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

(Final report on integrated 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 three major components (cellulose, hemicellulose and lignin) and facilitate efficient conversion into chemicals and building materials. One of these processes is the so-called organosolv process, in which the lignocellulose is treated with organic solvents, of which ethanol has so far been considered state of the art. 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 depicting possible future biorefinery configurations. Besides several biomass feedstock options and alternative technological configurations, the scenarios comprise several valorisations of the lignocellulose fractions: lignin, C5 sugars from hemicellulose and C6 sugars from cellulose (after enzymatic hydrolysis). These valorisations include production of polyols from lignin for polyurethane/polyisocyanurate (PUR/PIR) foams and fermentation of the sugar streams to chemicals (C5 sugars to xylonate and C6 sugars to acetone). This report covers the integrated sustainability assessment. It is based on the integrated life cycle sustainability assessment (ILCSA) methodology and joins and integrates results from the prior environmental, techno-economic, social, SWOT and biomass potentials assessments.

One central result is that the further technological development of the organosolv-based biorefinery concept within this project has led to significant progress in environmental, social and economic sustainability. This is primarily the result of three particularly successful developments that have been achieved:

1. Replacing the previous state-of-the-art ethanol organosolv fractionation process by an acetone-based process directly improves sustainability performance mainly via reduced energy demand and investments.

2. A new pre-extraction process can significantly mitigate two main limitations for the sustainability of lignocellulose biorefineries on an industrial scale: biomass availability and the ability to produce high-value products. This process enhances feedstock flexibility, among others allowing the use of sustainably available biomass residues, and enables the production of higher quality biomass fractions that may also allow previously unreachable product applications. Pre-extraction comes at the cost of increased sustainability impacts and should therefore be applied where advantageous for yields and better lignin usability.

3. Sustainability can also be improved by a promising new use option for lignin: Lignin is modified with ethylene carbonate (EC) for use as a polyol in PUR/PIR foams that can be applied for building insulation.


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It can be concluded that the further development of this lignocellulose biorefinery concept holds great potential for greenhouse gas savings and positive contributions to rural economies, including its own economic viability, while doing no significant harm to other environmental and social sustainability targets. Despite all the progress made, however, none of the assessed possible future biorefinery configurations is capable of reliably achieving any of these goals yet - particularly not concurrently. These not yet sufficient results, however, do not question the acetone organosolv biorefinery concept as such but rather underline that reaching a viable overall concept requires further optimisation particularly in those aspects that have not been the primary target of development.

The following key recommendations for further development and implementation were derived from these results and conclusions:

- Take the next step in **optimising reactor design and process conditions** by switching focus from beech stem wood that is good to process **to a flexible co-processing of particularly low-density biomass residues**, which is superior in terms of sustainable biomass availability and already technically feasible but – at least so far – less efficient. Feedstock densification for low-density feedstocks as straw and grass could also be helpful in this regard. This could resolve the current trade-off between an efficient and thus more sustainable conversion, as observed for scenarios using beech wood, and a more sustainable feedstock provision, as observed for scenarios using biomass residues such as straw and roadside grass.

- Target **more sustainable use options for the intermediates C5 sugars from hemicellulose and C6 sugars from cellulose** than those that were researched in this project to obtain a sustainable overall biorefinery concept. To achieve this, aim at an efficient replacement of energy-intensive fossil-based materials and chemicals, preferably in markets where consumers and industrial clients are willing to pay green premiums for bio-based products. Politics needs to support this by ensuring that these products are really replaced instead of just increasing the amounts of products used.

- Develop an integrated utilities concept which is mainly based on **renewable wind and solar power**, including the replacement of heat-driven processes by electricity-driven ones. In this regard, the use of heat pumps and specifically mechanical vapour recompression heat pumps should be explored.
- Policy-makers must actively work towards a balance between interests of different stakeholders such as future biorefinery operators and other potential biomass users as well as nature conservation requirements in order to prevent stranded investments. To this end, **one-sided incentives for biofuels and bioenergy** must be replaced by sector-independent support and effective **sustainability criteria for biomass residues** based on location-specific thresholds/limits must be consistently implemented across all biomass-using sectors. In the mid- to long-term, holistic **biomass allocation plans** should be developed at national and European level.

Further 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 a sustainable technology option to make best use of available biomass in a future defossilised economy.

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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.

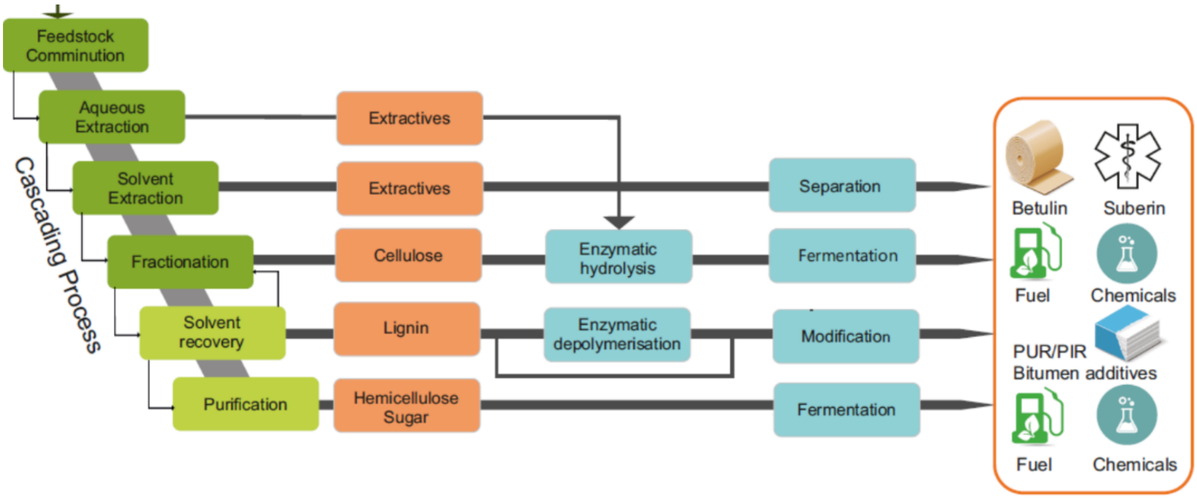


Figure 1: Overview of the UNRAVEL concept.

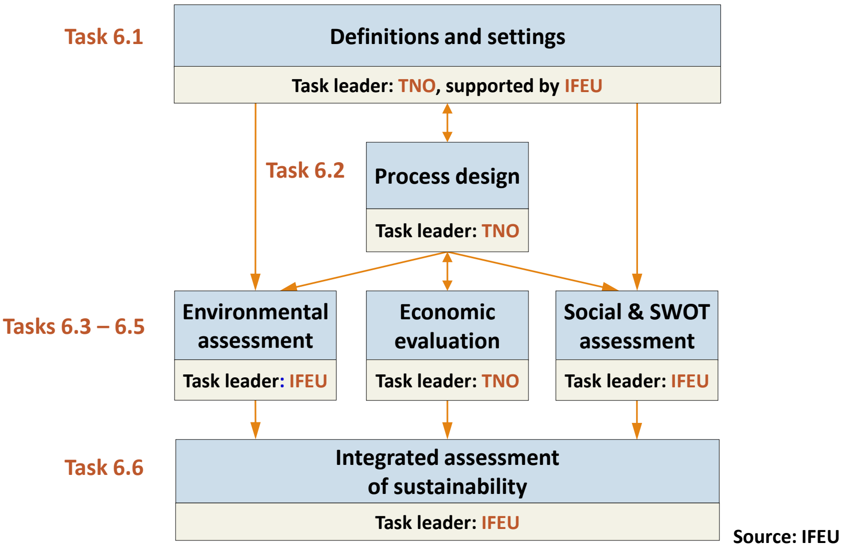
One main motivation for the UNRAVEL project is to improve the technology, economics and further sustainability impacts of advanced pre-treatment, separation and conversion technologies for complex lignocellulosic biomass. The sustainability assessment within this project ensures that process and product 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 integrated sustainability 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] and joins results from the environmental assessment [Keller et al. 2021], social and biomass potentials assessment [Keller & Rettenmaier 2022] and the economic assessment [Dijkstra & Kroon 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 2.2.2). 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], which is briefly introduced in section 2.1. The structure of WP 6 that implements this integrated life cycle sustainability assessment is depicted in Figure 2.



Source: IFEU

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

As a prerequisite for the integrated life cycle sustainability assessment, common goal and scope definitions and other common settings are imperative which apply equally to the environmental, economic and social assessment. Only then can the results of these individual assessments, which always have to be interpreted against the background of the underlying (common) goal and scope definitions, be combined in a meaningful way. These common definitions and settings are described in section 2.2. Specific definitions and settings that are only relevant for the environmental, economic as well as the social and biomass availability assessment can be found in the respective reports [Dijkstra & Kroon 2022; Keller et al. 2021; Keller & Rettenmaier 2022] whereas specific definitions and settings for the integrated sustainability assessment are described in section 2.3.

2.1 ILCSA methodology in a nutshell

The analysis of the life cycles within UNRAVEL follows the integrated life cycle sustainability assessment (ILCSA) methodology (Figure 3). The methodology, described in detail in [Keller et al. 2015], builds upon existing frameworks. ILCSA is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP guidelines for social life cycle assessment [Benoît Norris et al. 2020]. ILCSA extends them with features for ex-ante assessments such as the identification of implementation barriers that increase the value for decision makers. This flexibility allows for focussing on those sustainability aspects relevant in the respective decision situation using the best available methodology for assessing each aspect within the overarching ILCSA. Furthermore, it introduces a structured discussion of results to derive concrete conclusions and recommendations. See section 2.3 for details on the procedure selected in this study.

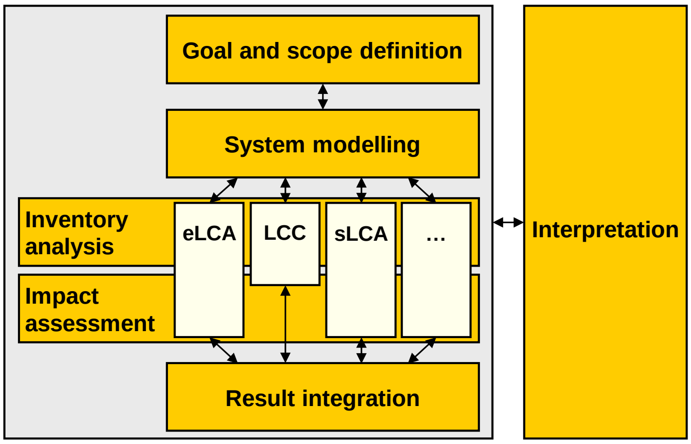


Figure 3: Schematic workflow of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015].It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle assessment, (e)LCA, life cycle costing, LCC, social life cycle assessment, sLCA and analyses of other sustainability-relevant aspects.

2.2 Common definitions and settings

A well-founded sustainability assessment requires common definitions and settings on which the environmental, economic and social assessment 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.

2.2.1 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?

2.2.2 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). As far as available, generic datasets for the EU are used. Otherwise, the Netherlands are used as example complemented by sensitivity analyses for France and Eastern Europe. This is in particular the case for the economic and social assessments.

2.3 Specific definitions and settings for ILCSA

The integrated sustainability assessment in UNRAVEL is based on the integrated life cycle sustainability assessment (ILCSA) methodology [Keller et al. 2015]. In the following sub-sections, specific settings and methodological choices are detailed.

2.3.1 General approach

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

Weighting and mathematical integration

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

Structured discussion

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

2.3.2 Collection of indicators and results

Indicators and results for all scenarios are provided by the parallel assessments of individual sustainability aspects [Dijkstra & Kroon 2022; Keller et al. 2021; Keller & Rettenmaier 2022]. They are collected in overview tables. In some cases, indicators are selected or aggregated by the authors of the respective individual assessment to focus on the most relevant aspects for decision support.

The integrated sustainability assessment of this project is based on:

- 10 quantitative environmental indicators from life cycle assessment
- 3 semi-quantitative environmental indicators from life cycle environmental impact assessment
- 3 quantitative economic indicators
- 5 quantitative and 2 qualitative social indicators
- 1 qualitative indicator on sustainable feedstock availability

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

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly. Green boxes represent overall advantageous results, i.e. an improvement compared to a situation without UNRAVEL. Orange and red boxes represent overall disadvantages, i.e. a deterioration compared to a situation without UNRAVEL. Yellow boxes represent a minor sustainability impact. This way of categorising results supports the identification of options that perform best among all studied options but also maintains the quantitative information on the sustainability of a scenario. Results are collected for all assessed main scenarios. Additional results such as from sensitivity analyses based on dedicated scenarios, which are only relevant for one aspect of sustainability, are not collected. Results from these very specific analyses, e.g. identified boundary conditions that are necessary to reach the environmental performance of a certain main scenario, are part of the result summaries in chapter 4. They are taken into account for the overall conclusions (section 6.1) and recommendations (section 6.2).

2.3.3 Additional indicators

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

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

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

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

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

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

GHG abatement costs are expressed in Euro per tonne of CO_2 equivalents. Costs can refer to subsidies, costs covered by a company or green premiums paid by customers depending on the perspective and GHG emissions expressed in CO_2 equivalents.

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

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

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

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

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

Taken together, abatement costs for environmental burdens such as greenhouse gas emissions can help to decide how mitigations of environmental burdens can be reached for the lowest price or even with profits. However, abatement costs have to be interpreted carefully because in many situations their robustness and comparability are poor. For further details and a critical review of the method see [Pehnt et al. 2010].

2.3.4 Benchmarking

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

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

A subsequent categorisation of the benchmarking results reflects the robustness of advantages or disadvantages over the benchmark. For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question whether a scenario performs better than the benchmark regarding a certain indicator. Therefore, these quantitative differences are categorised into very advantageous [++], advantageous [+], neutral [0], disadvantageous [-], or very disadvantageous [--]. Two results are rated as not substantially different if the difference is below a threshold of 5% of the range from the best results to the worst result among all scenarios regarding a specific indicator. The certainty of this rating is evaluated by additionally taking the range of the data into account. For all qualitative indicators, rating of differences is done analogously but without applying minimum differences.

2.3.5 Overall comparison

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

3 System description

3.1 Overview of the UNRAVEL concept

An overview of the UNRAVEL concept is depicted in Figure 1 in chapter 1. A more detailed life cycle scheme of the basic scenario is depicted in Figure 4 in section 3.2.

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 integrated sustainability assessment are summarised in Table 2. More information on the particular scenarios is described in sections 3.2.1 - 3.2.13. While in section 3.2.1 the basic scenario is described in detail, sections 3.2.2 - 3.2.13 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 2: Final selection of scenarios analysed within the integrated sustainability assessment.

Scenario	Description	Section
Beech wood		
Basic scenario (beech)	Feedstock: beech stemwood, 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 (ethanol organosolv)	Difference to basic scenario: fractionation via ethanol organosolv instead of Fabiola™ fractionation process.	3.2.5
Herbaceous biomass		
Wheat straw	Difference to basic scenario: feedstock: wheat straw instead of beech stemwood.	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 stemwood, 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 stemwood.	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
Wheat straw, regional sensitivity analysis		
Wheat straw, France	As wheat straw, economic and social data for France used.	3.2.13
Wheat straw, Eastern Europe	As wheat straw, economic and social data for Eastern Europe used.	3.2.13

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 4). This scenario is based on generic EU data where available. Otherwise, data for the Netherlands are used as example (see also section 2.2.2 'Geographical scope').

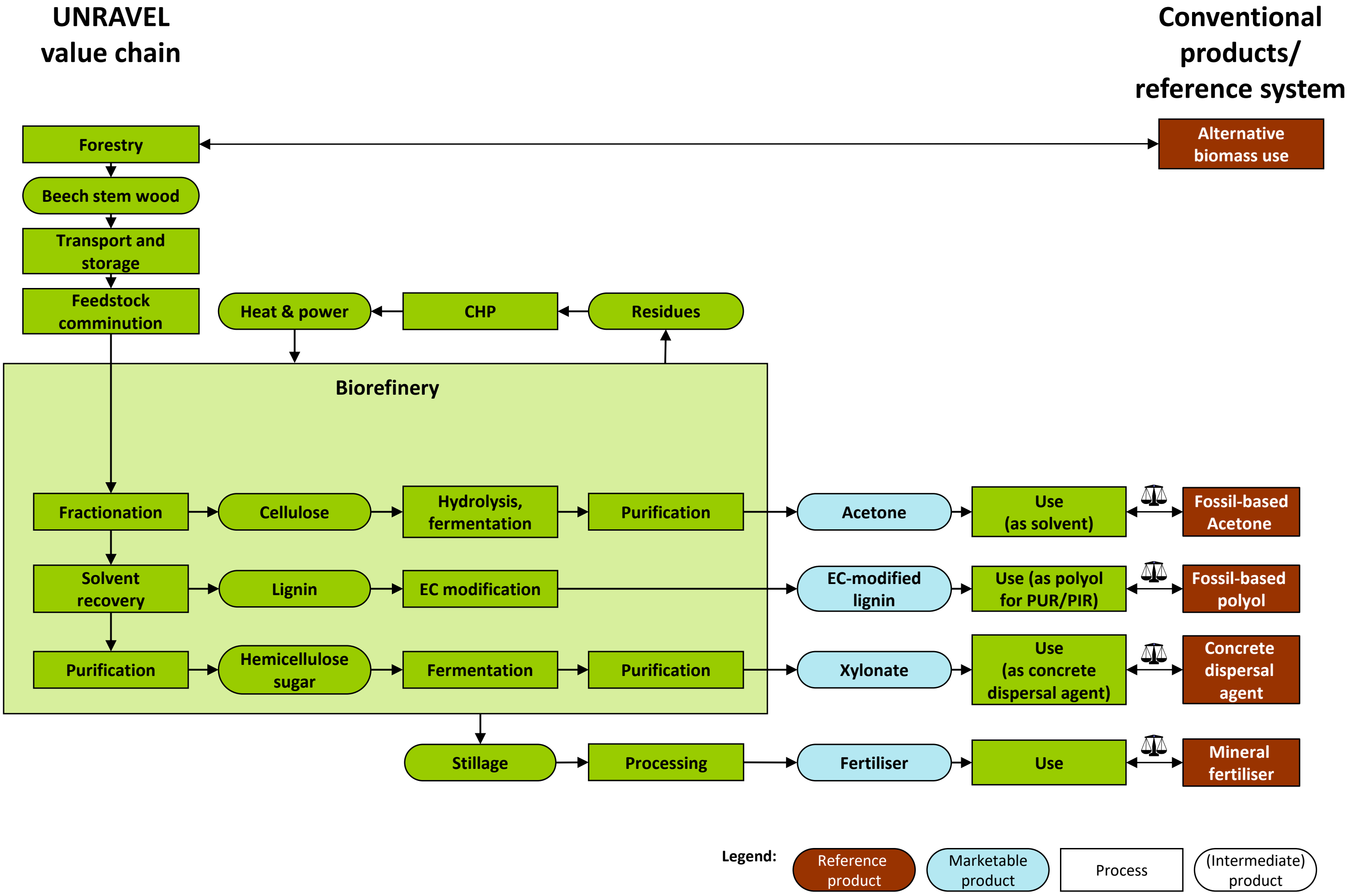


Figure 4: Life cycle scheme of the basic scenario (beech).

