BioSPRINT

Biorefining of sugars via Process Intensification

Research and Innovation action (RIA) – Horizon 2020-BBI-2019-SO2-R6

Improve biorefinery operations through process intensification and new end products

D6.7

Integrated sustainability assessment of hemicellulose-based products

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Abbreviations used

Abbreviation / Terms	Description
ACR	Agitated cell reactor
CAPEX	Capital expenditures
Fraunhofer CBP	Fraunhofer Center for Chemical-Biotechnological Processes
D	Deliverable
FhG	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
GA	Grant agreement
GHG	Greenhouse gas(es)
GHS	Globally harmonized system of classification and labelling of chemicals
HAZOP	Hazard and operability
HMC	Hemicellulose
5-HMF	5-(Hydroxymethyl)furfural
IFEU	IFEU - Institut für Energie- und Umweltforschung Heidelberg gGmbH
ILCD	International reference life cycle data system
ILCSA	Integrated life cycle sustainability assessment
IRR	Internal rate of return
LCA	Life cycle assessment
LCI	Life cycle inventory
LCT	Life cycle thinking
MIBK	Methyl isobutyl ketone
MVR	Mechanical vapor recompression
NPV	Net present value
PHMF	Phenol-5-hydroxymethylfurfural
PU	Polyurethane
REACH	Registration, evaluation, authorisation of chemicals
ROI	Return on invest
RTR	Rotating tube reactor
SDR	Spinning disc reactor
SEA	Socio-economic assessment
SETAC	Society of Environmental Toxicology and Chemistry

TEA	Techno-economic assessment
TRL	Technology readiness level
UPM	UPM-Kymmene Oyj
WACC	Weighted average cost of capital

1 Executive summary

In order to replace fossil raw materials such as crude oil or natural gas, the products made from them should in future be based on renewable carbon sources. In addition to synthetic hydrocarbons (via Direct Air Capture), lignocellulosic biomass such as wood, straw or other biogenic residues is particularly suitable. The biomass can be converted either thermochemically or biochemically. Biochemical conversion involves fractionating the biomass into its lignin, cellulose and hemicellulose components in biorefineries. So far, however, lignin and cellulose have been the main products, while hemicellulose has only been used for energy production, as a fuel or as an auxiliary material for other production processes.

The BioSPRINT project (‘Biorefining of sugars via Process Intensification’, GA No. 887226) therefore investigated innovative, intensified processes for the optimised production of novel bio-based products from hemicellulose (HMC). These novel bio-based products are substitutes for fossil-based polyurethane (PU) foam and wood laminate binder. However, a novel concept for the production of bio-based products from HMC does not automatically imply that the overall sustainability performance is better. Therefore, the R&D work in BioSPRINT included an integrated life cycle sustainability assessment (ILCSA), the results of which are presented here.

The aim of this study is to i) evaluate the potential sustainability benefits of the innovative processes and to ii) compare the HMC-based products with their conventional/fossil equivalents in terms of implications for sustainability. Another important goal of the study is to identify optimisation potentials to determine focal areas for the further development of the BioSPRINT concept. The study joins the previous assessments of environmental, techno-economic, socio-economic as well as process and product safety aspects into an overall picture and analyses them collectively to give an integrated view of the implications for sustainability associated with the BioSPRINT concept.

The sustainability assessment focuses on process intensification measures in the processing HMC streams from three different biorefinery pre-treatments and/or the products derived from them. The pre-treatments were Fraunhofer CBP’s ethanol organosolv pulping process (concept A), UPM’s pulping process (concept B) and a steam explosion pulping process (concept C). From the investigated streams, the furans 5-(hydroxymethyl)-furfural (5-HMF) and furfural were co-produced in the project using innovative, intensified processes. From these, furfural-containing polyols and a 5-HMF-containing resin were developed. The corresponding end products are the PU foam and the wood laminate binder mentioned above. These innovative, intensified processes were compared with theoretically modelled, non-intensified biorefinery concepts based on state-of-the-art technologies.

