organosolv technology in the project. It causes significantly lower

environmental impacts than the commonly used ethanol organosolv process, mainly due to its lower energy and solvent demand. The project objective to reduce the carbon footprint by at least 15% is clearly exceeded based on expectations for upscaling (reduction of about 30% if implementation succeeds as expected).

- Regarding the **downstream processing** of the three intermediate fractions obtained from the organosolv process, namely lignin, C5 from hemicellulose and C6 from cellulose, into products the following findings were obtained:

  - The modification of **lignin** with ethylene carbonate (EC) for use as a polyol in PUR/PIR is associated with clear environmental advantages. Lignin valorisation was one of the focus areas of this project and this newly developed successful lignin use option is one of several studied in this project.

  - The conversions of **C5 from hemicellulose** into xylonate and **C6 from cellulose** into acetone turned out not to make full use of the potential to avoid emissions by substituting conventional products. Although these explorative research activities produced valuable scientific findings as such, substantially increased environmental benefits are not to be expected based on gained experience even if these processes were developed further. Nevertheless, fermentability of the fractions was found to be good so that many other environmentally friendly products seem attainable. LCA can help to identify suitable pathways.

Resulting from the heterogeneous environmental performance of the downstream processing options, only some of the biorefinery scenarios as investigated in this study can achieve overall environmental benefits. Environmental sustainability of the scenarios with the given product spectrum in particular requires overcoming the following constraints:

- Very high energy and material efficiencies must be achieved. This requires optimal performance in many aspects at the same time.

- Biomass needs to be available without substantial competition.

- Bio-based products really need to replace fossil-based products (as postulated in the comparisons underlying the LCA) and not just increase the amounts of products used.

- Residue extraction from and thus intensification of forestry and agriculture always comes along with the risk of adverse local environmental impacts on soil, water and biodiversity. This could only be justified if other substantial benefits for climate and other environmental aspects are certainly achieved, which is in conflict with very high demands to technological development such as the very high yields to be reached on industrial scale mentioned above.

Conclusions

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The mixed results do not disprove the organosolv biorefinery concept as such or any improvements achieved within this project. Rather, it underlines the importance of exploring and developing environmentally beneficial biorefinery process modules as successfully done in this and other projects. These generally advantageous modules are then to be optimised individually, combined according to local biomass availability and market demands, and integrated to create environmentally friendly lignocellulose biorefineries.

Among the modules studied in this project, the pre-extraction, the core process using acetone organosolv and the lignin conversion into polyols are promising elements for future environmentally friendly biorefineries that should be developed further.

Recommendations

The following goals should be addressed with priority from an environmental perspective to further improve the promising biorefinery process modules identified above:

- Reduce the energy demand of the core process and fractionation as far as possible.

- Further improve material use efficiency of the core process and lignin conversion.

- Develop an integrated utilities concept mainly based on renewable wind and solar power including replacing heat-driven processes by electricity-driven ones.

These goals are directed at all stakeholders. Specific recommendations to various stakeholder groups on how to address the goals via individual sub-goals, support and implementation measures and corresponding strategies are detailed in the report. These can serve as a guideline to further develop the analysed lignocellulose biorefinery concept based on the acetone organosolv technology into an environmentally friendly technology option to make best use of available biomass in a future defossilised economy.

Content

1 Introduction

The UNRAVEL project aims for an efficient and feasible conversion of second generation biomass from forestry and/or agriculture into chemicals and building materials. Biomass streams will undergo Fabiola™ organosolv fractionation in order to boost delignification, recovery yields and purity of their main constituents. The product streams obtained from fractionation are lignin, C6 sugars and a C5 sugars stream. Various valorisations of the product streams are addressed such as lignin for PUR/PIR, and fermentation of the C5 and C6 sugar streams into chemicals, see Figure 1.

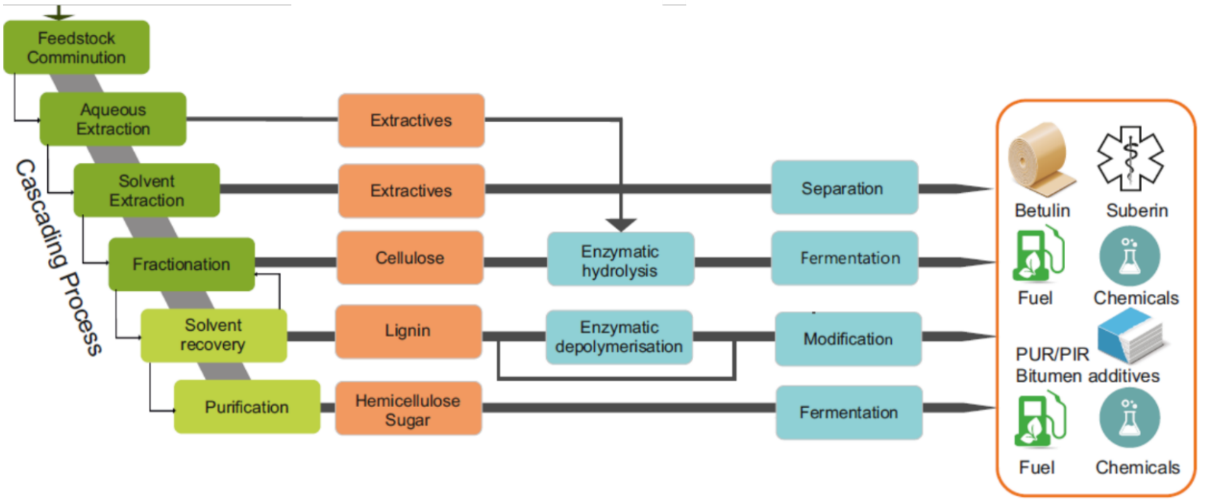

Figure 1: Overview of the UNRAVEL concept.

One main motivation for the UNRAVEL project is to improve the technology, economics and further sustainability impacts of advanced pre-treatment, separation and conversion technologies for complex lignocellulosic biomass. The sustainability assessment within this project ensures that process and product improvements indeed lead to a more sustainable performance over the whole life cycle.

Work package 6 of the UNRAVEL project conducts an integrated life cycle sustainability assessment analysing the three main pillars of sustainability: environment, economy and society. This document contains the environmental assessment of the scenarios defined commonly for all parts of the integrated sustainability assessment based on mass and energy balances from Task 6.2 on process design [Dijkstra & Luzzi 2022].

2 Methodology

In order to achieve reliable and robust sustainability assessment results, it is inevitable that the principles of comprehensiveness and life cycle thinking (LCT) are applied. Life cycle thinking means that all life cycle stages for products are considered, i.e. the complete supply or value chains, from the production of biomass, through processing in the biorefinery and production of the end user products, to product use and end-of-life treatment / final disposal (see section 2.1.2). Through such a systematic overview and 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 avoided or at least minimised. The performance of each product and co-product is compared to alternative reference products.

This assessment is based on the methodology of Integrated Life Cycle Sustainability Assessment (ILCSA) [Keller et al. 2015]. The structure of WP 6 that implements this integrated life cycle sustainability assessment is depicted in Figure 2.

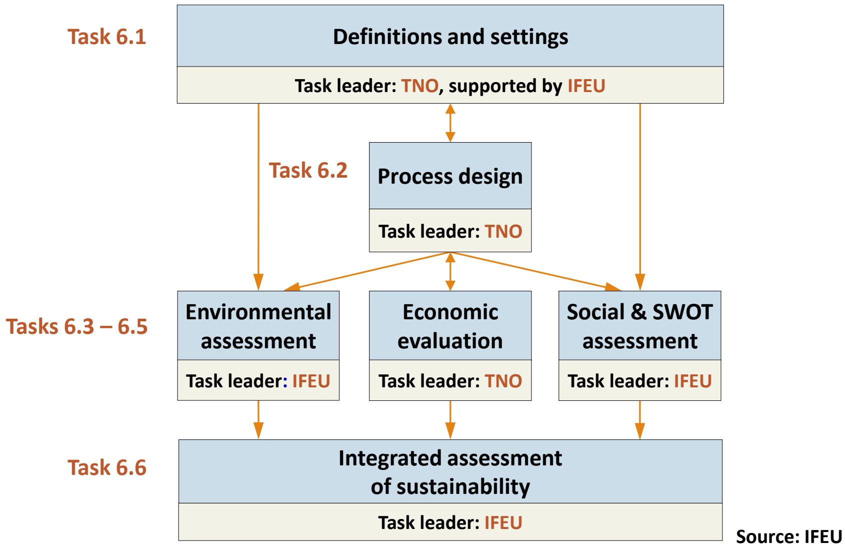

Figure 2: Structure of the work package on sustainability assessment in UNRAVEL.

Common definitions and settings such as goal and scope of the assessment are described in section 2.1 and the specific methodologies and settings applied for the environmental assessment are described in section 2.2 for life cycle assessment and section 2.3 for life cycle environmental impact assessment.

2.1 Common definitions and settings

A well-founded sustainability assessment requires common definitions and settings on which the environmental, economic and social assessment will be based. They ensure consistent data and results for the integrated sustainability assessment. This chapter summarizes the settings for the sustainability assessment that were discussed and agreed upon with all partners on an internal workshop on definitions and settings on February 5th, 2019 in Limerick (Ireland) [Dijkstra et al. 2019]. It comprises the basis for the whole sustainability assessment in this work package.

2.1.1 Goal

The goal of this work is to assess the sustainability of the UNRAVEL value chains in a streamlined and comprehensive manner, covering the main aspects of sustainability: environment, economy and society.

Main purpose

- Decision support
- Support pilot case development

Addressees

Decision makers in:

- Policy
- Research
- Industry
- General public

Guiding questions

These guiding questions are the basis of the sustainability assessment. It is the goal of the final report at the end of the project to answer these questions.

Main question is formulated as follows:

How far and under which conditions can the UNRAVEL biorefinery concept contribute to a more sustainable supply of the targeted products?

Sub-questions:

- How does the studied biorefinery concept compare from a sustainability perspective to (a) conventional products and (b) to other use options of the same biomass, in particular other state-of-the-art biochemical biorefinery concepts?
    - Is the objective reached to reduce OPEX and carbon footprint of the pre-treatment by 30% and 15%, respectively?
    - How do specific results for the different perspectives on sustainability (such as environmental, economic, social) differ from each other?
    - To which extent do the pre-extractions impact sustainability compared to current practice without pre-extractions, and to which extent do the different options for lignin valorisation impact sustainability?

  - Which sections or unit operations therein determine the results significantly and what are the optimisation potentials?
  - What is the influence of feedstocks on this?
  - What is the influence of possible transitions in the economy (e.g. renewable energy, oil and feedstock price)?
- Which barriers (e.g. technological) and limitations may hinder the industrial-scale implementation of UNRAVEL or require changes to the concept that affect sustainability?
  - Is the objective reached to develop an economically viable process for purification of the hemicellulose hydrolysate for effective fermentation into chemical building blocks?
  - Is the objective reached to develop high value applications for lignin i.e. its application in PUR/PIR and as polymer fillers?

2.1.2 Scope

With the scope definition, the objective 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. Resulting definitions and settings are used in the subsequent analyses (tasks) to guarantee the consistency between the different assessments of environmental, economic and social implications.

The comprehensiveness and depth of detail of the sustainability assessment can differ considerably depending on its goal.

System boundaries

Entire life cycles (value chains) are analysed from cradle to grave

- *I.e.* from production of inputs to the disposal of the products
- Applies to products and conventional reference products

The system boundaries include a part that is modelled in detail (foreground system, within battery limits) and a part for which data is supplemented from other sources.

Technical reference, timeframe

Mature technology at industrial scale (“nth plant”) will be analysed. The reference year will be 2030 for a mature, full scale industrial production. The life cycle sustainability assessment evaluates scenarios depicting potential mature technology in 2030 based on available measured data, expert knowledge and where necessary literature sources.

Geographical scope

EU (no biomass from outside EU considered)

2.2 Specific definitions and settings for life cycle assessment (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 UNRAVEL project is carried out largely following these ISO standards on product life cycle assessment. According to the ISO standards, a LCA consists of four iterative phases):

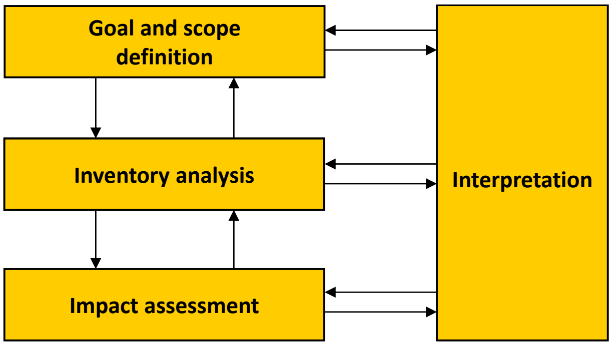

Figure 3: Phases of an LCA[ISO 2006a; b].

- 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 a 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.

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 UNRAVEL 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 [Ramirez Ramirez et al. 2020; Zimmermann et al. 2020].

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

I Data sources

Primary data on mass and energy balances is provided by Task 6.2 on process design [Dijkstra & Luzzi 2022], which has collected inputs from all technology development partners in the project. Further secondary data such as on background processes were taken from IFEU's internal database [IFEU 2021], from the ecoinvent database [Ecoinvent 2020] and from literature data where necessary.

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]. This is the case for the UNRAVEL systems. Hence, a consequential modelling approach is applied in this assessment.

III Co-products handling

As explained in section 2.1.2, 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. 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.

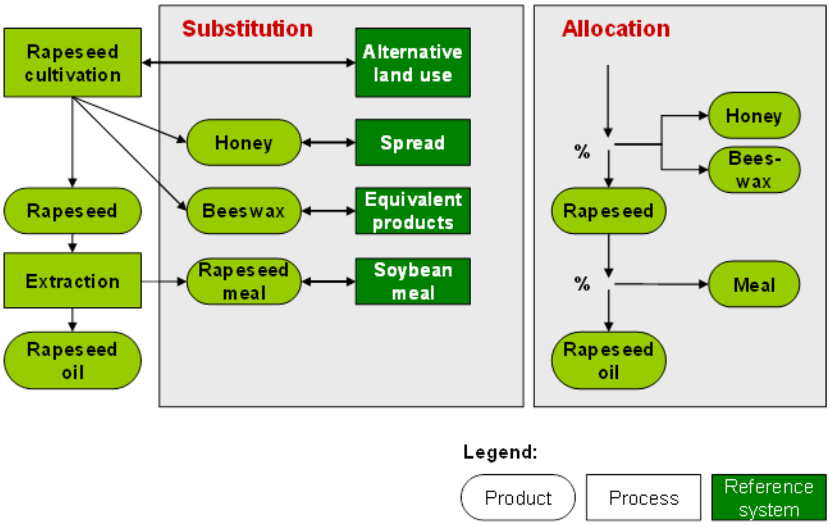

Figure 4: Exemplary illustration of methodological approaches for co-product accounting.

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 UNRAVEL project. The corresponding specifications of these LCIA elements are described in the following sections including

I Impact categories and LCIA methods

II Normalisation

III Weighting.

I Impact categories and LCIA methods

All main environmental issues related to the UNRAVEL 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. Potential environmental impacts can be analysed at midpoint or at endpoint level. For environmental assessments within technology development projects such as UNRAVEL, 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. This project assesses the midpoint indicators listed in Table 1. The LCIA methods follow the recommendations in [Detzel et al. 2016].

Table 1: Overview on included midpoint impact categories.

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]
Photochemical ozone formation (photo smog)	[van Zelm et al. 2008]
Particulate matter formation	[de Leeuw 2002]
Land use (Distance-to-Nature-Potential [DNP])	[Fehrenbach et al. 2019]
Phosphate rock use	[Reinhardt et al. 2019]

This set of methods also includes two long-neglected impact categories covering environmental issues: phosphate rock footprint and land use footprint:

The phosphate rock demand is dominated by phosphorus requirements of agricultural processes or fermentation processes and 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. 2019]. This approach includes both the degree of human influence on a natural area and the distance of that area to the undisturbed state.

Impact categories that are irrelevant for the UNRAVEL value chains are excluded from this study. This is the case for ionising radiation, for example. Furthermore, impact categories are excluded (i) that are still too immature to provide conclusive results or (ii) that cannot ensure sufficient LCI data quality for the reference year 2030 (i.e. impact categories on toxicity). 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 UNRAVEL 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. 2015] are taken. These values refer to the year 2010 and the EU 28 countries.

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.

2.3 Specific definitions and settings for life cycle environmental impact assessment (LC-EIA)

There are a number of environmental management tools that differ both in terms of subject of study (product, production site or project) and in their potential to address environmental impacts occurring at different spatial levels. Environmental life cycle assessment (LCA), for example, addresses potential environmental impacts of a product system (see section 2.2). However, for a comprehensive picture of environmental impacts, also local/site-specific impacts on environmental factors like e.g. biodiversity, water and soil have to be considered. Although methodological developments are under way, these local/site-specific impacts are not yet covered in standard LCA studies. Thus, for the time being, LCA has to be supplemented by elements borrowed from other tools.

The methodology applied in this project borrows elements from environmental impact assessment (EIA) [and partly from strategic environmental assessment (SEA)] and is therefore called life cycle environmental impact assessment (LC-EIA) [Keller et al. 2014; Kretschmer et al. 2012].

2.3.1 Introduction to environmental impact assessment methodology

Environmental impact assessment (EIA) is a standardised methodology for analysing proposed projects regarding their potential to affect the local environment. It is based on the identification, description and estimation of the project's environmental impacts and is usually applied at an early planning stage, i.e. before the project is carried out. EIA primarily serves as a decision support for project management and authorities which have to decide on approval. Moreover, it helps decision makers to identify more environmentally friendly alternatives as well as to minimise negative impacts on the environment by applying mitigation and compensation measures.

The environmental impacts of a planned project depend on both the nature/specifications of the project (e.g. a biorefinery plant housing a specific production process and requiring specific raw materials which have to be delivered) and on the specific quality of the environment at a certain geographic location (e.g. occurrence of rare or endangered species, air and water quality etc.). Thus, the same project probably entails different environmental impacts at two different locations. EIA is therefore usually conducted at a site-specific/local level. These environmental impacts are compared to a situation without the project being implemented ("no-action alternative").

Regulatory frameworks related to EIA

Within the European Union, it is mandatory to carry out an environmental impact assessment (EIA) for projects according to the Council Directive 85/337 European Economic Community (EEC) of 27 June 1985 "on the assessment of the effects of certain public and private projects on the environment" [CEC 1985]. This Directive has been substantially amended several times. In the interests of clarity and rationality the original EIA Directive has been codified (put together as a code or system, i.e. in an orderly form) through Directive 2011/92/EU of 13 December 2011 [European Parliament & Council of the European Union 2011]. The latter has once again been amended in through Directive 2014/52/EU of 16 April 2014 [European Parliament & Council of the European Union 2014].

EIA methodology

An EIA covers direct and indirect effects of a project on certain environmental factors. The list of factors has been substantially altered with the 2014 amendment (addition and deletion of factors) [European Parliament & Council of the European Union 2014] and currently covers the following ones:

- population and human health
- biodiversity (previously: fauna and flora)
- land (new), soil, water, air and climate
- material assets, cultural heritage and the landscape
- the interaction between these factors

Please note: the relatively new factor "land" is indirectly addressed in the conflict matrices (via the factors "soil" and "landscape") since implementing rules for the new factor "land" are lacking or under development. Moreover, we continue to address the two factors "fauna" and "flora" separately, since we think that "biodiversity" alone wouldn't cover all aspects that were previously addressed under "fauna" and "flora" (e.g. the conservation/Red List status of species). This way, more specific recommendations can be derived.

An EIA generally includes the following steps:

- Screening
- Scoping
- EIA report
    - Project description and consideration of alternatives
    - Description of environmental factors
    - Prediction and evaluation of impacts
    - Mitigation measures
- Monitoring and auditing measures

Screening

Usually an EIA starts with a screening process to find out whether a project requires an EIA or not. According to Article 4 (1) and Annex 1 (6) of the EIA Directive, an EIA is mandatory for "Integrated chemical installations, i.e. those installations for the manufacture on an industrial scale of substances using chemical conversion processes, in which several units are juxtaposed and functionally linked to one another and which are"

- "for the production of basic plant health products and of biocides" (6d) or
- "for the production of basic pharmaceutical products using a chemical or biological process" (6e).

Referring to Annex 1 (6) of the EIA Directive, an EIA would be required if one of the studied facilities was implemented.

Scoping

Scoping is to determine what should be the coverage or scope of the EIA study for a project as having potentially significant environmental impacts. It helps in developing and selecting alternatives to the proposed action and in identifying the issues to be considered in an EIA. The main objectives of the scoping are:

- Identify concerns and issues for consideration in an EIA.
- Identify the environmental impacts that are relevant for decision-makers.
- Enable those responsible for an EIA study to properly brief the study team on the alternatives and on impacts to be considered at different levels of analysis.
- Determine the assessment methods to be used.
- Provide an opportunity for public involvement in determining the factors to be assessed, and facilitate early agreement on contentious issues.

EIA report

An EIA report consists of a project description, a description of the status and trends of relevant environmental factors and a consideration of alternatives including against which predicted changes can be compared and evaluated in terms of importance.

- Impact prediction: a description of the likely significant effects of the proposed project on the environment resulting from:
    - The construction/installation of the project; temporary impacts expected, e.g. by noise from construction sites.
    - The existence of the project, i.e. project-related installations and buildings; durable impacts expected e.g. by loss of soil on the plant site.
    - The operation phase of the project; durable impacts expected, e.g. by emission of gases.

Prediction should be based on the available environmental project data. Such predictions are described in quantitative or qualitative terms considering e.g.:

- Quality of impact
- Magnitude of impact
- Extent of impact
- Duration of impact

Mitigation measures are recommended actions to reduce, avoid or offset the potential adverse environmental consequences of development activities. The objective of mitigation measures is to maximise project benefits and minimise undesirable impacts.

Monitoring and auditing measures

Monitoring and auditing measures are post-EIA procedures that can contribute to an improvement of the EIA procedure.

Monitoring is used to compare the predicted and actual impacts of a project, so that action can be taken to minimise environmental impacts. Usually, monitoring is constrained to either potentially very harmful impacts or to impacts that cannot be predicted very accurately due to lack of baseline data or methodological problems.

Auditing is aimed at the improvement of EIA in general. It involves the analysis of the quality and adequacy of baseline studies and EIA methodology, the quality and precision of predictions as well as the implementation and efficiency of proposed mitigation measures. Furthermore, the audit may involve an analysis of public participation during the EIA process or the implementation of EIA recommendations in the planning process.

2.3.2 Settings for LC-EIA

Within this project, a set of different technological concepts to convert second generation biomass from forestry and/or agriculture into chemicals and building materials, is analysed. Each concept is defined by its inputs, the conversion, the downstream processes and the final products.

Environmental impact assessment (EIA), is usually conducted specifically for a planned (actual) project (see chapter 2.3.1). For the purpose of this project, which neither encompasses the construction of an actual industrial scale facility, it is therefore not appropriate to perform a full-scale EIA according to the regulatory frameworks. Monitoring and auditing measures, for example, become redundant if a project is not implemented, as they are post-project procedures. Consequently, monitoring and auditing measures will be omitted within this project. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the systems investigated in this project at a generic level to inform further technology development.

The elements of EIA used in this project are shown in Figure 5.

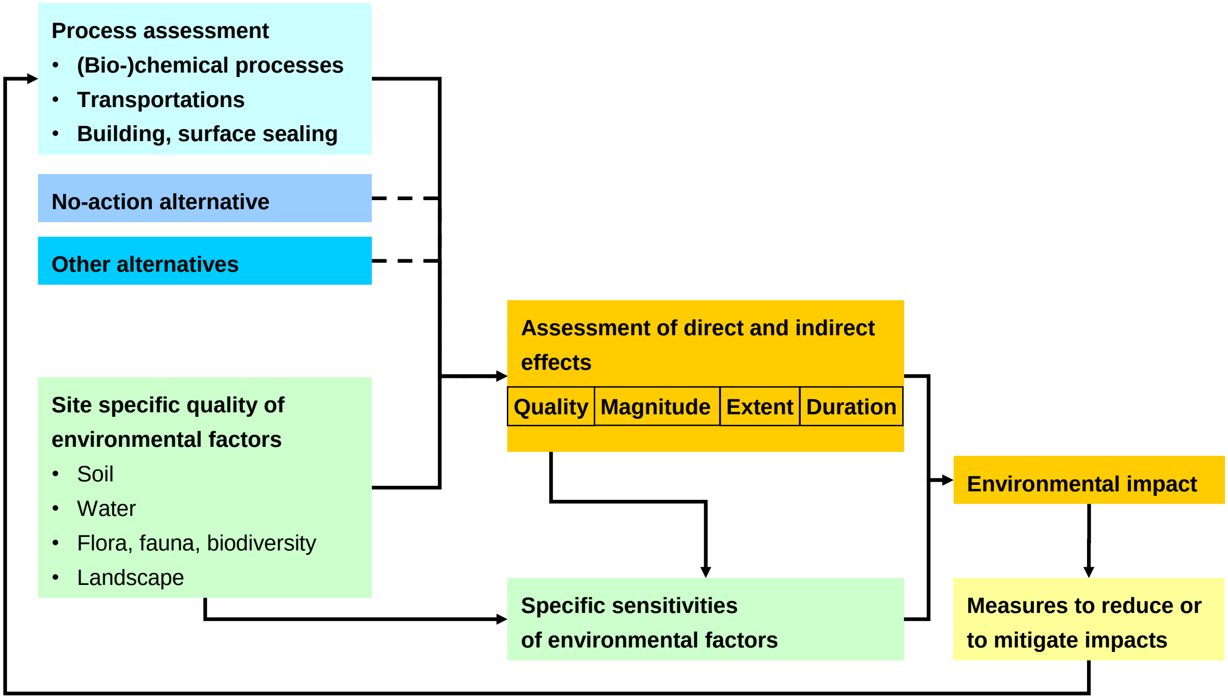

Figure 5: Structure of an LC-EIA.

Reference systems

Generally, an EIA compares a planned project to a so-called "no-action alternative" (a situation without the project being implemented) in terms of environmental impacts. This assessment is restricted to one specific project or site such as a processing facility. Production sites for raw material inputs (e.g. biomass) and/or the impacts associated with the end use of the manufactured products are usually not considered.

Within this life cycle based sustainability assessment, the scope, and therefore also the reference system, of the LC-EIA was chosen to encompass all life cycle stages from raw material provision through conversion up to the use of the final products. This corresponds to a life cycle perspective and goes beyond the regulatory frameworks for EIA.

Impact assessment

The assessment of local environmental impacts along the life cycle is carried out as a qualitative benefit and risk assessment. This is useful if no certainty exists regarding the possible future location of biomass production sites and conversion facilities.

For this qualitative impact assessment, so-called conflict matrices are used. These present in an aggregated manner the types of risk associated with each of the scenarios including a ranking of the impacts into five categories from A (low risk) to E (high risk). An example is given in the following Table 2.

Table 2: Example for comparison of scenarios regarding the risks associated with their implementation.

Type of risk	Scenario 1	Scenario 2	Scenario 3	Scenario 4	...
Soil erosion					
Soil compaction					
Eutrophication					
Accumulation of pesticides					
Depletion of groundwater					
Pollution of groundwater					
Pollution of surface water					
Loss of landscape elements					
Loss of habitat/biodiversity					

Categories (A = low risk, E = high risk): A B C D E

For products from dedicated biomass feedstock types, which are used to provide the reference products of the UNRAVEL system, feedstock-specific conflict matrices are used. An example is provided in the following Table 3.

In these feedstock-specific conflict matrices, the environmental impacts of biomass use are compared to a reference system (relative evaluation) and evaluated as follows:

- “positive”: compared to the reference system, biomass use is more favourable
- “neutral”: biomass use shows approximately the same impacts as the reference system
- “negative”: compared to the reference system, biomass use is less favourable.

Finally, mitigation measures could be deducted from these conflict matrices. However, since the sustainability assessment within this project is not targeting a specific location, mitigation measures are omitted.

Table 3: Example of risks associated with the cultivation of a specific annual/perennial crop.

Type of risk	Affected environmental factors								
	Ground water	Surface water	Soil	Plants/Biotopes	Animals	Climate/Air	Landscape	Human health/ recreation	Biodiversity
Soil erosion									
Soil compaction									
Eutrophication									
Accumulation of pesticides									
Pollution of groundwater									
Pollution of surface water									
Loss of landscape elements									
Loss of habitat/biodiversity									

Categories: positive - neutral – negative

3 System description

3.1 Overview of the UNRAVEL concept

An overview of the UNRAVEL concept is depicted in Figure 6. The feedstocks and products for the sustainability analysis are indicated in blue text.