This scenario uses beech stemwood in pulp wood / energy wood quality such as obtained from forest thinnings. After harvesting the beech stemwood, 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 stemwood 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.

The preferential evaporation of solvent in the falling film evaporator results in a low solvent content of the slurry, which induces the lignin precipitation in precipitation vessel. The solvent rich overhead vapour of the falling film evaporator is sent to a distillation where part of the water and the small amounts of furfural are removed. Minor amounts of CO_2 being formed during fractionation 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 filtration 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

The filtrate from lignin filtration, which is lean in lignin and solvent, 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).

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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 is used to concentrate after which the sodium xylonate is obtained via cooling crystallisation, after which it 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.

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.

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.

3.2.5 Reference (ethanol organosolv)

In the reference scenario the currently common state-of-the-art ethanol organosolv fractionation process is used instead of the Fabiola™ acetone organosolv process. Both processes were assessed using the same approach and settings while certain technological parameters deviate due to the different nature of the processes. 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 rectification column to achieve the required solvent concentrations in the lignin precipitation section.

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.

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 stemwood (Figure 5). 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 non-lignocellulose 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.

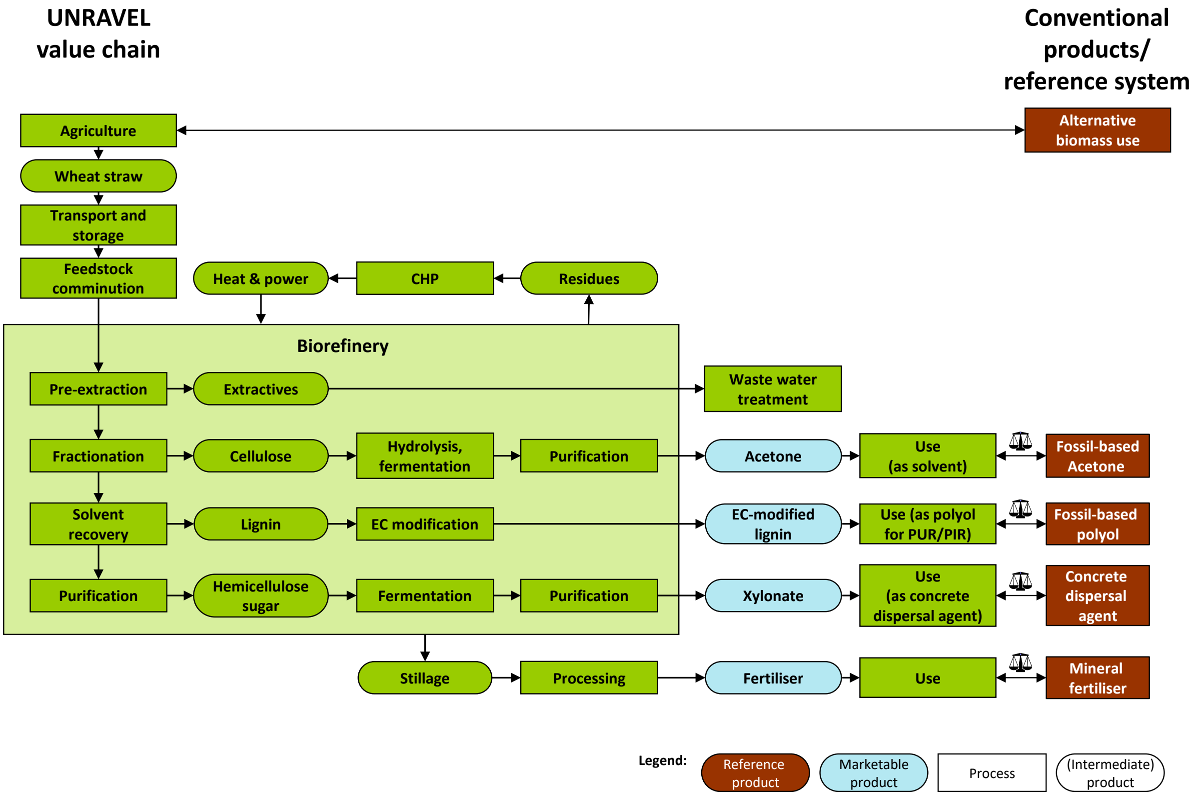

Figure 5: Life cycle scheme of the scenario 'wheat straw, pre-extraction'.

3.2.8 Roadside grass, pre-extraction

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

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 stemwood.

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 stemwood. Furthermore, as in scenario 'wheat straw, pre-extraction', the fractionation process is preceded by a pre-extraction process (see section 3.2.7).

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3.2.11 Mixed feedstock, alternating

In the scenario 'mixed feedstock, alternating' wheat straw as well as branches and tops of birch trees including their bark and residual foliage are used in alternating campaigns as biomass feedstock instead of beech stemwood. 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.

3.2.12 Physically mixed feedstock

In the scenario 'physically mixed feedstock' wheat straw as well as branches and tops of birch trees including their bark and residual foliage are mixed physically and then used as biomass feedstock instead of beech stemwood. 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.

3.2.13 Wheat straw, regional sensitivity analyses

In particular economic and socio-economic conditions can be highly heterogeneous in the EU. Therefore, economic and socio-economic background data is not available on a generic EU level. In addition to the data on the Netherlands, which is exemplarily used in the main scenarios, these sensitivity analyses use data for France and semi-generic data for Eastern Europe.


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3.3 Additional sensitivity analyses

The scenarios described in section 3.2 are analysed taking into account variability in various input data such as the use of various background data sets including electricity provision from several sources or using social risk data from several related sectors. All results of these sensitivity analyses that do not lead to further insights but substantiate existing conclusions are described in [Dijkstra & Kroon 2022; Keller et al. 2021; Keller & Rettenmaier 2022].

Competition for biomass caused by the biomass use of potential UNRAVEL biorefineries is an important indirect effect on the background system that can prevent other established uses of that biomass. This indirect effect can cause considerably different overall environmental impacts which leads to additional conclusions and recommendations. Results are displayed in this report exemplarily for the environmental impact category 'climate change'. Further details and results can be found in [Keller et al. 2021]. The scenario extension behind this sensitivity analysis is described in the following taking the basic scenario using beech stemwood as an example.

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 stemwood 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 stemwood from the use in a combined heat and power plant (illustrated in Figure 6). 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. The sensitivity analysis shown in this report depicts the exemplary situation that biomass formerly used in a CHP is withdrawn and instead used in the biorefinery. Results from this sensitivity analysis are shown in chapter 5 as 'climate change incl. competition'. Sensitivity analyses regarding other competitions performed in the environmental assessment did not show substantial differences in the results.

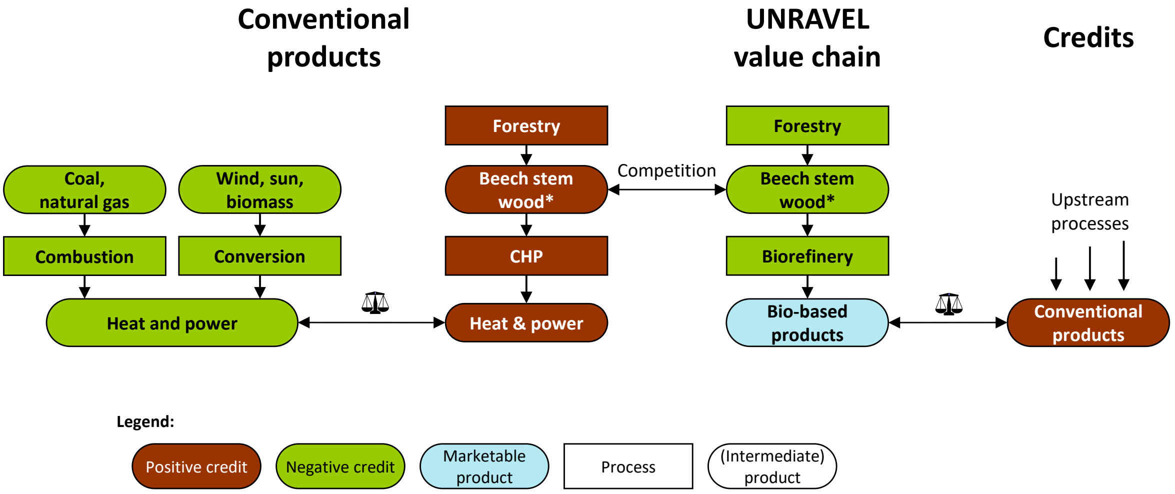

Figure 6: Life cycle scheme of the beech wood scenario including the competing use of beech stemwood for energy in a combined heat and power plant. *Quality: energy/pulp wood.*

4 Summaries of assessments of individual sustainability aspects

In a first step of the sustainability assessment, environmental, social and economic sustainability aspects were analysed individually [Dijkstra & Kroon 2022; Keller et al. 2021; Keller & Rettenmaier 2022] based on the same definitions, settings and data (see chapters 2 and 3). As a basis for further analyses, this chapter contains summaries of the assessments of individual sustainability aspects (sections 4.1 - 4.3). Details can be found in the assessment reports [Dijkstra & Kroon 2022; Keller et al. 2021; Keller & Rettenmaier 2022]. The results from these individual assessments are combined, extended and jointly assessed in chapter 5.

4.1 Summary: environmental assessment

The environmental assessment analysed all environmental implications of the scenarios described in section 3.2. The environmental assessment consists of two parts: a screening life cycle assessment (LCA) which addresses impacts at global and regional level and a life cycle environmental impact assessment (LC-EIA) for impacts at local level. For the applied methodology and further details please refer to the original environmental assessment report [Keller et al. 2021]. The most important results and conclusions are summarised in the following.

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 (see Figure 7).
- 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. Greenhouse gas emissions can be reduced by 30% if implementation succeeds as expected. This clearly exceeds the project objective to reduce the carbon footprint by at least 15%.

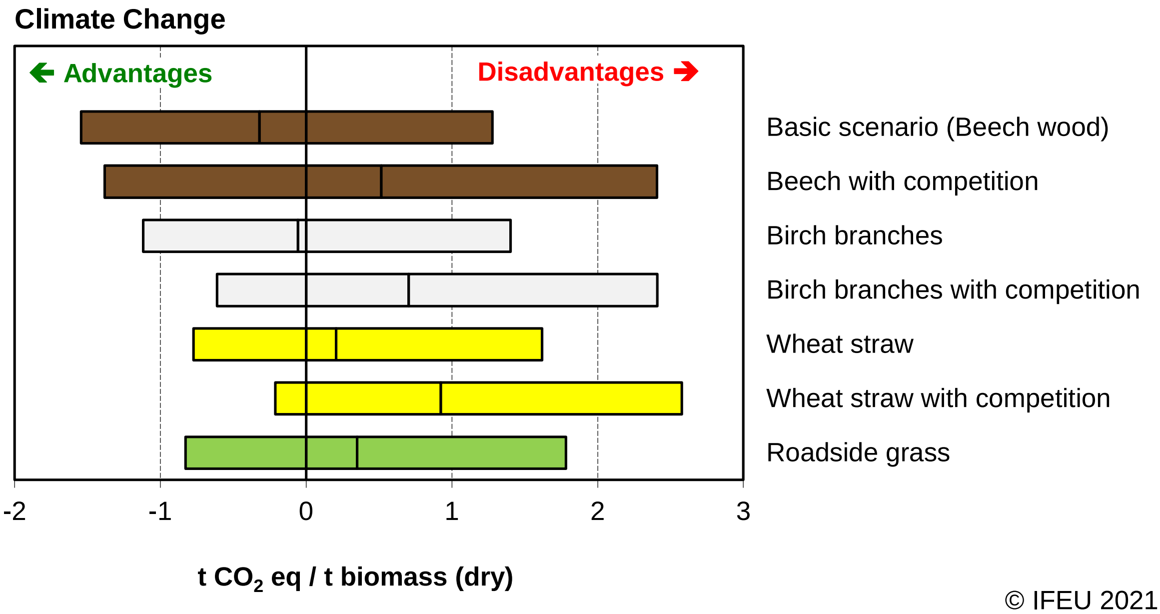

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Figure 7: Comparison of life cycle greenhouse gas emissions of various scenarios of the UNRAVEL biorefinery using different feedstocks (with and without competing uses, all without pre-extraction). Bars display ranges from optimistic via typical to 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).

- 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 (see also Figure 8):
  - 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 (see Figure 9). 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.

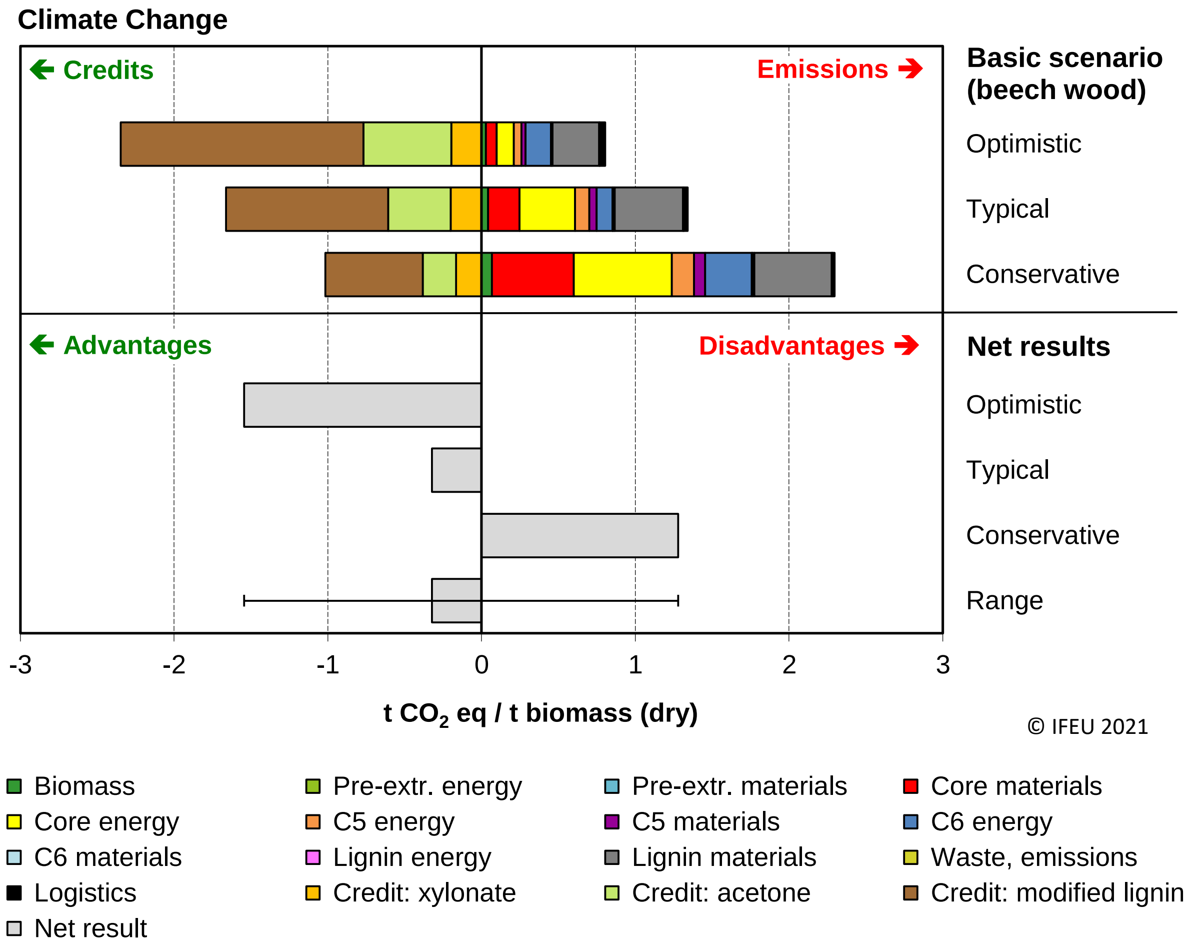

Figure 8: Comparison of life cycle greenhouse gas emissions of the basic scenario (beech wood) of the UNRAVEL biorefinery with those of substituted conventional products. Sub-scenarios under a range of possible boundary conditions primarily relating to technology development result in a range of possible results.

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.

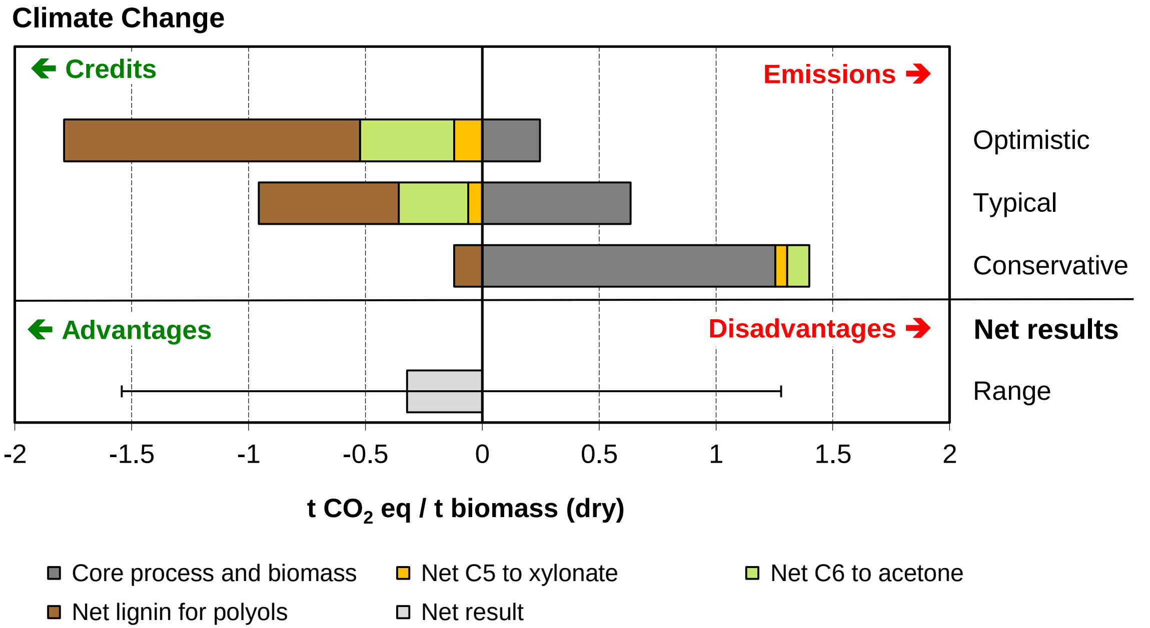

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Figure 9: Contributions of the use of C5, C6 and lignin fractions to compensating greenhouse gas emissions of the core process in the basic scenario (beech wood. Net emissions of the fractions include credits for substituted conventional products. 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).