The main result of this comparison is that the process-intensified concepts show a slightly, but not significantly better sustainability performance. Only the process-intensified Fraunhofer concept shows a significantly better performance compared to the non-intensified concept, especially from an economic point of view. However, for all process-intensified concepts, technological issues need to be resolved. A more detailed analysis is required when a higher technology readiness level (TRL) is achieved. When comparing the HMC-based products with their conventional/fossil equivalents, conclusions can only be drawn partially as not all of the underlying analyses considered the entire life cycle from biomass extraction to end of life, and in some cases, the effects along the supply chains were not taken into account. This second comparison shows that, from an environmental perspective, improvements in bio-based product formulations and product portfolios are needed to outperform conventional/fossil reference systems. From all other sustainability perspectives, the bio-based systems could have slight advantages over their conventional/fossil counterparts.

For these reasons, further research into bio-based products from HMC streams and their production processes is essential.

Deliverable Keywords: ILCSA; Integrated Life Cycle Sustainability Assessment; sustainability, biorefinery, lignocellulosic biomass, hemicellulose, furfural, 5-hydroxymethyl furfural

2 Introduction

In the future, renewable carbon sources should replace fossil raw materials such as crude oil or natural gas. The only renewable carbon source is CO_2 from air. It can either be captured by direct air capture (DAC) and further processed into larger molecules, or the large molecules that biomass builds up from CO_2 through photosynthesis of biomass can be broken down. Lignocellulosic biomass such as wood, straw or other biogenic residues are particularly suitable as a carbon source. It can be separated in biorefineries into its components lignin, cellulose and hemicellulose (HMC). So far, however, it is mainly lignin and cellulose that have been used for products, while HMC has only been used for energy production, as a fuel or as an auxiliary material for other production processes.

The BioSPRINT project ('Biorefining of sugars via Process Intensification') project, therefore, investigated innovative processes for the optimised production of novel bio-based products from HMC. The bio-based products are alternatives to the fossil products PU foam and wood laminate binder. Figure 1 shows the overall concept of the BioSPRINT intensified biorefinery concept.

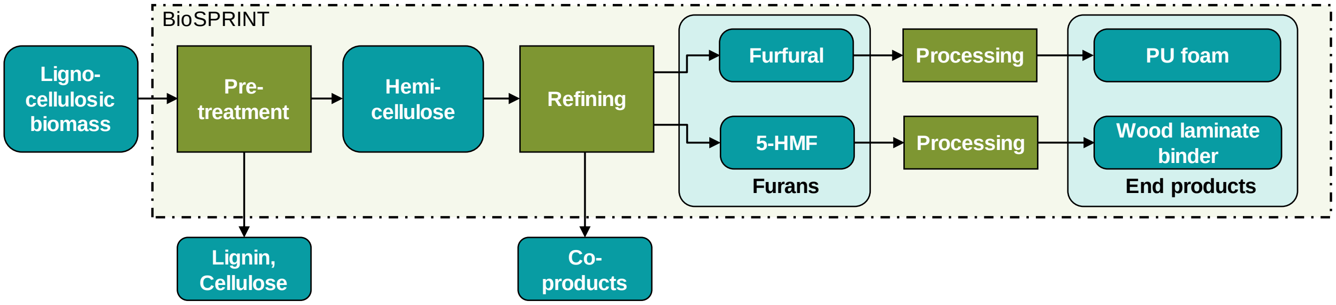

Figure 1: Flow diagram of lignocellulosic biomass use for polymer applications and BioSPRINT's field of activity.

However, it is unclear how the BioSPRINT concept compares from a sustainability point of view with i) state-of-the-art biorefining technologies and ii) the provision of the end products from fossil sources. Therefore, the aim of the present study is to evaluate the potential sustainability benefits of the innovative processes and to compare the HMC-based products with those of their conventional/fossil equivalents.

This integrated life cycle sustainability assessment (ILCSA) study integrates environmental, techno-economic, social and safety aspects. Chapter 3 describes the definitions and settings, both common to all underlying analyses and specific to the ILCSA study. The systems analysed, i.e., the BioSPRINT concept, a theoretically modelled state-of-the-art biorefinery concept and the fossil reference system, are detailed in Chapter 4. Chapter 5 summarises the contributing studies on which the ILCSA is based. Chapter 6 presents the results of the comparison of the BioSPRINT concept with the two reference concepts. The key findings, conclusions and recommendations are summarised in Chapter 7.

2.1 Mapping project’s outputs

Purpose of this section is to map BioSPRINT’s Grant Agreement (GA) commitments, both within the formal Deliverable and Task description, against the project’s respective outputs and work performed.