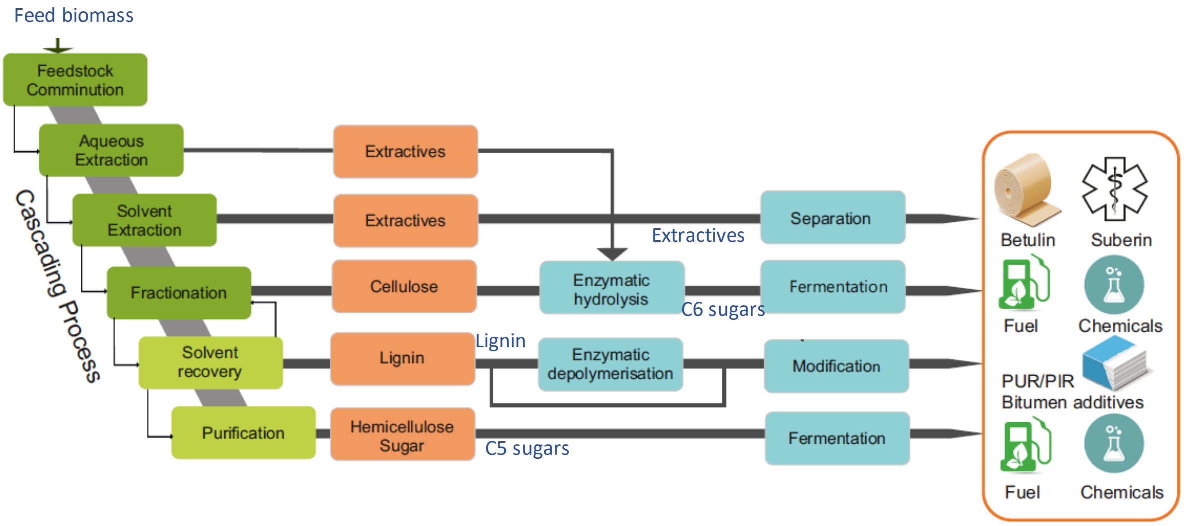

Figure 6: Overview of all sections and main products in the UNRAVEL concept. Feedstocks and products for the sustainability analysis are indicated in the blue text outside of the boxes.

Feedstock biomass is comminuted to the required particle size. Extraction by an aqueous medium and/or a solvent (biomass pre-extraction) is done to improve in particular downstream processing, lignin purity, C5 sugar yield and offers the possibility of extractives valorisation. The comminution and pre-extraction steps are both optional and may depend on feedstock type and composition.

The main step is then fractionation by the organosolv process. The key technology evaluated is the aqueous acetone fractionation, known as the Fabiola™ process, This involves treatment in a mixture of acetone, water with acid added in order to separate the biomass into the three main fractions: lignin, cellulose and hemicellulosic sugars. Lignin application in PUR/PIR foams or as a filler in polymers is being studied The cellulose is sent to enzymatic hydrolysis after which the resulting C6 sugars are used for fermentation towards chemicals. Specifically, fermentation towards acetone is considered in the analysed scenarios. The (detoxified) C5 sugars are also fermented towards fuels or chemicals. Specifically, fermentation towards xylonate (i.e. sodium xylonate, the sodium salt of xylonic acid) is depicted in the scenarios.

3.2 Scenarios

This section describes the analysed UNRAVEL scenarios. The scenarios analysed within the environmental assessment are summarised in Table 4. More information on the particular scenarios is described in sections 3.2.1 - 3.2.12. While in section 3.2.1 the basic scenario is described in detail, sections 3.2.2 - 3.2.12 highlight the differences compared to the basic scenario. All analysed scenarios are based on mass and energy balances from detailed process modelling, which is described in detail in D6.3 on process design [Dijkstra & Luzzi 2022].

Table 4: Final selection of scenarios analysed within the environmental assessment.

Scenario	Description	Section
Beech wood		
Basic scenario (beech)	Feedstock: beech stem wood, C5 fraction used for production of xylonate, C6 fraction used for production of acetone, lignin used for production of polyols for PUR/PIR via EC modification; residues to CHP.	3.2.1
Lignin to fillers	Difference to basic scenario: lignin used for production of light weight fillers via TMP modification.	3.2.2
Residues to heat only	Difference to basic scenario: heat plant instead of CHP.	3.2.3
Lignin combustion	Difference to basic scenario: lignin exported for combustion as benchmark.	3.2.4
Reference	Difference to basic scenario: fractionation via ethanol organsolv instead of Fabiola™ fractionation process.	3.2.5
Herbaceous biomass		
Wheat straw	Difference to basic scenario: feedstock: wheat straw instead of beech stem wood.	3.2.6
Wheat straw, pre-extraction	As wheat straw, pre-extraction process before fractionation.	3.2.7
Roadside grass, pre-extraction	Difference to basic scenario: feedstock: roadside grass instead of beech stem wood, pre-extraction process before fractionation.	3.2.8
Hardwood branches incl. bark		
Birch & bark	Difference to basic scenario: feedstock: birch branches including bark instead of beech stem wood.	3.2.9
Birch & bark, pre-extraction	As birch & bark, pre-extraction process before fractionation.	3.2.10
Mixed feedstock (birch & bark + wheat straw)		
Mixed feedstock, alternating	Alternating feedstock campaigns (based on wheat straw, pre-extraction and birch & bark, pre-extraction).	3.2.11
Physically mixed feedstock	Physically mixed feedstock (based on wheat straw, pre-extraction and birch & bark, pre-extraction).	3.2.12

3.2.1 Basic scenario (beech)

In this section, the basic scenario is described. In the basic scenario beech wood is used as biomass and lignin is used to produce polyols for PUR/PIR foams via EC (ethylene carbonate) modification (Figure 7).

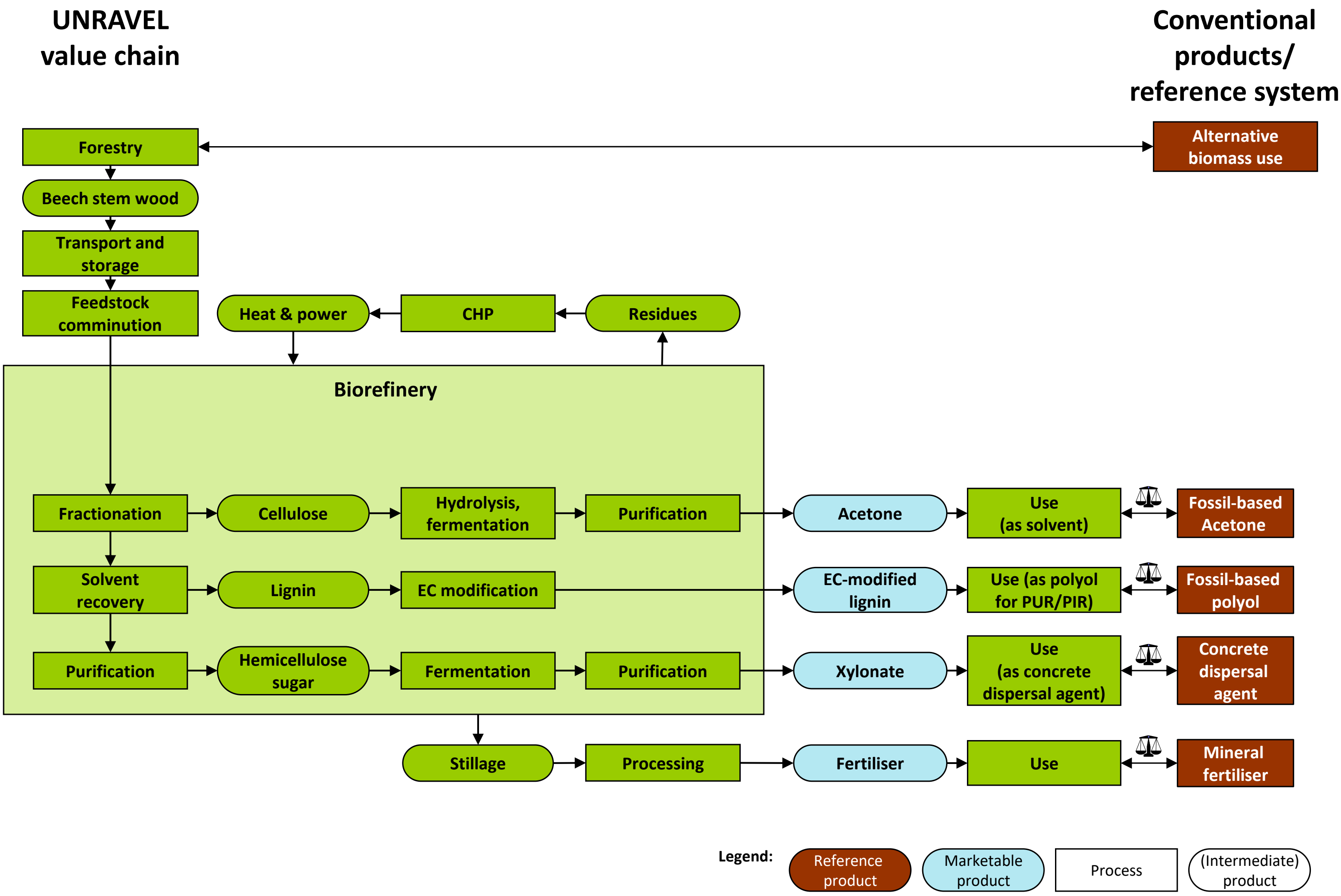

Figure 7: Life cycle scheme of the basic scenario (beech).

This scenario uses beech stem wood in pulp wood / energy wood quality such as obtained from forest thinnings. After harvesting the beech stem wood, it is *transported*, *stored* and again transported to the biorefinery. The plant is assumed to be a greenfield plant with a capacity of processing 300 000 t biomass (dry matter) per year. In *feedstock comminution* the beech stem wood is chipped.

Afterwards, the sized feedstock is *fractionated* within the Fabiola™ fractionation process based on acetone organosolv technology. Beech wood is pre-heated with steam after which Fabiola™ fractionation is performed in batch-wise mode using a mixture of acetone with water and sulphuric acid.

C6 pathway


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From the resulting slurry, pulp is separated and washed with a solvent/water mixture and then with water. The resulting liquid streams are recycled and the wet cellulose pulp is sent to enzymatic *hydrolysis*. Here, cellulase enzymes are added to produce glucose from the pulp. Enzymes are bought from outside the biorefinery. From the resulting slurry the solid residue is filtered off, and the export aqueous C6 sugars stream with mainly glucose is obtained.

Lignin is precipitated using the LigniSep process: The liquor from pulp filtration is mixed with solvent depleted lignin dispersion and is pumped to a falling film evaporator where solvent preferentially evaporates and that is connected to a precipitation vessel with low solvent content (e.g. <8%). The overhead vapour of the falling film evaporator is connected to a rectification column where solvent again is preferentially evaporated resulting in a concentrated solvent fraction at the column head and a lowering of the solvent concentration in the precipitation vessel below the set limit. From the overhead product the small amounts of furfural are removed and minor amounts of CO_2 being formed during fractionation together with other light components are stripped off before this stream is recycled. With this stream also some other light components are removed, if present.

Afterwards, nutrients, sodium hydroxide for pH control and microorganisms inoculum are added for the *fermentation*. The fermentation is aerobic and hence, the fermenter is sparged with air and is a batch process. Acetone is both recovered from the condensate of the overhead vapour as well as from the fermentation broth. Both streams are sent to an acetone recovery column where acetone is obtained via the top stream and stillage as the bottom product.

Lignin pathway

The lignin slurry from precipitation is sent to a separation step to recover lignin. The lignin is washed with water to recover the attached acetone. The resulting wet lignin is dried to obtain the core process lignin intermediate. From the large variety of possible lignin valorisation the route selected for the UNRAVEL project is to modify lignin with EC (ethylene carbonate) for application in PUR/PIR foams. For this, lignin is first milled to a sufficiently small particle size. The PUR/PIR application requires a very low moisture content of the lignin and drying is necessary. The dried lignin is then undergoing the *EC-modification* in which it is functionalized into a polyol with desired properties. The lignin-based polyol then replaces parts of the polyol that is used as one of the two main feedstocks for PUR/PIR production.

C5 pathway

Spent liquor is sent to the C5 column where the remaining solvent is removed and recycled to produce a crude C5 sugars stream. This stream is sent to detoxification to remove toxic compounds for the fermentation process and results in the C5 sugars product stream (hemicellulose sugar).

Nutrients and microorganisms inoculum is added to the hemicellulose sugar stream for the *fermentation* to xylonate. The fermentation is aerobic hence the fermenter is sparged with air, and is a (fed) batch process. Sodium hydroxide is added for pH control. The product stream is then *purified* using small amount of sorbent for decolouration. Multi-effect evaporation of water induces crystallization of the salt, which can be filtered, dried and obtained as the final xylonate product stream. More specifically, this stream is sodium xylonate, which is the sodium salt of xylonic acid.

Solvent recycling and residue valorisation

All recycle streams containing a mixture of solvent and water are recycled to the organosolv pulping feed stream. A make-up solvent stream compensates for any solvent losses. All residues emerging within the above mentioned life cycle stages inside the biorefinery are used as feedstock in a combined heat and power plant (CHP). The obtained heat and power is used in the biorefinery and therefore reintegrated.

Replaced conventional products

1 kg of modified lignin replaces 1 kg of polyols that are synthesised from fossil-based petrochemicals in an application for PUR/PIR foams. Acetone replaces chemically identical fossil-based acetone, which is produced by standard petrochemical processes (mainly via the cumene process). Xylonate replaces gluconate that is otherwise produced via a similar fermentation process as modelled for the UNRAVEL scenarios from a range of conventional “1st generation” sugars on a 1:1 molar basis in an application as concrete dispersal agent.

3.2.2 Lignin to fillers

In the scenario ‘lignin to fillers’, the lignin is undergoing a *trimethyl phosphate* (*TMP)-modification* instead of EC-modification. The TMP-modified lignin then replaces glass bubbles that are used as light weight polymer fillers.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.3 Residues to heat only

In the scenario ‘residues to heat only’, all residues emerging in biorefinery processes are used as feedstock in a heat plant instead of a CHP. Therefore, only heat is reintegrated in the biorefinery processes that would otherwise be produced by natural gas.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.4 Lignin combustion

In the scenario 'lignin combustion', the lignin is not used for producing high value chemicals but energetically as a solid biofuel.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.5 Reference

In the reference scenario the currently common state-of-the-art ethanol organosolv fractionation process is used instead of the Fabiola™ acetone organosolv process utilising acetone instead of ethanol as a solvent. Using ethanol as a solvent instead of acetone impacts the fractionation yields. Ethanol also reacts with C5 sugars to produce ethylated sugars for which no application is considered. The relative volatility of solvent (compared to water) is lower for ethanol resulting in a higher heat demand in solvent recovery, as well as the necessity for an additional distillation column to achieve the required solvent concentrations in the lignin precipitation section.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.6 Wheat straw

In the 'wheat straw' scenario wheat straw is used as biomass feedstock instead of beech wood. Alternatively, other cereal straws such as barley straw could be used with similar performance.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.7 Wheat straw, pre-extraction

In the scenario 'wheat straw, pre-extraction' also wheat straw is used as biomass feedstock instead of beech stem wood (Figure 8). Furthermore, a pre-extraction process using water and acetone is added before fractionation of the biomass: The biomass is washed with water/solvent mixtures at elevated temperature to wash out unwanted components primarily to improve biomass fractionation characteristics. The biomass including residual acetone is sent to the fractionation process. The resulting extractives stream is sent to *wastewater treatment*. Currently, no technically viable route for valorisation of extractives obtained during pre-extraction could be identified and valorisation therefore has not been considered.

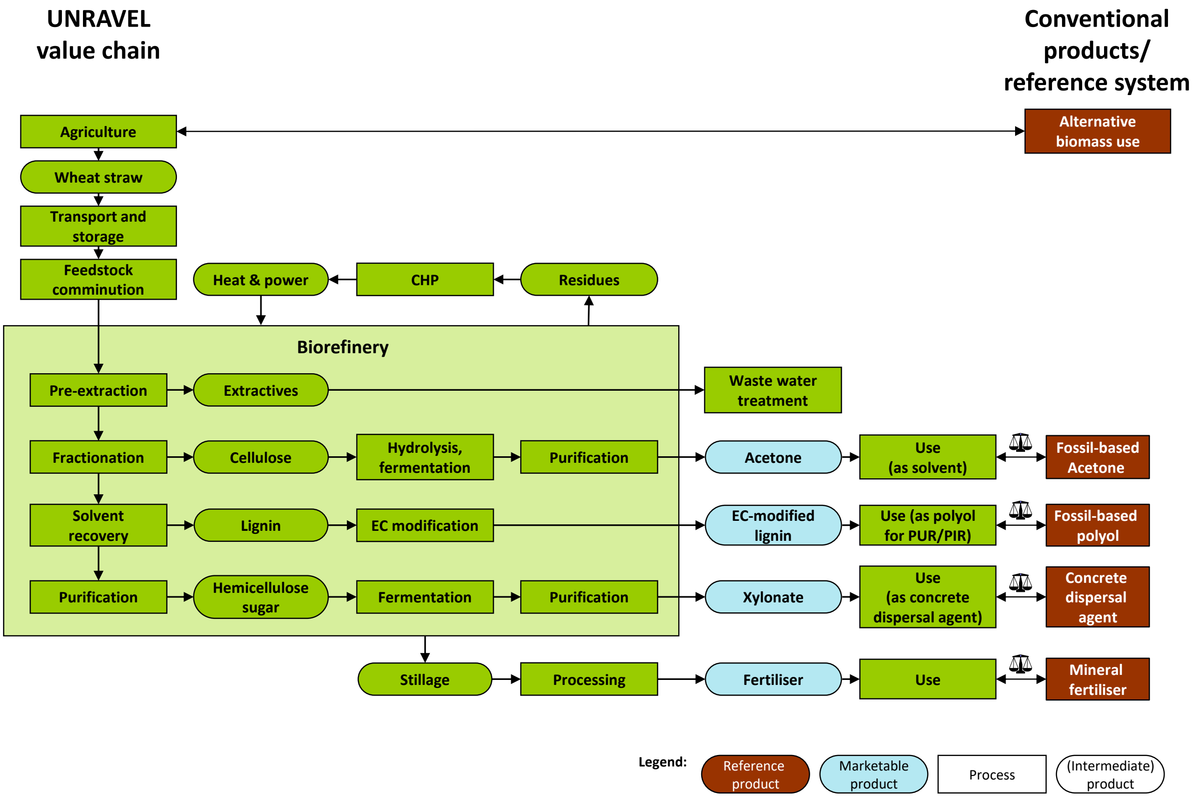


Figure 8: Life cycle scheme of the scenario 'wheat straw, pre-extraction'.

3.2.8 Roadside grass, pre-extraction

In the scenario 'roadside grass, pre-extraction', roadside grass is used as biomass feedstock instead of beech stem wood. As in scenario 'wheat straw, pre-extraction', the fractionation process is preceded by a pre-extraction process (see section 3.2.7)

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.9 Birch & bark

In the 'birch & bark' scenario branches and tops of birch trees including their bark and residual foliage is used as biomass feedstock instead of beech stem wood.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.10 Birch & bark, pre-extraction

In the scenario ‘birch & bark, pre-extraction’ also branches and tops of birch trees including their bark and residual foliage is used as biomass feedstock instead of beech stem wood. Furthermore, as in scenario ‘wheat straw, pre-extraction’, the fractionation process is preceded by a pre-extraction process (see section 3.2.7).

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.11 Mixed feedstock, alternating

In the scenario ‘mixed feedstock, alternating’ wheat straw and branches and tops of birch trees including their bark and residual foliage are used in alternating campaigns as biomass feedstock instead of beech stem wood. Furthermore, as in scenario ‘wheat straw, pre-extraction’, the fractionation process is preceded by a pre-extraction process (see section 3.2.7). The feed considered is 50% for each feedstock on a dry weight basis.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.2.12 Physically mixed feedstock

In the scenario ‘physically mixed feedstock’ wheat straw and branches and tops of birch trees including their bark and residual foliage are mixed physically and then used as biomass feedstock instead of beech stem wood. Furthermore, as in scenario ‘wheat straw, pre-extraction’, the fractionation process is preceded by a pre-extraction process (see section 3.2.7). The feed considered is 50% for each feedstock on a dry weight basis.

For a better overview, the life cycle scheme can be found in the annex of this report (chapter 10).

3.3 Sensitivity analyses

The scenarios described in section 3.2 are analysed in this report taking into account various possible background systems such as electricity provision from several sources or variations in the reference system of conventional production of the same products. These sensitivity analyses are described in the respective results sections. Furthermore, important indirect effects of the UNRAVEL system on the background system are analysed such as those caused by competition for feedstocks that can prevent other established uses of that biomass. The scenario extensions behind these sensitivity analyses are described in the following.

Beech wood in energy/pulp wood quality that arises mostly from thinning of forests is completely used. It is plausible that additional use of beech stem wood in a UNRAVEL biorefinery would not lead to relevant amounts of additional thinning as in the basic scenario but instead to a withdrawal of this feedstock from other applications. This could either lead to additional biomass feedstock supply or less biomass use and supply of equivalent products e.g. from fossil resources.

One example is the withdrawal of beech stem wood from the use in a combined heat and power plant (illustrated in Figure 9). In this case, the heat and power not produced by beech wood would have to be replaced by other energy sources mainly from fossil fuels. Another

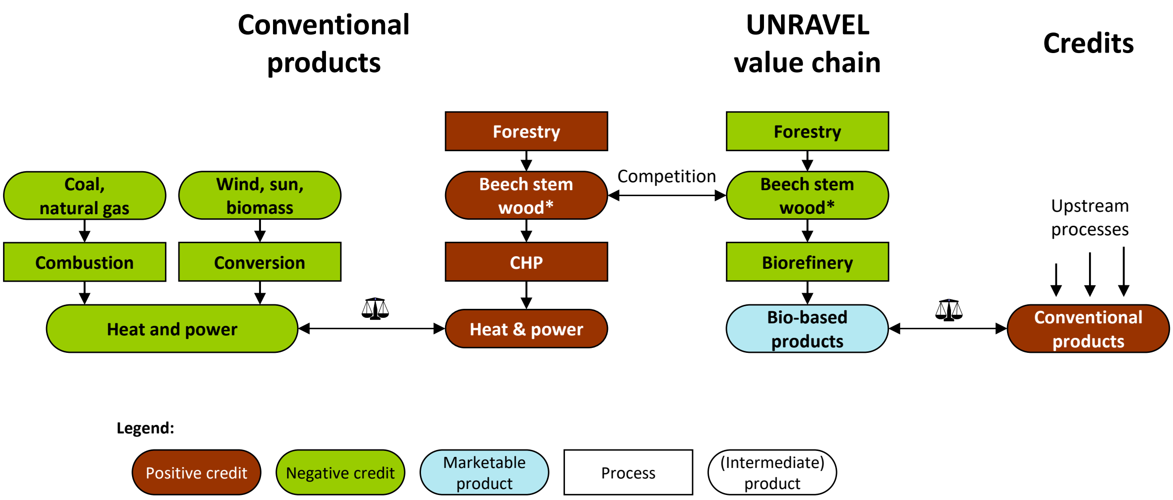


Figure 9: Life cycle scheme of the beech wood scenario including the competing use of beech stem wood for energy in a combined heat and power plant. *Quality: energy/pulp wood.*

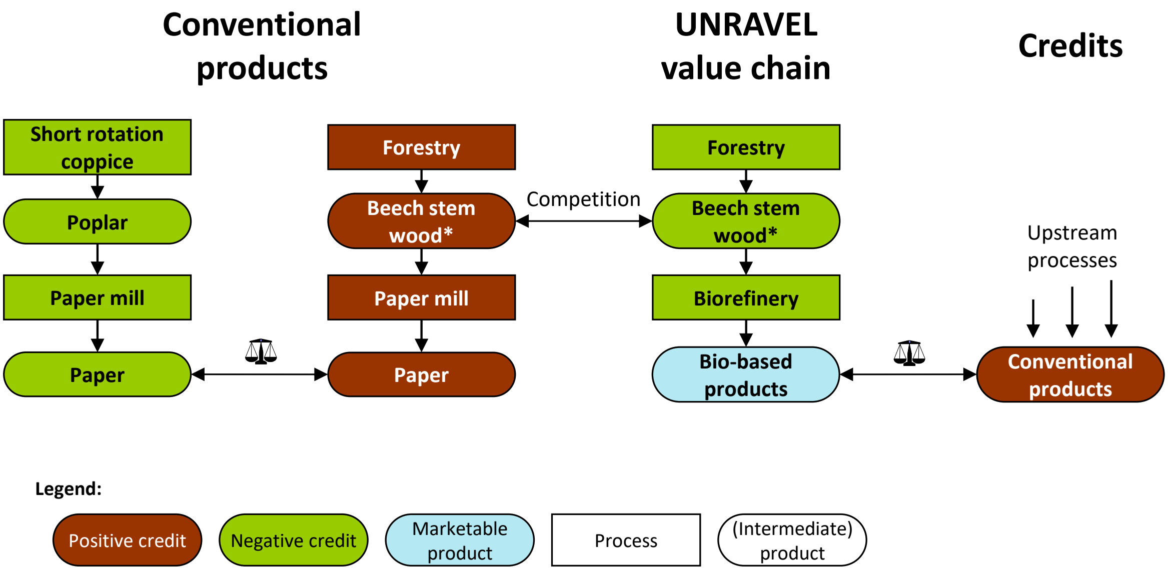


Figure 10: Life cycle scheme of the beech wood scenario including the competing use of beech stem wood for paper production and its potential indirect effect on pulp wood supply. *Quality: energy/pulp wood.*

example would be the withdrawal of beech wood from the production of paper (Figure 10). In this case, another pulp wood feedstock, such as poplar from short-rotation coppice, would have to be provided to produce the same amount of paper. The sensitivity analyses performed on feedstock competition are summarised in Table 5.

Table 5: Sensitivity analyses performed on feedstock competition.

Name	Description	Additional burdens caused
Beech wood		
CHP	Beech wood formerly used in a CHP is instead used in the biorefinery.	Heat and power formerly produced by a wood-fired CHP have to be additionally supplied mainly from fossil fuels.
Pellets	Beech wood formerly used for the production of wood pellets used in domestic heating is instead used in the biorefinery.	Heat formerly produced by wood pellets in domestic heating has to be additionally supplied from natural gas.
Poplar short rotation coppice (SRC)	Beech wood formerly used for the production of paper is instead used in the biorefinery.	Paper formerly produced with pulp from beech wood has to be instead produced with pulp from other sources as for example poplar short rotation coppice.
Wheat straw		
CHP	Wheat straw formerly used in a CHP is instead used in the biorefinery.	Heat and power formerly produced by a wheat straw-fired CHP have to be additionally supplied mainly from fossil fuels.
Birch tops and branches incl. bark		
CHP	Wheat straw formerly used in a CHP is instead used in the biorefinery.	Heat and power formerly produced by a CHP fired by birch branches incl. bark have to be additionally supplied mainly from fossil fuels.
Pellets	Birch branches incl. bark formerly used for the production of wood pellets used in domestic heating is instead used in the biorefinery.	Heat formerly produced by pellets from birch tops and branches incl. bark in domestic heating has to be instead supplied from natural gas.

4 Results on global and regional environmental impacts

A screening life cycle assessment (LCA) was carried out to assess the global and regional environmental impacts of the UNRAVEL system based on scenarios on potential implementations of the UNRAVEL biorefinery concept converting lignocellulosic biomass residues from forestry and agriculture into chemicals and building materials. For details on the methods and analysed systems see chapters 2 and 3. First, an overview of the environmental impacts of the basic scenario is given in section 4.1. Sections 4.2 to 4.4 analyse the potential environmental impacts of the main technological development carried out within the UNRAVEL project. Finally, optimisation needs for the future technology development of the UNRAVEL concept are described in section 4.5.

4.1 Overview of environmental impacts

The following section gives an overview on the environmental impacts of the UNRAVEL system using the basic scenario as an example (see description in section 3.2.1). Assessed environmental impact categories are described in section 2.2.3.

Figure 11 compares the life cycle greenhouse gas emissions of the basic scenario using beech wood as a biomass source with those of substituted conventional products.

Depending on the possible boundary conditions set in the respective sub-scenarios, there can be clear greenhouse gas emission savings as well as substantial additional emissions if a potential future UNRAVEL biorefinery would substitute conventional products. In the typical scenario, there is a slight advantage for the UNRAVEL biorefinery over the conventional system. This is however not conclusive, because boundary conditions can vary. Therefore, sub-scenarios using typical, optimistic and conservative settings for boundary conditions are calculated for each scenario. This range is based on a multitude of parameters such as efficiencies, which could turn out better or worse if the UNRAVEL concept was realised after further development on an industrial scale. It is unlikely that the ends of the resulting overall range of results are reached because most parameters are independent and it is unlikely that they all turn out to be the best or worst plausible way at the same time.