Conclusions

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.

4.2 Summary: economic assessment

The economic assessment addresses the profitability of the process at commercial scale based on the scenarios and data described in section 3.2. For the applied methods and further details please refer to the original assessment report [Dijkstra & Kroon 2022].

The concept evaluated is the fractionation of biomass into three main fractions and valorisation of these fractions (see Figure 1 in chapter 1). C6 is valorised to acetone, C5 to xylonate and lignin is valorised with ethylene carbonate (EC) to modified lignin as a polyol replacement in PUR/PIR production (insulation foams). Optionally, biomass may be pre-extracted (upgraded) to improve the fractionation and improve lignin quality.

The basic scenario is fractionation of beech wood without pre-extraction. Plant location is Rotterdam. Residues are used for combined heat and power. Plant size was 300 ktonnes/yr of biomass dry matter basis for all scenarios (see also section 3.2.1).

Scenarios that were defined for variation of biomass feedstock, technology and plant location are summarised in Table 2 in section 3.2. These include alternative feedstocks, systems with and without pre-extraction, a different route for lignin valorisation: using trimethyl phosphate (TMP) modification to produce a hydrophobic lignin, and lignin combustion for heat generation and combustion of the residue stream to heat only rather than to combined heat and power. The scenarios also included mixed feedstocks (physically mixed as well as operation with the same feedstock ratio).

The investments of the process were assessed using a model-based cost estimation approach in the Aspen Process Economic Evaluator software. For the prices of feedstocks, consumables utilities and products, an inventory of representative market prices from open literature was made. Using these, the concept has been evaluated against the several key performance indicators such as the *total depreciable capital*, *OPEX* (total operating expenses excluding depreciation, and including biomass feedstock costs). The *total capital investment (TCI)*, internal rate of return *IRR* and net present value *NPV* have been calculated but proved difficult to interpret because these were often negative. The preferred final indicators therefore used were the *total depreciable capital (TDC)* and the *green premium* required. The green premium required is the percentage of additional income compared to the market price of conventional products the biorefinery replaces, that is required for economic viability that includes a return on capital of 10%. This additional income may come from a higher market value of renewable products for instance from producers of products for the consumer market or from mandatory measures from the government. The government could also choose for feed-in subsidies. Also other climate or sustainability policy or societal or public shifts will lead to higher market values. The uncertainty range of each of the key performance indicators was assessed using optimistic and pessimistic scenarios. The uncertainty range does not include the positive effects of a more stringent or a more developed climate policy. It does also not include the effects of a further development or optimization of the investigated processes.

Results for the basic scenario show that the main investments are in the core fractionation process of biomass into intermediates: lignin, C5 (hemicellulosic) sugars and C6 sugars (glucose). Here, the most significant contributions are for the filtrations, fractionation percolators, and solvent recovery columns. A significant and uncertain contribution is from a vapour compressor. The enzymatic hydrolysis contribution is also significant. This could be omitted in the case of producing a pulp product as an alternative to the C6 intermediate. Considering the investment in valorisations, that of the C6 to acetone is the most significant, whereas those of lignin modification and C5 to xylonate are relatively lower. Total capital investments were found to be 328 MEUR, the NPV was found -178 MEUR before tax, IRR -2% before tax.

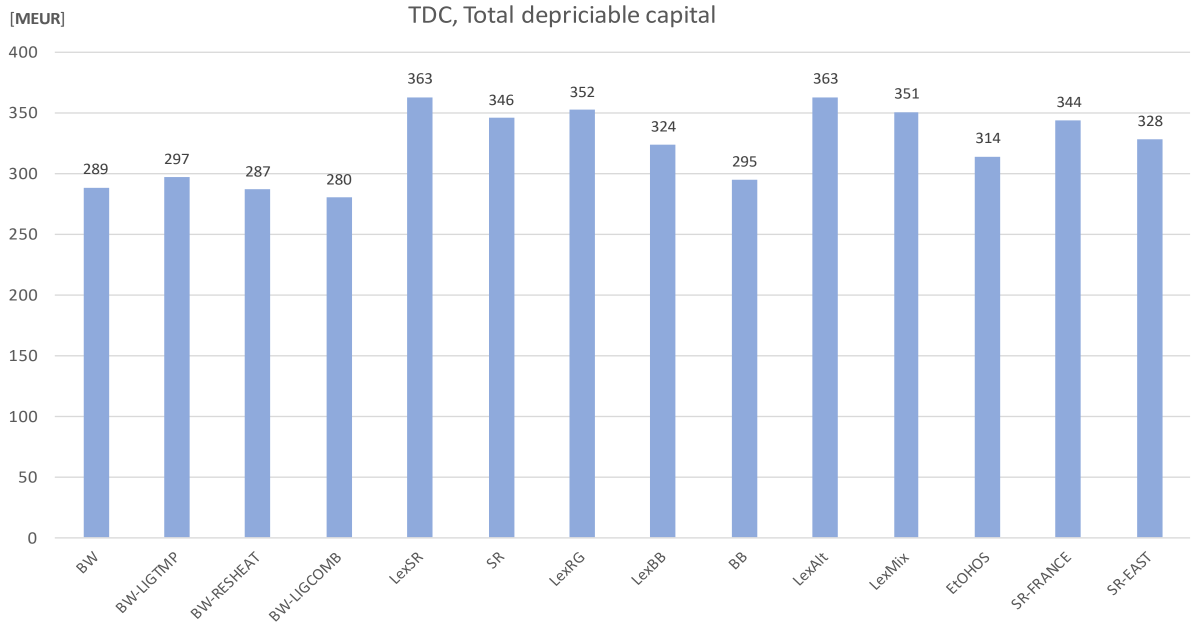

Figure 10: Investments (total depreciable capital) for all scenarios. Abbreviations: BW: basic scenario (beech); BW-LIGTMP: lignin to fillers; BW-RESHEAT: residues to heat only; BW-LIGCOMB: lignin combustion; LexSR: wheat straw, pre-extraction; SR: wheat straw; LexRG: roadside grass, pre-extraction; LexBB: birch & bark, pre-extraction; BB: birch & bark; LexAlt: mixed feedstock, alternating; LexMix: physically mixed feedstock; EtOHOS: reference (ethanol organosolv); SR-FRANCE: wheat straw, France; SR-EAST: wheat straw, Eastern Europe.

The investments in terms of total depreciable capital (Figure 10) for the different scenarios as depicted in Table 2 in section 3.2 show that the lowest investments are for the systems with beech wood as a feedstock. Residue streams have a lower density leading to a larger fractionation reactor and larger liquid flow rates thus higher equipment investments. A breakdown by contributions of the various sections to total bare equipment costs of the basic scenario is depicted in Figure 11. Pre-extraction typically adds 11% to the investments. Remote locations, with lower labour costs, generally have slightly lower investment.

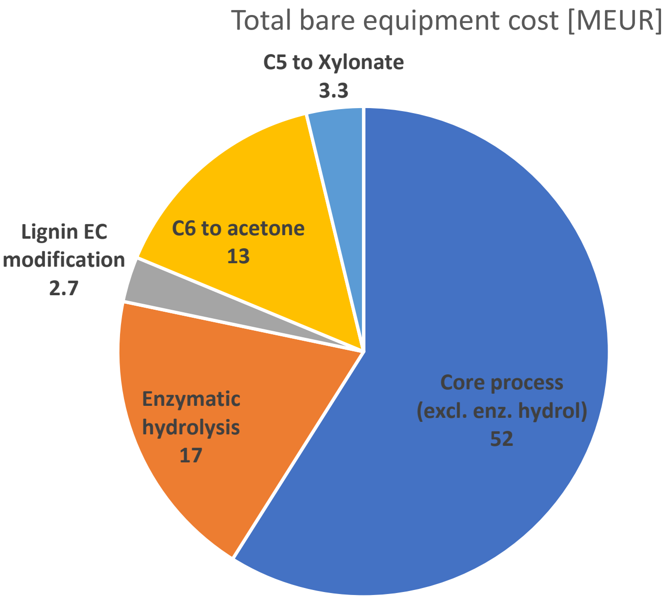

Figure 11: Total bare equipment costs for the basic scenario. Enzymatic hydrolysis that is part of core process is listed separately.

Figure 12 summarises the results of the green premium fee that is required for each of the scenarios. The best results are for those scenarios with the lowest green premium required. This is the case for the basic scenario and for the very similar scenario 'residues to heat only' for which residues from enzymatic hydrolysis and spent sorbent are used for heat only. High-value valorisation of lignin proves very important since if these are used for heat purposes ('lignin combustion') or for lower value application using TMP modification ('lignin to fillers'), the green premium is more than double that of the base scenario. For the other biomass feedstocks, it is not the price of the biomass (which is only a bit higher for wheat straw) which lead to an increase in the needed green premium, but in the higher costs for amount of feedstocks and other inputs and the lower amount of high value products (like modified lignin or hydrophobic lignin) at the same level of (dry) biomass input. The investment cost in pre-extraction (especially in the wheat straw and road site grass cases) play only a limited role in the increase of the green premium.

Scenarios with pre-extraction have similar or only slightly reduced performance compared to their counterparts without pre-extraction using the same feedstock. However, higher product values could possibly be obtained. This is not quantified in the results, but could in practice be very likely if lignin and C5 streams prove to have additional quality for the pre-extraction scenarios and, hence, higher revenues.

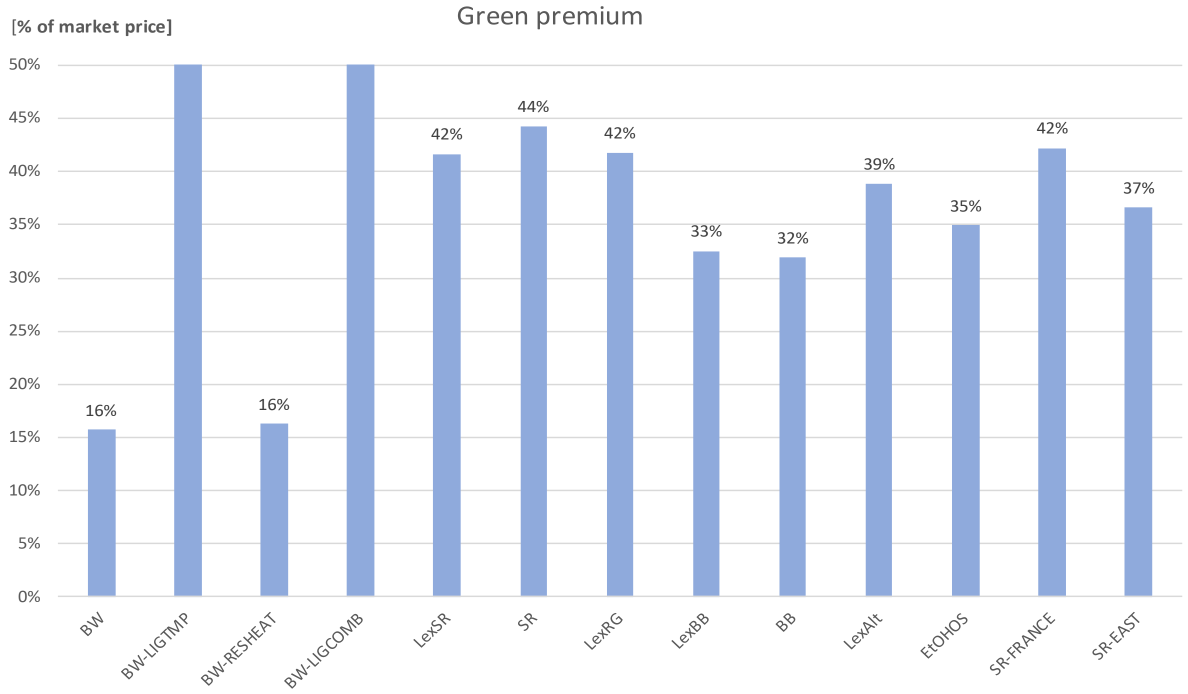

Figure 12: Green premium required to reach feasibility including a return on capital of 10%. For an explanation of the abbreviations see Figure 10.

The economics of the Fabiola technology using acetone-based organosolv in the basic scenario are better than that of the reference scenario that uses ethanol organosolv. The Fabiola technology (basic scenario) would lead to a green premium of about 15% while the ethanol organosolv scenario requires a green premium of about 35%. Here capital costs, operating costs and revenues were found to be more favourable for Fabiola. Operation in alternative locations (France, Eastern Europe) was found to be slightly favourable compared to the reference scenario. Assessing the uncertainties, it was found that significant uncertainties exist in investments as well as in costs and revenues for all scenarios. For that reason, optimistic and conservative scenarios were defined combining variations in investments and feedstock prices. The basic optimistic sub-scenario was the only scenario that could do without a green premium. For the other scenarios the green premium required for the optimistic scenario was however very low.

Two mixed feedstocks scenarios were evaluated (‘mixed feedstock, alternating’ and ‘physically mixed feedstock’). Both scenarios can improve logistics and the availability of biomass. The most favourable scenario was that of physical mixing of feedstocks, though the results are within the range of the two separate feedstocks. Alternating operation with the two feedstocks implies that the plant investments are that of the most unfavourable feedstock (i.e., the feedstock with lowest bulk density), leading to slightly worse economic performance compared to the physically mixed feedstock.

Summarising the results, it is concluded that the study has shown favourable prospects for the UNRAVEL concept. The best economics was found for the beech wood scenario. Residue type feedstocks such as straw and residues, birch wood with branches, mixed residues, might however be preferred given that there is less competition other uses. The green premium required for these scenarios is higher to some extent, but also not far off. Pre-extraction may be applied for if it leads to higher lignin value, or if required by the application. Alternative organosolv fractionation equipment specially aimed at low density biomass, reduced equipment cost and lower liquid/solid ratios could improve the prospects especially for these technologies, and lower the difference in green premium required. The value of lignin proved important in valorisation, and for pre-extraction an assessment of added value of improved quality lignin is of importance to explore its full potential.

4.3 Summary: social assessment and biomass availability

This assessment analysed social risks and benefits of potential future biorefineries according to the concept under investigation as well as social and environmental aspects of sustainable biomass availability based on three analyses: (i) a social life cycle assessment (sLCA) using the social hotspot database, (ii) an analysis of strengths, weaknesses, opportunities and threats covering further positive and negative social impacts as well as (iii) a complementary analysis on the availability of lignocellulosic biomass that is environmentally and socially sustainable. The analysis is based on the scenarios described in section 3.2. For the applied methodology and further details please refer to the original assessment report [Keller & Rettenmaier 2022]. The most important results and conclusions are summarised in the following.

Social risks

The general level of social risks in the supply chain is comparable for potential biorefineries according to the UNRAVEL concept and their conventional competitors, which is largely independent of the analysed technical configuration. An overview of the social risks and avoided social risks of the basic scenario are shown in Figure 13. These **risks mostly arise from indirect suppliers outside of the EU** and are in particular related to occupational health and safety, governance aspects including corruption, and procurement from high conflict zones. Actual social impacts are however no physical consequences of the examined supply chain processes but are very much dependent on their management. Therefore, a comparison of the generic risk levels between the options can only **guide process development** to avoid input materials, which are mostly produced under unacceptable conditions, which is not the case for any of the assessed scenarios. In particular, none of the analysed European **biomass feedstocks** brings about exceptionally high risks in the supply chain while imported biomass, which is not foreseen in the analysed concept, may be connected to substantial risks. Therefore, feedstock choice can concentrate on other selection criteria if competition is avoided that may otherwise indirectly lead to increased biomass imports into the EU.

Relevant social risks in the supply chain that have been identified in this study are no reason to refrain from implementation but rather entail obligations. They need to be **managed and monitored during implementation and operation** of a future biorefinery. Relevant social risks (social hot spots) associated with the assessed potential biorefinery supply chains are in particular:

- Biomass supply, in particular in Eastern European countries
- Provision of lignin modifiers and, to a lower extent, also of other input chemicals
- Energy and transportation (depending on process efficiency)

These social risks in the supply chain should be taken as starting points to design a strategy of monitoring and mitigating risks.

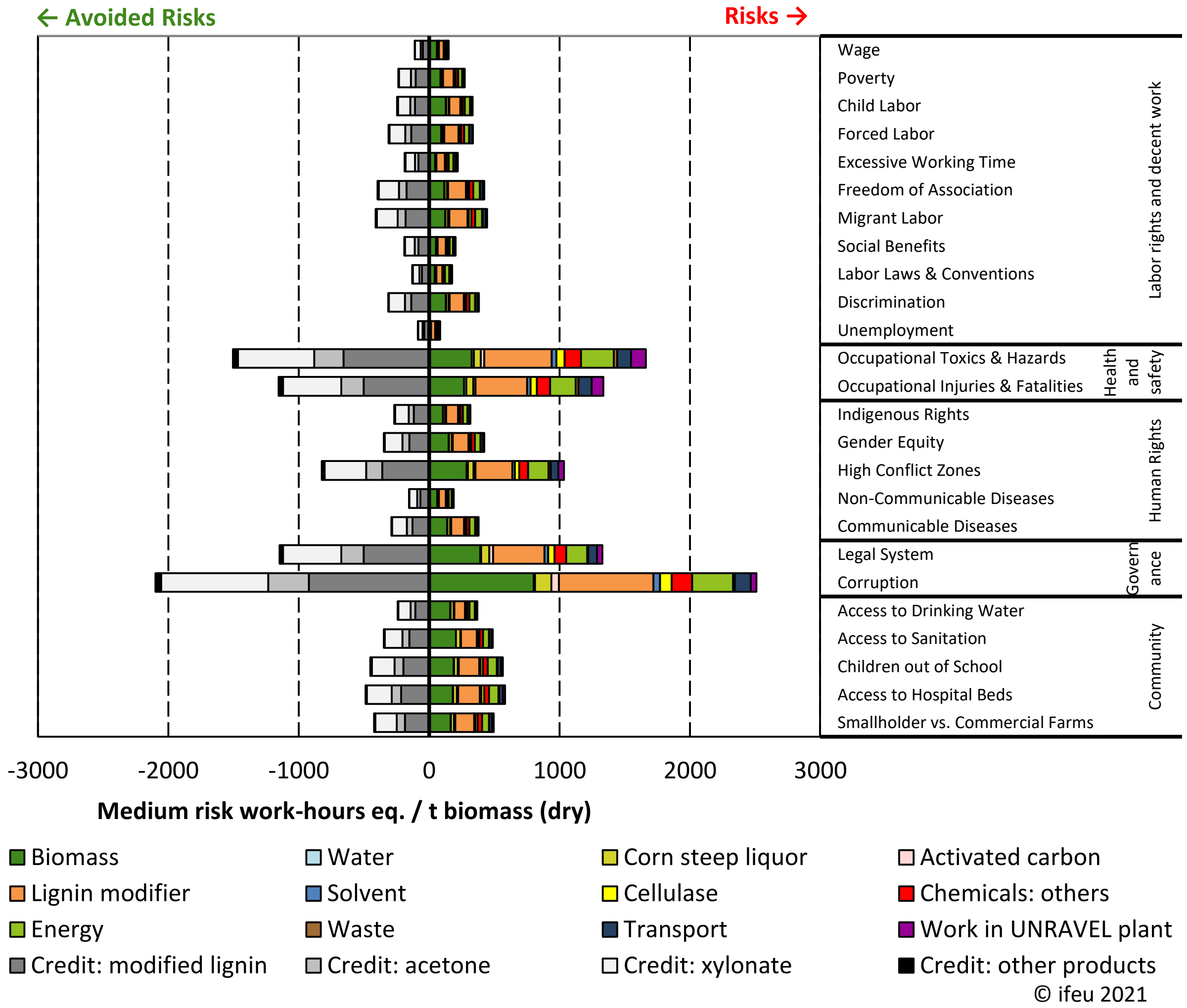

Figure 13: Overview of social risks and avoided risks at subcategory level of the basic scenario: Biomass feedstock: beech wood; country: Netherlands; boundary conditions: typical.