Table 1: Adherence to BioSPRINT’s GA Deliverable & Tasks Descriptions

<table>
<tr><th colspan="2">BioSPRINT Task</th><th>Respective Document Chapter(s)</th><th>Justification</th></tr>
<tr><td>Task 6.6 – Integrated life cycle sustainability assessment (ILCSA)</td><td>The results from the previous analyses (T6.2-T6.5) are integrated to identify and depict the most sustainable pathways among the BioSPRINT value chains compared to all reference systems. IFEU will use a multi-criteria evaluation software tool following the innovative methodology of ILCSA covering all sustainability indicators chosen.
From these analyses, the most sustainable pathways will be depicted as well as all optimisation potentials. As one central element of ILCSA, potential barriers against and unintended side-effects of the implementation of those scenarios that have been identified to be in principle sustainable will be analysed. This will lead to conclusions and recommendations on strategies for a sustainable implementation of the targeted BioSPRINT products.</td><td>Chapter 3
Chapter 4
Chapter 5
Chapter 6
Chapter 7</td><td>Chapter 3 describes the methodology used by the ILCSA and the definitions and settings common to all the underlying analyses (T6.2-6.5).
Chapter 4 describes the systems analysed and the scenarios of all the underlying analyses.
Chapter 5 summarises the underlying analyses (T6.2-T6.5).
Chapter 6 integrates the underlying analyses and identifies sustainable pathways, optimisation potentials and potential barriers.
Chapter 7 summarises and concludes the results of Chapter 6 and gives recommendations on strategies for implementing sustainable products.</td></tr>
<tr><th colspan="4">BioSPRINT Deliverable</th></tr>
<tr><td colspan="4">D6.7 Integrated sustainability assessment of hemicellulose-based products
The deliverable provides the final results of the integrated life cycle sustainability assessment carried out at T6.6.</td></tr>
</table>

3 Methodology

To achieve reliable and robust sustainability assessment results, it is inevitable that the principles of comprehensiveness and life cycle thinking (LCT) are applied. LCT means that all life cycle stages for products are considered, i.e., the complete supply or value chains, from the extraction of biomass, through processing in the biorefinery and production of the end user products, to product use and end-of-life treatment. 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. All three classical 'pillars of sustainability' will be analysed using techniques that are based on life cycle thinking (environmental life cycle assessment, social life cycle assessment and life cycle costing). Moreover, sustainability-related aspects of process safety, product safety and technological barriers are included in the overall assessment.

This assessment is based on the methodology of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015], which is briefly introduced in Section 3.1.

As a prerequisite for the integrated life cycle sustainability assessment, common goal and scope definitions and other common settings are imperative which equally apply to the contributing studies addressing one single sustainability perspective each. Only then can the results of these parallel 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 defined in [Wowra et al. 2023] and described in Section 3.2. Specific definitions and settings that are only relevant for the environmental, economic, technological, and socio-economic as well as the process and product safety assessment can be found in the respective reports [Crnomarkovic & Eijkenboom 2024; Eijkenboom & Crnomarkovic 2024; Kekkonen et al. 2023; Rettenmaier et al. 2024] whereas specific definitions and settings for the integrated sustainability assessment are described in Section 3.3.

3.1 ILCSA methodology in a nutshell

The analysis of the life cycles within BioSPRINT follows the integrated life cycle sustainability assessment (ILCSA) methodology. 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 to 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 3.3 for details on the procedure selected in this study.

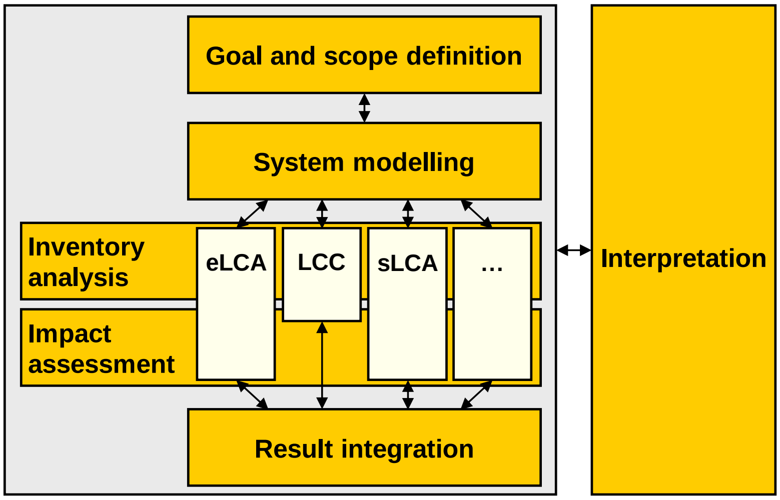

Figure 2: Schematic workflow of integrated life cycle sustainability assessment (ILCSA) [Keller et al. 2015]. It provides a framework to integrate several life cycle based assessments such as (environmental) life cycle assessment, eLCA, life cycle costing, LCC, social life cycle assessment, sLCA, and analyses of other sustainability-relevant aspects.