Having a look at the most relevant inputs, it can be seen that the greatest climate impacts are caused by the energy required for the core process and for C6/cellulose downstream processing as well as the material demand for the core process and lignin downstream processing (ethylene carbonate). Sulphuric acid and cellulase used in the core process are also important for other environmental impacts such as acidification, eutrophication or the phosphate footprint, as is the biomass used for the land use footprint. At the same time,

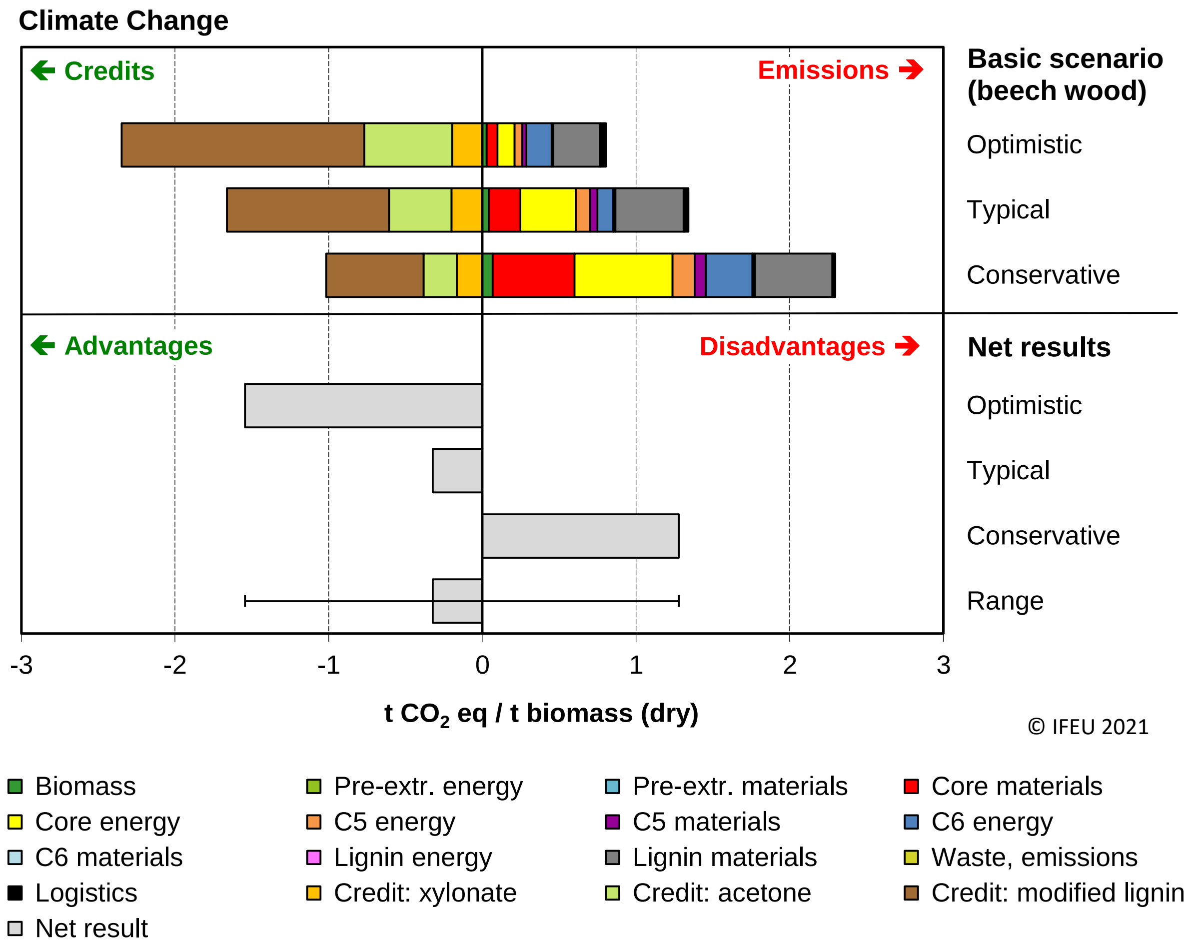


Figure 11: Comparison of life cycle greenhouse gas emissions of the basic scenario (beech wood) of the UNRAVEL biorefinery with those of substituted conventional products. Sub-scenarios under a range of possible boundary conditions primarily relating to technology development result in a range of possible results.

How to read Figure 11: The first bar shows the global warming potential (GWP100) of the basic scenario using beech wood under optimistic boundary conditions, most importantly postulating very successful further efficiency improvements. This scenario causes emissions of 0.8t CO_2 equivalents per tonne of dry biomass (positive values) and avoids 2.3t CO_2 equivalents per tonne of dry biomass (negative values).
The first grey bar presents the resulting net greenhouse gas emission savings of 1.5t CO_2 equivalents per tonne of dry biomass, which is calculated as the difference between the respective emissions and the credits for the optimistic sub-scenario. The bar at the bottom of the figure (named "Range") shows the net global warming potential of the basic scenario under typical boundary conditions (grey bar) as well as the range from alternative optimistic to conservative boundary conditions (error bars). This type of illustration is also used in following figures.

almost all of these hot spots show a large variability between sub-scenarios reflecting optimistic, typical and conservative versions of possible future technology development. Therefore, they represent key starting points for further technology development. Additional figures showing the contributions of different inputs to further environmental impact categories besides climate change for the basic scenario can be found in the annex (section 10.2). This initial picture of aspects to be developed further needs to be extended by results from other scenarios and further analyses to derive a complete hot spot and optimisation potential analysis (section 4.5) as a basis for recommendations to technology developers (section 6).

Figure 12 shows the results of all environmental impact categories assessed for the basic scenario using beech stem wood as biomass feedstock (for details of assessed impact categories see section 2.2.3). It can be seen that also in other assessed impact categories besides climate change there can be disadvantages and advantages of the UNRAVEL biorefinery compared to the substituted conventional products. Natural land use and phosphate rock use are exceptions, since for these impact categories there are always disadvantages for this scenario, even under optimistic boundary conditions (see Figure 41 and Figure 42 in the annex for contributions). Disadvantages in phosphate rock use mainly result from the

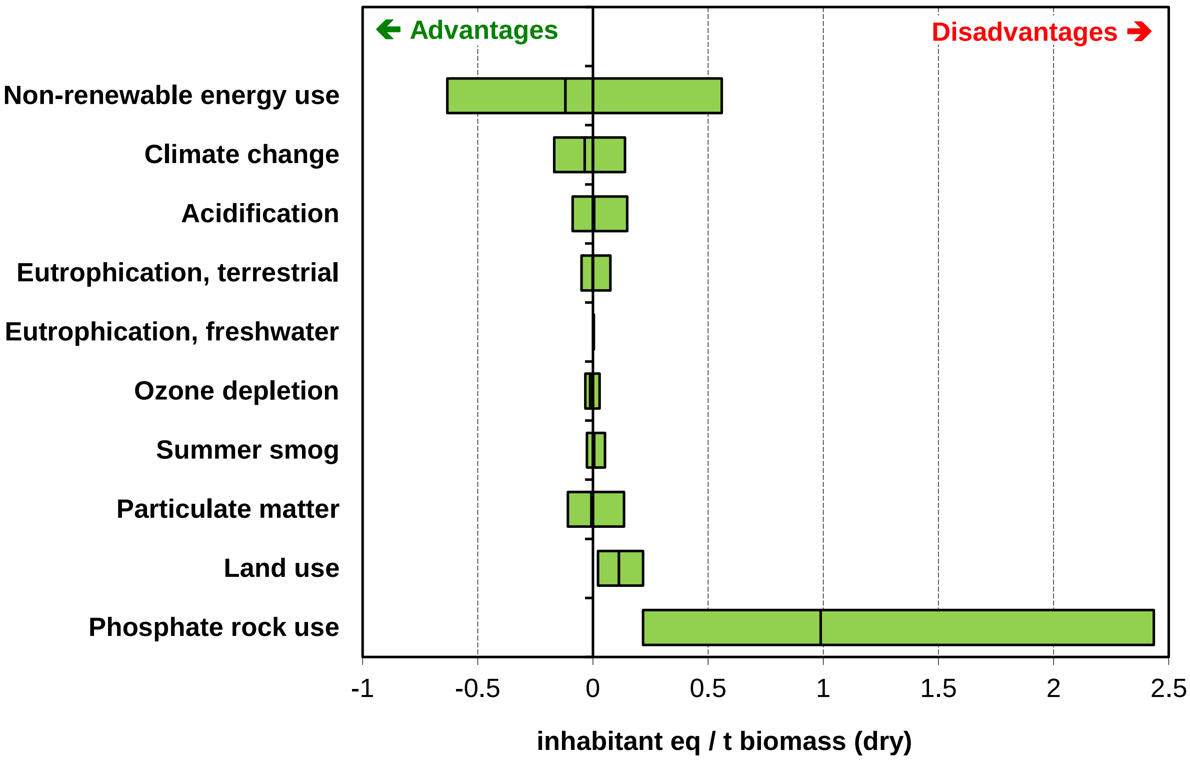


Figure 12: Normalised LCA results (given in inhabitant equivalents) of the basic scenario (beech wood) compared to its reference products for all analysed impact categories. The bars show the results under a range of possible boundary conditions from optimistic via typical to conservative primarily relating to technology development.

How to read Figure 12 (second bar on climate change): The basic scenario can result in a large range of greenhouse gas emissions. Under optimistic boundary conditions (the leftmost side of the bar) it saves as much greenhouse gas emissions per tonne of dry biomass as 0.14 inhabitants of the EU cause each year (inhabitant equivalents). Under typical boundary conditions it saves 0.04 inhabitant equivalents per tonne of dry biomass (vertical line inside the bar). Under conservative boundary conditions (the rightmost side of the bar), the scenario contributes as much to additional climate change per tonne of dry biomass as 0.17 inhabitants cause annually. This bar corresponds to the bar at the bottom of Figure 11 where the same emissions are given in absolute units (CO_2 equivalents).

provision of cellulase (produced externally in a fermentation process using conventional "1st generation" sugars as inputs). Cultivation of crops such as sugar beet and the fermentation process require substantial amounts of phosphate and are not always optimised for its reuse.

Taken together, this basic scenario of a potential future UNRAVEL biorefinery can only partially translate the potentials of the technology into environmental benefits. The following sections 4.2 to 4.4 analyse the improvements that have been achieved in the project and section 4.5 shows further potentials for optimisation such as finding more environmentally advantageous use options of the C5 and C6 fractions.

Key findings and conclusions:

- For the basic scenario, many possible boundary conditions result in a wide range of possible outcomes, ranging from clear disadvantages to clear advantages in almost all environmental impacts. Only in the case of natural land use and phosphate resource use there are always disadvantages, partially originating from purchased enzymes.
- Hot spots of environmental impacts can be identified for this basic scenario. These include energy and solvent demand for the fractionation process and ethylene carbonate demand for lignin modification. Together with results from other scenarios, hot spot analysis can guide further development from an environmental sustainability perspective.
- If all process parameters can be improved further (as depicted in the sub-scenario with optimistic technology development) and if enough beech wood is sustainably available (as assumed in this basic scenario), substantial environmental benefits can arise. If this cannot be ensured, then the biorefinery as depicted in this basic scenario as one of several scenarios is not recommended for implementation from an environmental perspective but instead has to be developed further as discussed in the following sections.

4.2 Progress in core process development

This section analyses which progress was made by developing an acetone-based organosolv fractionation technology termed Fabiola™ compared to the classical ethanol organosolv process. Furthermore, the remaining environmental burdens caused by the core process are assessed.

Figure 13 compares the life cycle greenhouse gas emissions of the basic scenario using the acetone organosolv process with the reference scenario using the conventional ethanol organosolv process.

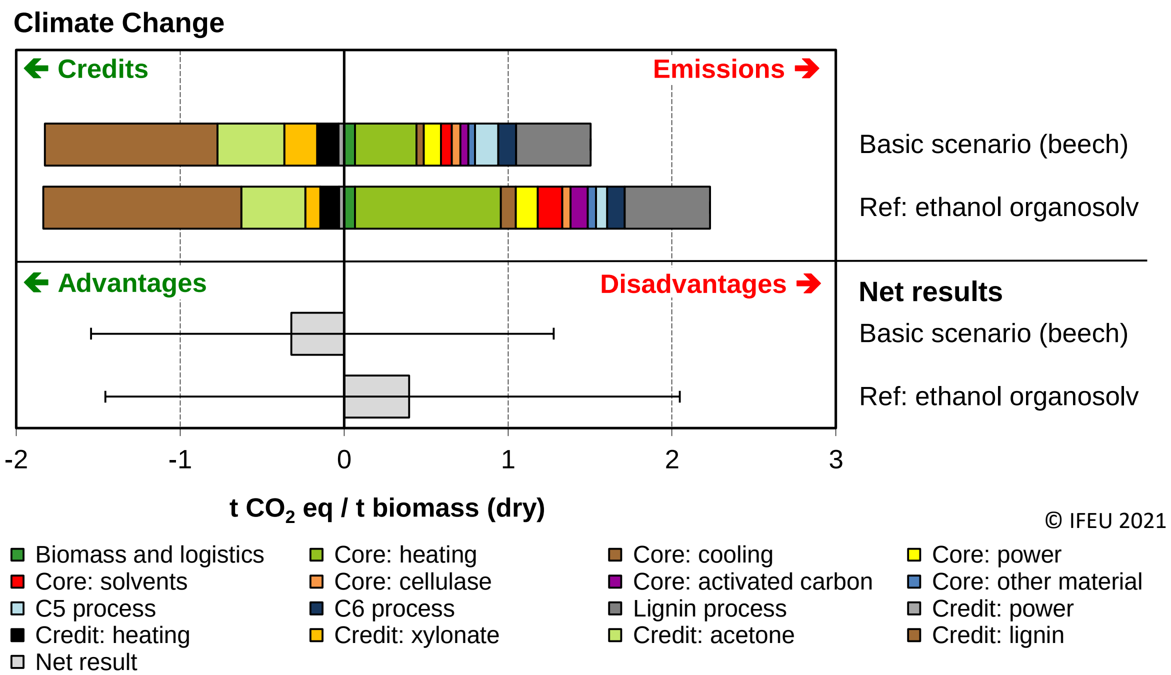


Figure 13: Comparison of life cycle greenhouse gas emissions of the basic scenario using the Fabiola process (acetone organosolv) with those of the reference scenario using the conventional ethanol organosolv process. Error bars indicate the range from optimistic to conservative.

Using the acetone organosolv technology in a potential UNRAVEL biorefinery would cause significantly less greenhouse gas emissions than using the conventional ethanol organosolv process (Figure 13). The carbon footprint of the conversion process is reduced by about 30% under typical conditions at similar credits for avoided emissions. This exceeds the project objective (to reduce the carbon footprint compared with the state-of-the-art bio-based operation by at least 15%) by a factor of two. Main reasons are the considerably lower energy demand (especially heat input for solvent recovery), but also the lower solvent demand of the process (because of avoided side reactions of ethanol with sugars). In total, using the acetone organosolv process would result in slight net advantages, while using the conventional ethanol organosolv process leads to net disadvantages regarding climate change in the basic scenario under typical conditions. Similar improvements can be seen for most environmental impact categories. Some conditions may however exist under which the ethanol organosolv process performs better than the acetone organosolv process because the result ranges are overlapping and several parameters contributing to these ranges are independent from each other for acetone and ethanol organosolv processes.

Despite comprehensive optimisations, the core process using the acetone organosolv process still is responsible for a large share of environmental burdens of the UNRAVEL biorefinery. Depending on the assessed impact category the core process is responsible for 1/3 – 2/3 of the environmental burdens (see figures of the other assessed impact categories in annex, section 10.2). Besides the high energy and solvent demand, also the cellulase and activated carbon used in the core process contribute to a large share of the overall environmental burdens.

Since the utilisation of energy plays an important role for the environmental impact of a UNRAVEL biorefinery, different options for energy provision are analysed in the following.

As a first aspect, the source of electricity could make a difference. Additional renewable electricity from wind or solar power could be used instead of a grid mix containing a share of renewables. This could lead to a slight reduction of greenhouse gas emissions of the UNRAVEL biorefinery (Figure 14). It has to be considered, however, that the share of renewables is expected to rise for the substituted conventional products, too, so that also the credits would decrease over time. Consequently, using additional renewable electricity would certainly decrease the global warming potential of the UNRAVEL biorefinery in comparison to the reference system, but only to some extent.

As a second aspect, heat demand can partially be covered by energy recovery from internal biorefinery residues while the rest is set to be provided from natural gas. Residues from the biorefinery can be used either for heat generation only or for combined generation of electricity and (less) heat (Figure 14). Depending on the environmental impact and the source of the additional energy required there may be advantages for one or the other. The tendency is: The more renewable electricity is used, the more likely there are advantages for a pure heating plant leading to lower natural gas consumption.

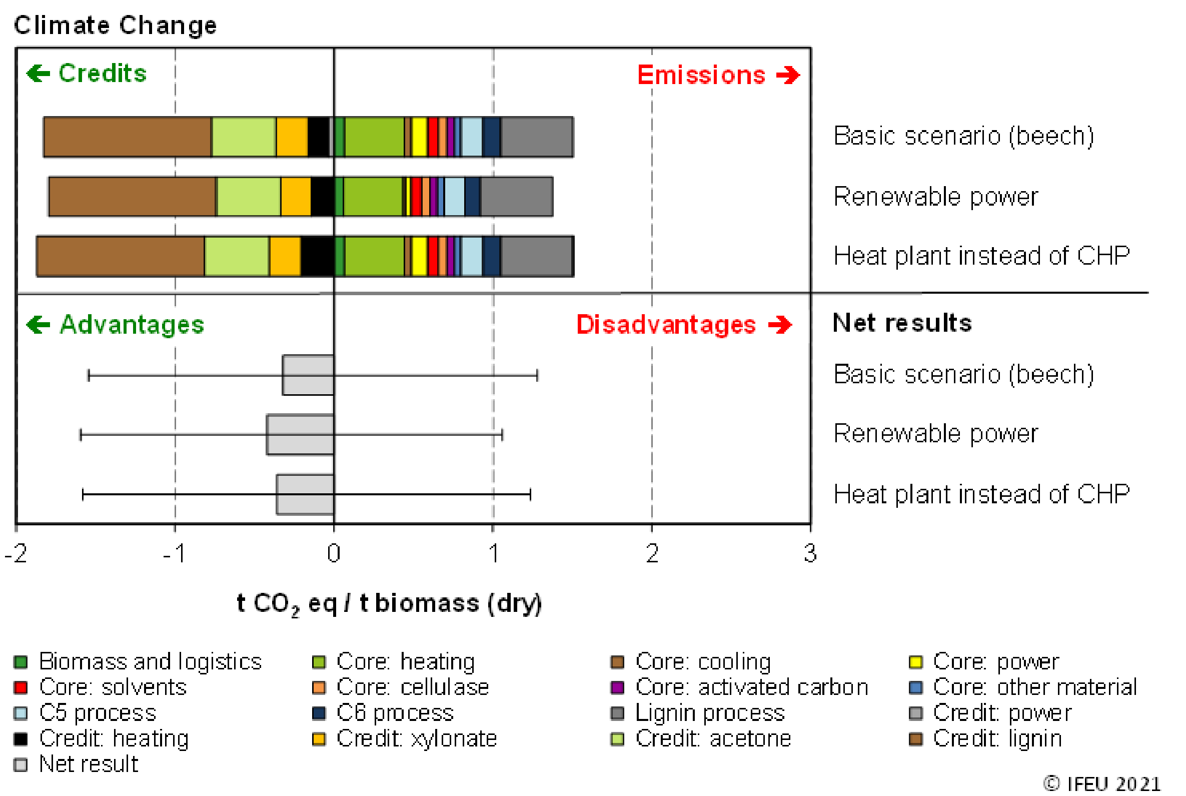


Figure 14: Comparison of life cycle greenhouse gas emissions of the basic scenario (using fossil and renewable power[1]) and using a heat plant instead of a combined heat and power plant (CHP). Error bars indicate the range from optimistic to conservative.

Generally, energy supply for the biorefinery needs to be decarbonised as far as possible. Processes driven by heat as energy source should be substituted as far as possible by other processes using electricity: The availability of wind and solar power will be much higher in the future than that of renewable energy carriers for medium and high temperature heat provision such as biomass. Examples of such substitution could be resistive electric heating, but potentially more interesting is using heat pumps and specifically mechanical vapour recompression in the distillation columns present in the process instead of heating. That way, more effective use can be made of the renewable electricity and additional demand could be kept to a minimum.

[1] The basic scenario is based on a mix that is plausible for the EU in 2030 with an emission factor of about 250 g CO_2 eq. per kWh.

Key findings and conclusions:

- Much has been achieved through the development of the core process based on acetone organosolv technology in the UNRAVEL project. The acetone organosolv technology causes significantly lower environmental impacts than the commonly used ethanol organosolv process, mainly because of its lower energy and solvent demand, and should therefore be preferentially used in future plant concepts.
- The core process using the acetone organosolv technology still causes the largest share of the total environmental burdens (1/3 – 2/3 for most environmental impact categories).
- The main drivers are the high demand for energy, solvents, cellulase and activated carbon. As a priority, their demand should be reduced and their supply optimised.
- Using renewable electricity, preferably from wind and solar power, and energy recovery from available processing residues can only achieve a certain reduction of environmental impacts.
- For reducing and supplying the remaining heating and cooling demand, an integrated concept mainly based on renewable electricity, possibly using (mechanical vapour recompression) heat pumps, must be developed in the future.

4.3 Progress in lignin use

Two different valorisation routes for lignin were studied in the UNRAVEL project, which target different material use options by chemical modification. This is compared to energy recovery from lignin as a fall-back option.

Figure 15 compares the life cycle greenhouse gas emissions of the basic scenario producing a) lignin modified by ethylene carbonate used as a polyol in polyurethane applications, b) a variant producing lignin modified by trimethyl phosphate (TMP) used as filler in polymers and c) a scenario, in which the lignin fraction is used for energy recovery through combustion.

The modification of lignin with ethylene carbonate for the use as a polyol in PUR/PIR shows the least environmental impact compared to the two other analysed scenarios. Looking at the greenhouse gas emissions, the production of ethylene carbonate modified lignin is the only analysed scenario with net advantages under typical boundary conditions. Also in the other assessed environmental impact categories, EC-modified lignin performs better than the combustion of lignin. One exception is land use, where lignin combustion can have slight advantages depending on the substituted energy mix. The more the share of renewable energy in replaced alternative energy sources grows in the future the more advantageous the material use of lignin, in particular the use as polyol in PUR/PIR analysed here, will become.

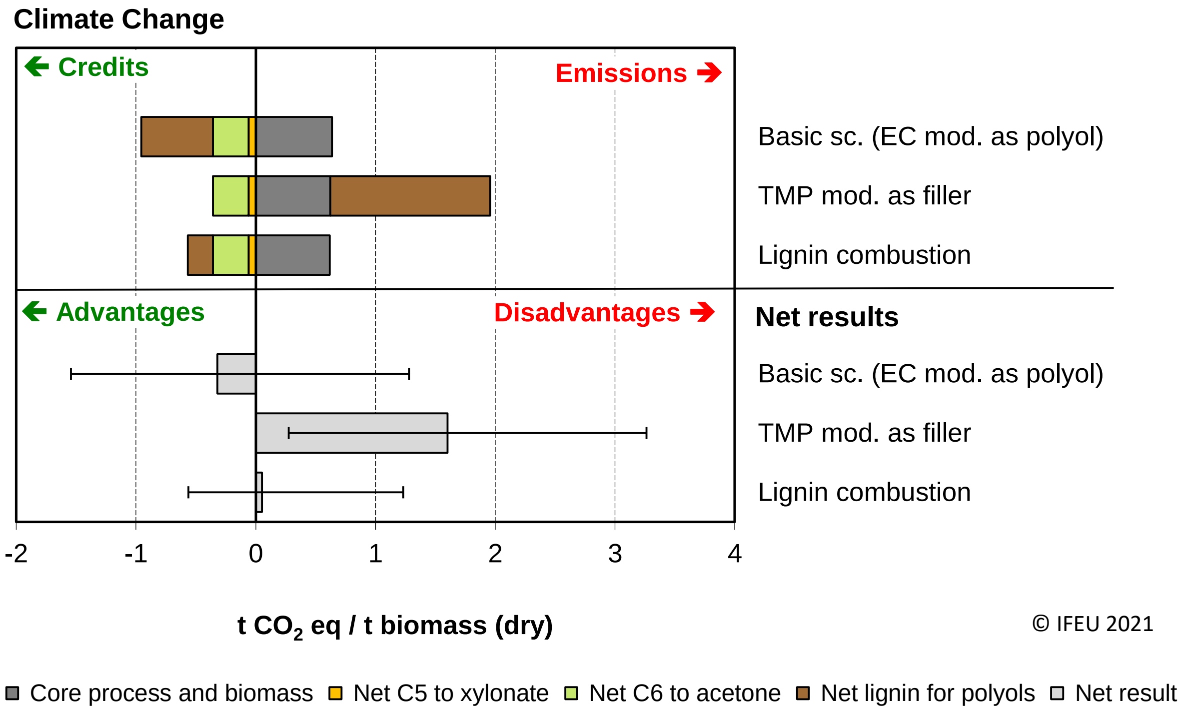


Figure 15: Comparison of life cycle greenhouse gas emissions of three scenarios with different uses of lignin: a) basic scenario producing ethylene carbonate (EC)-modified lignin, b) scenario producing trimethyl phosphate (TMP)-modified lignin and c) combustion in a combined heat and power plant. Error bars indicate the range from optimistic to conservative. Net emissions of the fractions include credits for substituted conventional products.

Thus, the production of ethylene carbonate modified lignin displays an environmentally promising use of lignin and can be seen as a successfully developed product in the UNRAVEL project. Therefore, this new lignin use option should be upscaled with priority and implemented in compatible lignocellulose biorefineries.

Moreover, producing trimethyl phosphate-modified lignin as a filler in polymer applications leads to significantly higher greenhouse gas emissions compared to the production of ethylene carbonate modified lignin. This results from higher process- and input-related burdens as well as from lower avoided emissions by substitution of glass bubbles as conventional light weight fillers. It is even considerably worse regarding climate change than the combustion of lignin which currently is the most basic use option. Even under optimistic boundary conditions, the production of trimethyl phosphate-modified lignin is disadvantageous regarding climate change when compared to substituted conventional products. This ranking by environmental performance in the order 1: ethylene carbonate modified lignin, 2: lignin combustion and 3: trimethyl phosphate-modified lignin can be confirmed for all other assessed impact categories.

Key findings and conclusions:

- The modification of lignin with ethylene carbonate for use as a polyol in PUR/PIR is associated with clear environmental advantages compared to the combustion of lignin for energy recovery as the most basic use option. This new lignin use option successfully developed in this project should be upscaled with priority and implemented in compatible lignocellulose biorefineries if the performance depicted in the analysed scenarios can be reached in practise.
- From an environmental point of view, the production of TMP-modified lignin as filler is disadvantageous compared to all other options examined, based on the available data. Here, the investigated preliminary conversion and utilisation concept would still have to be significantly revised. In particular, replacement of conventional products should aim at energy- and material-intensive ones.

4.4 Competition for feedstocks and progress in its mitigation by pre-extraction

The UNRAVEL biorefinery process is able to handle a multitude of different feedstock sources. The biomass feedstocks beech stem wood (pulp wood quality), birch tops and branches including bark (forest residue), wheat straw (agricultural residue) and roadside grass were analysed in this LCA study.

4.4.1 Environmental effects of feedstocks other than beech wood

For all of the four analysed feedstock types, in terms of climate change there can be clear disadvantages as well as clear advantages of the UNRAVEL biorefinery compared to the substituted conventional products (see Figure 16, bars without competition). Under typical boundary conditions of the assessed basic scenario, beech stem wood use can achieve slight climate change mitigation, birch branches use does not substantially affect the climate and wheat straw as well as roadside grass use results in additional climate change. This mainly results from different processing efficiencies leading to different ratios of energy and material inputs to the core process per amount of product generated as well as from fertiliser needed to compensate for extracted straw (see also Figure 34 and following in the annex).

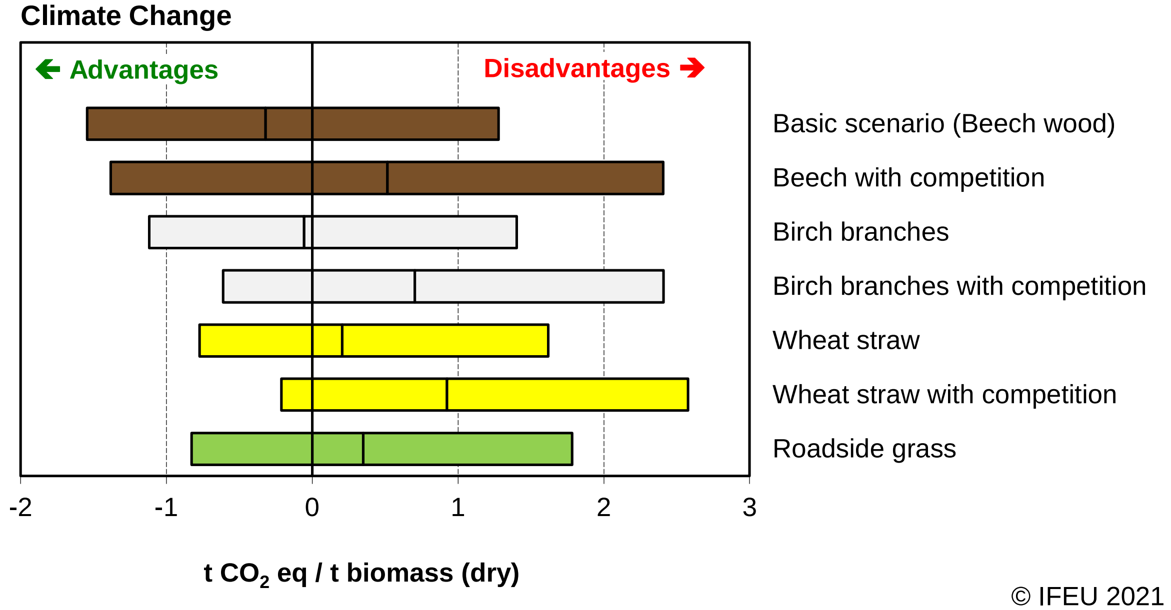


Figure 16: Comparison of life cycle greenhouse gas emissions of various scenarios of the UNRAVEL biorefinery using different feedstocks (with and without competing uses, all without pre-extraction). Bars display ranges from optimistic via typical to conservative boundary conditions m relating to technology development. Indirect effects of competition include forgone emission savings by withdrawal of biomass from CHPs (see section 3.3 for details).

How to read Figure 16 (second bar): If competition about beech pulp or energy wood leads to a shortage on the market, other advantageous beech wood uses cannot be supplied anymore and the range of greenhouse gas emissions shifts towards disadvantages (compared to first bar without competition). It now ranges from savings of 1.4t CO_2 equivalents per tonne of dry biomass under optimistic boundary conditions to additional emissions of 2.4t CO_2 eq/t dry biomass under conservative boundary conditions. The vertical line inside the bar for the beech with competition scenario gives the value for the sub-scenario under typical boundary conditions (additional emissions of 0.5t CO_2 eq/t dry biomass).