Work in the biorefinery itself and connected to the supply of high-end inputs and services is only connected to comparatively **low risks**, mainly related to occupational health and safety. This can and needs to be addressed using existing up to date concepts. Further **risks can arise from the emergence of a single powerful economic actor** in a rural environment such as operators of large biorefineries. This requires fair negotiations in particular about wages and biomass supply as well as strategies aiming at local employment and procurement.

Last but not least, this project seeks to contribute to a **transition from a fossil-based economy** with all its established networks, infrastructure and employment **to a bio-based economy**. This can only lead to the desired sustainability benefits if fossil-based processes are actually shut down, which is very likely to cause adverse social impacts on the stakeholders connected to processes that are to be phased out. This transition needs to be actively managed by politics to mitigate social impacts in particular on **employees in regions with a strong fossil-based industry**. Additionally, products could become more expensive for consumers at least in a transition phase especially because of high investment requirements. Impacts of **potentially increased inflation** on vulnerable societal groups need to be mitigated by politics by implementing suitable measures.

Social benefits

Besides mitigation of climate change, another main motivation behind support for a future bio-based economy is the **creation of jobs and prospering local economies** in rural areas. Large biorefineries using lignocellulosic residues as feedstock are expected to contribute to this goal in particular via creating a stable demand for biomass and thus income and jobs in agriculture and forestry. Moreover, tax revenues and revenues for state-owned forests are increased while the municipalities' costs for road maintenance are reduced if roadside grass is used. Additionally, high quality jobs are created in the biorefinery itself and at high-tech specialty suppliers.

The full realisation of these potential benefits however requires a **location in less privileged rural areas, equal employment opportunities** and a **local procurement** approach that should be a prerequisite for public support. Furthermore, **training programmes** and enhanced **health and safety measures** for local workforce may be needed to improve local employment instead of causing an influx of external workforce and/or bad working conditions that could create social friction.

Sustainable biomass availability

Feedstock supply can be a critical bottleneck for any biorefinery, with a significant impact on social and environmental sustainability. Through its focus on lignocellulosic residues and especially its flexibility to shift between and to mix feedstocks, the biorefinery concept under investigation is designed from the outset to avoid competition with food/feed production and to minimise competition with existing users of the same residues. Despite this general advantage, competition about biomass can still be a limiting factor. In contrast to genuine biomass residues, technically favourable **lower-grade stemwood** (pulpwood/energy wood) seems to be already largely used. Therefore, the **sustainable availability of lignocellulosic residues** has been analysed based on studies covering the EU-wide availability of the feedstocks cereal straw, forest residues and roadside grass, which are relevant for the biorefinery concept under investigation, taking into account sustainability restrictions and existing uses. An overview of sustainable, available biomass potentials for lignocellulosic residue feedstocks considered within the UNRAVEL project are displayed in Figure 14.

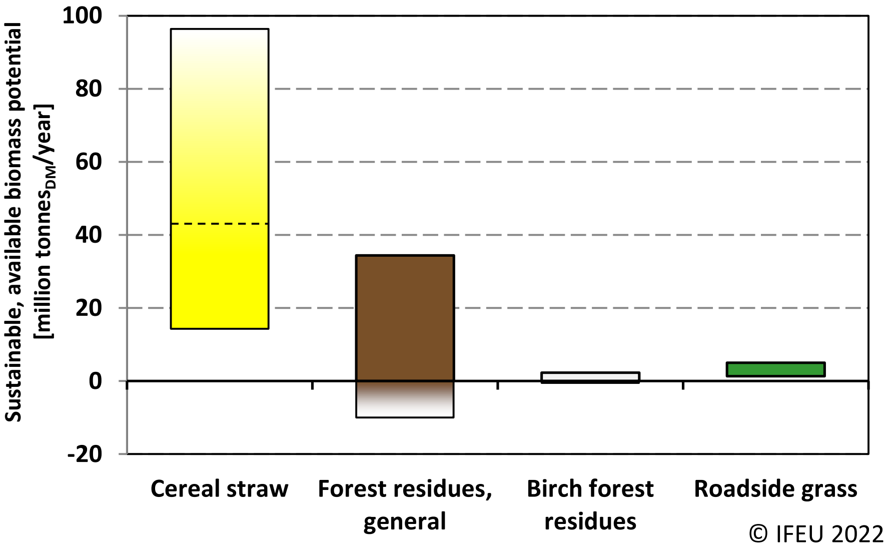

Figure 14: Overview of sustainable, available biomass potentials for lignocellulosic residue feedstocks considered within the UNRAVEL project.

The most important lignocellulosic residues in the EU are cereal straw and forest residues. The sustainable, available potential for **cereal straw** is reported to be in the range of **around 30 million tonnes (dry matter content) per year** (Mt_{DM}/year). A current increase in biofuel production capacity from straw triggered by a dedicated mandate in the current renewable energy directive (RED II) may however already absorb substantial parts of this straw in the next years.

For **forest residues** it is debated if and at which locations this resource could be already **overused** or if on the contrary up to **35 Mt_{DM}/year** could still be sustainably available, depending on location-dependent sustainability restriction and current use. A small fraction is represented by tops and branches of birch trees, which were exemplarily researched in this project. An option to increase the amount of forest residues and also lower-grade stemwood available for material use would be to **replace other uses that do not require the carbon contained in the biomass** as such, i.e. primarily combustion for heat and power generation, by other renewable alternatives such as solar and wind power and by substantially decreasing the energy demand through better insulated buildings. However, if the use of wood by small businesses or for domestic heating was to be restricted, financial support would be required to balance socio-economic impacts, in particular on low-income households.

Roadside grass represents a so far largely unused sustainable resource that should be used as far as logistically possible. Its sustainable, available potential amounts to about **3 Mt_{DM}/year** and thus represents a small but nevertheless worthwhile expansion of the biorefinery's feedstock spectrum.

Besides these feedstocks analysed in details, the Fabiola™ process used in the UNRAVEL concept has been shown to be able to use a wide range of other low to medium volume feedstocks including different hardwoods, corn stover, rapeseed straw, bagasse, tomato stems, miscanthus, sorghum, switchgrass, willow and walnut, partially requiring pre-extraction.

The sustainably available amounts of lignocellulose biomass feedstock are sufficient to feed several large-scale biorefineries. At the same time, they are very location-dependent and may vary annually. Therefore, it is important to ensure during the **site selection process** that sufficient biomass is available for all local users, including the biorefinery. A feedstock-flexible concept such as the one developed in this project can be crucial to avoid potential negative impacts on environmental and social sustainability.

5 Results and discussion: integrated sustainability assessment

The integrated sustainability assessment joins and connects results on individual sustainability aspects to give an integrated view on the sustainability of the UNRAVEL concepts.

In a first step (section 5.1), indicators and results for all major scenarios were collected from the assessments of individual sustainability aspects (for summaries see sections 4.1 - 4.3). The scenarios already include a comparison to the so called reference systems, i.e. the alternative processes and products that would be replaced. This results in an overview of all relevant sustainability impacts.

In a second step (section 5.2), scenarios are compared to each other to determine which advantages and disadvantages may result from the realisation of selected front-runner scenarios.

5.1 Overview of sustainability impacts

5.1.1 Selection of scenarios and indicators

All twelve scenarios that have been analysed for their impacts on environment, economy and society in previous assessments were selected for the integrated sustainability assessment (see chapter 3). Two regional sensitivity analyses of economic impacts and social risks were added based on the wheat straw scenario to provide additional insights on regional variability (see section 3.2.13). For completeness, these sensitivity analyses were supplemented with results on environmental impacts, social benefits and biomass availability from the underlying generic wheat straw scenario.

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

For the integrated sustainability assessment, the indicators of the life cycle assessment (LCA) and the economic assessment were adopted directly. As described in the environmental assessment report [Keller et al. 2021], competition for biomass feedstocks can have an effect on the environmental impacts of the UNRAVEL concept. To exemplarily highlight the effects, the indicator 'climate change incl. competition' was added, which represents an analysis of ‘climate change’ using an extended scope of study including indirect effects of competition for biomass residues. Indicators on local environmental impacts (LC-EIA) have been combined into three summarising indicators. To depict the social risks mainly arising from the supply chain, the 25 indicators of the social life cycle assessment were grouped into the 5 quantitative impact categories (‘labour rights and decent work’, ‘human rights’, ‘health and safety’, ‘governance’ and ‘community’) provided by the social hotspot database (SHDB) [Benoît Norris et al. 2019]. Important qualitative results from the SWOT analysis on social aspects were condensed into the qualitative indicators ‘creating quality employment’ and ‘strengthening rural economies’. The results of the assessment of sustainable available biomass potentials were summarised as qualitative indicator ‘sustainable feedstock availability’.

5.1.2 Additional indicators

The combination of economic and selected environmental indicators into abatement costs can yield additional information on the efficiency e.g. of potential policy measures. For example, greenhouse gas (GHG) abatement costs could indicate, how much reduction in emissions could be achieved per Euro of additional costs or incentives. The calculation of such indicators is detailed in section 2.3.2. As GHG abatement costs represent an efficiency indicator, they are only defined in the case that the primary goal is met, this is, that there are greenhouse gas emission savings compared to the replaced processes (i.e. the reference scenario). In this case, however, no assessed scenario reaches robust GHG savings. Therefore, GHG abatement costs can be misleading and were not calculated.

5.1.3 Categorisation

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly (Table 4): Green boxes represent overall advantageous results, i.e. an improvement compared to a situation without UNRAVEL. Orange and red boxes represent overall disadvantages, i.e. a deterioration compared to a situation without UNRAVEL. Yellow boxes represent a minor sustainability impact (see section 2.3.2 for further explanations). The economic indicators ‘investments’ and ‘OPEX’, which do not comprise a direct comparison to the reference system, are categorised according to percentiles of the overall result range. This way of categorising results supports the identification of options that perform best among all studied options but also maintains the quantitative information on the sustainability of a scenario.

Table 3: Overview of sustainability indicators selected for the integrated assessment.

Impact category	Short description
Environment: global/regional impacts	
Non-renewable energy use	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Climate change	Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases.
Climate change, incl. competition	Same impact category as 'climate change' but the analysed system additionally includes indirect effects from competition about biomass feedstocks as described in section 3.3.
Acidification	Shift of the acid/base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword “acid rain”).
Eutrophication, terrestrial	Input of excess nutrients into terrestrial ecosystems directly or indirect via gaseous emissions and erosion (e.g. nitrogen species such as ammonia and nitrogen oxides).
Eutrophication, aquatic	Input of excess nutrients into aquatic (marine or freshwater) ecosystems directly or via input into soils and gaseous emissions (e.g. nitrogen and phosphorous, keyword “algal bloom”).
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword ‘ozone hole’).
Summer smog	Formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword “ozone alert” or “Photochemical smog”).
Particulate matter formation	Damage to human health due to air pollutants, such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, key-word ‘London smog’).
Land use	Occupation of land at varying degrees of human influence on a natural area [Fehrenbach et al. 2015, 2019].
Phosphate rock use	Depletion of the limited phosphate resources and contribution to increasing scarcity [Reinhardt et al. 2019].
Environment: local impacts	
Soil	Soil quality is affected e.g. by erosion, compaction or organic matter content.
Water	Local water availability for ecosystems and its quality.
Biodiversity	Local biodiversity among animals and plants.
Economy	
Investments (total depreciable capital)	Overall investment in the plant in equipment including all indirect costs, facilities etc.

Impact category	Short description
Operating expenditures (OPEX)	Ongoing costs excluding depreciations and profit margins for running the biorefinery.
Green premium required	Percentage of additional income required from product sales or feed-in-premiums compared to the market price of conventional products the biorefinery replaces.
Society	
Social risks: Labour rights & decent work	Risk of unfair conditions of work or labour accords violations in the value chain; such as child labour, low wages, forced labour, excessive working time or suppression of workers association.
Social risks: Health & safety	Risk along the value chain of high prevalence of occupational injuries and deaths, as well as high exposure to workplace hazards.
Social risks: Human rights	Risk of human right violations along the value chain; such as infringements of indigenous rights, weakness of gender equality, potential for high conflicts and prevalence of diseases.
Social risks: Governance	Risk of manufacturing processes located in countries or regions with weak legal systems, with high risk of corruption or poor law enforcement.
Social risks: Community	Risk of negative impacts along the value chain to the local community; such as school for children, drinking water, sanitation, hospital beds and land ownership of small land holdings.
Creating quality employment	Creation of safe jobs under good working conditions in an economically resilient company.
Strengthening rural economies	Expansion of economic opportunities in rural areas by building business ‘eco systems’ around new big economic actors, generating income and improving infrastructure and services.
Sustainable feedstock availability	Amount of unused biomass residue that can additionally be extracted without significantly harming the environment, e.g. by reducing soil quality.

5.1.4 General sustainability performance

The results for life cycle comparisons of all selected scenarios to their respective conventional reference systems under typical boundary conditions are shown in Table 4. The results for the conservative and optimistic variants of the assessed scenarios can be found in the annex (Table 8 and Table 9 in section 10.2). Independent of scenario-specific relative advantages and disadvantages, several general results can be indicated for the UNRAVEL system.

Under typical conditions, all scenarios show both advantages and disadvantages compared to a situation without UNRAVEL: results highlighted in both orange/red and green are included in each scenario column Table 4. Climate change mitigation can only be achieved if there is no feedstock competition and under specific boundary conditions. For most of the other environmental impacts assessed, there are disadvantages under typical boundary conditions.

Moreover, all scenarios assessed offer an opportunity to create jobs and stimulate the local economy, while not being economically viable without additional green premiums voluntarily paid for bio-based products. Nevertheless, there are scenarios that seem feasible with a manageable green premium on top of typical market prices. The general level of social risks in the supply chain is comparable for potential biorefineries according to the UNRAVEL concept and their conventional competitors, which is largely independent of the analysed technical configuration. In summary, under typical conditions, climate change mitigation together with a creation of jobs and a support of the local economy can only be achieved in a few specific constellations. However, this could be at the expense of other environmental impacts, the social risks would not be reduced and economic feasibility would only be guaranteed with a certain green premium.

Given considerable uncertainty and various choices to make during the upscaling and implementation of the UNRAVEL biorefinery system, the sustainability assessment outcomes under typical conditions are far from certain. Many possible boundary conditions (conservative to optimistic sub-scenarios) result in a wide range of possible outcomes, ranging from clear disadvantages to clear advantages in almost all sustainability impacts (see overview tables of the conservative (Table 8) and optimistic (Table 9) sub-scenarios in section 10.2). The most critical influence results from the level of process efficiencies that can finally be reached on industrial scale. Assuming conservative boundary conditions, just a few analysed scenarios would achieve some minor sustainability benefits. This clearly shows that the further development of the process must achieve at least the efficiencies set in the scenarios under typical conditions. Under optimistic boundary conditions, most scenarios generate benefits in nearly all sustainability aspects and a few scenarios show no sustainability disadvantages at all. On the one hand, the optimistic sub-scenario is unlikely to be achieved, as a large number of process parameters/efficiencies would have to reach their optimum. On the other hand, not all possible scenarios could be considered, which means that there is further potential for optimising the sustainability of a biorefinery according to the UNRAVEL concept by various technological developments. For more information on these optimisation potentials, see the conclusions in 6.1.

Table 4: Overview of results for life cycle comparisons of UNRAVEL scenarios to their alternatives under typical conditions. Results originate from assessments of individual sustainability aspects [Dijkstra & Kroon 2022; Keller et al. 2021; Keller & Rettenmaier 2022].

		Typical performance			
		UNRAVEL scenarios			
	Scenario name in report	Basic scenario (beech)	Lignin to fillers	Residues to heat only	Lignin combustion
Indicator	Unit				
Environment					
Non-renewable energy use	GJ / t biomass DM input	-4.1	27.6	-4.7	1.4
Climate change	t CO2 eq / t biomass DM input	-0.32	1.60	-0.36	0.05
Climate change incl. competition	t CO2 eq / t biomass DM input	0.52	2.44	0.48	0.89
Acidification	kg SO2 eq / t biomass DM input	0.2	5.0	0.4	1.8
Eutrophication, terrestrial	g PO4 eq / t biomass DM input	-2	368	10	137
Eutrophication, aquatic	g PO4 eq / t biomass DM input	17	17	17	17
Ozone depletion	g CFC-11 eq / t biomass DM input	-0.7	-0.3	-0.6	-0.4
Summer smog	kg NMVOC eq / t biomass DM input	0.3	3.4	0.3	1.5
Particulate matter formation	kg PM2,5 eq / t biomass DM input	-0.2	4.4	-0.1	1.6
Land use	m² aL-eq · a / t biomass DM input	271	290	271	263
Phosphate rock use	kg phosphate rock eq / t biomass DM input	23	977	23	24
Soil	-	–	–	–	–
Water	-	o	o	o	o
Biodiversity	-	o	o	o	o
Economy					
Investments	Million EUR	289	297	287	289
OPEX	€ / t biomass DM input	613	612	619	402
Green premium required	% of total product revenue	16%	99%	17%	95%
Society & biomass availability					
Social risks: labor rights and decent work	Thousand medium risk work-hours eq. / t biomass DM input	0.4	-1.3	0.4	0.4
Social risks: health and Safety	Thousand medium risk work-hours eq. / t biomass DM input	0.3	-2.1	0.4	0.3
Social risks: human Rights	Thousand medium risk work-hours eq. / t biomass DM input	0.5	-0.8	0.5	0.4
Social risks: governance	Thousand medium risk work-hours eq. / t biomass DM input	0.6	-1.4	0.6	0.6
Social risks: community	Thousand medium risk work-hours eq. / t biomass DM input	0.6	-0.6	0.6	0.5
Creating quality employment	-	o	o	o	o
Strengthening rural economies	-	+	+	+	+
Sustainable biomass availability	-	–	–	–	–

Table 4: (continued).