Looking at environmental burdens typically caused by agriculture such as terrestrial eutrophication (Figure 17), a clear difference can be seen for the agricultural residue straw: The use of this feedstock leads to additional environmental burdens under all assessed conditions mainly resulting from fertiliser use. Besides this, the ranking of feedstocks is identical resulting mostly from different processing efficiencies, i.e. more or less products produced per similar amounts of inputs. This also can be observed in other agriculture-associated environmental impact categories as for example acidification.

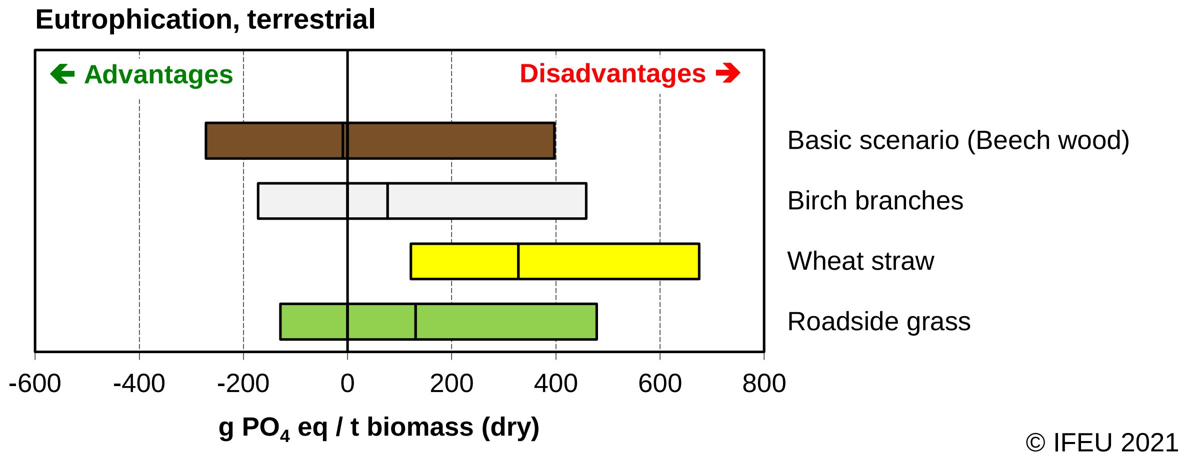


Figure 17: Comparison of terrestrial eutrophication of various scenarios of the UNRAVEL biorefinery using different feedstocks.

With the exception of roadside grass, all analysed feedstock types are already used to a greater or lesser extent depending on the region in the EU and year-to-year variation. So generally biomass of all analysed types is available on the market for UNRAVEL biorefineries but competition about feedstocks is plausible. Competition is expected to be strongest for beech wood and birch branches, followed by straw with strong local variations. Only roadside grass is currently hardly used at all (see biomass potential assessment in [Keller et al. 2022]). Therefore, scenarios were used to analyse the potential effects of the UNRAVEL biorefinery withdrawing beech wood, birch branches and straw from other uses (see detailed information in section 3.3).

4.4.2 Effects of competition about feedstocks

The competition for feedstocks may generate additional environmental burden (see Figure 16). From a climate change perspective, the analysed feedstock competitions lead to more greenhouse gas emissions in all analysed sub-scenarios (optimistic, typical, and conservative) because savings by other competing feedstock uses are not possible anymore. The extent of foregone savings depends on the outcompeted use. The analysed scenarios include wood pellets for residential heating and biomass-fired combined heat and power (CHP) plants. The ranking from beech stem wood over birch branches with bark to wheat straw remains the same. Additional greenhouse gas emissions arise from each scenario under typical conditions showing that the UNRAVEL biorefinery is less advantageous than the replaced competing feedstock use. Under optimistic boundary conditions, however, a biorefinery based on the UNRAVEL concept can still achieve advantages over all alternative uses considered.

These results show that under current boundary conditions and from an environmental point of view, the use of biomass feedstock in a potential UNRAVEL biorefinery is less favourable than using the feedstock for energy generation in a CHP unless the biorefinery is highly optimised (see section 4.5 for optimisation options). As long as biomass CHPs are needed to replace fossil fuels, the UNRAVEL biorefinery concept therefore needs to be developed further to become environmentally more competitive.

Key findings and conclusions:

- Similar environmental benefits as discussed for beech wood can be achieved with all other analysed feedstocks, too, provided that they are sustainably available in sufficient amounts. However, significantly higher process efficiencies must be achieved for grassy feedstocks in particular. Only wheat straw causes disadvantages even under optimistic boundary conditions regarding typical agriculture-associated environmental impacts such as eutrophication and acidification because its removal results in an increased need for fertiliser.
- Competition can turn advantages into disadvantages if feedstock is taken away from other beneficial uses. This indirect effect prevents emission savings elsewhere. The severity depends on the outcompeted feedstock use and its boundary conditions.
- If there is no competition for biomass, the GHG saving potentials are highest for beech wood, followed by birch branches, straw and roadside grass. However, competition for these feedstocks, and thus the risk to prevent environmental benefits elsewhere, also tends to decrease in the same order (beech wood > birch branches > straw > roadside grass). To resolve this conflict, a balanced and flexible feedstock concept needs to be found that is adapted to the availability of truly unused feedstocks at the respective location and respective time in order to maximise the overall environmental benefits and minimise the burdens.
- As long as biomass CHPs are still needed to replace fossil energy provision, any other use of combustible biomass to be implemented on a large scale needs to achieve very high emission reductions to be environmentally more competitive. The UNRAVEL biorefinery concept as depicted in the analysed scenarios does not yet fully exploit its potentials to achieve this and should be developed further as discussed in this report.

4.4.3 Effects of feedstock flexibility due to pre-extraction

The UNRAVEL biorefinery concept also developed a pre-extraction process before the core process to enhance the purity, quality and usability of gained intermediate products (for details see section 3.2.7). Not all of these factors can be fully accounted for in an LCA as discussed below. This section shows those environmental impacts due to the introduction of this process that can be quantified based on available mass and energy balances.

Figure 18 compares the life cycle greenhouse gas emissions of a potential UNRAVEL biorefinery without and including a pre-extraction process. Because this is not needed for beech wood, the scenarios analysed in this figure are based on the feedstock wheat straw.

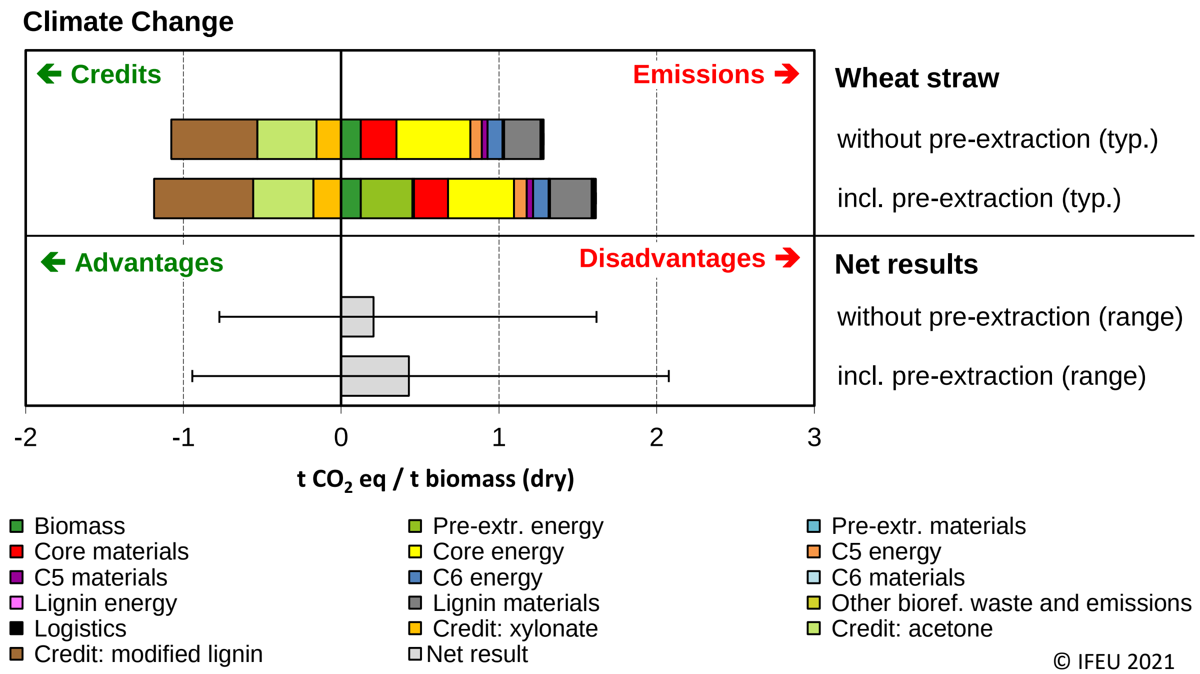


Figure 18: Comparison of life cycle greenhouse gas emissions of the UNRAVEL biorefinery using wheat straw as biomass feedstock without and including a pre-extraction process preceding the core process. Error bars indicate the range from optimistic to conservative.

Using a pre-extraction process leads to additional environmental burdens mainly because of additional processing steps and their energy demand. This can be compensated if higher yields are achieved as included in sub-scenarios under optimistic conditions (see the leftmost ends of the error bars in Figure 18). Thus, the analysed scenarios on pre-extraction process can be advantageous or disadvantageous from an environmental perspective, depending on the boundary conditions. This process has so far been optimised for extraction efficiency. In further process development, the amounts of water and solvent for extraction and connected energy demand should be reduced as far as possible for specific biomass streams and required product quality. Also, using dedicated pre-extraction equipment aimed at low solvent to biomass ratio could provide further improvements. Furthermore, integration of process streams (using effluents from other parts of the biorefinery for pre-extraction) to lower the water use and waste water amount could be possible.

In Figure 19 all analysed feedstock types are compared without and including a pre-extraction process. It shows that also for birch branches and bark, similar to wheat straw, the use of a pre-extraction process can lead to even more advantageous as well as more disadvantageous environmental impacts.

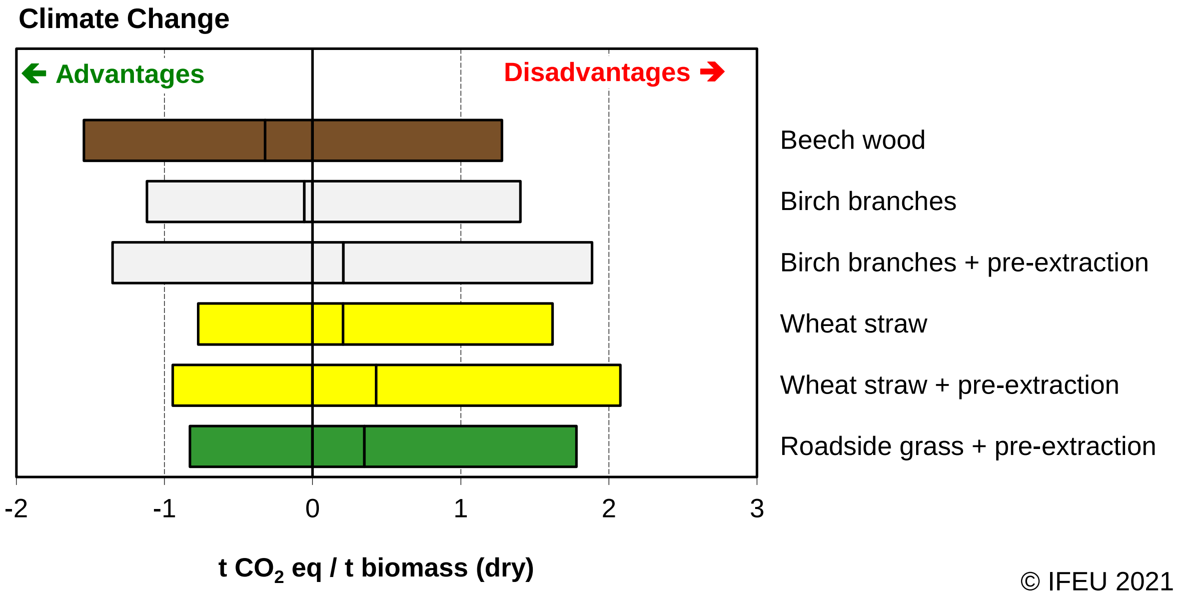


Figure 19: Comparison of life cycle greenhouse gas emissions of various scenarios of the UNRAVEL biorefinery using different feedstocks without/including a pre-extraction process.

In general, pre-extraction of biomass feedstock can have the following effects, which could partially be covered by our quantitative analysis and partially not:

– Additional energy demand (certain, covered in Figure 19).
– Possibly higher quality and purity of generated intermediate streams (C5, C6 and lignin stream) leading to products that can replace conventional products with higher environmental impacts. This would improve results but is out of scope of this analysis and adds valuable perspectives beyond this study.
– Option to make additional, so far underutilised biomass feedstocks usable. This can increase feedstock flexibility and therefore help to avoid competition for biomass feedstocks. This could avoid negative effects shown in Figure 16 e.g. in case of feedstock shortages.
– Potentially slightly higher yields of intermediates and products, which are covered in the optimistic sub-scenarios in Figure 19 (left end of bars).
– Potentially reduced corrosion of equipment. Extended lifetime will reduce environmental impacts to a certain extent but this is not expected to compensate for substantial parts of the additional energy demand.
– For some feedstocks, the extract contains valuable components that could be separated and valorised instead of sending the extract to wastewater treatment as in the analysed scenarios. If dedicated production or extraction of these components elsewhere is replaced, this could generate additional environmental credits.
– Potential to recycle nutrients via spreading extracts on fields (not covered here).

Taken together, pre-extraction so far only pays off under certain boundary conditions but opens up valuable opportunities for benefits to be explored in further process development.

Key findings and conclusions:

- Pre-extraction can broaden the feedstock spectrum and help to avoid competition by making underutilised residues such as roadside grass usable. If this avoids environmental disadvantages caused by competition or if more conventional products can be substituted, additional expenditures for pre-extraction could be overcompensated.
- By improving the quality of the C5/hemicellulose and C6/cellulose fractions, pre-extraction could also enable further utilisation options of these fractions and ultimately reduce the overall impact through higher credits.
- Under certain conditions, pre-extraction of birch branches and straw could lead to slight environmental benefits even without improving the usability of feedstocks and/or intermediates. This however depends on counteracting effects of energy demand and yields and could only be reached under analysed optimistic boundary conditions. Therefore, pre-extraction should primarily aim at enabling environmentally beneficial uses of feedstocks and/or intermediates.

4.4.4 Effects of feedstock flexibility by mixed feedstock processing

One particular biomass source that can be processed by employing pre-extraction as developed in UNRAVEL is mixed lignocellulosic residues. No significant difference between fractionation efficiencies for physically mixed feedstocks and processing of the same biomass components in alternating campaigns could be found in experiments (see Table 10 and Figure 12 in [Smit et al. 2021]). Therefore, the models for the sustainability assessment scenarios have identical mass and energy balances for the biorefinery. Differences that could arise are therefore discussed mainly qualitatively:

The main advantage of mixed feedstock processing could be the ability to use a wide variety of **additional biomass residues as feedstock** that are available only in small amounts, which are not sufficient for dedicated biorefinery campaigns, and biomass residues that are intrinsically heterogeneous such as cuttings from landscaping or gardening. Mixed organic waste from food processing or even households could be considered although this has not been confirmed technically and will probably not be a main source for first biorefineries to be implemented. This could make a biorefinery according to the UNRAVEL concept extremely flexible in its feedstock choice and could thus help to avoid potential negative environmental effects from feedstock competition as discussed in section 4.4.2.

Logistics can be simplified and optimised if different feedstocks could be mixed and transported together. Potentials for biomass that could otherwise be processed in dedicated biorefinery campaigns however seem limited because the required amounts are so high that separate transportation should not be limiting. Biomass storage could be in tendency reduced if mixed campaigns are scheduled instead of dedicated campaigns because waiting times for the fitting campaign are eliminated. This could reduce environmental impacts if deterioration (rotting) of feedstock could be avoided or even partial drying at high environmental burdens that may be necessary to stop rotting. On the contrary, blending biomass types to achieve certain advantageous properties of the mix may also increase storage demand.

Pre-extraction and fractionation may require more water, solvent and energy for mixed feedstocks because a common rather intense protocol may have to be followed that can treat all kinds of biomass (as modelled for the analysed scenarios) instead of making full use of optimisation potentials discussed in section 4.4.3. This could otherwise be optimised to the minimum that is required for each separate feedstock. Although it is unclear how high these optimisation potentials are on industrial scale, this could be the major drawback of mixed feedstock processing from an environmental point of view. On the contrary, biomass blends with certain advantageous properties such as particle size distributions or composition may reduce material and/or energy demands in particular in the fractionation process. Therefore, mixing after pre-extraction but before fractionation may be an advantageous option.

The **usability and quality of lignocellulose fractions** may be affected positively, negatively or not at all. This will have to be determined in further process development and upscaling.

Taken together, the option to use mixed biomass feedstocks allows greater flexibility that could increase environmental benefits although this cannot be modelled yet. If it should turn out to be disadvantageous on industrial scale, this can simply be avoided by operating the biorefinery in dedicated campaign mode.

Key findings and conclusions:

- Mixed feedstock processing is technically possible and can lead to environmental benefits under certain conditions. The performance of the process itself is not expected to change much based on available experience but the additional flexibility that mixed processing brings about can be valuable.
- A potential drawback could be that pre-extraction and fractionation of mixed feedstock may have to use more intense protocols and thus have less potential for further reductions in energy demand.
- The benefits include the possibility to use lower quality unsorted feedstocks, to use feedstocks available in small amounts at a time not sufficient for switching the plant to a dedicated campaign, to streamline logistics and to some extent avoiding competitive use of biomass. Concrete environmental benefits depend on local feedstock markets at a given time and cannot be quantified in this study. In particular increased resilience against unforeseen feedstock shortages could nevertheless have substantial positive effects.

4.5 Optimisation needs for future technology development

The UNRAVEL project successfully addressed several important issues along the value chain of the studied lignocellulose biorefinery concept (sections 4.2-4.4). Nevertheless, environmental impacts of scenario including these achievements can reach from advantages to disadvantages but typically hardly reach advantages over their conventional counterparts (see section 4.1 for scenarios on beech wood and section 4.4 for all other feedstocks). Moreover, it depends on many boundary conditions whether and where the biomass feedstock used for potential UNRAVEL biorefineries could be sustainably available in the future without competition with other types of use (see also [Keller et al. 2022] for a biomass potentials analysis). If UNRAVEL biorefineries would withdraw biomass from other beneficial uses such as energy provision, this could lead to net environmental disadvantages under many boundary conditions (section 4.4). This means that other environmentally friendly uses of biomass with limited availability are preferable to an industrial scale biorefinery based on the unmodified UNRAVEL concept despite all achievements. This could be changed by an optimisation of selected aspects of the concept before implementation.

To achieve net environmental advantages the use of the lignocellulose fractions must generate environmental benefits that are substantially higher than the environmental burdens of the core/fractionation process. This still needs to be optimised. The greatest greenhouse gas emission savings arise from the use of the modified lignin fraction as polyol (Figure 20).

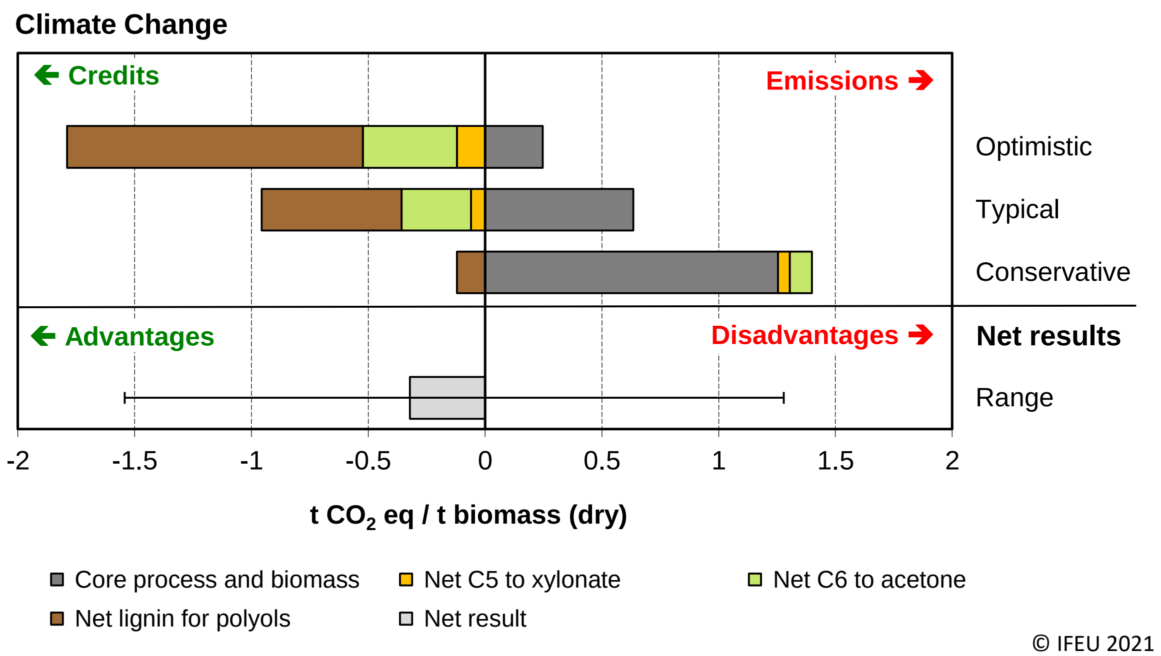


Figure 20: Contributions of the use of C5, C6 and lignin fractions to compensating greenhouse gas emissions of the core process in the basic scenario (beech wood. Net emissions of the fractions include credits for substituted conventional products. Sub-scenarios under a range of possible boundary conditions primarily relating to technology development result in a range of possible results (indicated by error bars).

Depending on the boundary conditions, the lignin fraction accounts for 2/3 to 100 % of the greenhouse gas emission savings of a potential UNRAVEL biorefinery. In comparison to lignin, the use of acetone from the C6/cellulose fraction contributes to a much lesser extent to the compensation of the core process expenses. The use xylonate from the C5/hemicellulose stream shows almost negligible advantages. Under conservative boundary conditions, both the use of C5 and the C6 fraction even cause additional greenhouse gas emissions. Similar findings can be made for other environmental impacts.

Consequently, overall benefits would only be reached under very high energy and material efficiencies, which may not be possible to reach. Thus, alternative uses of C5/hemicellulose and C6/cellulose should be found that are significantly more environmentally beneficial. Nevertheless, converting parts of the C6 stream to produce internally used acetone could be beneficial to get independent of fossil resource-based inputs in the long run. Since fermentability of the C5 and C6 fractions is generally good, many other products seem attainable. Therefore, by choosing another product portfolio, the acetone organosolv biorefinery concept could be made much more future proof than if only incremental efficiency improvements were pursued.

The environmental assessment shows that the core process (sections 4.2), the conversion of lignin for use as polyol (section 4.3) and the pre-extraction (section 4.4) already reach a good environmental performance. Nevertheless, these can and should be incrementally optimised to increase environmental benefits. The optimisation in further process development should focus on the following hot spots that were determined by combining insights from all analysed scenarios including all feedstocks:

- Pre-extraction should primarily be optimised for the lowest energy use that is still sufficient to make each specific feedstock usable for the respective targeted use of the biomass fractions (Figure 18 in section 4.4).
- Most aspects of the core process should be optimised as far as possible because of their large contributions to impacts: reduction of energy, solvent, cellulase and activated carbon demand and increase of yields (Figure 11 and Figure 13 in sections 4.1 and 4.2).
- The emissions of acetone to the air should be kept to a minimum to limit contributions to summer smog/ozone formation (Figure 39 in the annex). Modelling data is currently based on a fully enclosed process and shows little acetone emissions. In practice, acetone added in the pre-extraction and the core process may evaporate from different intermediates and products inside and outside the biorefinery.
- Ethylene carbonate use efficiency for lignin modification should be optimised (see section 4.1).
- Phosphate and nitrogen inputs to all fermentation processes including the external process to produce purchased cellulase should be reduced as far as possible and nutrients remaining in residual fractions such as used fermentation media should be reused by applying these as fertilisers to fields.

- If C5 and or C6 are to be used via fermentative processes, energy demand in particular for product recovery should be optimised (Figure 11 in section 4.1) and inputs of nitrogen and phosphorous should be reduced as far as possible to reduce the impacts on phosphorous resources and the emissions to soil and water by using stillage as fertiliser (Figure 35 and Figure 36 in the annex).

By considering and implementing the aforementioned optimisation steps, an environmentally sustainable biorefinery with significant environmental advantages over current alternative uses of biomass feedstocks is expected to be achievable.

Key findings and conclusions:

- The use of the lignocellulose fractions must clearly overcompensate the environmental burdens of the core/fractionation process. This is not the case and thus it is highly uncertain if the whole biorefinery scenarios as analysed in this study could achieve overall environmental benefits. This would require reaching very high energy and material efficiencies and biomass availability without substantial competition which both cannot be ensured.
- The greatest environmental benefits arise from the use of lignin.
- The use of C5/hemicellulose hardly contributes to compensating the expenses of the core process, and the use of the C6/cellulose fraction does not make full use of the potential either. Therefore, searching for alternatives is promising and necessary. Experience from studied applications nevertheless suggests that fermentability of the fractions is generally good and that many other products seem attainable. That way, the studied acetone organosolv biorefinery concept could be made much more future proof than if only incremental efficiency improvements were pursued.
- Pre-extraction, core process and lignin use for polyols already reached a good overall environmental performance and should be further improved by incremental optimisations. Process development should focus on the energy demand for pre-extraction, the energy and material demand in the core process, a maximised use efficiency of ethylene carbonate for lignin modification and reduced acetone emissions to air.
- These mixed overall results on global and regional environmental impacts are due to the approach followed in the UNRAVEL concept. It focussed on improving certain aspects of the biorefinery such as pre-extraction, core process and lignin use and on exploring further previously less studied use options for C5 and C6. Although this concept cannot be implemented as is, it was very successful from an environmental standpoint if beneficial elements are added to the “tool box” for designing environmentally beneficial lignocellulose biorefineries adapted to local biomass availability and market demands in a next step.

5 Results on local environmental impacts

Local environmental impacts associated with the UNRAVEL systems (section 5.1) and conventional systems providing equivalent products (section 5.2) were studied following the life cycle environmental impact assessment (LC-EIA) methodology (see section 2.3.1). They are compared in section 5.3.

5.1 Lignocellulose-based systems

Following the descriptions of the systems in chapter 3 the UNRAVEL systems are divided into several life cycle stages. For the purpose of the LC-EIA, the following stages are evaluated:

– Biomass feedstock provision (see sections 5.1.1 to 5.1.4)
– Biomass feedstock conversion (see section 5.1.6)

Biomass provision takes place in one location and biomass conversion is partly, spatially separated. Thus, intermediate transport and logistics steps are required (see section 5.1.5).

The following scenarios focus on the provision of feedstock from forestry (beech stem wood and birch tops and branches incl. bark), wheat straw as an agricultural residue and roadside grass:

– The scenario for beech stem wood in pulp wood quality is based on extracting additional thinning material leading to overall shortened rotation cycles compared to traditional forestry
– For birch tops and branches incl. bark the investigated scenario for a potential biorefinery is based on the use of these residues with the reference system of leaving 100% of the residues on site.
– For wheat straw the investigated scenario for a potential biorefinery is based on a sustainable use of approx. 1/3 of wheat straw (i.e. once every three years) compared to the reference system of leaving the straw on the field, i.e. ploughing in the residues for soil organic carbon (SOC) maintenance.
– For roadside grass the investigated scenario for a potential biorefinery is based on the use of this unused biomass feedstock with the reference system of leaving 100% of the residues on site.

5.1.1 Provision of beech wood

Forest and wood is interrelated with the history of mankind since wood ever since was used as feedstock, building and raw material as well as energy source. Furthermore forests usually act as a carbon sink and as a reservoir for biodiversity with a huge potential for sustainable development.

A fundamental risk of using stem wood as a feedstock for biorefineries might result from reduced rotation cycles thus leading to a negative soil nutrient balance (export > import).

Harvesting woody biomass based on reduced rotation cycles means a non-sustainable loss of carbon which can result in depletion of the topsoil, which in general acts as storage for nutrients, water and substrate for the roots. Especially the organic material is essential for soil fertility and thus the structure and life in the topsoil. Good yield with plantations are to be achieved on rich soils as the topsoil is able to act as a nutrient buffer to a certain extent. Use of fertiliser might gain importance with an intensification of harvesting as a consequence of growing demand. The potential danger of spreading neophytes like Himalayan balsam (*Impatiens glandulifera*) or Japanese knotweed (*Reynoutria japonica*) by circulating operating vehicles might influence biodiversity negatively on the long term [Winter et al. 2009]. Table 6 summarises the risks associated with the provision of hardwood stems (reduced rotation cycles) on the environmental factors.

Table 6: Risks associated with the provision of additional hardwood stems (thinning material) leading to overall shortened rotation cycles compared to traditional forestry.

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	neutral		neutral						
Soil compaction	**neutral / negative**[1]	neutral		neutral	neutral				neutral
Loss of soil organic matter	**neutral / negative**[1]			**neutral / negative**[1]	**neutral / negative**[1]				**neutral / negative**[1]
Soil chemistry / fertiliser	**neutral / negative**[1]	neutral	neutral		neutral				neutral
Nutrient leaching	neutral	neutral							
Eutrophi-cation	neutral	neutral	neutral	neutral[1]	neutral				neutral
Water demand		neutral	neutral	neutral					neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				**neutral / negative**[2]	**neutral / negative**[2]				**neutral / negative**[2]
Loss of species				**neutral / negative**[2]	**neutral / negative**[2]				**neutral / negative**[2]

1: Negative in case of reduced rotation cycles

2: Negative due to spreading of neophytes

Since most of the forests in Central Europe are under management and no longer natural, the reference system for the potential use of hardwood stems is traditional forestry where hardwood forests are growing for a long time before the trees are harvested. Carbon is accumulated in the biomass of the trees. Since trees grow older and the ratio of woody debris is increasing, habitats for species linked with it are provided. Examples for species under special protection due to European regulations (habitat directive, birds directive) are for instance the Black woodpecker (*Dryocopus martius*), the Hermit beetle (*Osmoderma barnabita*) or bats, which are dependent on old trees. With shortened rotation cycles, these structures might decline and negative effects on species within their natural habitats will increase thus causing not only impacts on individuals but on population level. Thus, there is a risk for biodiversity loss.

5.1.2 Provision of forestry residues such as birch tops and branches incl. bark

Forest productivity depends on soil quality and the availability of water resulting in regionally specific production rates. Since any use of wood is correlated with a loss of the ecosystem's nutrients, the intensity of forestry therefore has an effect on the sustainability issues. The main objective of forestry in central Europe is to keep the balance between growth and use of the system. Examples from literature indicate that an intensified use of the biomass can result in considerable losses in growth rates [Meiwes 2009].

Wood residues originate from harvesting (sawdust, break-of branches), the provision of stem wood (removal of tops and branches) and thinning. Amounts of available residues can vary quite a lot depending on the harvesting practice (use of harvester < motor-manual felling), physical relief of the woodland (the higher the slope the bigger the amount of residues) and the processing procedure (on site processing > processing on a centralised processing site).

Thinning is a process to remove especially younger trees allowing the remaining trees to maintain higher growth rates. Thinning material as well as wood residues usually is removed and sold, as there is a growing market (e.g. paper industry, firewood in case of the reference system). The demand for forestry residues is increasing and is expected to increase further in the future because of various decarbonisation strategies building on forestry residues.

As wood residues left on site (woody debris) are crucial for nature conservation and biodiversity an intensified use of wood residues is expected to affect the environmental factors of soil (decrease in soil organic matter) and biodiversity on the long term.

Therefore, a no action scenario for a maximum of sustainability in forestry is leaving 100% of wood residues on site is positive for the environment. Compared to the reference system the use of wood residues for a biorefinery is expected to have impacts on soil organic matter. In addition a lack of habitats especially for saproxylic animals (e.g. beetles) and other animals living on woody debris (e.g. wood bird like the Black woodpecker or bats) is expected on the long term. Table 7 summarises the assessment of hardwood provision as biorefinery feedstock based on forestry residues compared to the reference scenario of leaving 100% thinning wood on-site.

Table 7: Risks associated with the provision of wood residues (forestry residues) compared to the reference system of leaving 100 % of the biomass on-site.

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	neutral		neutral						
Soil compaction	neutral	neutral		neutral	neutral				neutral
Loss of soil organic matter	negative			neutral	negative				negative
Soil chemistry / fertiliser	negative	neutral	neutral		neutral				neutral
Nutrient leaching	neutral	neutral							
Eutrophi-cation	neutral	neutral	neutral	neutral[1]	neutral				neutral
Water demand		neutral	neutral	neutral					neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				negative	negative				negative
Loss of species				neutral	neutral				neutral

5.1.3 Provision of wheat straw

Wheat is grown on deep, heavy and nutrient-rich high quality soils and needs good drainage. Intensive agricultural use primarily leads to impacts on soil. Weed and pest control is obligatory, increasing the risk of soil compaction which is usually linked to negative aspects on the diversity of arable flora and epigeous fauna. Especially the young plants require application(s) of nitrogen fertiliser (app. 150 kg / ha) which increases the risk of nutrient leaching and eutrophication. Intensive cereal cultures are grown as monocultures and this generally leads to impacts on soil, water, plants / biotopes, animals and biodiversity.

Following the scenario of a potential use as UNRAVEL product in a refinery it is assumed, that approx. 67% of the straw yield is left on the field as residues. This approach is sustainable as [Panoutsou et al. 2012] estimate that an export of 40 % of straw in case of wheat and barley will maintain the carbon cycle.

In the reference system of conventional use it is assumed that 100% of the straw is left on the field and ploughed in the soil to maintain the soil organic carbon (SOC) stock. Since both systems are sustainable, differences in impacts on the environmental factors between a conventional system (100% residues left on field) and the sustainable use of straw (approx. 33 %, i. e. once every three years) in context with a use as UNRAVEL product in a refinery are low. In case of intensified use of straw in the UNRAVEL systems based on sustainable production conditions, farmers might be encouraged to use long-stalked cereal varieties which would lead to slightly positive effects for arable plants, since long-stalked varieties reduce the amount of pesticides necessary for weed control due to higher competitiveness. This might result in an increased number of animals linked to arable land (arthropods) and an increased biodiversity.

An unsustainable excessive extraction of straw beyond the levels required to maintain soil fertility, which is not covered by this scenario, would in contrast have multiple negative effects. The first and most affected would be the loss of soil organic matter. This poses risks because wrong but nevertheless possible socioeconomic incentives may press farmers to cross the threshold from sustainable to unsustainable straw extraction (see also section 4.4).

Table 8 summarises the risks associated with the use of wheat straw in the UNRAVEL systems compared to no use of straw.

Table 8: Risks associated with the sustainable provision of straw from wheat / barley compared to the reference system of "straw left on field" (ploughing in).

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	neutral		neutral						
Soil compaction	neutral	neutral		neutral	neutral				neutral
Loss of soil organic matter	neutral			neutral	neutral				neutral
Soil chemistry / fertiliser	neutral	neutral							
Eutrophi-cation	neutral	neutral	neutral	neutral	neutral				neutral
Nutrient leaching		neutral							
Water demand		neutral		neutral	neutral				neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				**neutral / positive[1]**	**neutral / positive[1]**				**neutral / positive[1]**
Loss of species				**neutral / positive[1]**	**neutral / positive[1]**				**neutral / positive[1]**

1: Positive in case of long-stalked varieties since less weed control is necessary.

5.1.4 Provision of roadside grass

Roadside grass is obtained when grassy/herbaceous biomass along the thousands of kilometres of road verges in Europe is cut (usually several times per year). The verges are maintained by law for traffic safety reasons. Today, these grass cuttings are almost always left where they fall. Over time, the resulting mulch increases the fertility of the soil, meaning the grass grows with increasing vigour and needs to be cut more frequently.

Table 9: Risks associated with the provision of roadside grass compared to the reference system of "mulched in situ".

Type of risk	Affected environmental factors								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Land-scape**	**Human health and recreation**	**Bio-diversity**
Soil erosion	**neutral / positive**		**neutral / positive**						
Soil compaction	**neutral / positive**	**neutral / positive**		**neutral / positive**	**neutral / positive**				**neutral / positive**
Loss of soil organic matter	neutral			neutral	neutral				neutral
Soil chemistry / fertiliser	neutral	neutral							
Eutrophi-cation	positive	positive	positive	positive	positive				positive
Nutrient leaching		neutral							
Water demand		neutral		neutral	neutral				neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				**neutral / positive**	**neutral / positive**				**neutral / positive**[1]
Loss of species				**neutral / positive**	**neutral / positive**				**neutral / positive**[1]

Switching to a cut & collect method would reduce the nutrient input into ecosystems which in turn could boost biodiversity since specialist species adapted to low soil nutrient contents would be favoured. For a real positive impact on species and habitat types, a low cutting frequency would be required, e.g. twice a year in spring and in late summer once plants have bloomed and seeded. This could however only be possible to realise at selected sites because biorefinery logistics requires a steady stream of biomass and technical drying for storage needs to be avoided. Harvesting technology, including various types of suction equipment, is still under development and should ensure minimal impact on insects and invertebrates. Collecting the biomass could also reduce trench maintenance frequency which usually involves heavy digging/milling machinery and associated impacts on soil. Table 9 summarises the risks associated with the use of roadside grass in the UNRAVEL systems compared to not using it.

5.1.5 Transport and logistics

Impacts of logistics are expected from

- Transportation infrastructure
- Storage facilities

Transportation infrastructure

Transportation and distribution of feedstock will mainly be based on trucks and railway / ships with need of roads and tracks / channels. Depending on the location of a potential biorefinery there might be impacts resulting from the implementation of additional transportation infrastructure. In order to minimise transportation it would make sense from an economic point of view to build a plant close to feedstock production. As far as it is necessary to build additional roads environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species).

Storage facilities

A prospected biorefinery with a capacity of 300.000 t / year needs a guaranteed feedstock supply, provided either by onsite storages (e.g. wood stems) or storage facilities in the refinery, to facilitate short-term feedstock supply and protection against weather impacts.

Especially in case of straw a huge storage capacity is necessary due to the low specific weight density. As straw can only be harvested once a year it has to be either stored on-site in foil-covered piles or in roofed buildings to minimise damage due to humidity (mould) or vermin. Additional buildings cause sealing and compaction of soil, loss of habitats (plants, animals) and biodiversity as well as reduced groundwater infiltration.

Wood stems can be stored on-site for a while for a just in time delivery as the feedstock is available throughout the year. Wood chips as feedstock for a potential biorefinery might be delivered just in time or produced locally at the plant. In this case it is necessary to dry the chips, either in air and / or in special drying facilities, to provide a suitable moisture content for the biorefinery.

5.1.6 Biomass conversion

Feedstock processing and provision of the product portfolio is done in a biorefinery. The local environmental impacts associated with the implementation of a biomass conversion unit will be considered in the following chapter. It will be done as a benefit and risk assessment, based on the investigation of potential effects on the environmental factors compared to reference scenarios.

Following impact identification and prediction, impact evaluation is the formal stage at which the significance is determined. Impact significance depends on the joint consideration of its characteristics (quality, magnitude, extent, duration) and the importance (or value) that is attached to the resource losses, environmental deterioration or alternative uses.

Impacts are related to the

1. Construction phase
2. Project itself: buildings, infrastructure and installations
3. Operation phase

Following the LCA approach, the expected impacts are compared to reference systems. In order to pre-estimate the range of potential impacts two contrarious scenarios for the location of a potential biorefinery were chosen:

- Greenfield scenario (Table 10): since new space for new industrial sites is generally restricted it is assumed as a worst case-scenario that the biorefinery would be constructed in the open landscape e.g. on fallow land
- Brownfield scenario (Table 11): less and / or lower impacts are expected on former industrial zones where most of the area is already sealed and at least parts of traffic infrastructure might be available

Referring to the different impact categories associated with the implementation of a project it becomes obvious, that differences between the two scenarios are not to be expected during construction phase and the operation phase. Impacts expected during the project-related phase due to implemented buildings infrastructure and installations differ from the location of a potential plant. In case of a Brownfield scenario less impacts are expected than in a Greenfield scenario, where additional land has to be sealed.

Table 10: Technology related impacts expected from a UNRAVEL biorefinery in a Greenfield scenario.

Technology related factor	Environmental factors							
	Water W	Soil S	Flora (plants) P	Fauna (animals) A	Climate / air quality C	Land-scape L	Human health H	Bio-diversity B
1 Construction phase								
1.1 additional temporary land use for construction sites	W1.1	S1.1	P1.1	A1.1	C1.1	L1.1		B1.1 (→ A1.1)
1.2 risk of collisions and road kills during construction				A1.2			H1.2	B1.2 (→ A1.2)
1.3 emission of noise				A1.3			H1.3	B1.3 (→ A1.3)
1.4 visual disturbance during construction				A1.4		L1.4	H1.4	B1.4 (→ A1.4)
1.5 emission of substances and odour	W1.5	S1.5			C1.5		H1.5	B1.5
2 Project related: buildings, infrastructure and installations								
2.1 drain of land resources for project related buildings and installations	W2.1	S2.1	P2.1	A2.1	C2.1 (→ P2.1)	L2.1 (→P2.1)		B2.1 (→ P2.1, A2. 1)
3 Operation phase								
3.1 emission of noise (biorefinery)				A3.1		L3.1	H3.1	B3.1 (→ A3.1)
3.2 emission of gases and fine dust (biorefinery)		S3.2	P3.2	A3.2	C3.2		H3.2	B3.2 (→ A3.2)
3.3 emission of light (biorefinery)				A3.3		L3.3	H3.3	B3.3 (→ A3.3)
3.4 drain of water resources for production (biorefinery)	W3.4		P3.4	A3.4			H3.4	
3.5 waste water production and treatment (biorefinery)	W3.5		P3.5	A3.5				
3.6 traffic (collision risk, emissions)	W3.6	S3.6		A3.6		L3.6	H3.6	B3.6 (→ A3.6)
3.7 electromagnetic emissions from high-voltage transmission lines				A3.7			H3.7	
3.8 risk of accidents, explosion, fire in the plant or storage areas, GMO release	W3.8	S3.8	P3.8	A3.8	C3.8		H3.8	B3.8

Potential impacts

Likely significant impacts

Potentially significant impacts dependent on the local surroundings of the plant

→ **Impacts due to the interaction of environmental factors**

Table 11: Technology related impacts expected from a UNRAVEL biorefinery in a Brownfield scenario.

Technology related factor	Environmental factors							
	Water W	Soil S	Flora (plants) P	Fauna (animals) A	Climate / air quality C	Land-scape L	Human health H	Bio-diversity B
Construction phase								
additional temporary land use for construction sites	W1.1	S1.1	P1.1	A1.1	C1.1	L1.1		B1.1 (→ A1.1)
risk of collisions and road kills during construction				A1.2			H1.2	B1.2 (→ A1.2)
emission of noise				A1.3			H1.3	B1.3 (→ A1.3)
visual disturbance during construction				A1.4		L1.4	H1.4	B1.4 (→ A1.4)
emission of substances and odour	W1.5	S1.5			C1.5		H1.5	B1.5
Project related: buildings, infrastructure and installations								
drain of land resources for project related buildings and installations			P2.1	A2.1				B2.1 (→ P2.1, A2.1)
Operation phase								
emission of noise (biorefinery)				A3.1		L3.1	H3.1	B3.1 (→ A3.1)
emission of gases and fine dust (biorefinery)		S3.2	P3.2	A3.2	C3.2		H3.2	B3.2 (→ A3.2)
emission of light (biorefinery)				A3.3		L3.3	H3.3	B3.3 (→ A3.3)
drain of water resources for production (biorefinery)	W3.4		P3.4	A3.4			H3.4	
waste water production and treatment (biorefinery)	W3.5		P3.5	A3.5				
traffic (collision risk, emissions)	W3.6	S3.6		A3.6		L3.6	H3.6	B3.6 (→ A3.6)
electromagnetic emissions from high-voltage transmission lines				A3.7			H3.7	
risk of accidents, explosion, fire in the plant or storage areas, GMO release	W3.8	S3.8	P3.8	A3.8	C3.8		H3.8	B3.8

Potential impacts

Likely significant impacts

Potentially significant impacts dependent on the local surroundings of the plant

→ **Impacts due to the interaction of environmental factors**

Key findings and conclusions:

- Hardwood stems: Using stem wood from additional thinnings essentially reduces rotation cycles and entails the risk of negative soil nutrient and soil carbon balances. Also, less old growth trees would have a negative impact on biodiversity.
- Forest residues: The use of wood residues is bearing long-term risks compared to the reference system of traditional forestry where wood residues and thinning material usually are left onsite. The residues basically contribute to soil organic matter balance and carbon sequestration.
- Cereal straw: If sufficient straw is left on the field and ploughed in, impacts from removing remaining straw are comparable to the reference system of ploughing it in, too. Excessive extraction beyond the levels required to maintain soil fertility would in contrast have multiple negative effects including the loss of soil organic matter
- Roadside grass: Collecting roadside grass instead of mulching it offers potential environmental benefits in terms of reduced nutrient input into ecosystems. This in turn might favour specialist plants and thus boost biodiversity.
- In comparison, the use of excess/surplus cereal straw and roadside grass are rated largely neutral and neutral to positive, respectively, meaning that low risks are associated with these biomass types. Using woody biomass, however, is connected with considerable risks in terms of soil nutrient and soil carbon balance and the forests' ability to act as a carbon sink and as a habitat for species.

5.2 Conventional systems

Following a life cycle-oriented approach, the objective of the environmental assessment is to compare potential impacts of a UNRAVEL biorefinery with other conventional (mainly fossil-driven) reference systems (see section 3.2.1). Reference technologies compared to UNRAVEL include:

- Petrochemicals using feedstock from a crude oil refinery
- Petrochemicals using feedstock from a natural gas refinery
- Fermentation products using sugar from annual crops processed in a sugar refinery

Crude oil refinery

Oil refineries process crude oils into useful products e.g. naphtha, diesel or kerosene. The crude oil comes from oil production platforms (via pipelines or tankers) and is separated into fractions by fractional distillation. The fractions at the top of the fractionating column have lower boiling points than the fractions at the bottom. The heavy bottom fractions are often cracked into lighter, more useful products. All of the fractions are processed further in other refining units. The majority of the products are used for energy purposes.

Natural gas refinery

Natural gas processing is usually done on-site and goes along with the exploitation, either on land (on shore) or off-shore. Depending on the quality of the natural gas it is necessary to separate ingredients like water, nitrogen, carbon dioxide and higher-valence hydrocarbons. The processing of acidic gas integrates a removal of hydrogen sulphide (H_2S) in a gas scrubbing process. The international transportation is done via pipelines or special cargo vessels. Natural gas is to a large extent used for energy production.

Sugar refinery

In sugar mills, crops with high sugar content such as sugar beet or sugar cane are first washed and comminuted. The sugar (sucrose) is then dissolved using an alkaline solution. By removing various organic and inorganic by-products, the resulting juice is thickened by heating before crystallising it. The resulting crystal suspension is separated from the mother liquor by centrifugation. After drying, refined sugar is produced.

Crops high in starch (maize, potatoes or wheat) can also be used: Sugar is obtained through enzymatic fermentation of the starch. Besides being used as food, this sugar can be fermented to ethanol (e.g. as fuel) or chemicals such as gluconate, which is the conventional product replaced by xylonate produced in the UNRAVEL biorefinery.

5.2.1 Feedstock provision

Following the LCA approach, an assessment of feedstock provision in conventional reference systems is conducted, which in case of UNRAVEL are crude oil and gas provision for the petrochemicals. For the fermentation products which are part of the conventional reference systems, sugar beet and wheat are considered as (biomass) feedstocks. Each is related with different types of risks causing potential impacts on the environment. Impacts of transportation are taken into consideration as well.

Crude oil / gas provision

Impacts of crude oil / gas provision are expected to affect all environmental factors. The impacts are classified as unfavourable for the environment. Drilling processes especially in combination with the production of oil and water based mud and the huge demand of water [Ziegler 2011] bear significant risks for the environment. Further significant impacts are expected from transportation especially the implementation of pipelines.

Both value chains (crude oil / gas provision) include high risks of environmental impacts related with accidents, which in case of crude oil provision exceed the risks of gas provision by far (see e.g. [Wikipedia 2021] for a list of spills). Basically the environmental factors soil, water, plants / biotopes, animals and biodiversity are affected. Table 12 summarises potential impacts on environmental factors on the value chains for both crude oil provision and gas provision as exploitation and refining are very often done simultaneously.

Table 12: Impacts on environmental factors related with crude oil / gas provision; potentially significant impacts are marked with thick frames; reference scenario: no use.

Technological factor	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Prospection	negative			negative	negative				negative
Drilling / mining	negative	negative	negative	negative	negative		negative		negative
Waste (oil based and water based mud)	negative	negative	negative	negative	negative				negative
Demand of water (process water)		negative	negative	negative	negative		negative		negative
Emissions (exhaust fumes, water, metal)		negative	negative	negative	negative	negative		negative	
Land requirements	negative	negative	negative	negative	negative	negative	negative		negative
Demands of steel (tubes, equipment)	negative			negative	negative		negative		
Transportation (carriers, pipelines)	negative	negative	negative	negative	negative	negative	negative	negative	negative
Refining / processing	negative	negative	negative	negative	negative		negative	negative	negative
Accidents (traffic, pipeline leakage)	negative	negative	negative	negative	negative		negative	negative	negative

Sugar beet

The cultivation of sugar beet e.g. for gluconate production requires a high soil quality. Highest yields are achieved on deep soils with homogenous structure. As the young plants are endangered by overgrowth from the surrounding arable flora, an intensive weed control is required. Due to a high number maintenance cycles and heavy vehicles (e.g. high applications of fertiliser [120-160 kg N / ha], need of weed and pest controls) there is a high risk of soil compaction. A consequence is an increased risk of nutrient leaching, affecting both groundwater and superficial water, especially by runoff during heavy precipitations. Ploughing of leaves after harvesting in fall will not compensate the loss of nutrients in total (fruit : leave ratio ≈ 1.2 : 0.8 [Schlegel et al. 2005]), so additional supply of organic fertiliser is necessary for soil balance. Intensive processing, use of heavy machines for the application of fertiliser and weed control in combination with the risk of erosion due to late soil coverage can affect plant and animal diversity. Thus succeeding crops (e.g. legumes, winter wheat) are recommended and help to minimise erosion. Potential impacts on landscape are comparable to the reference system of non-rotational fallow land.

Loss of habitat types and species might cause impacts if there is a change in habitat quality e.g. woodland is converted to arable land. The cultivation of sugar beet on arable land is not expected to cause a loss of habitats. Table 13 summarises the risks associated with cultivation of sugar beet on the environmental factors.

Table 13: Risks associated with the cultivation of sugar beet (ploughing of leaves) compared to the reference system of non-cropping (rotational fallow land).

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	negative[1]		negative						
Soil compac-tion	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral / negative[1,2]			neutral / negative[1,2]	neutral / negative[1,2]				neutral / negative[1]
Soil chemistry/ fertiliser	negative	negative							
Eutrophi-cation	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control / pesticides'		negative	negative	negative	negative				negative
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral / negative[1]	neutral / negative[1]				neutral / negative[1]
Loss of species				neutral / negative[1]	neutral / negative[1]				neutral / negative[1]

1: Negative impact can be minimised in case of crop rotation (succeeding crop), e.g. winter wheat;
2: Ploughing of leaves is usually not enough to compensate loss of nutrients)

Wheat grains

Starch crops such as wheat or maize can be used for sugar production and thus are important feedstocks for the production of chemicals via fermentation. The starch crop primarily used in Europe for this purpose is wheat. Due to intensive maintenance cycles the cultivation of wheat is basically linked with negative impacts on the environment if compared to fallow land as a reference system. Intensive cultivation and maintenance is responsible for soil compaction and as a consequence impacts on plants / biotopes and animals are expected. For industrial processes, winter grain is favoured as biomass yields are higher due to a longer vegetation periods. The impact on soil of winter grain is lower in comparison with sugar beet and maize, as soil coverage during winter minimises the risk of erosion [Schlegel et al. 2005].

Succeeding crops can help to minimise erosion effects due to uncovered soil. Soil and groundwater will additionally be affected due to intensive maintenance, use of fertiliser as well as weed and pest control. Especially the need of fungicides is relatively high in case of grain production. Table 14 summarises the risks on the environmental factors associated with cultivation of wheat compared to rotational fallow land as reference system.

Table 14: Risks associated with the cultivation of wheat and straw left on the field (ploughing) compared to the reference system of "non-cropping" (rotational fallow land).

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health and recreation	Bio-diversity
Soil erosion	neutral / negative[2]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of SOM	neutral / negative[2]			neutral / negative[2]	neutral / negative[2]				negative
Soil chemistry / fertiliser	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative							
Water demand		negative		negative	negative				neutral
Weed control / pesticides		neutral / negative[1,2]	neutral / negative[1,2]	neutral / negative[1,2]	neutral / negative[12]				neutral / negative[1,2]
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral / negative[1,2]	neutral / negative[1,2]				neutral / negative[1,2]
Loss of species				neutral / negative[1,2]	neutral / negative[1,2]				neutral / negative[1,2]

1: Negative in case of short stemmed varieties; long-stalked varieties afford less weed control
2: Negative impact can be minimised by crop rotation; e.g. winter wheat and / or double cropping

5.2.2 Conversion

Impacts from implementing a refinery for conversion and use of conventional (fossil) feedstock are expected from:

- the construction of the plant
- buildings, infrastructure and installations on-site as well as to the

– operation of a prospective plant

Construction phase

Impacts related with the construction of a plant are temporary and not considered to be significant.

Buildings, infrastructure and installations (size and height of the plant)

Refineries need processing facilities, energy generation, administration buildings, waste water treatment etc., which usually goes along with sealing of soil. Differences are expected regarding the location of a plant as shown in a worst case approach with Greenfield scenario and Brownfield scenario (see section 5.1.6).

Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up plants from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape.

Operation phase

Impacts from operating a conversion plant are expected from:

– emission of noise (refinery)
– emissions of gases and fine dust
– emission of light (refinery)
– drain of water resources for production (refinery)
– waste water production and treatment (refinery)
– traffic (collision risks, emissions)
– electromagnetic emissions
– risk of accidents, explosion, fire in the plant or storage areas

Significance of impacts might vary with the type of technology and the location of a potential plant. A decision on a case-by-case-basis is necessary anyway.

Key findings and conclusions:

- In the conventional reference system, both fossil feedstock (for petrochemicals) and biomass feedstock from dedicated crops (for fermentation products) is provided. Both types of feedstocks are associated with significant impacts.
- Local environmental impacts from the conversion of crude oil / natural gas as well as sugar / starch into products are mostly expected from the operation phase.
- Impacts can be reduced substantially if they are built on e.g. disused industrial areas (“brownfield”) instead of on e.g. agricultural land (“greenfield”).

5.3 Comparison: Lignocellulose-based vs. conventional systems

5.3.1 Feedstock provision

The provision of feedstock is linked to local environmental impacts varying according to the type of feedstock and the technology.

Biomass feedstock

There are fundamental differences in provision technologies which in case of biomass feedstock are linked with different land management types for biomass extraction and cultivation (forestry and agriculture). Table 15 gives an overview on biomass-specific differences with regards to environmental factors. The feedstock is grouped into biomass feedstocks for the lignocellulose-based systems (hardwood stems, forestry residues, wheat straw and roadside grass) and biomass feedstocks for the conventional systems. The reference scenarios for hardwood stems is no use (traditional forestry). For forestry residues, wheat straw and roadside grass are compared to the reference scenario of leaving the biomass on site. Traditional use of straw (for bedding and fodder) can be neglected as no difference is expected if it is returned to the field in the form of manure. Sugar beet and wheat as dedicated crops are compared to rotational fallow land, i.e. not using the field.

Table 15: Biomass-specific environmental impacts versus different reference scenarios.

Type of risk	Lignocellulose-based systems				Conventional systems	
	Hardwood stems	Forestry residues	Wheat straw	Roadside grass	Sugar beet	Wheat grains
Soil erosion	C	C	C	B	E	C
Soil compaction	D	C	C	B	E	C
Soil organic matter	D	D	C	C	E	D
Soil chemistry / fertiliser	D	D	C	C	E	D
Eutrophication	C	C	C	A	E	D
Nutrient leaching	C	C	C	C	D	D
Water demand	C	C	C	C	E	D
Weed control / pesticides	C	C	C	C	E	E
Loss of habitat / species diversity	D	D	C	B	D	D
Loss of landscape elements	C	D	C	B	C	C

Impacts are ranked into five comparative categories (A, B, C, D, E); “A” is assigned to the best options concerning the factor, “E” is assigned to unfavourable options concerning the factor;

Reference systems:
Hardwood stems: no use (traditional forestry); Forestry residues: left in forest; Wheat straw: straw left

on field (ploughing); Roadside grass: cut/mulched and left on site; Wheat grains and sugar beets: fallow land (rotational).

The comparison is based on the types of risks described in the previous sections using five comparative categories in form of alphabetic characters from “A” to “E”. As can be seen in Table 15, the risk associated with using lignocellulosic biomass (mainly residues) are smaller than using dedicated crops. However, it has to be kept in mind that sugar beet or wheat are only 1/3 of the conventional reference system which consist of both biomass feedstock (for fermentation products) and fossil feedstock (for petrochemicals).

Fossil feedstock

The types of risks expected from provision of conventional, non-renewable feedstock are fundamentally different and in general are based on extraction technologies focussing on components below the earth’s surface. Major impacts by crude oil and gas provision are caused by land requirements. Moreover, heavy impacts on water are expected, e. g. because of the use of process water (crude oil). Transportation from overseas resource areas produces considerable emissions affecting air quality and thus wild life environment and human health. The risk combined with accidents might be almost equal in crude oil and gas provision as both value chains are dealing with hazardous substances. Table 16 summarises major implications of the considered value chains in comparison with the no-action alternative.

Table 16: Potential impacts on the environment related to different value chains regarding the provision of petrochemical feedstocks in conventional systems; reference system: no use.