Typical performance									
UNRAVEL scenarios									
Wheat straw, pre-extraction	Wheat straw	Roadside grass, pre-extraction	Birch & bark, pre-extraction	Birch & bark	Mixed feedstock, alternating	Physically mixed feedstocks	Reference (ethanol organosolv)	Wheat straw, France	Wheat straw, Eastern Europe
7.2	3.4	6.5	4.3	-0.2	5.7	5.7	7.2	3.4	3.4
0.43	0.21	0.35	0.21	-0.06	0.32	0.32	0.40	0.21	0.21
1.15	0.92	0.35	0.97	0.70	1.06	1.06	1.24	0.92	0.92
2.7	2.5	1.7	1.4	1.1	2.1	2.1	1.5	2.5	2.5
370	335	141	130	83	250	250	142	335	335
930	918	21	24	14	477	477	17	918	918
3.3	3.3	0.1	-0.2	-0.4	1.5	1.5	0.5	3.3	3.3
1.6	1.3	1.1	1.2	0.9	1.4	1.4	0.9	1.3	1.3
1.8	1.6	1.1	0.9	0.7	1.4	1.4	0.7	1.6	1.6
-39	-31	-17	-37	-37	-38	-38	320	-31	-31
50	51	25	23	24	37	37	25	51	51
o	o	+	–	–	o	o	–	o	o
o	o	o	o	o	o	o	o	o	o
o	o	+	–	–	o	o	o	o	o
363	346	352	324	295	363	351	314	344	328
756	684	645	623	563	697	702	745	653	585
42%	44%	42%	33%	32%	39%	35%	35%	42%	37%
0.3	0.2	0.4	0.8	0.6	0.5	0.5	1.3	0.4	2.8
1.0	0.9	1.0	0.8	0.5	0.9	0.9	1.3	1.5	6.0
0.4	0.3	0.4	0.7	0.6	0.5	0.5	1.1	0.2	0.8
0.3	0.2	0.4	1.0	0.9	0.6	0.6	1.7	0.3	7.3
0.3	0.3	0.3	0.8	0.7	0.5	0.5	1.2	0.2	1.4
+	+	o	+	+	+	+	o	+	+
+	+	++	+	+	++	++	+	+	+
+	+	o	o	o	++	++	–	+	+

5.2 Comparison of scenarios

This chapter discusses advantages and disadvantages that are expected to arise from the realisation of different scenarios. None of the scenarios scores best in all indicators. Therefore, no best solution can be identified on an entirely scientific basis without value-based choices. This is an almost unavoidable result if the sustainability assessment of a system with a certain degree of complex is truly comprehensive. Valuable decision support can still be provided to involved stakeholders such as businesses and policy-makers if advantages and disadvantages of selected decision options are made transparent. The purpose of this comparison is to identify optimisation options and trade-offs to support further development.

To this end, all scenarios are compared to one benchmark scenario at a time. Alternatives are considered advantageous (+) and disadvantageous (-) regarding a certain aspect if they have a qualitative rating differing from the benchmark value by more than 5% of the total range of values for that indicator, respectively. The rating very advantageous (++) and very disadvantageous (- -) are given for a deviation by more than 50%. For qualitative ratings, thresholds of one or two grades on the used five part scale are applied. Only typical and optimistic scenario variants were selected for this analysis because the conservative ones turned out not to be sustainable at all and thus do not yield useful insights other than that they have to be avoided during further development.

5.2.1 Identification of benchmark scenarios

Several scenarios are identified as useful benchmarks, which perform best regarding certain groups of indicators. An additional benchmark is selected to identify regionally specific features.

Basic scenario (beech)

This scenario encompasses the use of beech stemwood as biomass feedstock for the Fabiola™ fractionation process based on acetone organosolv technology to produce polyols for PUR/PIR foams via EC (ethylene carbonate) modification. As all other scenarios were derived from this scenario, it is the most comparable with all other scenarios. Moreover, it performs best in many environmental and economic indicators. For additional information on this scenario, see section 3.2.1.

Physically mixed feedstock

One idea of the UNRAVEL concept is to develop a biorefinery that can process physically mixed feedstocks and therefore comprises 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. This is depicted in the scenario ‘Physically mixed feedstocks’. It is selected as benchmark because of its superior performance regarding social benefits and sustainable biomass availability.

This scenario encompasses the use of a physically mixed biomass feedstock consisting of wheat straw and branches and tops of birch trees including their bark and residual foliage. Moreover, a pre-extraction process is used to improve biomass fractionation characteristics. For additional information on this scenario see section 3.2.12.

Wheat straw

This scenario encompasses the use of wheat straw as biomass feedstock instead of beech wood. Alternatively, other cereal straws such as barley straw could be used with similar performance. This scenario was chosen for benchmarking because it allows a socio-economic comparison between different regions in Europe based on the same feedstock. For additional information on this scenario see section 3.2.6.

5.2.2 Benchmark I: Basic scenario (beech)

Table 5 shows the comparison of all other scenarios to the basic scenario (beech wood), which has been selected as benchmark because of its promising economic and environmental performance. If other scenarios would be implemented instead of the basic scenario (beech wood), this would entail the following advantages and disadvantages:


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Ethanol organosolv process compared to the acetone organosolv process

The classical ethanol organosolv process (scenario: ‘Reference (ethanol organosolv)’) shows clear disadvantages compared to the acetone-based organosolv fractionation technology termed Fabiola™ from an environmental, economic as well as social point of view. These disadvantages are mainly due to the higher energy and solvent demand. Lower efficiencies generate higher environmental burdens and significantly higher operating costs. The lower efficiency can also have negative impacts on social risks. The clear disadvantages of the reference scenario compared to the basic scenario show that the project goal of developing a more sustainable fractionation process has been achieved.

Lignin applications and use of processing residues

The production of TMP-modified lignin for use as light-weight fillers instead of glass bubbles (‘Lignin to fillers’) and lignin combustion for energy recovery show clear environmental and economic disadvantages compared to the basic scenario that depicts the production of EC-modified lignin for use as a polyol in PUR/PIR foams. This has several reasons:

- The production of TMP-modified lignin is associated with higher process- and input-related burdens as well as lower avoided emissions by substitution of conventional glass bubbles, which is why this scenario performs significantly worse with regard to most of the analysed environmental indicators. Furthermore, TMP modification shows a high required green premium due to material losses. In contrast, the production of TMP-modified lignin poses lower social risks compared to the other lignin applications but the differences are not robust taking uncertainty and applicability of underlying data into account.

- The combustion of lignin needs a very high green premium due to the low value of lignin as fuel and therefore is not considered an attractive option. Nevertheless, the combustion of lignin has the lowest operating costs compared to the other analysed scenarios because there is no further processing.

The energy recovery from processing residues arising within the UNRAVEL plant in a heat plant (‘Residues to heat only’) instead of a CHP as depicted in the basic scenario has no clear influence on the sustainability performance. The optimal solution depends on carbon intensities and prices of electricity and heat that would be purchased otherwise.

Comparison of different biomass feedstocks

In terms of economics and a number of global and regional environmental impacts (e.g. non-renewable energy use, acidification or eutrophication), alternative feedstock scenarios (from “Wheat straw, pre-extraction’ to ‘Physically mixed feedstocks’) show mainly disadvantages compared to the basic scenario using beech stemwood in a situation without competition about biomass feedstock. The disadvantages are mainly due to the fact that

- beech stemwood has the highest lignocellulose content and the lowest share of non-usable compounds (see Figure 15) and

- other feedstocks, such as in particular straw, have a low density, which means that they need larger equipment and a higher liquid to solid ratio. One reason for that is that the technology used in UNRAVEL is optimised for the use of beech stemwood, so that these disadvantages could be reduced or even eliminated by further developing the technology and adapting to other feedstocks.

Furthermore, the extraction of wheat straw from the field and the associated compensatory use of fertilisers result in significant disadvantages in terms of eutrophication. Recycling of nutrient-rich process effluents to the fields as fertiliser may in the future partially overcome this problem if logistical challenges can be solved.

Other feedstocks however also have certain advantages over the use of beech stemwood as in the basic scenario: Since all feedstocks other than beech wood are residues, they do not use additional land and therefore have a significant advantage regarding their land use footprints. Furthermore, alternative feedstocks can have advantages for nature conservation, especially with regard to soil and biodiversity: While forestry causes soil compaction, the collection process of straw is not significantly more detrimental than wheat cultivation if enough straw is left on the field. Furthermore, the removal of nutrients together with roadside grass is expected to increase biodiversity because nutrient-poor grassland comprises more species. In contrast, the removal of birch branches incl. bark can have a negative impact on the local environment because deadwood, which supports biodiversity in forests, disappears.

Regarding social aspects, the use of alternative biomass feedstocks can lead to both lower and higher social risks compared to beech stemwood, so that no clear picture of possible reductions or increases in social risks can be seen.

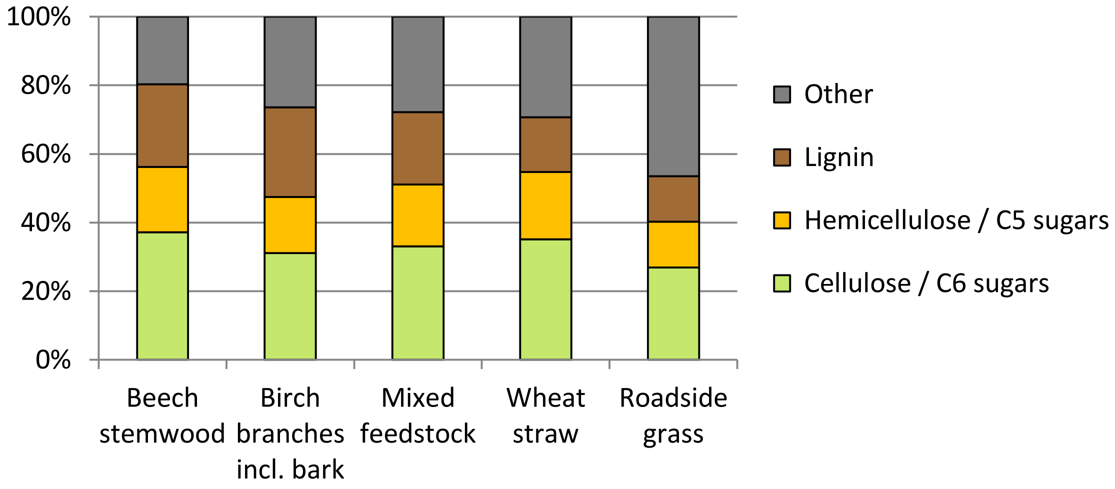

Figure 15: Lignocellulosic constituents of assessed feedstocks.

The role of feedstock competition

Available beech stemwood is currently completely used in our economy resulting in low sustainable biomass availability. This is why each additional use is expected to withdraw feedstock from other existing uses. This would lead to foregone environmental and social benefits in these other applications.

Potential effects are exemplarily quantified for climate change: The indicator 'climate change' shows the impacts of the UNRAVEL system compared to the production of equivalent conventional products. The indicator ‘climate change incl. competition’ covers an extended scope of study including indirect effects of competition for biomass. As beech stemwood is hardly available without competition, its result for the indicator ‘climate change incl. competition’ is set as benchmark and all other results for climate change with and without competition are compared to it. This shows mostly disadvantages for other feedstocks if they are competed for, too, but substantial to less relevant advantages if competition can be avoided.

This results from two counteracting effects: Although beech stemwood can be processed substantially more efficiently compared to wheat straw and roadside grass using current technology, resulting climate benefits could overcompensated by negative climate effects of competition. This is a trade-off that needs to be managed. It can also influence further dimensions of sustainability: Besides effects on climate change, competition for this feedstocks could lead to substantially increased prices and thus worse economic performance

Table 5: Comparison of all other scenarios to the benchmark scenario 'Basic scenario (beech)'. The indicator 'climate change incl. competition' shows results including indirect effects of competition for biomass.

		Benchmarking					
		UNRAVEL scenarios					
	Scenario name in report	Basic scenario (beech)	Lignin to fillers	Residues to heat only	Lignin combustion	Wheat straw, pre-extraction	Wheat straw
	Indicator						
Environment							
	Non-renewable energy use		– –	o	–	–	–
	Climate change	+	–	+	+	o	+
	Climate change incl. competition		–	o	–	–	–
	Acidification	B	– –	o	–	–	–
	Eutrophication, terrestrial	E	– –	o	–	– –	– –
	Eutrophication, aquatic	N	o	o	o	– –	– –
	Ozone depletion	C	–	o	o	– –	– –
	Summer smog	H	– –	o	–	–	–
	Particulate matter formation	M	– –	o	–	–	–
	Land use	A	o	o	o	++	++
	Phosphate rock use	R	– –	o	o	o	o
	Soil	K	o	o	o	+	+
	Water		o	o	o	o	o
	Biodiversity		o	o	o	o	o
Economy							
	Investments		–	o	o	– –	–
	OPEX		o	–	++	– –	– –
	Green premium required		– –	o	– –	–	–
Society & biomass availability							
	Labor rights and decent work		+	o	o	o	o
	Health and Safety		+	o	o	–	–
	Human Rights		+	o	o	o	o
	Governance		+	o	o	o	o
	Community		+	o	o	+	+
	Creating quality employment		o	o	o	+	+
	Strengthening rural economies		o	o	o	o	o
	Sustainable biomass availability		o	o	o	++	++

than calculated in this assessment. Additionally, advantages of wheat straw and roadside grass in terms of local environmental impacts cannot be realised if their processing efficiency remains unattractive.

Table 5: (continued). The situation with competition is set as default for this benchmark scenario and all results for climate change with and without competition of all scenarios are compared to it (see text for details).

Benchmarking							
UNRAVEL scenarios							
Roadside grass, pre-extraction	Birch & bark, pre-extraction	Birch & bark	Mixed feedstock, alternating	Physically mixed feedstocks	Reference (ethanol organosolv)	Wheat straw, France	Wheat straw, Eastern Europe
–	–	–	–	–	–	–	–
o	+	+	o	o	o	+	+
o	–	o	–	–	–	–	–
–	–	–	–	–	–	–	–
–	–	–	–	–	–	– –	– –
o	o	o	–	–	o	– –	– –
–	–	–	–	–	–	– –	– –
–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–
++	++	++	++	++	–	++	++
o	o	o	o	o	o	o	o
++	o	o	+	+	o	+	+
o	o	o	o	o	o	o	o
+	–	–	o	o	o	o	o
–	–	o	– –	–	–	–	–
–	–	+	– –	– –	– –	–	+
–	–	–	–	–	–	–	–
o	–	o	o	o	–	o	–
–	o	o	o	o	–	–	– –
o	–	o	o	o	–	+	–
o	o	o	o	o	–	o	– –
+	–	o	o	o	–	+	–
o	+	+	+	+	o	+	+
+	o	o	+	+	o	o	o
+	+	+	++	++	o	++	++

5.2.3 Benchmark II: Physically mixed feedstock

In Table 6, the comparison of selected scenarios to the scenario ‘Physically mixed feedstocks’ is depicted.

Table 6: Comparison of selected scenarios to the benchmark scenario ‘Physically mixed feedstocks’. The indicator 'climate change incl. competition' shows results including indirect effects of competition for biomass.

	Benchmarking			
	UNRAVEL scenarios			
Scenario name in report	Basic scenario (beech)	Wheat straw, pre-extraction	Wheat straw	Roadside grass, pre-extraction
Indicator				
Environment				
Non-renewable energy use	+	o	o	o
Climate change	+	o	o	o
Climate change incl. competition	o	–	–	o
Acidification	+	–	–	o
Eutrophication, terrestrial	+	–	–	+
Eutrophication, aquatic	+	–	–	+
Ozone depletion	+	–	–	+
Summer smog	+	o	o	o
Particulate matter formation	+	–	o	o
Land use	– –	o	o	o
Phosphate rock use	o	o	o	o
Soil	–	o	o	+
Water	o	o	o	o
Biodiversity	o	o	o	+
Economy				
Investments	+	–	o	o
OPEX	++	– –	+	++
Green premium required	+	–	–	–
Society & biomass availability				
Labor rights and decent work	o	o	o	o
Health and Safety	o	o	o	o
Human Rights	o	o	+	o
Governance	o	o	o	o
Community	o	+	+	+
Creating quality employment	–	o	o	–
Strengthening rural economies	–	–	–	o
Sustainable biomass availability	– –	–	–	– –

Table 6: (continued): The situation without competition is set as default for this benchmark scenario and all results for climate change with and without competition of all scenarios are compared to it.

Benchmarking					
UNRAVEL scenarios					
Birch & bark, pre-extraction	Birch & bark	Mixed feedstock, alternating	Physically mixed feedstocks	Wheat straw, France	Wheat straw, Eastern Europe
o	+	o		o	o
o	+	o		o	o
–	–	–	–	–	–
+	+	o		–	–
+	+	o	**B**	–	–
+	++	o	**E**	–	–
+	+	o	**N**	–	–
o	+	o	**C**	o	o
+	+	o	**H**	o	o
o	o	o	**M**	o	o
o	o	o	**A**	o	o
–	–	o	**R**	o	o
o	o	o	**K**	o	o
–	–	o		o	o
+	+	–		o	+
++	++	o		+	++
o	o	o		–	o
o	o	o		o	–
o	o	o		–	–
–	o	o		+	–
o	o	o		o	– –
–	o	o		+	–
o	o	o		o	o
–	–	o		–	–
– –	– –	o		–	–

The results show the following advantages and disadvantages if other scenarios would be implemented instead of ‘Physically mixed feedstocks’:

Alternating feedstock use compared to use of physically mixed feedstocks

The use of feedstocks in alternating campaigns shows a worse economic performance compared physically mixing the same feedstocks because equipment needs to be sized bigger resulting in higher investment costs. This has no significant relevance to environmental effects. While the use of physically mixed feedstock could lead to synergy effects (e.g. savings in logistics) compared to alternating feedstock use, more intensive pre-treatment of the mixture may be required. If these and other counteracting effects result in small net benefits or burdens regarding indicators other than investment costs could not be robustly quantified and therefore identical results are shown.