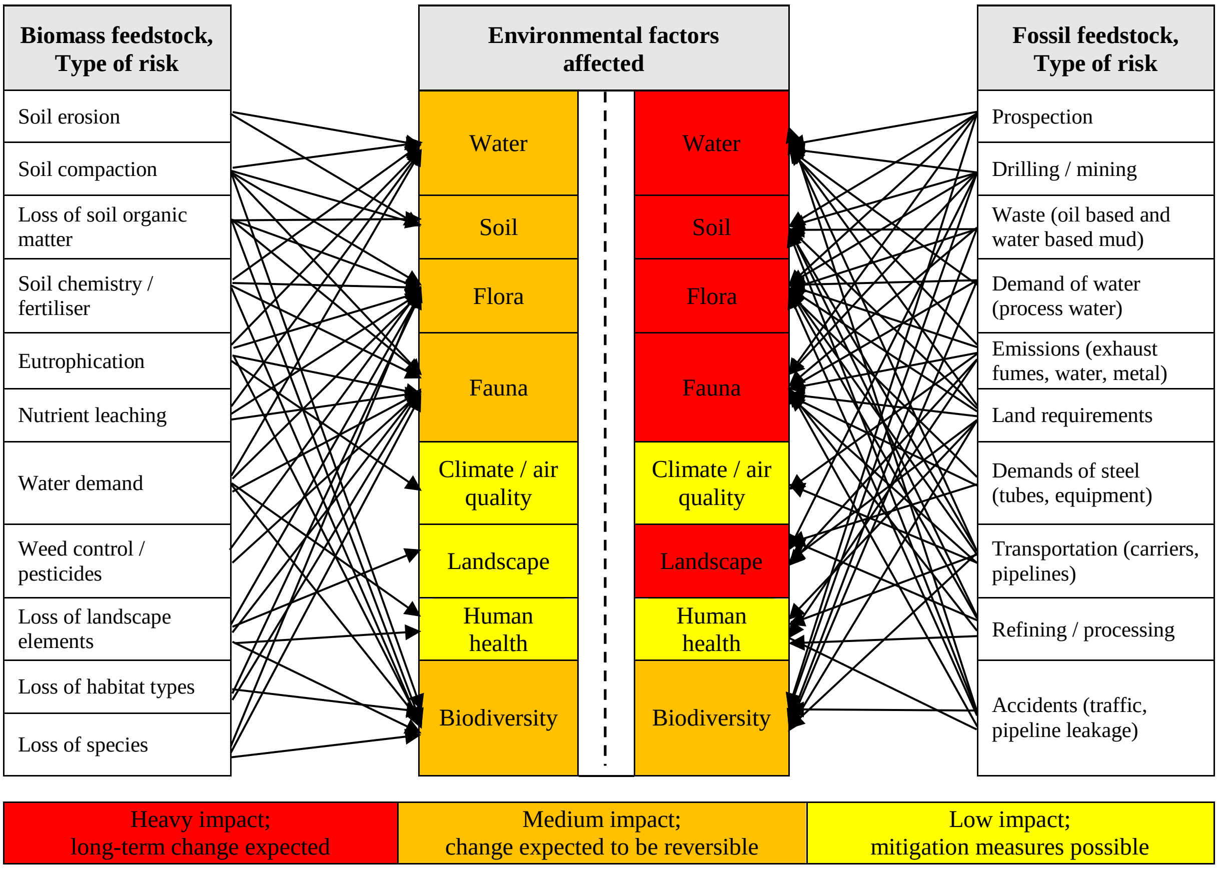
Technological factor	Crude oil / gas provision
Prospection	C
Drilling / Mining	E
Waste	D
Demand of water (process water)	C / D[2]
Emissions (exhaust fumes, dust, water, metal)	C / D[2]
Land requirements	C / D[1]
Demands of steel (tubes, equipment)	D
Transportation (carriers, pipelines)	D
Refining / processing / enrichment	D
Accidents (traffic, pipeline leakage)	E

Impacts are ranked in comparative categories; “A” and “B“ are assigned to the best options concerning the factor, but are not used in this case; “E” is assigned to unfavourable options concerning the factor; ; reference scenario: “no action”-alternative
1: Increased land requirements in on-shore production
2: Increased impact in crude oil provision

Comparison

As type of risks associated with these technologies are completely different in quality and quantity (cf. Table 15 and Table 16), a direct comparison is not possible. Nevertheless, Table 17 compares impacts on local environmental factors assuming a reference system of no use on a sustainability level, choosing three different impact categories: heavy, medium and low.

Table 17: Comparison of impact on environmental factors due to provision of bio-based and conventional feedstock regarding impact sustainability in three different categories; reference system: no use.



From a sustainability point of view, impacts related with the provision of bio-based feedstock are expected to be mostly reversible. For instance soil erosion due to agricultural cultivation or management, depletion of water due to use of fertiliser and pesticides or loss of habitats and species due to changes in land use can be compensated over a certain period of time, if the risk factor responsible for the impact was abandoned. However, most of the impacts from conventional fossil feedstock provision especially on water, soil, flora, fauna and landscape are expected to be long-term changes and non-reversible.

Overall, it is expected that feedstock provision for the lignocellulose-based systems (UNRAVEL) is causing less local environmental impacts than the conventional reference system which is the sum of crude oil / natural gas (for petrochemicals) and sugar / starch (for fermentation products) provision.

5.3.2 Conversion

Implementing a reference technology faces similar challenges as the implementation of a biorefinery working with the UNRAVEL concept. The most important impacts are related to

- the construction of the plant
- buildings, infrastructure and installations on-site as well as to the
- operation of a prospective plant.

The assessment of local environmental impacts in implementing and operating refineries shows that differences are to be expected from different technologies applied. Regardless of the technology, no differences are to be expected on a generic level during construction phases and related to buildings, infrastructure and installation. However, differences in local environmental impacts are expected during the operation of conventional refineries.

- Traffic
- Disposal of solid waste / residues and waste water (environmental factors: water, plants, animals, biodiversity)
- Drain of water resources for production (environmental factor: water)

Traffic

Additional traffic causes additional emissions and increases the risk of accidents. Local traffic is expected to be increased in the area of biorefineries with feedstock provision from the vicinity, which in case of a Greenfield scenario will exceed the impacts from a Brownfield scenario. Considering urban traffic impacts from the latter scenario might even be negligible.

Disposal of waste / residues

Bio-based refineries have a clear advantage regarding the disposal of organic residues as it can be used for combustion (energy production), animal feed or fertiliser.

Drain of water resources

Unfavourable for a biorefinery might be a substantially higher demand for water compared to fossil-driven, conventional refineries. The amounts however depend on aspects like the water reuse concept within the biorefinery. Furthermore, drain of water in regions with water scarcity increases the risk of droughts. While conventional refineries are often built along water reservoirs (sea, big rivers) for facilitation of cooling and transportation, agriculturally dominated regions with lower water availability may be more attractive for biorefineries.

Additional significant impacts are expected during operation of the plant, due to risks of explosions and fire in the plant or the storage areas, accidents and production / treatment of waste.

Overall, chemical plants of conventional technologies and prospective biorefineries according to the UNRAVEL concept do not differ significantly from each other. Therefore, on a generic level, the local environmental impact of a UNRAVEL biorefinery will not differ substantially from those of a conventional plant. This has been analysed previously in detail for a similar installations [Rettenmaier et al. 2013].

A major influence on the local environmental impact of a biorefinery is the chosen location (see section 5.1.6). While a biorefinery in a greenfield scenario (biorefinery will be constructed in the open landscape) has distinct local environmental impacts, a biorefinery in a brownfield scenario (biorefinery will be constructed in former industrial zones where most of the area is already sealed) shows substantially lower local environmental impacts.

Key findings and conclusions:

- Biomass feedstock provision for prospective biorefineries according to the UNRAVEL concept is expected to cause less local environmental impacts than feedstock provision for the conventional reference system.
- Local environmental impacts of conventional chemical plants and of prospective biorefineries according to the UNRAVEL concept do not differ significantly from each other.
- Impacts of new biorefinery plants can be reduced substantially if they are built on e.g. disused industrial areas (“brownfield”) instead of on e.g. agricultural land (“greenfield”).

6 Conclusions and recommendations

6.1 Conclusions

The results of this environmental assessment in chapters 4 and 5 show that the UNRAVEL project could achieve important steps towards the environmental sustainability of potential future biorefineries by introducing several successful innovations:

- A **new approach to pre-extraction** of biomass before organosolv fractionation can make previously not usable underutilised biomass residues such as roadside grass or mixed lignocellulosic residues available for lignocellulosic biorefineries. Although this requires additional energy, net effects can be positive if competition for feedstocks, possible pressure to resort to unsustainably sourced feedstocks in case of shortages and resulting environmental disadvantages can be mitigated.
- Additionally, much has been achieved through the **improvement of the core process** based on acetone organosolv technology in the UNRAVEL project. It causes significantly lower environmental impacts than the conventional ethanol organosolv process, mainly because of its lower energy and solvent demand, and should therefore be preferentially used in future lignocellulose biorefinery concepts.
- Regarding the **downstream processing** of the three intermediate fractions obtained from the organosolv process, namely lignin, C5/hemicellulose and C6/cellulose, into products the following findings were obtained:
    - The modification of **lignin** with ethylene carbonate for use as a polyol in PUR/PIR is associated with clear environmental advantages. Lignin valorisation was one of the focus areas of this project and this newly developed successful lignin use option is one of several studied in this project.
    - The conversions of **C5/hemicellulose** into xylonic acid and **C6/cellulose** into acetone turned out not to make full use of the potential to avoid emissions by substituting conventional products. Although these explorative research activities produced valuable scientific findings, substantially increased environmental benefits are not to be expected based on gained experience even if these processes were developed further. Nevertheless, fermentability of the fractions was found to be good so that many other environmentally friendly products seem attainable. LCA can help to identify suitable pathways.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Resulting from the heterogeneous environmental performance of the downstream processing options, only some of the biorefinery scenarios as investigated in this study can achieve overall environmental benefits. Environmental sustainability of the scenarios with the given product spectrum in particular requires overcoming the following constraints:

- Very high energy and material efficiencies must be achieved. This requires optimal performance in many aspects at the same time.
- Biomass needs to be available without substantial competition.
- Bio-based products really need to replace fossil-based products (as postulated in the comparisons underlying the LCA) and not just increase the amounts of products used.
- Residue extraction from and thus intensification of forestry and agriculture always comes along with the risk of adverse local environmental impacts on soil, water and biodiversity. This could only be justified if other substantial benefits for climate and other environmental aspects are certainly achieved, which is in conflict with very high demands to technological development mentioned above.

This result, however, does not generally disprove the organosolv biorefinery concept as such or any improvements achieved within this project. Rather, it underlines the importance of exploring and developing additional environmentally beneficial biorefinery process modules as successfully done in this and other projects. These generally advantageous modules should be optimised individually, combined according to local biomass availability and market demands, and integrated to create environmentally friendly lignocellulose biorefineries. Among the modules studied in this project, the pre-extraction, the core process using acetone organosolv and the lignin conversion into polyols are promising elements of future environmentally friendly biorefineries and should be developed further.

6.2 Recommendations

To further develop the analysed lignocellulose biorefinery concept based on acetone organosolv technology into an environmentally friendly technology option to make best use of available biomass in a future defossilised economy, we recommend the following concrete steps to the respective stakeholder groups:

To process developers and research funding agencies

- The **acetone organosolv** process (analysed here: Fabiola™) should be used preferentially compared to the ethanol organosolv process in future lignocellulose biorefinery concepts. Care should however be taken that acetone emissions to air are in practise as low as in the analysed scenarios.
- Aim to reduce the **energy demand** of the core process and pre-extraction with high priority. For the pre-extraction process, optimised solvent to biomass ratios and using adapted dedicated equipment are expected to comprise main savings potentials.
- **Material use efficiency** of the core process and lignin conversion should be increased as far as possible. This includes increasing the yields and reducing the demands for acetone, enzymes, activated carbon and lignin modifier (ethylene carbonate).
- It is recommended to use a process with a **falling film evaporator for lignin recovery** as modelled in the analysed scenarios (analysed here: LigniSep). Using previously common processes such as dilutive lignin precipitation would lead to lower lignin yield, higher energy demand and lignin fouling in the solvent recovery process.

– Find alternative **use options for the C5/hemicellulose and C6/cellulose streams** that preserve as much of their molecular structures as possible to reach environmental advantages over current and future competing processes. For example, it should be investigated if cellulose can be used (i) as such in form of fibres or (ii) as regenerated fibres such as viscose or lyocell preserving glycosidic bonds or (ii) depolymerised and converted into bigger molecules than acetone, as studied in this project, conserving as many C-C bonds as possible. Likewise, it should be studied if C5/hemicellulose could be separated and used at least in an oligomeric form.
– Develop an integrated utilities concept mainly based on **renewable wind and solar power** including replacing heat-driven processes by electricity-driven ones. Here the use of heat pumps and specifically mechanical vapour recompression heat pumps should be explored.
– The **valorisation of high-value extracts** from biomass can be environmentally beneficial depending on what is replaced by these extracts although the concentration turned out to be too low in the example betulin from birch branches studied in this project. It seems more promising to initially develop and optimise extractives valorisation in terms of feedstock, process and scale independent of a lignocellulose biorefinery. In a second step, it should be analysed how far the ability of the organosolv process to process wet biomass or suspensions can be taken advantage of to feed extracted biomass into a biorefinery for high value use. Likewise, existing **biomass extraction plants** in pharmaceutical, cosmetics, food and other industries should be screened **as potential feedstock sources** for organosolv biorefineries.

To potential industrial operators of a future biorefinery

– Strategic decisions concerning **the selection of the product portfolio** in particular determine early on whether a biorefinery has the potential to produce environmentally friendly products over the entire product life cycle. A multitude of factors and influences has to be considered for the selection of the product portfolio. Therefore, a rigorous analysis of the associated environmental impacts in the planning stages of a concrete biorefinery is strongly recommended, which needs to be more specific than this necessarily generic study that is designed to aid further technology development.


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– From an environmental standpoint it will be crucial for any biorefinery to have a **sustainable biomass supply concept** adapted to local availability of unused biomass that can be extracted from agriculture, forestry and other systems without environmental damage. This should also take into account that some feedstocks may not be sustainably available in some years. The feedstock flexibility of the UNRAVEL concept provides great preconditions that should be taken advantage of.

- Regarding the local environmental impacts of different biomass feedstocks investigated for the UNRAVEL concept, it could be shown that at generic level the use of herbaceous residues (excess/surplus cereal straw and roadside grass) is associated with considerably lower risks than the use of woody biomass which is connected with considerable risks in terms of **soil nutrient and soil carbon balance** and the forests' ability to act as a **carbon sink** and as a **habitat for species**. Operators should apply a diligent supply chain management to avoid any risks in this direction.
- Optimise **campaigns of mixed and separate feedstocks** primarily for the energy demand caused in pre-extraction and fractionation. Only apply **pre-extraction** if necessary.
- Try to find e.g. disused industrial **sites to build the biorefinery** ("brownfield") instead of using e.g. productive agricultural land ("greenfield"). This should however not lead to substantially increased transportation needs.

To political decision makers

- Establish **clear sustainability criteria for biomass residues** that are consistent across sectors with regard to how much of which residue can be extracted. This is needed to limit negative environmental impacts from excessive aggregate use. This requires clear aims and targets for conservation of nature and agricultural soils and their active management.
- In the mid- to long-term, **biomass allocation plans** should be developed at national and / or European level. Due to the fact that environmental burdens and social impacts of resource scarcity do not possess an adequate price, market mechanisms cannot replace these plans.
- In a first step, a **phase out of one-sided incentive** and support structures that give advantage to certain sectors, such as the biomass utilisation for energy purposes, should be initiated. Disincentives that promote inefficient utilisation of biomass may otherwise be a consequence, as opposed to a utilisation that could potentially achieve greater environmental benefits with the same quantity of biomass. Subsidisation schemes for biorefineries should be based on the actual achieved environmental benefits after an initial grace period for the establishment of the novel technology.
- **Support a further development** of sustainable building blocks and integrating concepts for future biorefineries using underutilised lignocellulosic residues. The long-term process of establishment of overall sustainable concepts should be initiated through the funding of demonstration plants.

Many of the recommendations listed here cannot be implemented without considerable financial and political resources. Therefore, all addressed stakeholders should work towards a consensus on a corresponding long-term strategy.

7 Abbreviations

C5	Sugars components with 5 carbon atoms (hemicellulosic sugars)
C6	Sugar components with 6 carbon atoms (cellulosic sugars)
CHP	Combined heat and power plant
DNP	Distance-to-Nature-Potential
EC	Ethylene carbonate
EU	European Union
GA	Grant Agreement
GWP	Global warming potential
ILCD	The International Reference Life Cycle Data System
IFEU	Institute for Energy and Environmental Research Heidelberg
ILCSA	Integrated life cycle sustainability assessment is a methodology for comprehensive sustainability assessment of products (see [Keller et al. 2015] for details) building on the LCSA principle
LCA	(environmental) Life cycle assessment, in this project a screening life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LC-EIA	Life cycle environmental assessment is a methodology for the assessment of local environmental impacts that cannot (yet) be adequately covered by LCA.
LCT	Life cycle thinking
OPEX	Operational expenses or operational cost assessment
PIR	Polyisocyanurate
PUR	Polyurethane
SEA	strategic environmental assessment
SOC	Soil organic carbon
TMP	Trimethyl phosphate
VDI	Verein Deutscher Ingenieure (Association of German Engineers)
WMO	World Meteorological Organization
WP	Work Package

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10 Annex

Section 10.1 shows the life cycle schemes of all UNRAVEL scenarios described in section 3.2. In section 10.2, additional LCA results are presented complementing those discussed in chapter 4.

10.1 Life cycle schemes of analysed UNRAVEL scenarios

10.1.1 Basic scenario (beech)

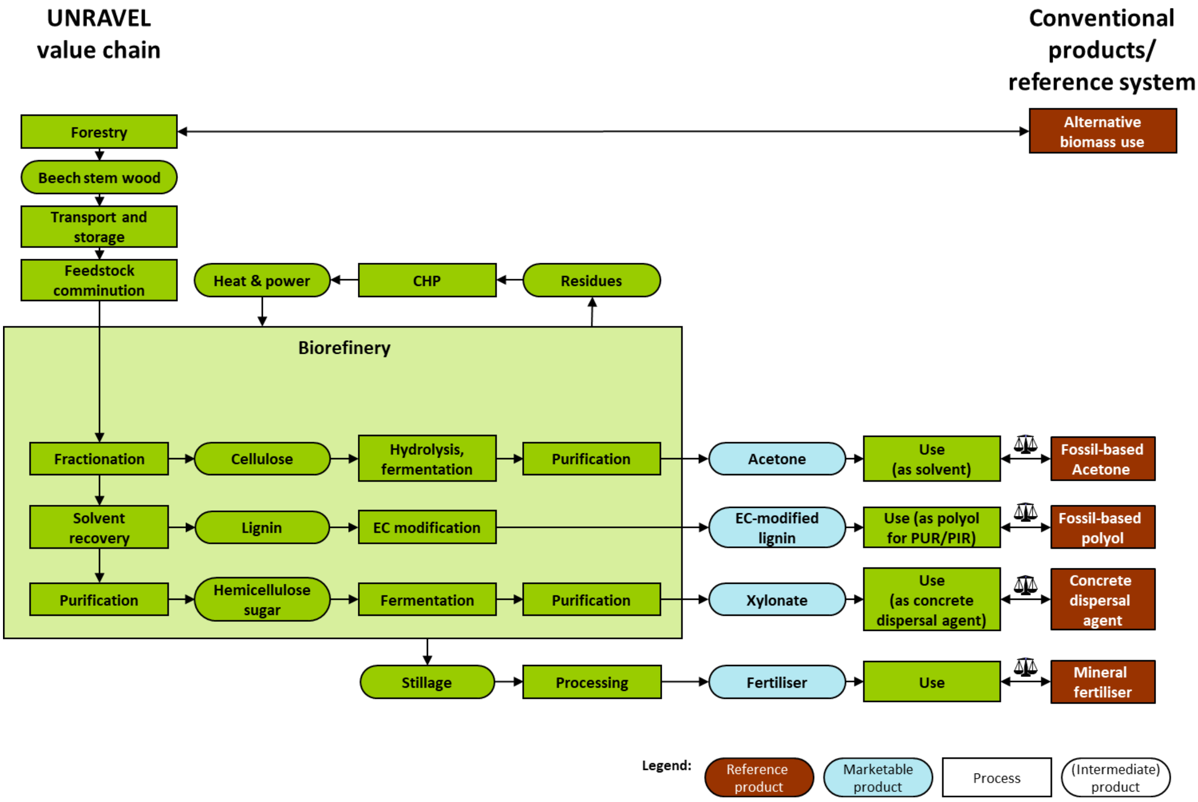

Figure 21: Life cycle scheme of the basic scenario (beech).

10.1.2 Lignin to fillers

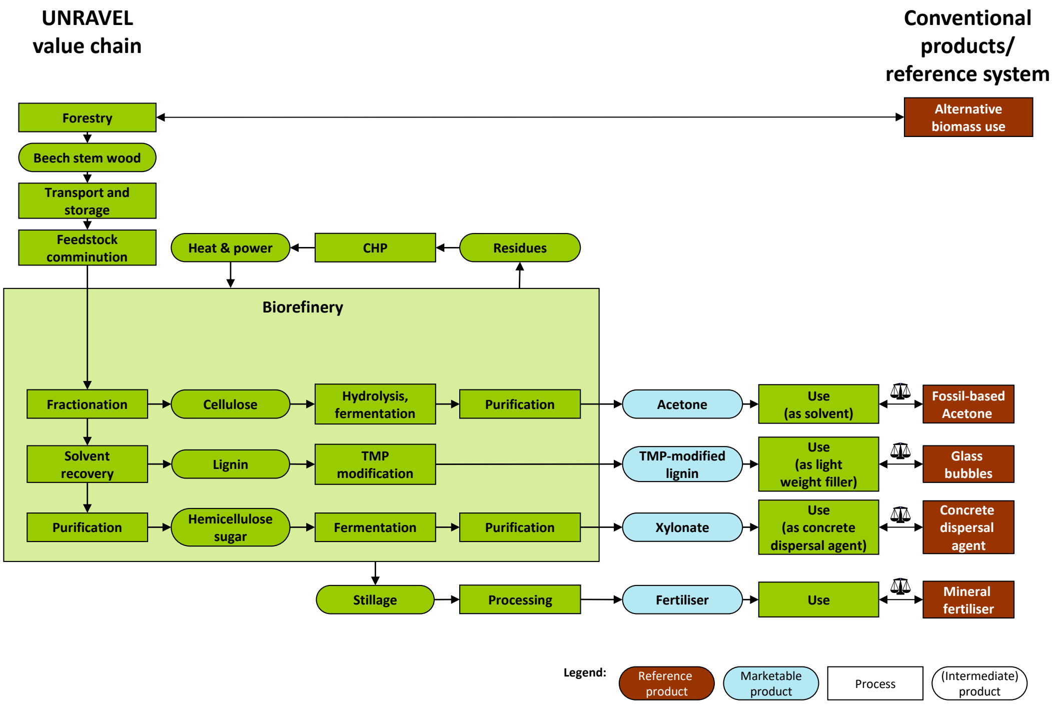

Figure 22: Life cycle scheme of the scenario 'lignin to fillers'.

10.1.3 Residues to heat only

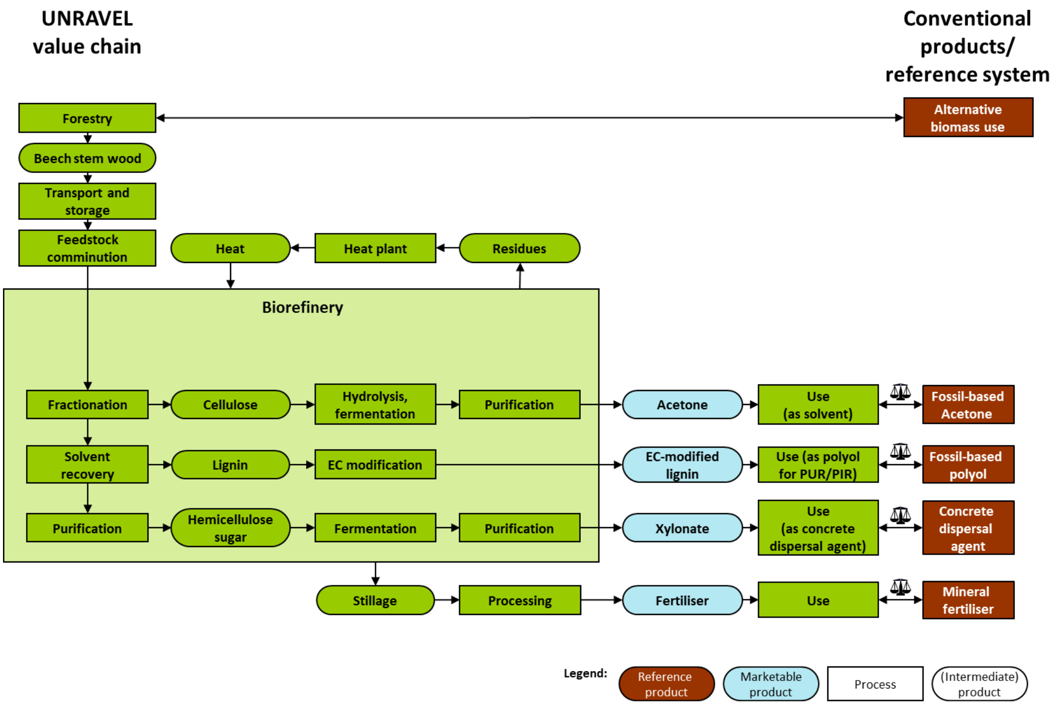

Figure 23: Life cycle scheme of the scenario 'residues to heat only'.

10.1.4 Lignin combustion

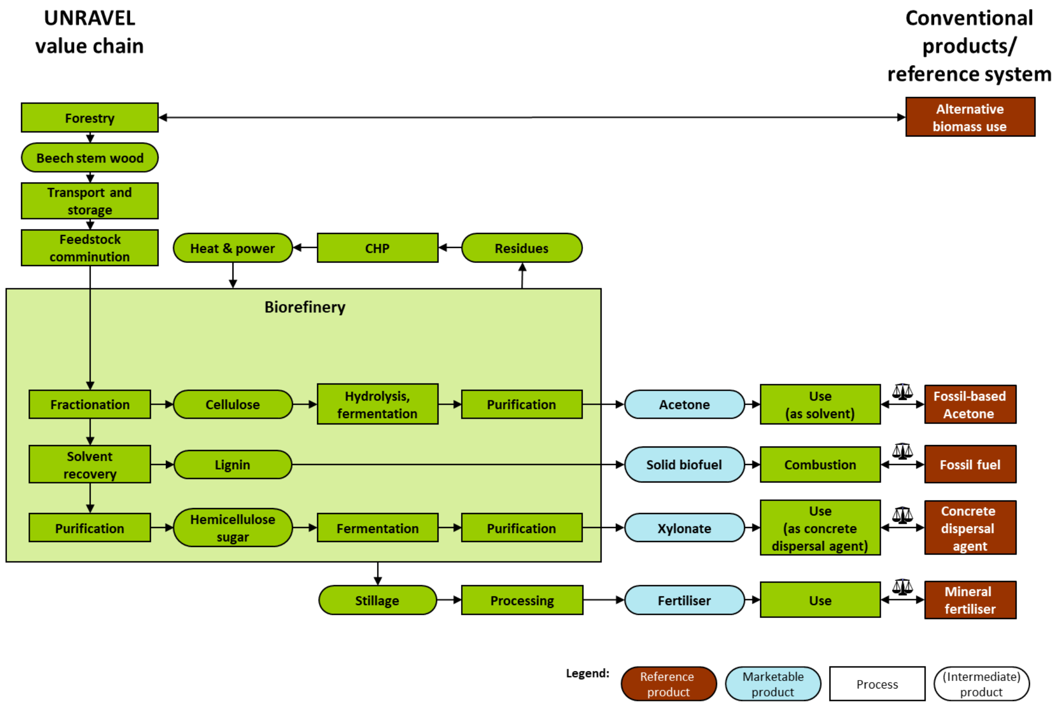

Figure 24: Life cycle scheme of the scenario 'lignin combustion'.

10.1.5 Reference

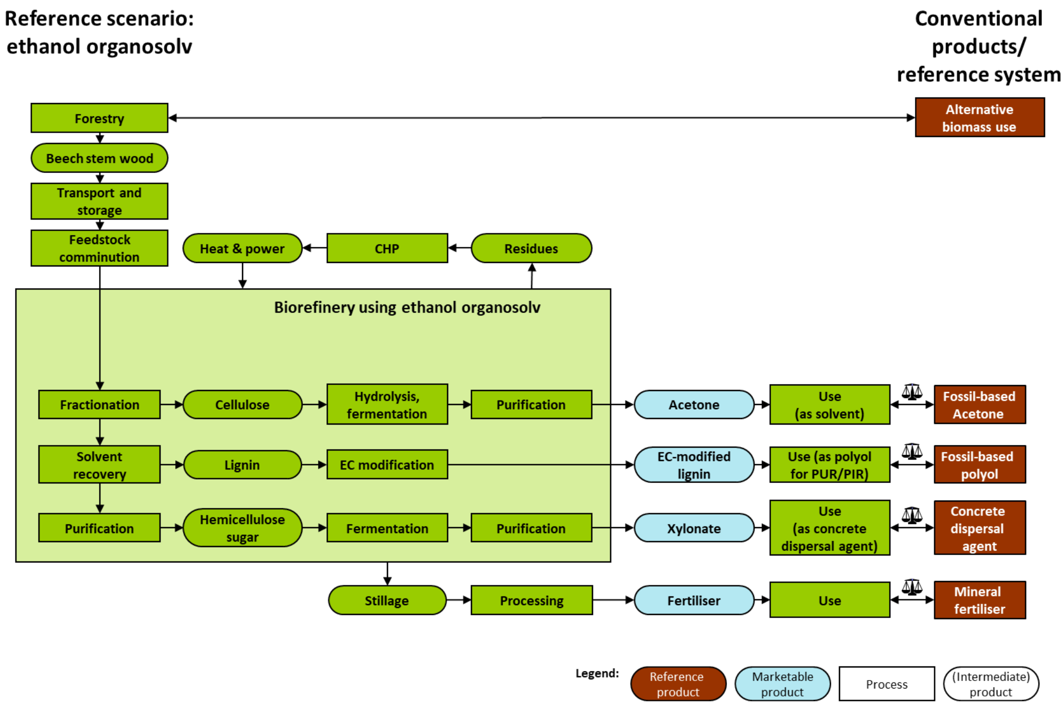

Figure 25: Life cycle scheme of the reference scenario.