Single feedstock use compared to use of several mixed feedstocks

In terms of environmental impacts and economic performance, the use of a mixed feedstock of wheat straw and birch branches incl. bark is in between the use of the individual feedstocks. Birch branches incl. bark performs better economically and in terms of a number of global environmental impacts (e.g. acidification or eutrophication). Regarding social risks, there are no significant differences between mixed and single feedstocks. Nevertheless, the use of physically mixed feedstocks may contribute more to strengthening rural economies, since flexible feedstock use also allows suppliers of smaller quantities to benefit from the biorefinery. In this respect, the analysed mixed feedstock scenario should be viewed as only one out of many possible configurations because roadside grass or even other lignocellulosic feedstocks could potentially be used in a mixture, too, although this was not analysed in detail. Furthermore, the sustainable biomass availability is significantly increased through the use of mixed feedstocks, as several regionally available feedstocks can be used at the same time and smaller supply volumes can be procured, too. Flexibility through the use of mixed feedstocks could reduce competition, which is seen as an inherent advantage of this scenario.

5.2.4 Benchmark III: Wheat straw


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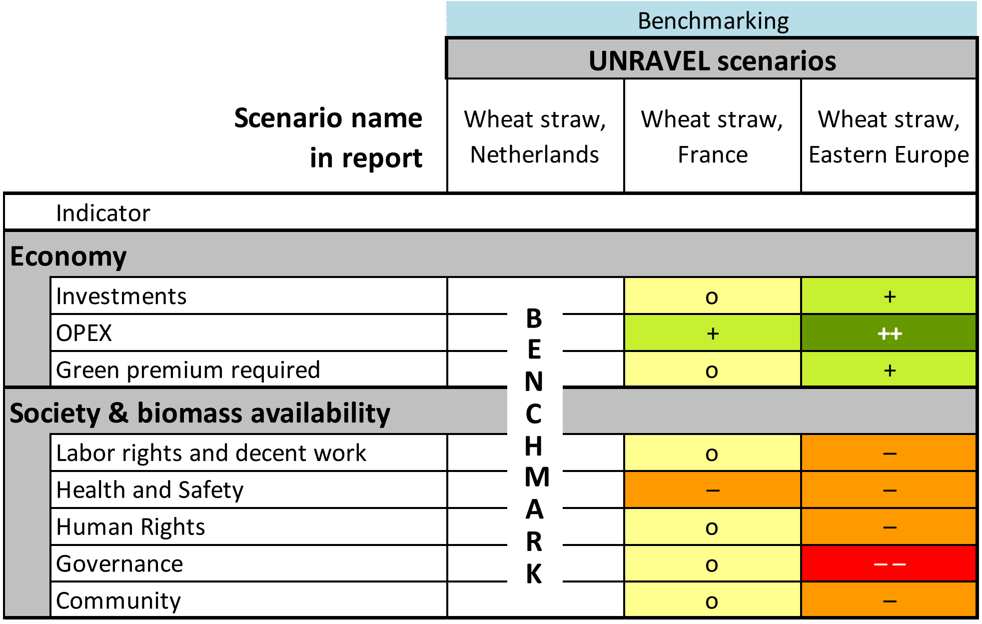
All scenarios were assessed based on generic European data as far as possible. Regarding socio-economic data and impacts, specific countries or regions had to be analysed. In Table 7, the standard wheat straw scenario using the Netherlands as exemplary location ('Wheat straw, Netherlands') is compared to further variants located in France and Eastern Europe. Only the country-specific results are displayed. The comparison allows for several advantages and disadvantages to be identified:

- A wheat straw-based biorefinery in Eastern Europe shows advantages in all three economic indicators. The lower feedstock costs in Eastern Europe have a direct impact on significantly reduced operating costs. Similarly, lower wages and material costs lead to decreased investment costs. The difference between a biorefinery in France and the Netherlands is considerably smaller.
- Feedstocks from analysed Western European countries tend to show lower social risks than from analysed Eastern European countries despite uncertainties in the data.
- Environmental impacts are expected to be different between locations but were not quantified for several reasons: In particular an increased use of renewable energy leads to environmental benefits as quantified in sensitivity analyses in the environmental assessment report. Although the current level of renewable energy and particularly electricity use in Eastern Europe is substantially lower than in the Netherlands or the EU average, pronounced changes could be possible depending on unpredictable political developments until 2030, which is the reference year of this assessment. Therefore, regional differences the decarbonisation of energy provision and resulting differences in environmental impacts were not quantified. Furthermore, differences in local environmental effects are very dependent on the location. However, the compared regions are so large that no robust generic differences could be found.

Table 7: Comparison of the region-specific wheat straw scenarios to the benchmark scenario 'Wheat straw, Netherlands'. Only economic, social and biomass availability indicators, as there are no differences in the environmental indicators.



	Scenario name in report	Wheat straw, Netherlands	Wheat straw, France	Wheat straw, Eastern Europe
		Benchmarking		
		UNRAVEL scenarios		
	Indicator			
Economy				
	Investments	**BENCHMARK**	o	+
	OPEX		+	++
	Green premium required		o	+
Society & biomass availability				
	Labor rights and decent work		o	–
	Health and Safety		–	–
	Human Rights		o	–
	Governance		o	– –
	Community		o	–

6 Conclusions and recommendations

6.1 Conclusions

Big steps forward have been made in this project towards a sustainable lignocellulose biorefinery concept. However, assessed scenarios of how lignocellulose biorefineries using an acetone organosolv process could be implemented do not reach a satisfactory overall sustainability performance yet. Concrete steps discussed below have been identified to overcome sustainability bottlenecks in further development.

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Achieved sustainability improvements

The results of this integrated sustainability assessment (see chapter 5) show that the UNRAVEL project has achieved important steps towards enhanced sustainability of potential future biorefineries by introducing several successful innovations:

- A **new approach to pre-extraction** of biomass prior to organosolv fractionation can make further sustainably available biomass residues such as roadside grass or mixed lignocellulosic residues usable for biorefineries. Although this requires additional energy inputs and investments, net impacts can be positive if competition for feedstocks, possible pressure to resort to unsustainably sourced feedstocks in case of supply shortages and resulting environmental, social and economic disadvantages can be mitigated. Additionally, pre-extraction can improve product quality and applicability opening up higher value and potentially more beneficial uses.

- Additionally, much has been achieved through the **improvement of the core process** based on acetone organosolv technology in the UNRAVEL project. It is significantly more sustainable and economically viable 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, hemicellulose/C5 sugars and cellulose/C6 sugars, 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 and economic advantages over other assessed lignin use options including combustion. 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 **hemicellulose/C5 sugars** into xylonic acid and **cellulose/C6 sugars** into acetone turned out not to make full use of the potential to generate revenues and 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 insights gained even if these processes were developed further. Nevertheless, fermentability of the fractions was found to be good so that many other, potentially more sustainable products seem attainable. Sustainability assessment using ILCSA can help to identify suitable pathways.

Overall sustainability performance

Recent policy strategies in the EU including the Green New Deal, the EU taxonomy and the Recovery and Resilience Facility [European Commission 2021b; European Parliament and Council 2020, 2021] focus on climate change mitigation, economic prosperity and social resilience as major sustainability goals. At the same time, these policy frameworks and the linked Do No Significant Harm principle [European Commission 2021a] aim to ensure that the environment is not significantly harmed in other aspects including biodiversity and that important transformation processes are not impeded. Biorefineries in general can support these sustainability goals in particular by contributing to climate change mitigation and by strengthening rural economies. However, a single focus on climate change mitigation is neither sufficient nor recommendable since biorefineries also have the potential to cause damage regarding other environmental impacts, which needs to be mitigated as far as possible.


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Despite all achievements of the UNRAVEL project, none of the assessed acetone organosolv biorefinery scenarios results in clear climate change mitigation and clear economic viability yet while prospects are favourable. This is common for technologies including biorefinery processes at the technology readiness level (TRL) currently reached by UNRAVEL. One major reason is that boundary conditions including efficiencies achievable on industrial scale are still quite uncertain. This leads to large result ranges for almost all scenarios reaching from disadvantageous to advantageous results. Furthermore, additional environmental burdens regarding biodiversity, acidification, use of phosphate resources and others as well as negative social impacts are possible but could be substantially reduced or avoided by implementing appropriate measures. In particular, it must be ensured that only sustainably available biomass residues are used as feedstock. It will be the task of future development and upscaling work to realise the potentials of the UNRAVEL concept while avoiding harm to environment and society. The following concrete steps have been identified to realise the potentials of the UNRAVEL concept and to reach clear sustainability advantages:

Steps towards further sustainability improvements

The comparison of many scenarios and sub-scenarios, complemented with sensitivity analyses, yields several important insights for the further development and upscaling of the assessed biorefinery concept on the following aspects:

Biomass feedstock: It must be ensured that only sustainably available biomass residues are used as feedstock. This firstly means that location-specific ecological extraction limits of biomass residues such as straw and forest residues need to be respected to avoid harming soils and biodiversity. Secondly, biomass should not be withdrawn from other productive uses which, as indirect effects, could prevent emission savings in those applications and entail social disadvantages by restricting the livelihoods of current users. For wood, the competition is generally high and increases with wood quality. Therefore, using beech wood is not recommended although its technical suitability leads to best economic viability and highest climate change mitigation potential without considering potential competition. However, if wood is withdrawn from energy use e.g. in a CHP, then climate performance is worse than if unused but lower quality feedstocks such as straw or roadside grass were used. Moreover, it has to be taken into account that the superior technical performance of beech wood chips is largely due to the fact that the current organosolv reactor design is optimised for this feedstock. Other low density feedstocks such as straw and roadside grass, which are much less or not at all competed for, would require an adaptation of the reactor design and processing conditions, possibly including feedstock densification, beyond what could be modelled in the assessed scenarios. This would improve processing efficiency and thus profitability and environmental impacts. The optimised organosolv reactor design for low density feedstocks and feedstock densification should therefore be developed with high priority.

The sustainably available amounts of lignocellulose biomass feedstock are sufficient to feed several large-scale biorefineries with a capacity of 300 000 tonnes (dry matter content) per year, as assessed in this report. At the same time, sustainable availability is very location-dependent and may vary annually. Therefore, it is important to ensure during the site selection process that sufficient biomass is available for all local users, including the biorefinery. As costs are lower in Eastern Europe, location search should start there. A feedstock-flexible concept such as the one developed in this project can be crucial to avoid potential negative impacts on environmental and social sustainability.

Core process: The core process is responsible for the highest investments and sustainability impacts and should therefore be optimised further regarding demand for energy and material inputs and installations. Nevertheless, energy demand will remain substantial and needs to be covered by additional wind and solar power as far as possible. Regarding equipment and investments, in particular the design and costing of pulp and lignin filtrations and vapour compressor in the organosolv fractionation are important elements in addition to the optimisation of the process for low-density feedstocks as discussed above.

Pre-extraction and downstream processing of biomass fractions: The potentials of pre-extraction to allow previously unreachable product applications via higher quality of intermediates, particularly lignin and hemicellulose/C5 sugars, and to enable feedstock flexibility as well as the use of further sustainably available biomass residues should be explored further. This is in line with the need to find more sustainable use options for hemicellulose/C5 sugars and cellulose/C6 sugars. Together with optimisations of the core process, this could create synergistic benefits regarding most sustainability aspects of potentially substantial but as yet unknown magnitude. Furthermore, markets should be targeted in which customers are willing to pay a certain green premium for bio-based products because this may be needed to ensure economic viability.

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Creation of suitable boundary conditions: Sustainability is not only dependent on an optimised process but also on the boundary conditions of its implementation. For operators of future biorefineries this in particular concerns environmentally and socio-economically sustainable procurement and employment. Besides sustainable biomass feedstock procurement, which is discussed above, this primarily relates to chemicals, energy and services. Risks in the supply chains of chemicals and energy mostly arise from indirect suppliers outside of the EU and are in particular related to occupational health and safety, governance aspects including corruption, and procurement from high conflict zones. Social risks in the supply chain that have been identified in this sustainability assessment are no reason to refrain from implementation but rather entail obligations. They need to be managed and monitored during implementation and operation of a future biorefinery.

Responsible procurement and employment can not only avoid risks but also create benefits. The realisation of potential benefits requires a location in less privileged rural areas, equal employment opportunities and a local procurement approach that should be important criteria for public support.

Politics needs to create conditions for equitable competition and negotiations between unequal partners. In this context, specific and partially new challenges are arising from competition about limited biomass residues. Such conflicts are already present or may arise e.g. between small and/or non-commercial biomass users, nature conservation and biorefinery operators as well as between the bioenergy sector that already receives substantial public support and the bio-based materials / chemicals sector that is currently lagging behind.

6.2 Recommendations

To further develop the analysed lignocellulose biorefinery concept based on acetone organosolv technology into a sustainable 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

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- The **acetone organosolv** process (analysed here: Fabiola™) should be developed 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 they were set in the analysed scenarios.
- Aim to reduce the **energy demand** of the core process and of the pre-extraction with high priority. For the pre-extraction process, optimised **solvent-to-biomass ratios** and the use of adapted dedicated equipment are expected to unlock main savings potentials and potentially also reduce investments. For the core process, it is advised to look into **feedstock densification and alternative organosolv reactor designs** especially for low-density feedstocks.
- Aim to optimise the process further for **processing physically mixed feedstocks** to exploit potentials including processing synergies, reduced investments and transportation costs, higher feedstock flexibility and the possibility to use feedstocks available only in smaller amounts.
- Focus on **feedstock flexibility** in the further process development to reduce social and environmental risks due to potential shortages of and competition for biomass feedstock. Feedstock flexibility is expected to be a competitive edge during location search and operation of a future biorefinery.
- **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 especially 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.

- To reduce investments, assess in more detail the design and **costing of pulp and lignin filtrations, and vapour compressor** in the organosolv fractionation given the combination of significant contribution and large uncertainty.

- Integrate alternative **use options for hemicellulose/C5 sugars and cellulose/C6 sugars** that preferably replace high-value and energy-intensive conventional products on markets where consumers are willing to pay green premium prices. Many promising options have already been or are currently developed in other projects so that new developments may not be required. A promising approach is to preserve as much of the molecular structures of the biomass fractions as possible to reach sustainability 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 hemicellulose/C5 sugars could be separated and used at least in an oligomeric form.

- Develop an integrated utilities concept that is mainly based on **renewable wind and solar power** including the replacement of heat-driven processes by electricity-driven ones. In this regard, 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 sustainable depending on which conventional product 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.

- Continue establishing a **network with high-end service providers and suppliers**, in particular with small and medium enterprises (SMEs) to gain social benefits.

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 sustainable 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, economic and social impacts in the planning stages of a concrete biorefinery is strongly recommended. That study needs to be more specific than the current study that was designed to aid further technology development.

- Initiate a location scouting process based on multiple sustainability criteria:
  - Use local sustainable biomass residue availability as primary criterion.
  - Target preferentially less privileged rural areas or regions that are particularly affected by the structural transformation and job losses in the fossil-based industry to induce positive change from a social perspective.
  - Analyse where lower price levels, particularly in Eastern Europe, can increase profitability.
  - Engage with local stakeholders early on and take their needs and views into account.
  - 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.

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- When candidate locations for a future biorefinery are identified, set up 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, reliably and at affordable prices. In particular, the higher risks of extracting forest biomass to impair the **soil nutrient and soil carbon balance** and the forests’ ability to act as a **carbon sink** and as a **habitat for species** need to be considered. Furthermore, it should also be taken into account that some biomass feedstocks may not be sustainably available in some years. The feedstock flexibility of the studied acetone organosolv concept provides great preconditions that should be taken advantage of. Additionally, conduct an analysis of current uses (commercial and non-commercial) of the targeted biomass residue flows.

Ensure that the buying power of the biorefinery does not endanger the businesses and livelihoods of existing users of the same biomass.

- Optimise **campaigns of mixed and separate feedstocks** primarily for the energy demand caused in pre-extraction and fractionation. Only apply **pre-extraction** if necessary.

Aim to use the economic power associated with a large-scale biorefinery in particular in a rural setting for the benefit of all stakeholders:

- Source as much as possible of the inputs and services locally.
- Invest in the qualification of the local workforce for the biorefinery itself, provide equal employment opportunities and provide incentives in particular for the biomass suppliers to follow this example. Prevent precarious working conditions at the biomass suppliers in particular among seasonal migrant workers.
- It is recommended that social reporting is taken into account when selecting suppliers in order to minimise negative social impacts in the supply chain of the biorefinery. Examples of these criteria are the provision of manufacturer-specific indicators, suppliers that include social indicators in sustainability reports e.g. following guidelines of the Global Reporting Initiative (GRI), or the possibility to carry out sustainability audits to the suppliers. These indicators, reports and audits should be focused on the hot spots identified in this report. This in particular applies to providers of biomass and providers of chemicals with higher tier suppliers outside of the EU.

To political decision makers


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- **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.
- Once a biorefinery concept is fully developed and a concrete proposed setup could be shown to be sustainable, the installation of a **first large-scale biorefinery** should receive **reliable support**. Connect this support to an environmentally and socially balanced implementation concept taking into account e.g. the above mentioned recommendations to potential industrial operators of a future biorefinery.

- Establish **clear sustainability criteria for biomass residues** that are consistent across all biomass-using sectors with regard to how much of which residue can be extracted. This is needed to limit negative environmental impacts from excessive cumulative use. This requires clear targets for conservation of nature and agricultural soils and their active management.

- In the mid- to long-term, holistic **biomass allocation plans** should be developed at national and European level to support a sustainable transition without stranded investments. Due to the fact that environmental burdens and social impacts of resource scarcity do not possess an adequate price, this cannot be achieved by market mechanisms alone. If a certain material use of limited biomass e.g. via biorefineries is overall more sustainable than its use for energy provision, then it should be given priority.

- In a first step towards sustainable biomass allocation, a **phase out of one-sided** incentives and support structures that give advantage to certain sectors, such as the biomass utilisation for energy purposes, should be initiated. This is needed to achieve fairness and greater environmental benefits with the same quantity of biomass. For all mature technologies, subsidy schemes should be based on the actual achieved sustainability benefits.

Besides concrete support for sustainable bio-based technologies, politics needs to actively manage long-term transition processes. This needs to complement what markets can achieve because of their inherent ignorance of external social and environmental costs, their inbuilt concentration on short-term success, their intrinsic need to grow despite strained planetary boundaries and multiple and partially imbalanced distortions of markets by regulatory interventions and subsidies. In particular in the light of the very small remaining carbon budgets that can still be emitted not to risk more than 1.5-2°C of global warming and the short remaining time of 1-3 decades for completing massive transitions, this additionally requires immediate policy changes. In particular, the following should be addressed:

- Set up **sufficiency strategies** to align consumption with levels that contribute to well-being. In a first step towards this, so-called **rebound effects need to be prevented** which includes ensuring that bio-based products really replace fossil-based products instead of leading to higher consumption.

- **Mitigate social impacts** on people who bear the negative consequences of transitions including employees and **regions that currently depend on fossil-based industries** and vulnerable societal groups that may suffer from **potentially increased inflation** due to costs of the transition. Attracting biorefineries to less privileged regions could be one potential measure where local biomass residue availability allows for it.

- Last but not least, transition strategies need to include a **science-based vision** of how a defossilised and climate-neutral circular economy could supply society with products that need to contain carbon without transgressing further planetary boundaries and without earmarking **limited resources** such as biomass, land or, transiently, renewable electricity for several applications in several sectors at the same time. To fully replace fossil resources in our economy, a range of substitutes is required. This needs to include biomass residues and suitable conversion processes such as those studied in this project but also other approaches such as converting captured CO_2 into chemicals and products using renewable electricity. Specific benefits of each technology should be taken advantage of to make best use of available resources.

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.


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7 Abbreviations

C5	Sugars compounds with 5 carbon atoms (hemicellulosic sugars)
C6	Sugar compounds with 6 carbon atoms (cellulosic sugars)
CFC	Chlorofluorocarbon
CHP	Combined heat and power plant
EC	Ethylene carbonate
EU	European Union
GA	Grant Agreement
GHG	Greenhouse gas
GRI	Global Reporting Initiative
ILCD	The International Reference Life Cycle Data System
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 LCT principle
IRR	Internal rate of return
LCA	(environmental) Life cycle assessment, in this project a screening life cycle assessment
LCC	Life Cycle Costing
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: principle behind LCA, sLCA, LCC, ILCSA and related methodologies taking into account effects including the whole supply chain and end of life.
NPV	Net present value
OPEX	Operational expenses
PIR	Polyisocyanurate
PUR	Polyurethane
RED II	Revised renewable energy directive (EU directive about the renewable energy use 2018/2001/EU)
SHDB	Social hotspot database
sLCA	Social life cycle assessment

SME	Small and medium enterprises
SWOT	Analysis of strengths, weaknesses, opportunities and threats
TCI	Total capital investment
TDC	Total depreciable capital
TMP	Trimethyl phosphate
TRL	Technology readiness level
WP	Work Package

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10 Annex

Section 10.1 shows the life cycle schemes of further UNRAVEL scenarios described in section 3.2. An overview on the integrated sustainability assessment results for life cycle comparisons of the conservative and optimistic variants are shown in section 10.2.

10.1 Life cycle schemes of analysed UNRAVEL scenarios

10.1.1 Lignin to fillers

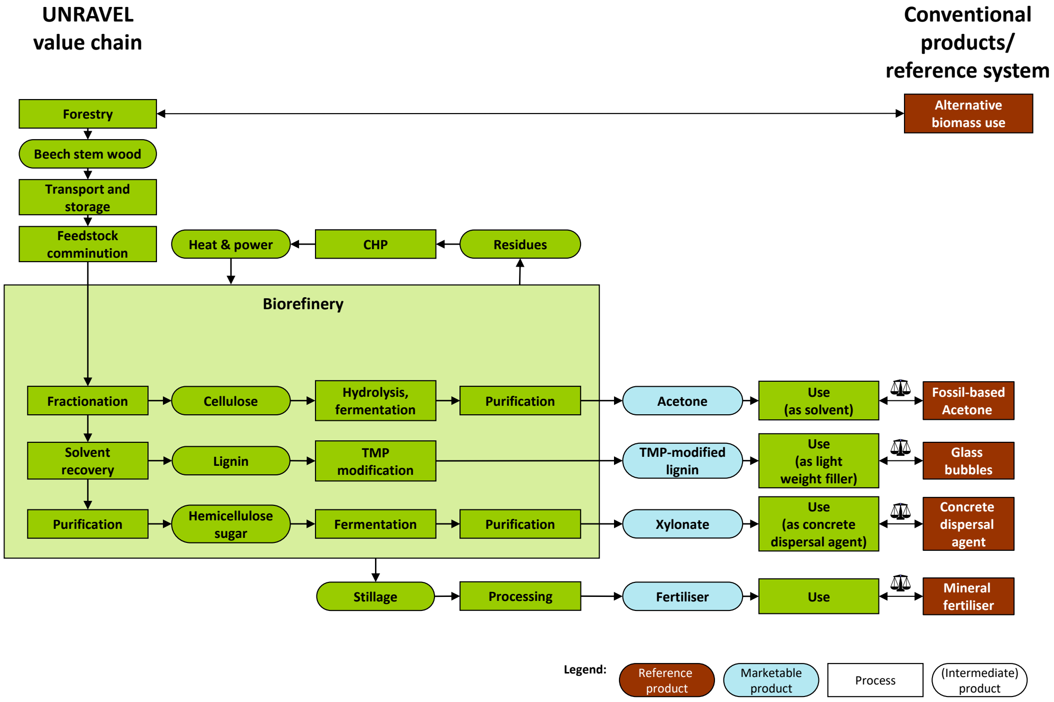

Figure 16: Life cycle scheme of the scenario ‘lignin to fillers’.

10.1.2 Residues to heat only

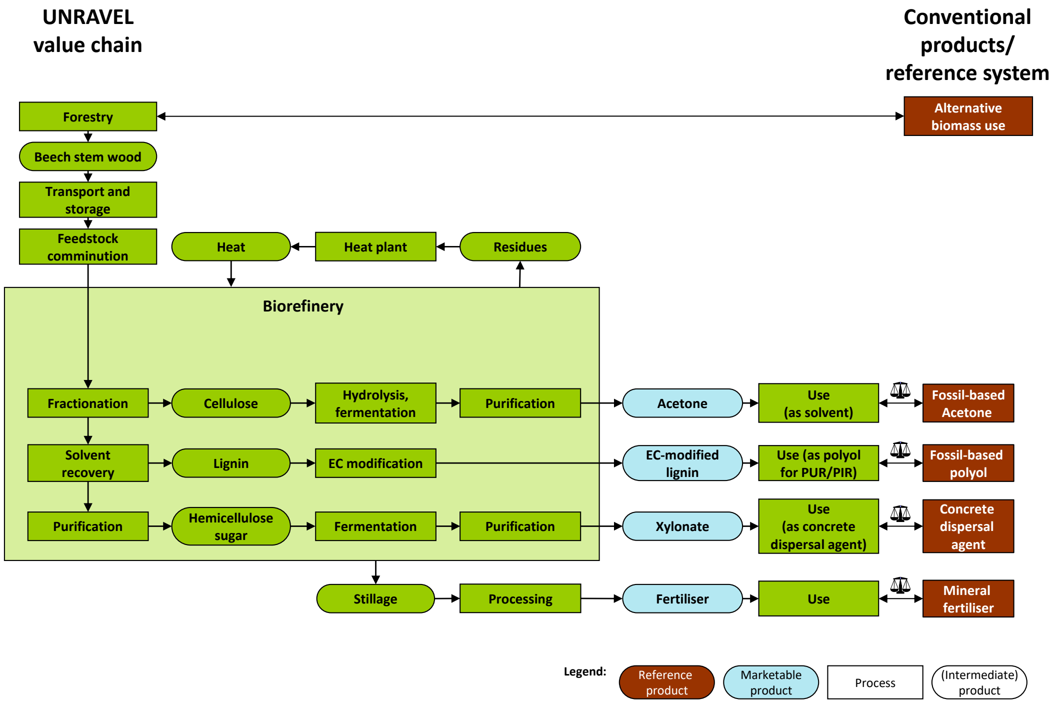

Figure 17: Life cycle scheme of the scenario 'residues to heat only'.

10.1.3 Lignin combustion

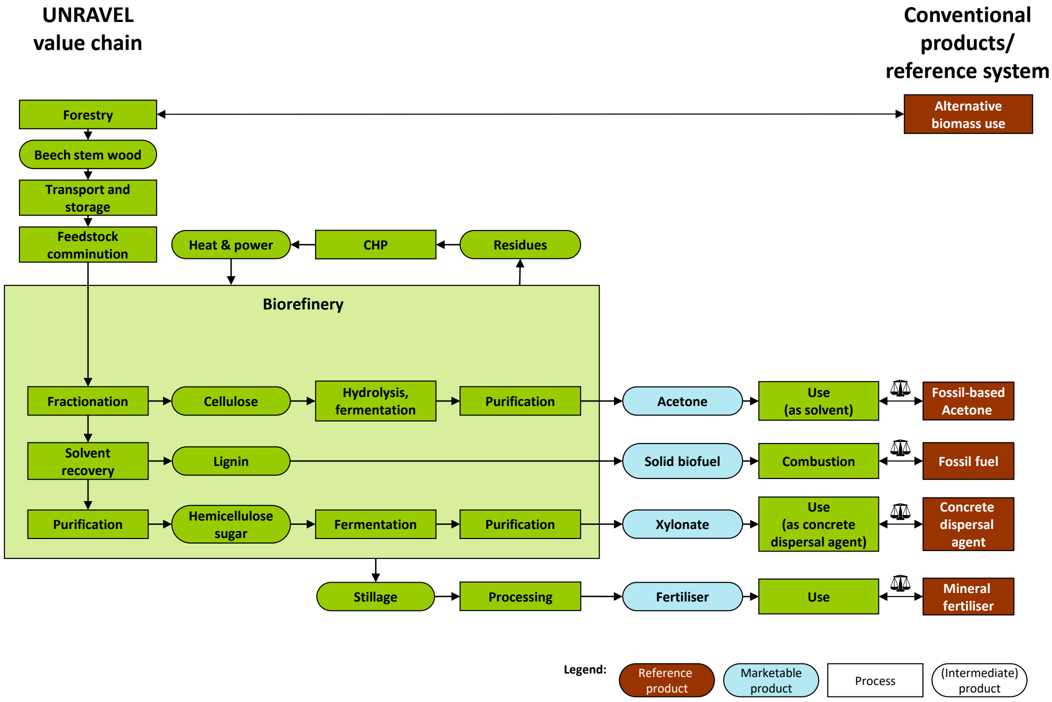

Figure 18: Life cycle scheme of the scenario 'lignin combustion'.

10.1.4 Reference (ethanol organosolv)

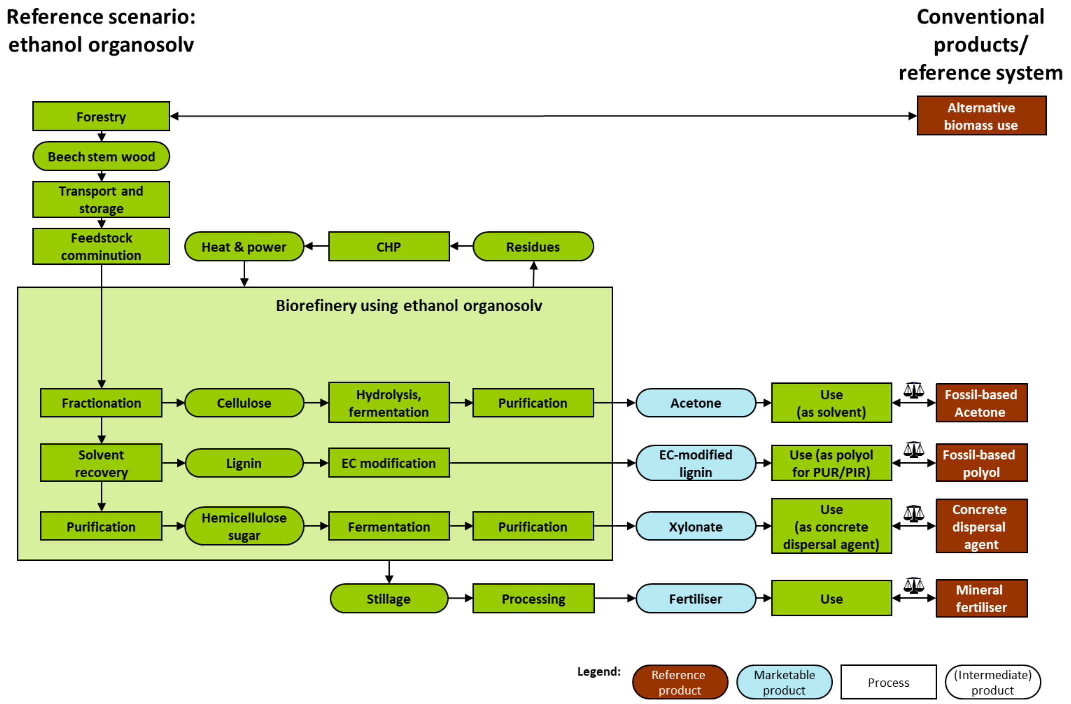

Figure 19: Life cycle scheme of the reference scenario.

10.1.5 Wheat straw

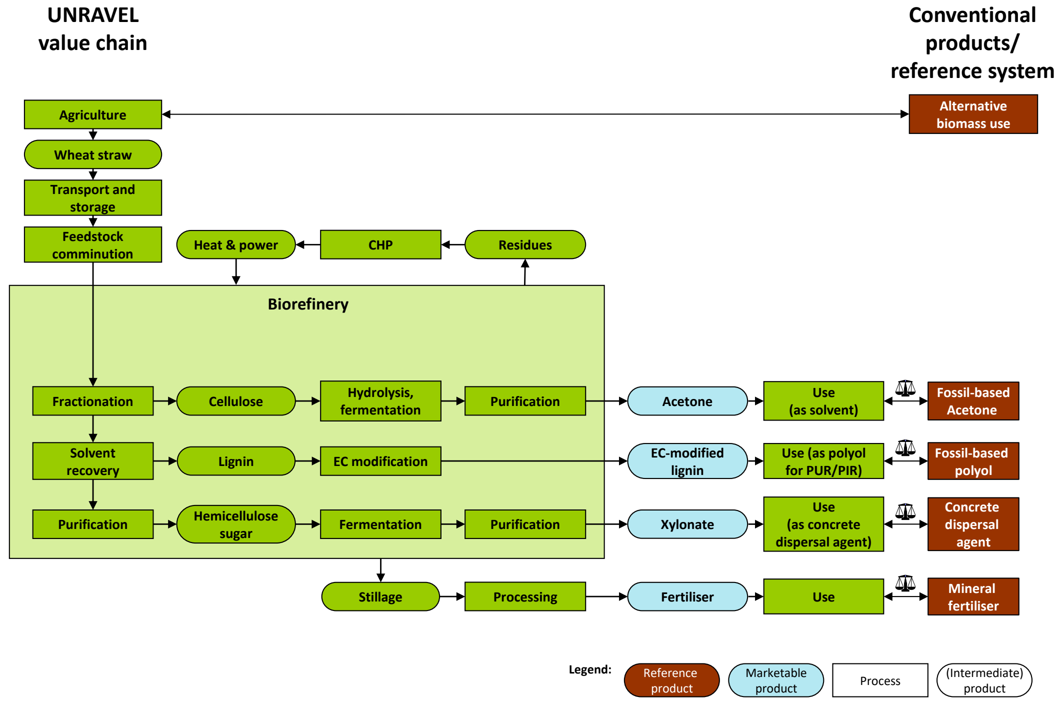

Figure 20: Life cycle scheme of the scenario ‘wheat straw’.

10.1.6 Roadside grass, pre-extraction

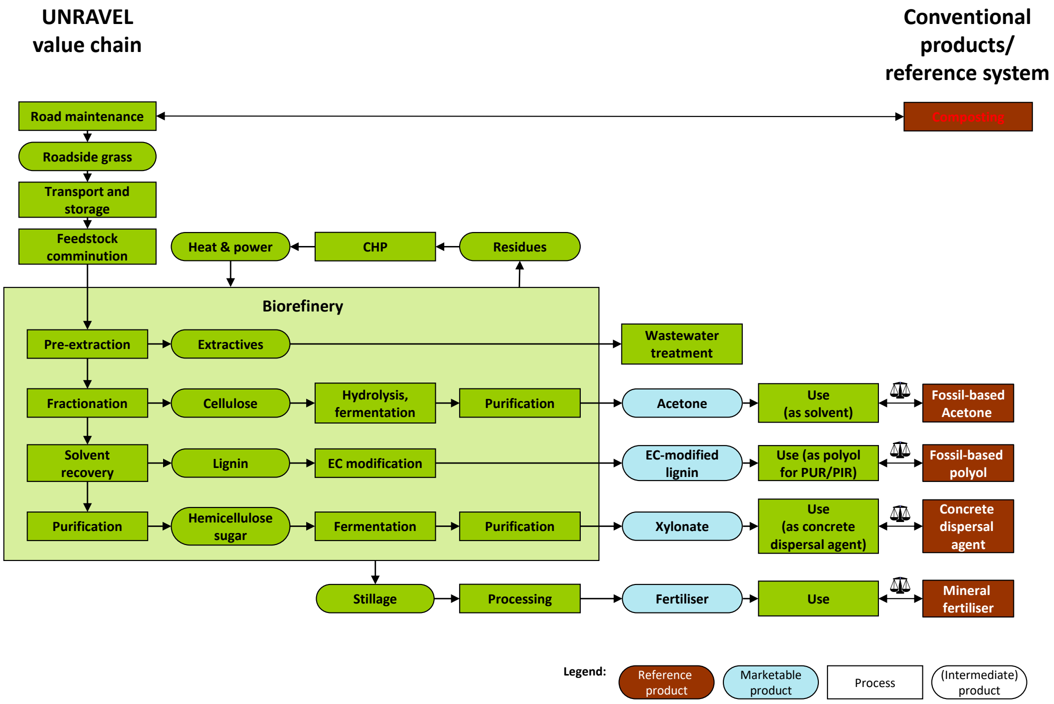

Figure 21: Life cycle scheme of the scenario 'roadside grass, pre-extraction'.

10.1.7 Birch & bark

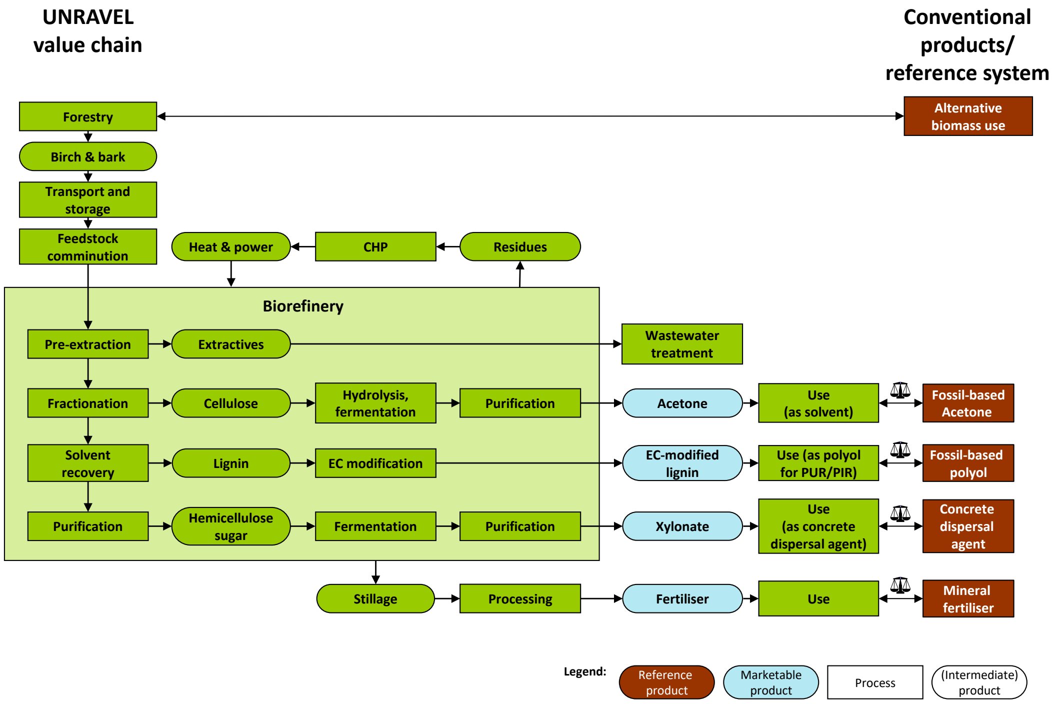

Figure 22: Life cycle scheme of the scenario 'birch & bark'.