10.1.6 Wheat straw

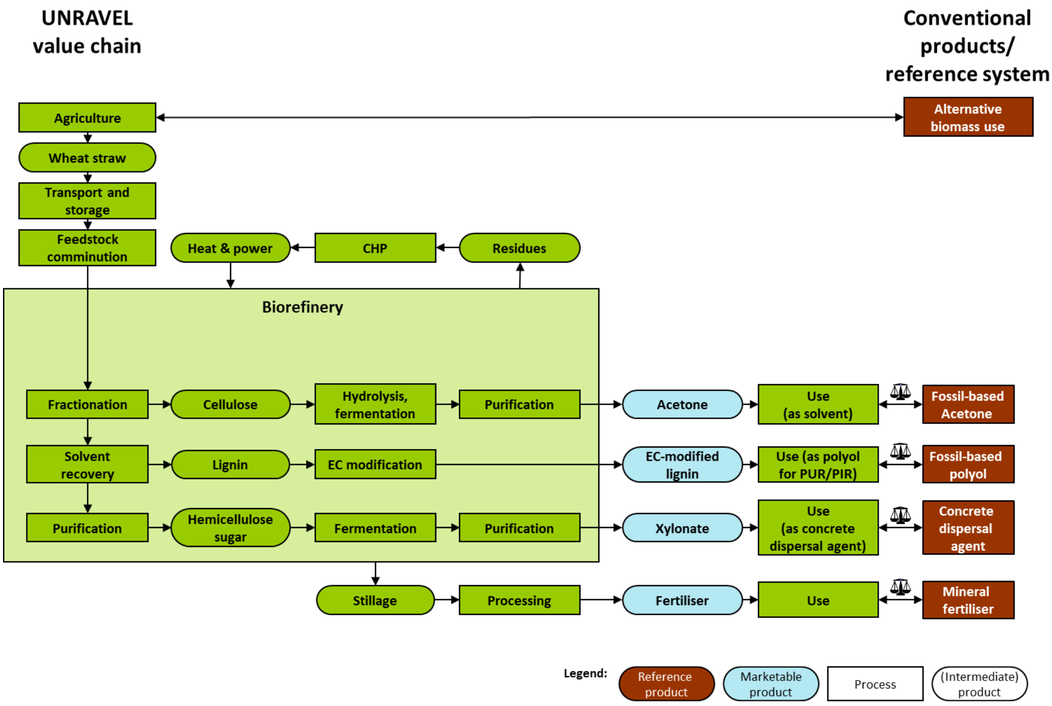

Figure 26: Life cycle scheme of the scenario 'wheat straw'.

10.1.7 Wheat straw, pre-extraction

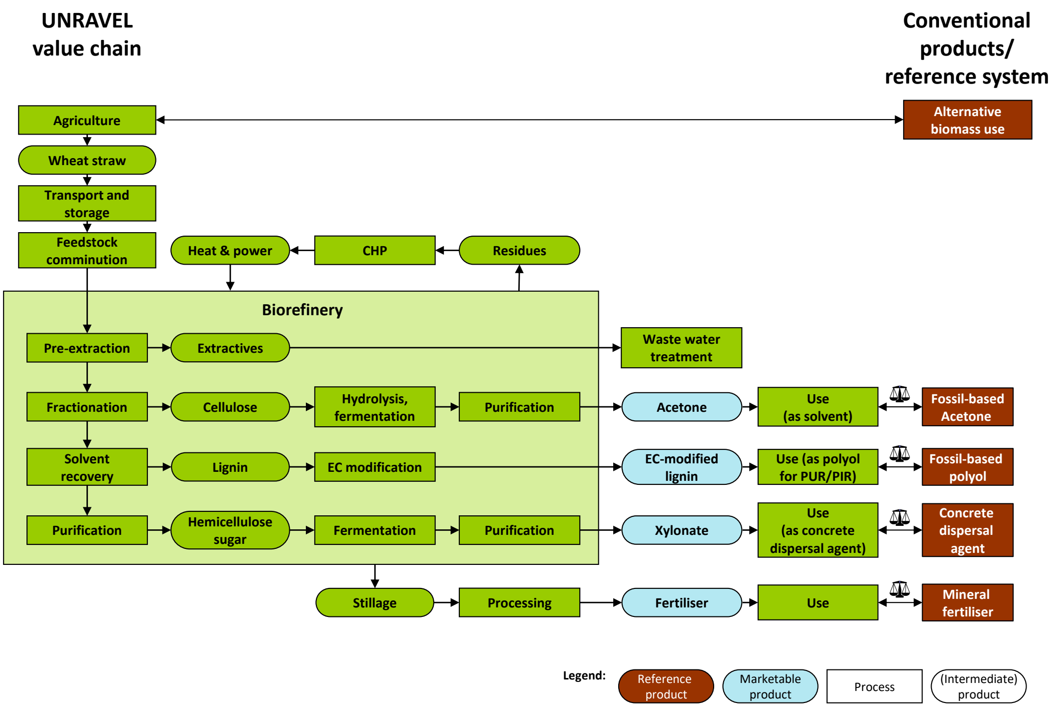

Figure 27: Life cycle scheme of the scenario 'wheat straw, pre-extraction'.

10.1.8 Roadside grass, pre-extraction

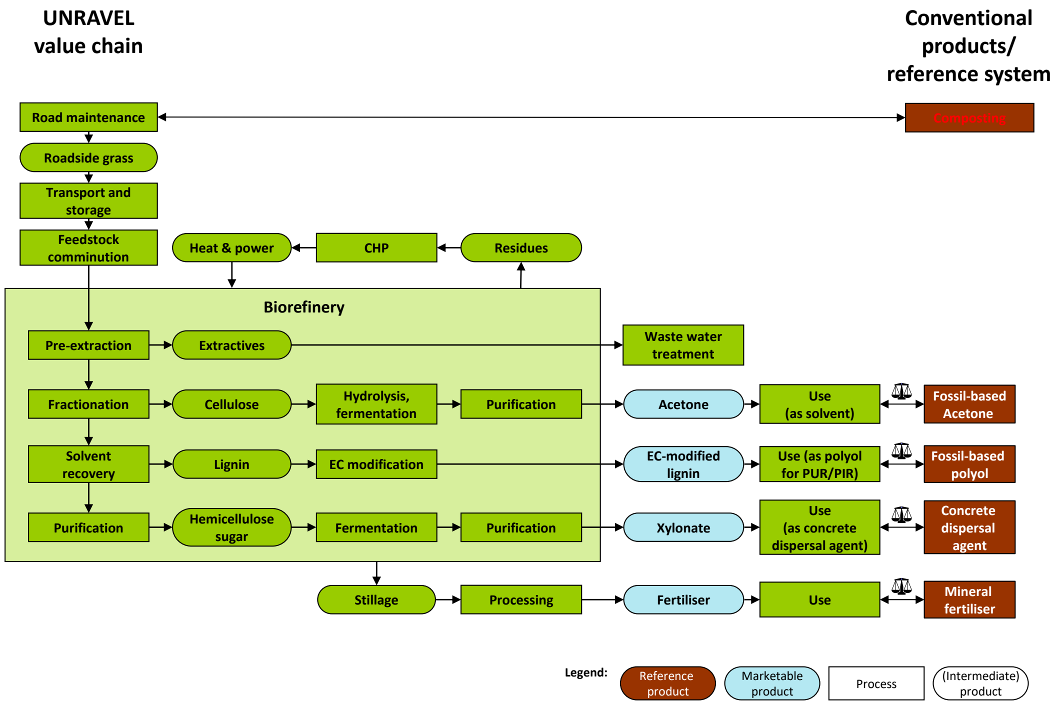

Figure 28: Life cycle scheme of the scenario 'roadside grass, pre-extraction'.

10.1.9 Birch & bark

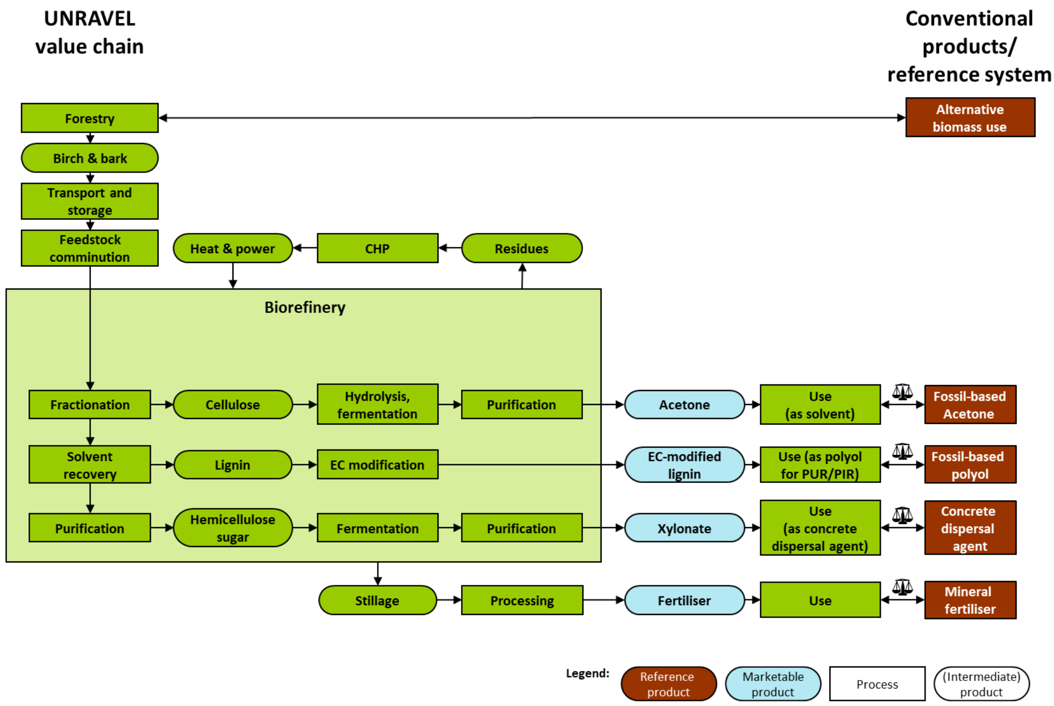

Figure 29: Life cycle scheme of the scenario 'birch & bark'.

10.1.10 Birch & bark, pre-extraction

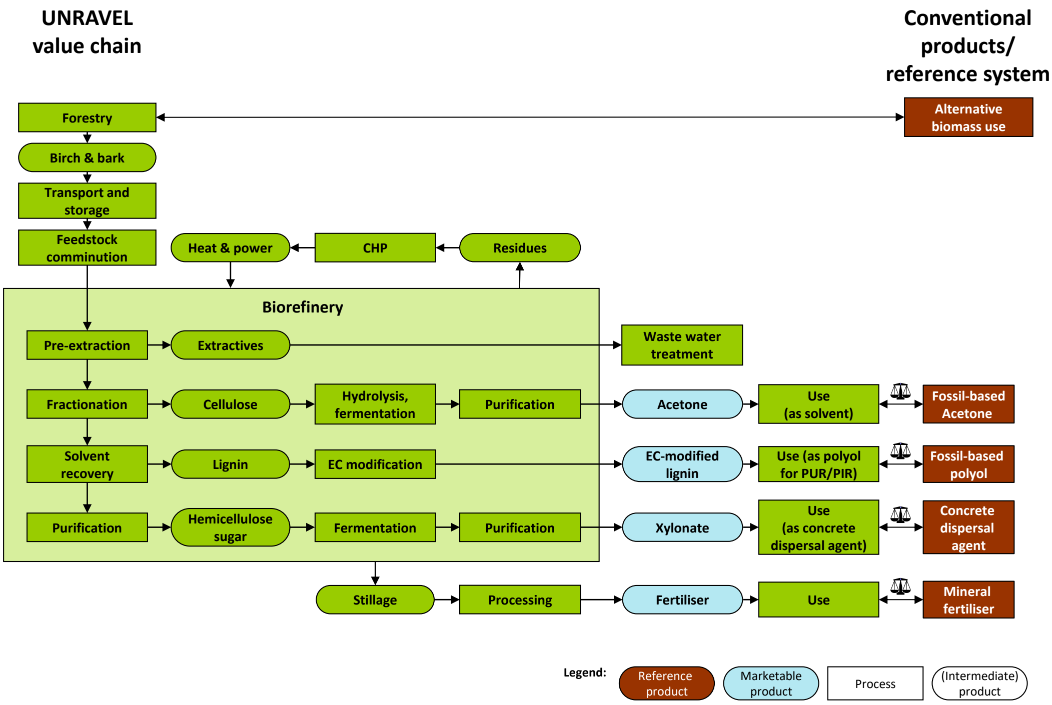

Figure 30: Life cycle scheme of the scenario 'birch & bark, pre-extraction'.

10.1.11 Mixed feedstock, alternating

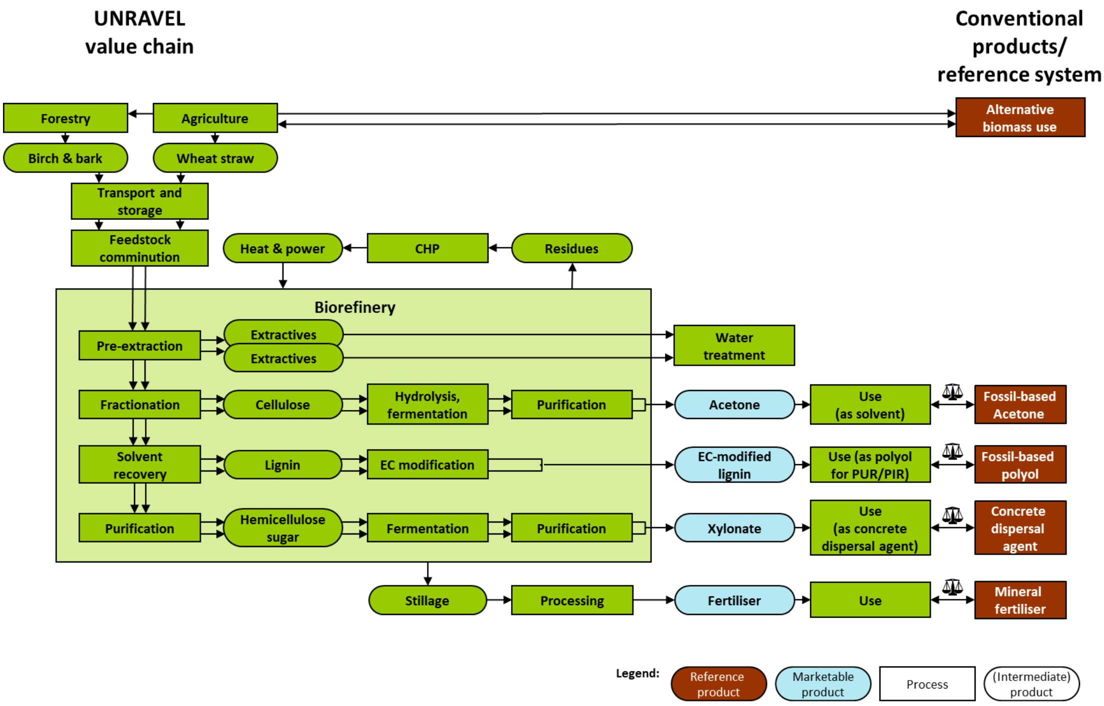

Figure 31: Life cycle scheme of the scenario 'mixed feedstock, alternating'.

10.1.12 Physically mixed feedstock

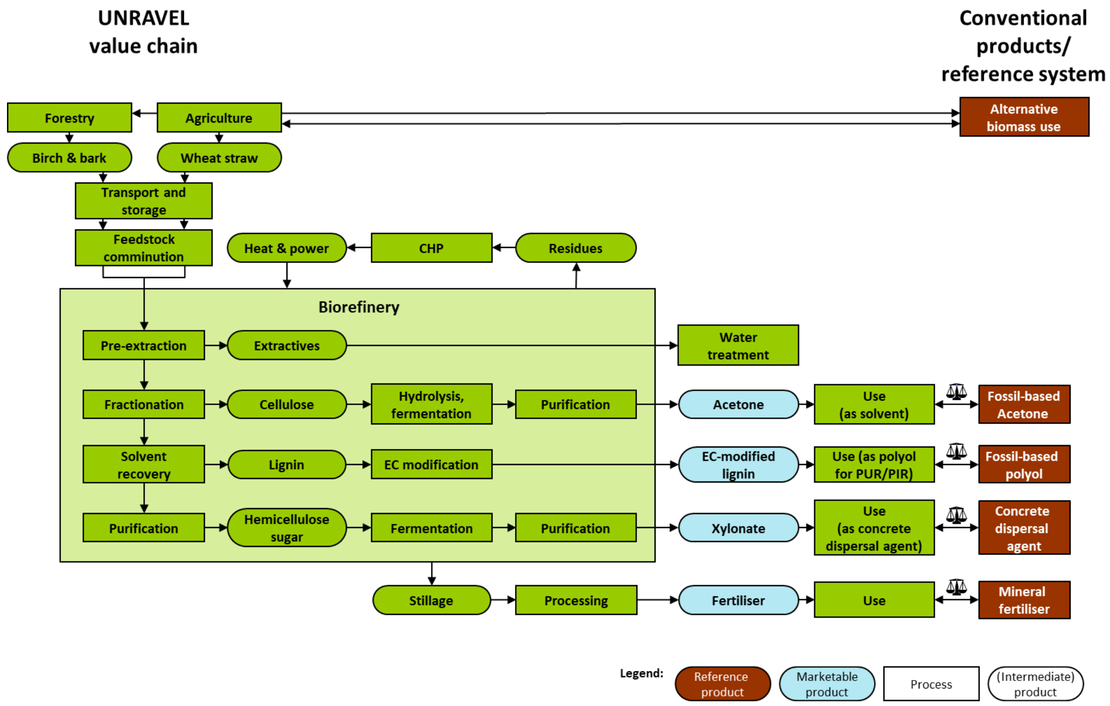

Figure 32: Life cycle scheme of the scenario 'physically mixed feedstock'.

10.2 Additional LCA results

This section provides additional detailed results extending those presented in chapter 4 on environmental impacts of the basic scenario (beech wood) and the scenario using wheat straw without pre-extraction (Figure 33 to Figure 42). Figure 43 shows an overview of the analysed environmental impacts of the wheat straw scenario without pre-extraction normalised to inhabitant equivalents.

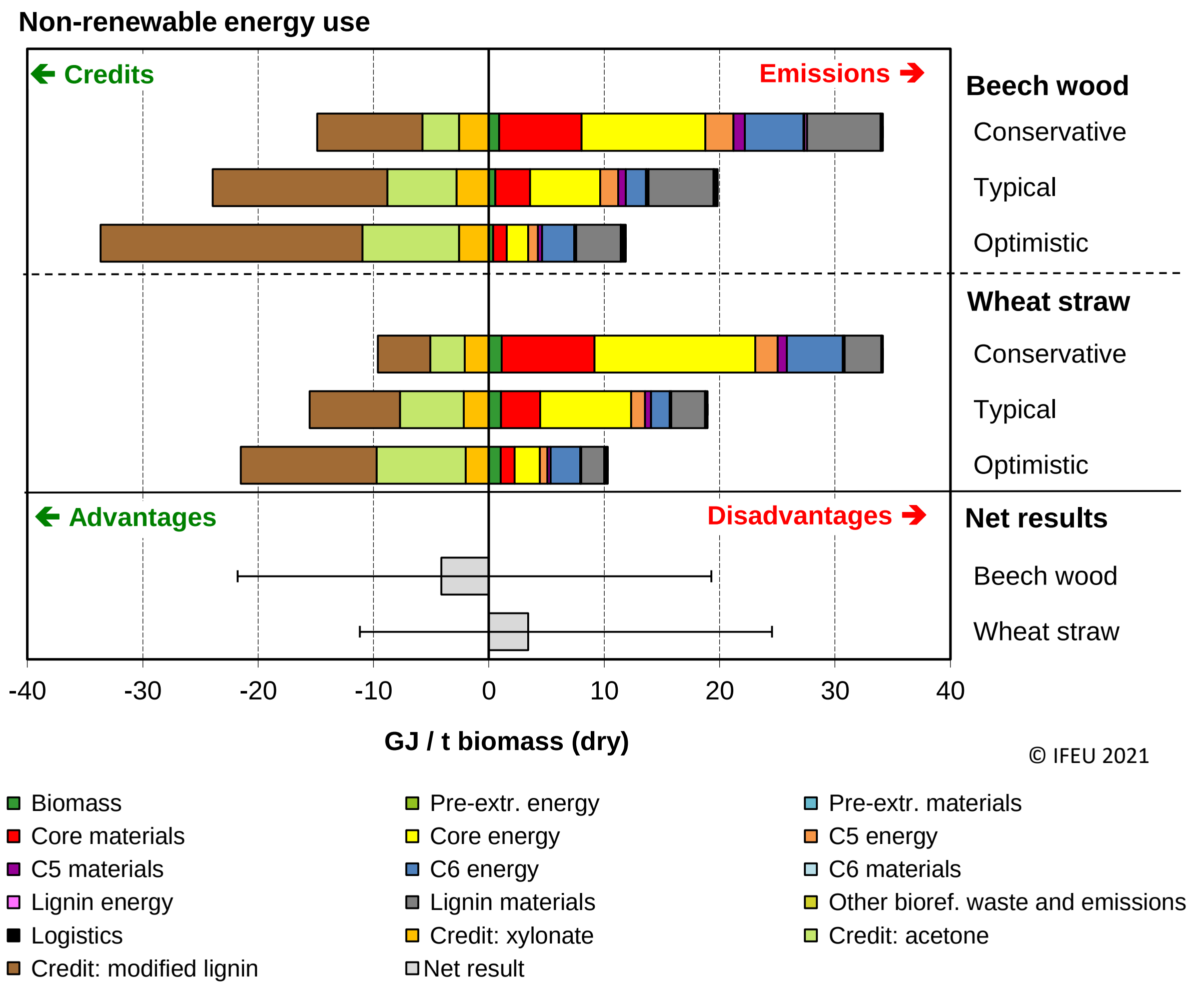

Figure 33: Cumulative non-renewable energy use of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

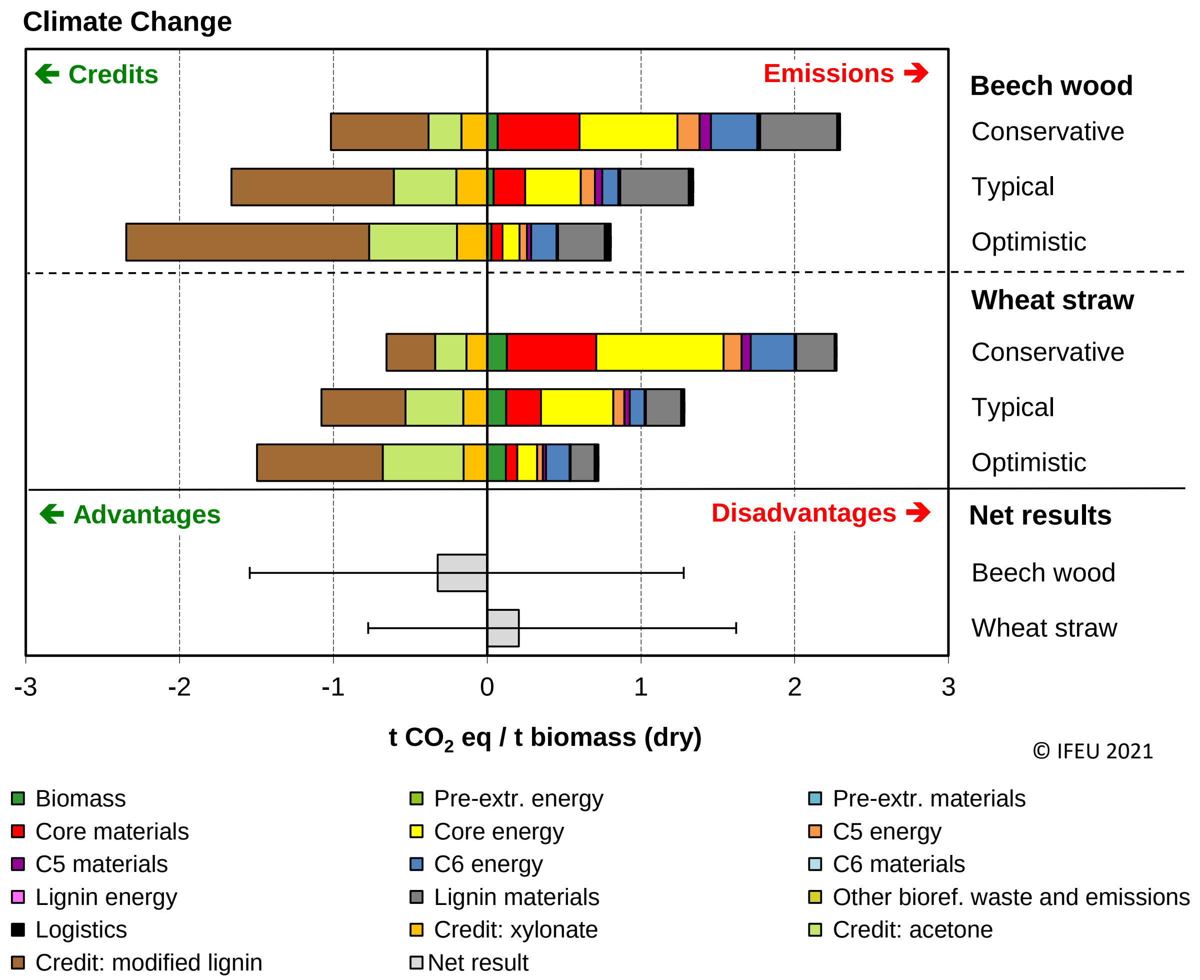

Figure 34: Global warming potential (GWP100) of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

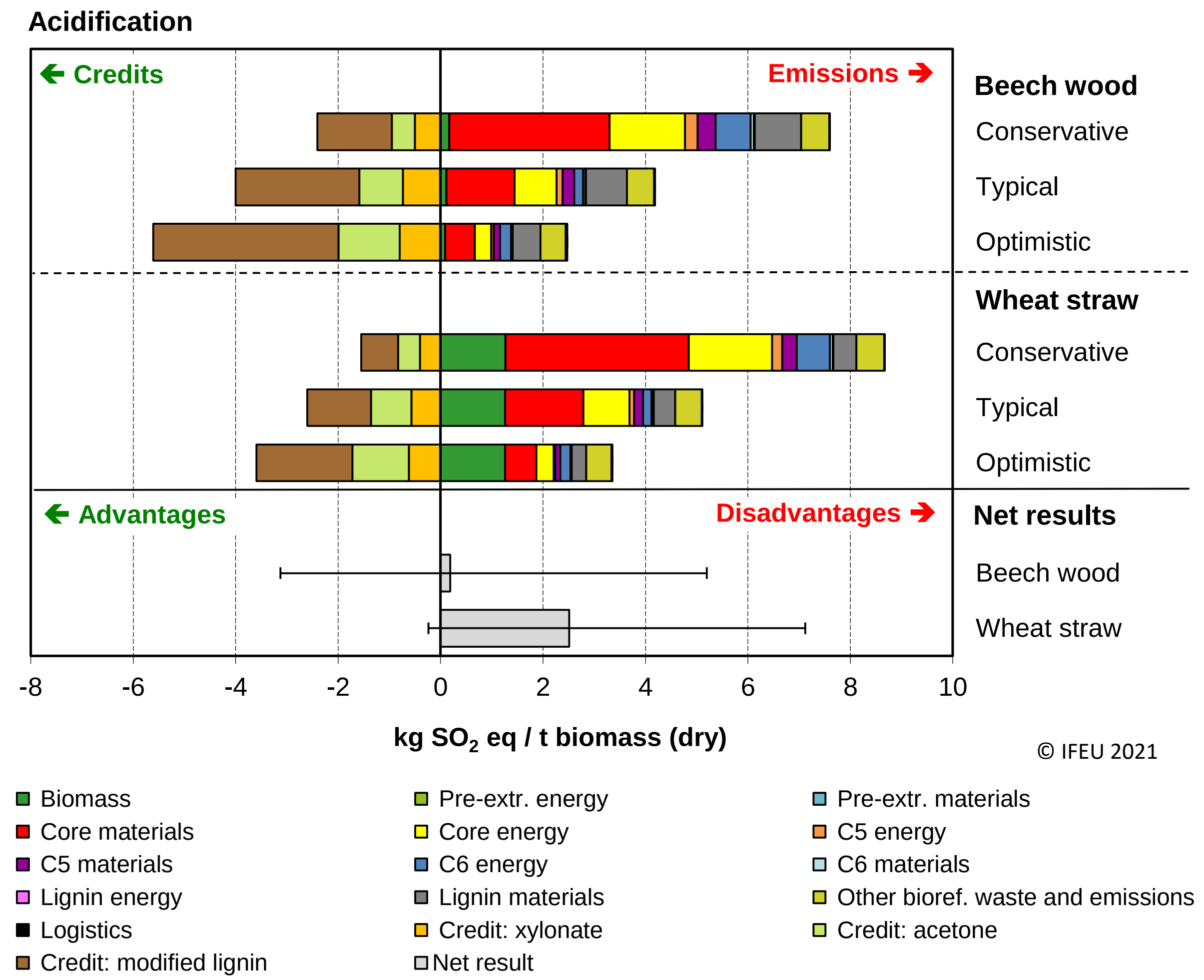

Figure 35: Acidification potential of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

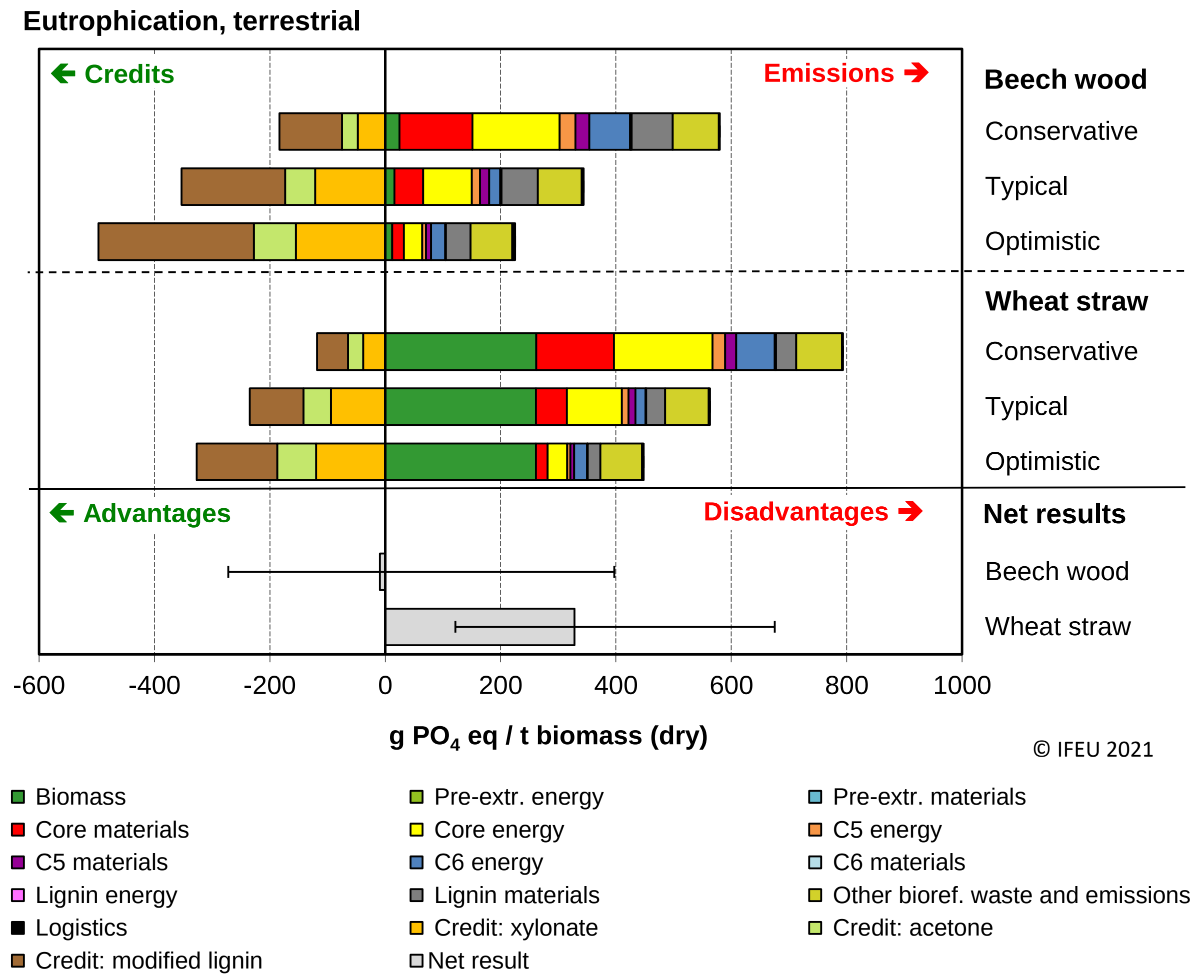

Figure 36: Terrestrial eutrophication potential of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

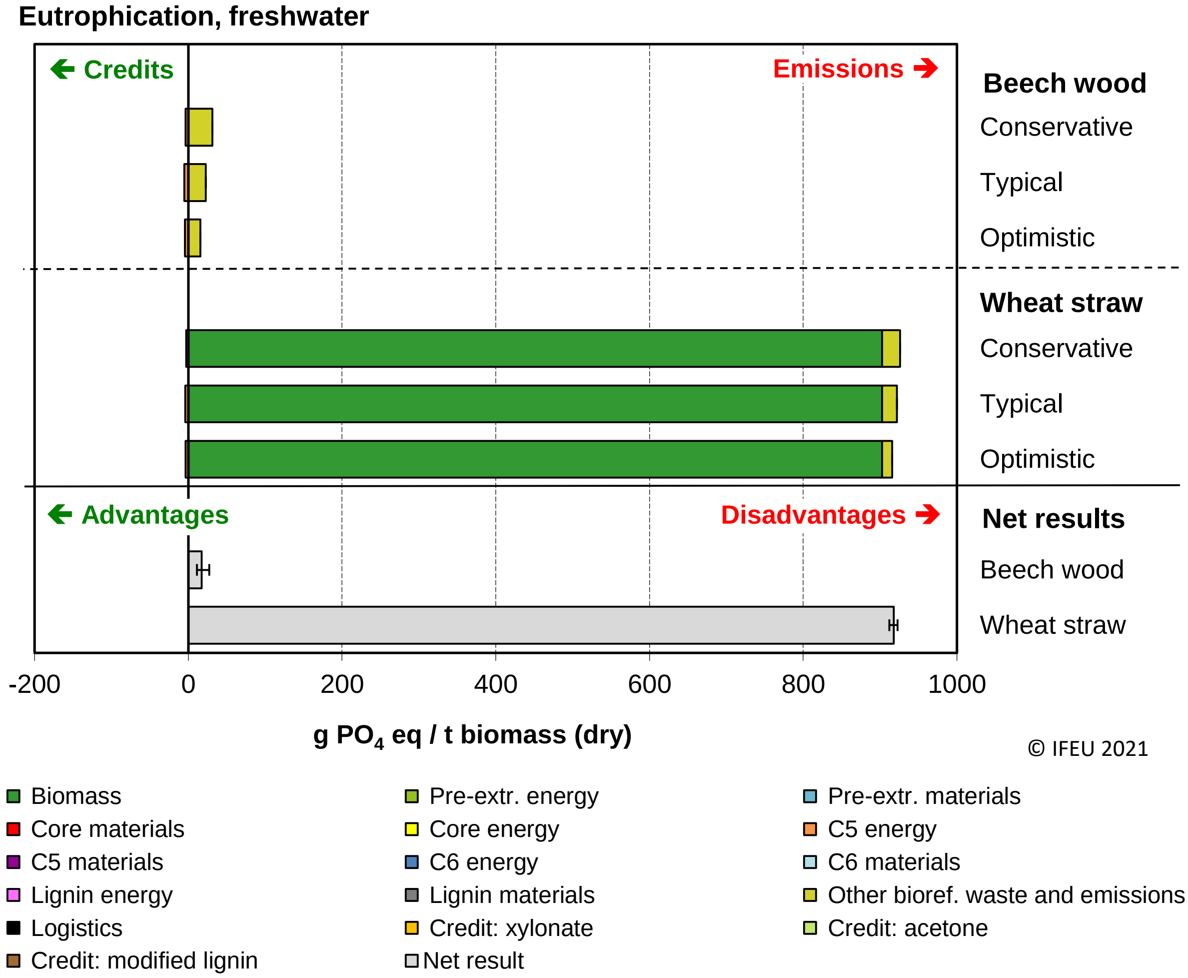

Figure 37: Freshwater eutrophication potential of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

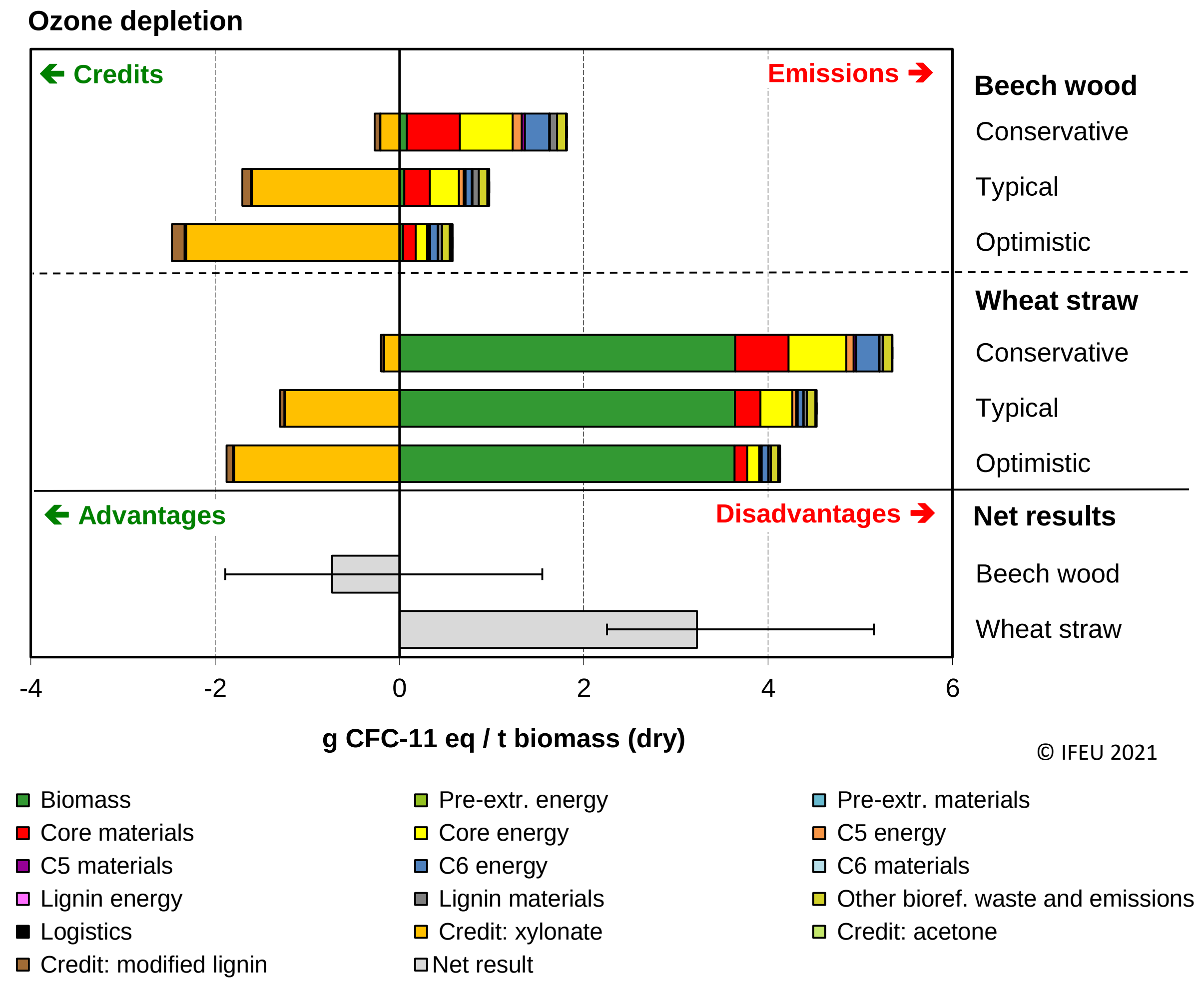

Figure 38: Ozone depletion potential (ODP) of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

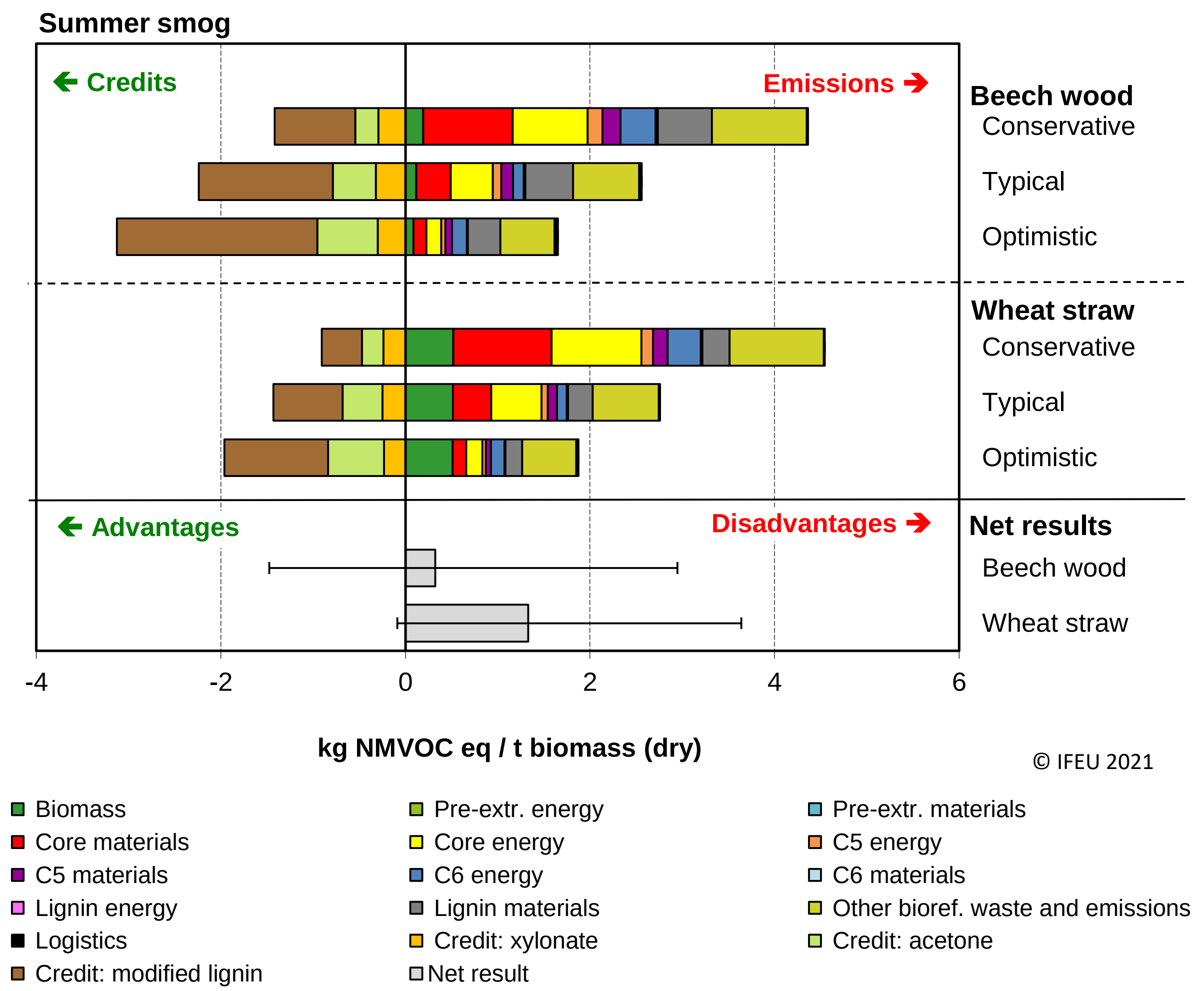

Figure 39: Photochemical ozone formation (summer smog) of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

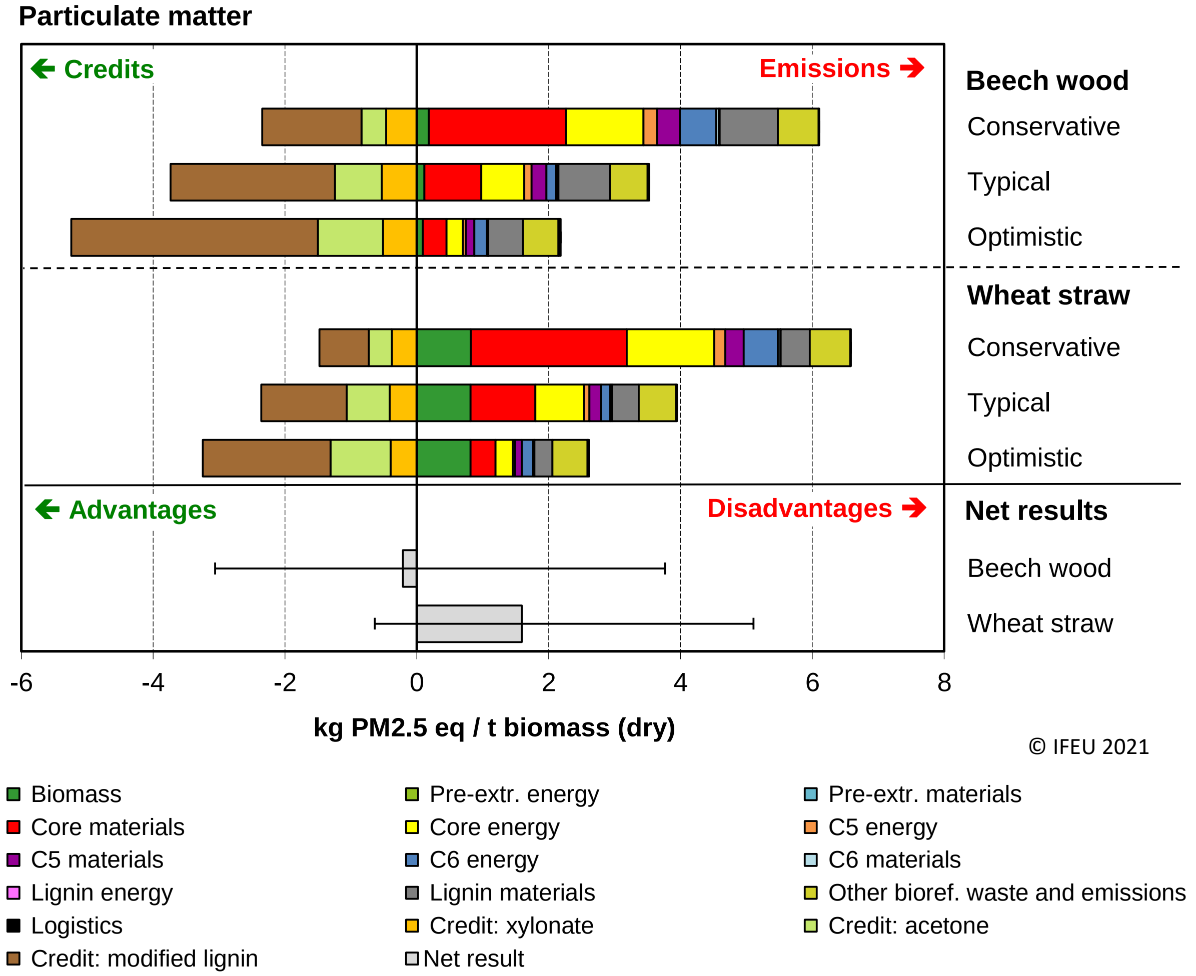

Figure 40: Particulate matter formation of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

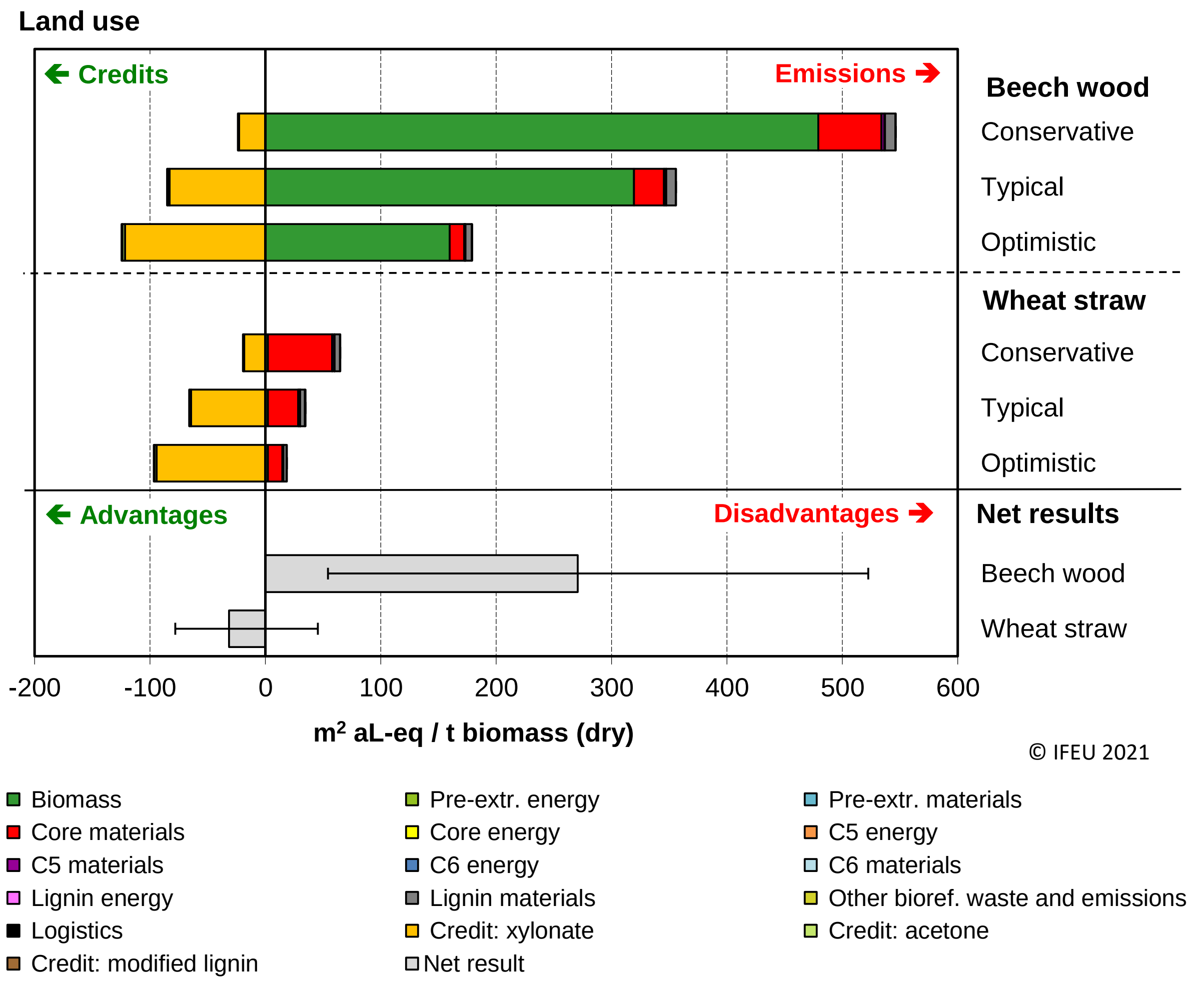

Figure 41: Land use footprint including an assessment of land use intensity expressed in equivalents to most intensively used areas of artificial land (aL) of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

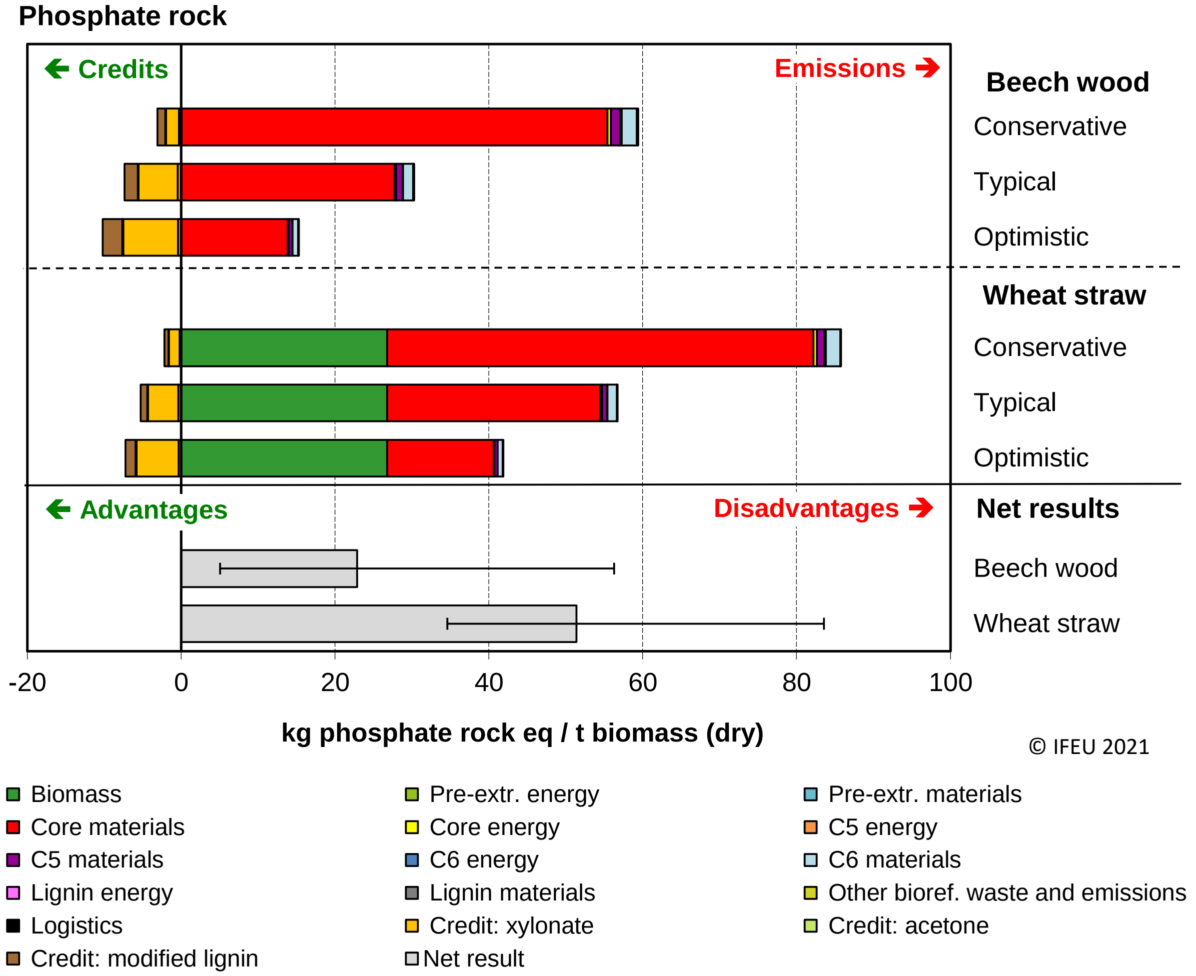

Figure 42: Phosphate rock use of the basic scenario (beech wood) and the scenario on wheat straw use without pre-extraction under typical, conservative and optimistic boundary conditions.

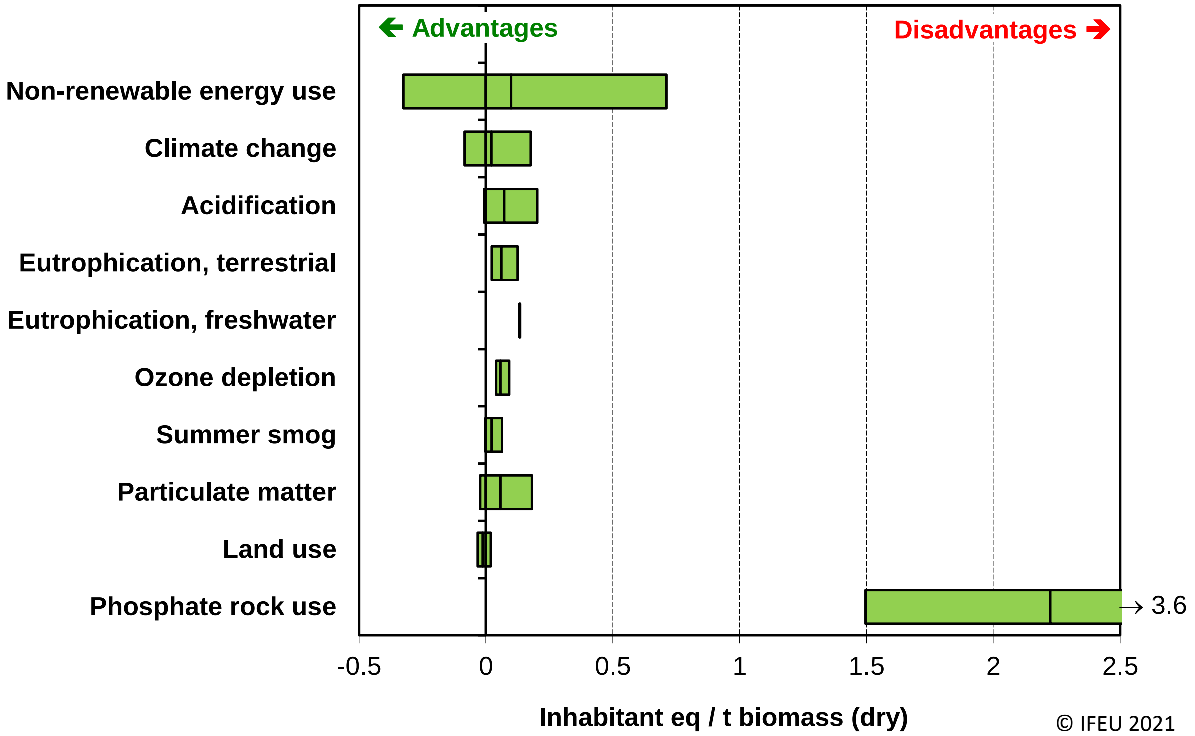

Figure 43: Normalised LCA results (in inhabitant equivalents) of the scenario on wheat straw use without pre-extraction for all impact categories. The bars show the results under a range of possible boundary conditions primarily relating to technology development.