10.1.8 Birch & bark, pre-extraction

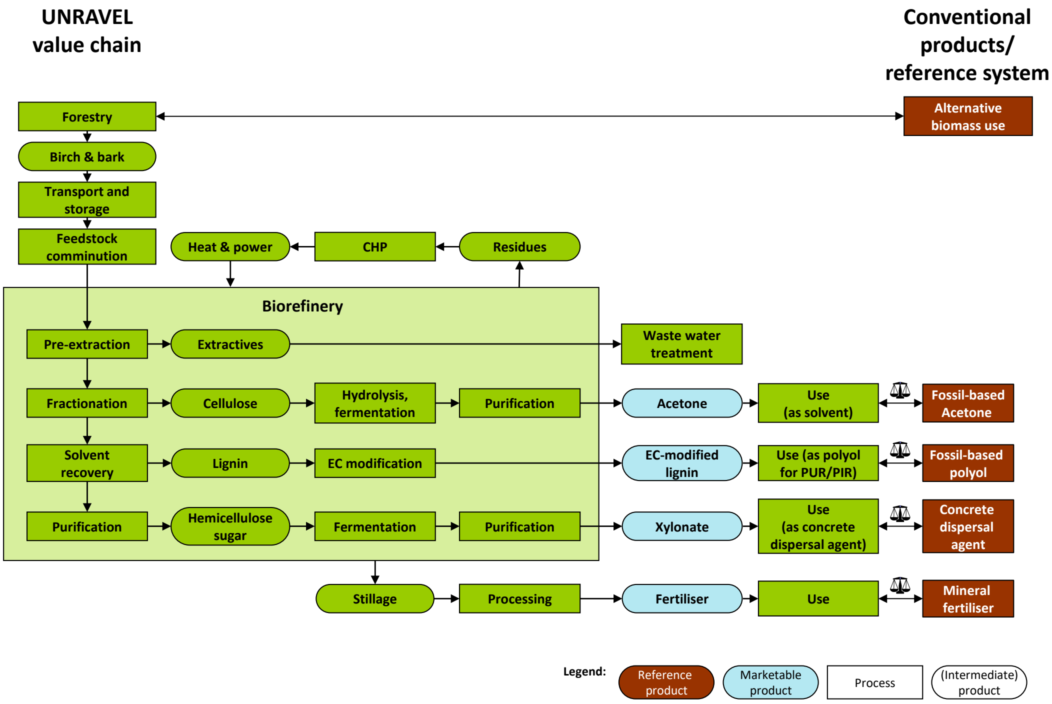

Figure 23: Life cycle scheme of the scenario 'birch & bark, pre-extraction'.

10.1.9 Mixed feedstock, alternating

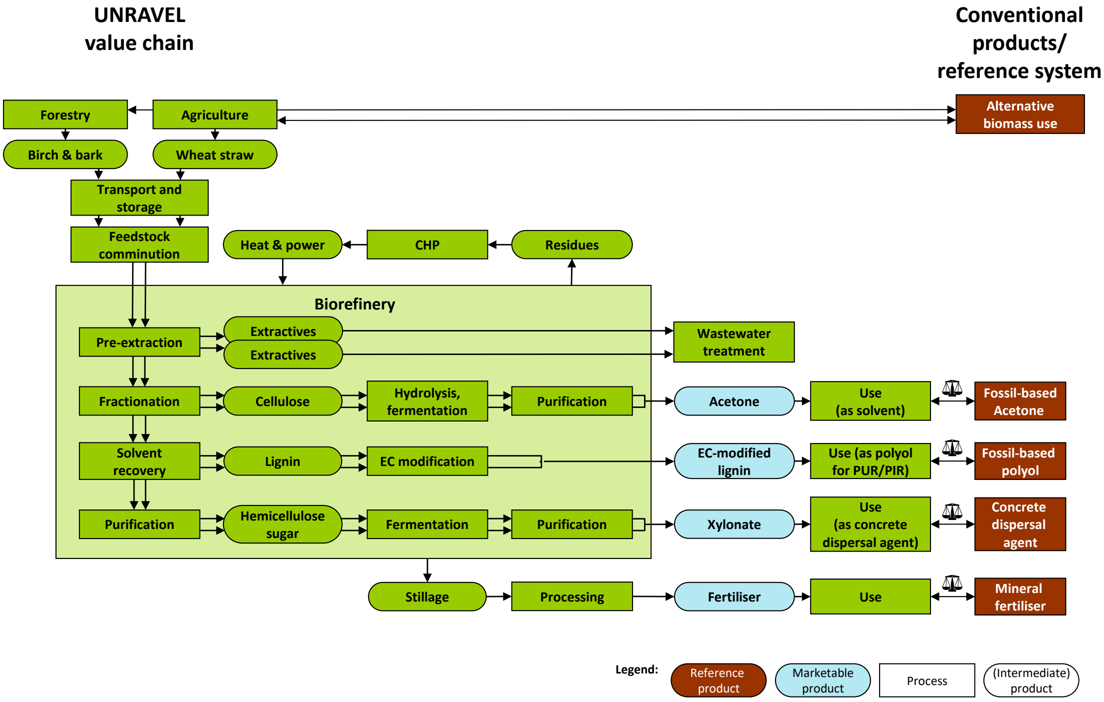

Figure 24: Life cycle scheme of the scenario 'mixed feedstock, alternating'.

10.1.10 Physically mixed feedstock

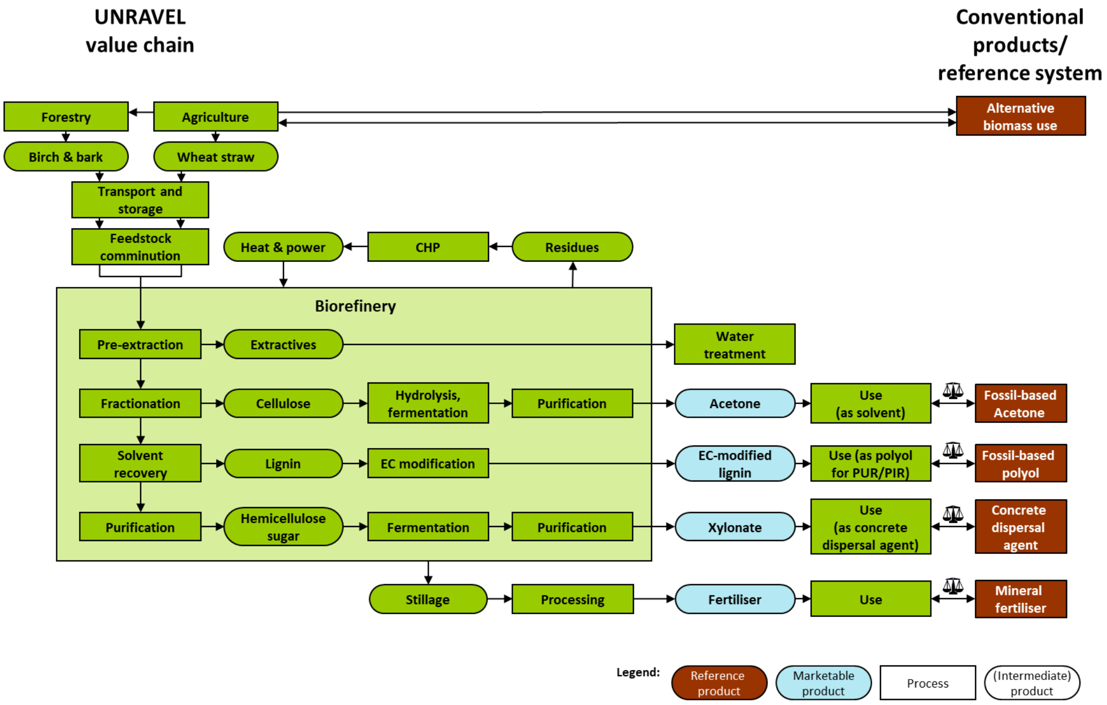

Figure 25: Life cycle scheme of the scenario 'physically mixed feedstock'.

10.2 Additional results: conservative and optimistic boundary conditions

The tables below show an overview of the integrated sustainability assessment results for life cycle comparisons of the conservative (Table 8) and optimistic (Table 9) sub-scenarios to their respective conventional reference systems.

Table 8: Overview of results for life cycle comparisons of UNRAVEL scenarios to their alternatives for conservative sub-scenarios.

		Conservative performance			
		UNRAVEL scenarios			
	Scenario name in report	Basic scenario (beech)	Lignin to fillers	Residues to heat only	Lignin combustion
Indicator	Unit				
Environment					
Non-renewable energy use	GJ / t biomass DM input	19.3	53.0	18.6	19.0
Climate change	t CO2 eq / t biomass DM input	1.28	3.26	1.24	1.23
Climate change incl. competition	t CO2 eq / t biomass DM input	2.39	4.38	2.35	2.34
Acidification	kg SO2 eq / t biomass DM input	5.3	10.9	5.4	5.8
Eutrophication, terrestrial	g PO4 eq / t biomass DM input	413	859	421	461
Eutrophication, aquatic	g PO4 eq / t biomass DM input	27	22	22	22
Ozone depletion	g CFC-11 eq / t biomass DM input	1.6	2.1	1.7	1.7
Summer smog	kg NMVOC eq / t biomass DM input	3.0	6.6	3.0	3.4
Particulate matter formation	kg PM2,5 eq / t biomass DM input	3.8	9.3	3.9	4.5
Land use	m² aL-eq · a / t biomass DM input	523	574	523	514
Phosphate rock use	kg phosphate rock eq / t biomass DM input	56	1 491	56	57
Soil	-	– –	– –	– –	– –
Water	-	–	–	–	–
Biodiversity	-	–	–	–	–
Economy					
Investments	Million EUR	433	446	430	433
OPEX	€ / t biomass DM input	722	762	730	499
Green premium required	% of total product revenue	46%	139%	46%	137%
Society & biomass availability					
Social risks: labor rights and decent work	Thousand medium risk work-hours eq. / t biomass DM input	2.5	1.4	2.6	2.0
Social risks: health and Safety	Thousand medium risk work-hours eq. / t biomass DM input	2.5	1.1	2.5	1.9
Social risks: human Rights	Thousand medium risk work-hours eq. / t biomass DM input	2.0	1.2	2.0	1.6
Social risks: governance	Thousand medium risk work-hours eq. / t biomass DM input	3.3	2.0	3.3	2.6
Social risks: community	Thousand medium risk work-hours eq. / t biomass DM input	2.1	1.4	2.2	1.8
Creating quality employment	-	o	o	o	o
Strengthening rural economies	-	–	–	–	–
Sustainable biomass availability	-	– –	– –	– –	– –

Table 8: (continued).

Conservative performance									
UNRAVEL scenarios									
Wheat straw, pre-extraction	Wheat straw	Roadside grass, pre-extraction	Birch & bark, pre-extraction	Birch & bark	Mixed feedstock, alternating	Physically mixed feedstocks	Reference (ethanol organosolv)	Wheat straw, France	Wheat straw, Eastern Europe
32.1	24.5	28.1	29.3	21.3	30.7	30.7	30.2	24.5	24.5
2.08	1.62	1.78	1.89	1.40	1.98	1.98	2.05	1.62	1.62
3.04	2.58	1.78	2.89	2.41	2.97	2.97	3.16	2.58	2.58
7.9	7.2	6.2	6.7	5.9	7.3	7.3	7.1	7.2	7.2
784	686	494	566	467	675	675	532	686	686
940	923	29	34	18	487	487	24	923	923
5.5	5.2	1.8	2.0	1.7	3.8	3.8	1.9	5.2	5.2
4.2	3.6	3.5	4.0	3.4	4.1	4.1	3.5	3.6	3.6
5.8	5.1	4.6	5.1	4.4	5.4	5.4	5.1	5.1	5.1
44	46	47	46	43	45	45	542	46	46
83	84	56	56	56	69	69	56	84	84
–	–	o	– –	– –	– –	– –	– –	–	–
–	–	o	–	–	–	–	–	–	–
–	–	o	– –	– –	– –	– –	–	–	–
545	519	528	486	442	545	526	471	516	493
904	819	773	727	655	826	830	880	778	688
64%	66%	64%	56%	56%	61%	58%	57%	64%	60%
2.2	2.0	1.9	2.7	2.4	2.5	2.5	3.3	2.0	5.8
3.0	2.7	2.6	2.8	2.4	2.9	2.9	3.3	3.5	10.3
1.8	1.6	1.6	2.2	1.9	2.0	2.0	2.6	1.3	2.1
2.7	2.4	2.4	3.5	3.1	3.1	3.1	4.3	2.4	12.7
1.8	1.6	1.5	2.3	2.0	2.0	2.0	2.7	1.6	2.6
o	o	o	o	o	o	o	o	o	o
o	o	+	–	–	o	o	–	o	o
o	o	o	–	–	o	o	– –	o	o

Table 9: Overview of results for life cycle comparisons of UNRAVEL scenarios to their alternatives for optimistic sub-scenarios.

		Optimistic performance			
		UNRAVEL scenarios			
	Scenario name in report	Basic scenario (beech)	Lignin to fillers	Residues to heat only	Lignin combustion
Indicator	Unit				
Environment					
Non-renewable energy use	GJ / t biomass DM input	-22.8	5.7	-23.9	- 8.2
Climate change	t CO2 eq / t biomass DM input	-1.60	0.22	-1.66	-0.58
Climate change incl. competition	t CO2 eq / t biomass DM input	-1.17	0.65	-1.23	-0.15
Acidification	kg SO2 eq / t biomass DM input	-3.4	0.9	-3.4	-0.1
Eutrophication, terrestrial	g PO4 eq / t biomass DM input	-299	11	-303	-21
Eutrophication, aquatic	g PO4 eq / t biomass DM input	11	11	11	11
Ozone depletion	g CFC-11 eq / t biomass DM input	-2.0	-1.9	-2.0	-1.5
Summer smog	kg NMVOC eq / t biomass DM input	-1.6	1.0	-1.6	0.6
Particulate matter formation	kg PM2,5 eq / t biomass DM input	-3.2	1.0	-3.2	0.2
Land use	m² aL-eq · a / t biomass DM input	56	51	57	50
Phosphate rock use	kg phosphate rock eq / t biomass DM input	5	602	5	7
Soil	-	o	o	o	o
Water	-	o	o	o	o
Biodiversity	-	o	o	o	o
Economy					
Investments	Million EUR	217	223	215	217
OPEX	€ / t biomass DM input	507	493	513	330
Green premium required	% of total product revenue	-14%	46%	-13%	54%
Society & biomass availability					
Social risks: labor rights and decent work	Thousand medium risk work-hours eq. / t biomass DM input	-1.3	-3.5	-1.3	-0.6
Social risks: health and Safety	Thousand medium risk work-hours eq. / t biomass DM input	-1.4	-4.7	-1.4	-0.8
Social risks: human Rights	Thousand medium risk work-hours eq. / t biomass DM input	-0.8	-2.4	-0.8	-0.3
Social risks: governance	Thousand medium risk work-hours eq. / t biomass DM input	-1.6	-4.1	-1.6	-0.6
Social risks: community	Thousand medium risk work-hours eq. / t biomass DM input	-0.8	-2.3	-0.8	-0.2
Creating quality employment	-	+	+	+	+
Strengthening rural economies	-	+	+	+	+
Sustainable biomass availability	-	o	o	o	o

Table 9: (continued).

Optimistic performance									
UNRAVEL scenarios									
Wheat straw, pre-extraction	Wheat straw	Roadside grass, pre-extraction	Birch & bark, pre-extraction	Birch & bark	Mixed feedstock, alternating	Physically mixed feedstocks	Reference (ethanol organosolv)	Wheat straw, France	Wheat straw, Eastern Europe
-14.4	-12.1	-12.2	-19.9	-16.6	-17.2	-17.2	-21.5	-12.1	-12.1
-0.99	-0.82	-0.88	-1.40	-1.17	-1.20	-1.20	-1.52	-0.82	-0.82
-0.60	-0.43	-0.88	-1.06	-0.82	-0.83	-0.83	-1.09	-0.43	-0.43
-1.1	-0.5	-1.7	-3.0	-2.2	-2.1	-2.1	-3.4	-0.5	-0.5
24	97	-155	-256	-198	-116	-116	-250	97	97
914	912	8	10	9	462	462	11	912	912
1.4	2.1	-1.5	-1.8	-1.6	-0.2	-0.2	-0.8	2.1	2.1
-0.5	-0.2	-0.6	-1.3	-0.9	-0.9	-0.9	-1.7	-0.2	-0.2
-1.3	-0.8	-1.6	-2.8	-2.1	-2.1	-2.1	-3.4	-0.8	-0.8
-116	-76	-76	-94	-84	-105	-105	121	-76	-76
32	35	8	6	7	19	19	8	35	35
o	o	++	–	–	o	o	o	o	o
o	o	+	o	o	o	o	o	o	o
o	o	++	–	–	o	o	o	o	o
272	259	264	243	221	272	263	236	258	246
601	543	504	518	470	565	568	608	523	481
18%	21%	17%	9%	8%	15%	9%	11%	19%	12%
-1.6	-1.1	-1.2	-1.1	-0.8	-1.3	-1.3	-0.8	-0.8	0.6
-1.0	-0.5	-0.6	-1.2	-0.9	-1.1	-1.1	-0.8	0.0	2.8
-1.0	-0.7	-0.7	-0.7	-0.4	-0.8	-0.8	-0.4	-0.6	-0.1
-2.1	-1.4	-1.5	-1.3	-1.0	-1.7	-1.7	-0.9	-1.1	3.5
-1.1	-0.7	-0.8	-0.6	-0.4	-0.8	-0.8	-0.3	-0.7	0.4
++	++	++	++	++	++	++	+	++	++
++	++	++	++	++	++	++	+	++	++
++	++	+	o	o	++	++	o	++	++