3.2 Common definitions and settings for the ILCSA and the contributing studies

The ILCSA covers a comprehensive set of sustainability aspects, including environmental, economic, societal and safety indicators, for which common definitions and settings have been established in the BioSPRINT project [Wowra et al. 2023]. This section summarises the common goal and scope of the ILCSA.

3.2.1 Goal definition

The ILCSA in BioSPRINT aims at identifying the implications of BioSPRINT pathways including all optimisation potentials for both processes and complete scenarios.

The main **aim of the study** is to provide decision support in two main areas:

- for the development of sustainable bio-based products based on a resource-efficient concept and,
- for an improved and intensified technology development compared to a non-intensified biorefinery concept.

The **target audiences** of the study are decision-makers in

- policy
- the scientific community
- the industry
- the general public.

Against this background, the **main guiding question** to be answered by the BioSPRINT sustainability assessment is defined as follows.

- **How far and under which conditions can hemicellulose (HMC) use according to the BioSPRINT biorefinery concept contribute to a more sustainable supply of the targeted products?**

Addressing the main question, consequently, leads to the following **sub-questions** relevant to the ILCSA:

1. **Sub-questions:**
   - How do the studied **intensified BioSPRINT biorefinery concepts** compare from a sustainability perspective
     i. to the conventional non-intensified biorefinery concepts and
     ii. to conventional (fossil) ways of providing the same product portfolio?

2. **Sub-questions:**
    - How do specific results for the different perspectives on sustainability (such as environmental, economic, social, and safety) differ from each other?
    - Which unit processes significantly influence the results and what are the optimisation potentials?
    - What is the influence of possible transitions in the economy (e.g., renewable energy) on the results?
3. **Sub-questions:**
    - Which barriers (e.g., technological) and limitations (e.g., biomass availability) may hinder the industrial-scale implementation of BioSPRINT or require changes to the concept affecting sustainability (such as using unsustainable biomass during shortages)?

3.2.2 Scope definition

The scope of an ILCSA study includes the definition of the subject of the study including the exact products and relevant systems to be analysed. The scope should be sufficiently well defined to ensure that the comprehensiveness, depth, and detail of the study are compatible and sufficient to achieve the stated goal (see Section 3.2.1).

In BioSPRINT, two biorefinery concepts with intensified process steps were developed to upgrade the hemicellulose (HMC) stream to furans and further to novel bio-based products.

- **Concept A**: suitable for streams containing large amounts of lignin in a solvent (e.g., ethanol), applied to black liquor stream based on an organosolv pre-treatment of beech wood **(FhG)**
- **Concept B**: suitable for HMC streams with low lignin content, applied to HMC stream based on UPM’s pre-treatment of hardwood **(UPM)**

As an excursus, the process intensification measures used in concept B are applied to a mixed HMC/cellulose stream based on a steam explosion pre-treatment of residual wheat straw **(concept C)**.

These systems were evaluated through separate analyses, namely an environmental life cycle assessment (LCA), a technical and economic assessment (TEA), a socio-economic assessment (SEA) and an assessment of product and process safety.

In the following, parameters relevant to the scope of the ILCSA, such as definitions of the systems and their functions, the technical references, and relevant scenarios as well as time and scale are described.

System boundaries

The ILCSA study requires delineating the investigated product system and its overall functions. The main system boundary chosen within BioSPRINT is a cradle-to-grave analysis, which allows us to consider all relevant process steps from resource extraction (e.g., the biomass extraction) up to the end of life of the derived end products (e.g., PU foams and wood laminates) and conventional reference products.

However, the choice of system boundaries depends on the question to be answered. For the comparison of the intensified BioSPRINT concept with a fossil refining concept, a cradle-to-grave analysis would answer the relevant questions (see **cradle-to-grave** system boundary in Figure 3). This system boundary was applied in the LCA. Due to slightly deviating objectives and challenging data availability, the TEA only considers the processes up to the production of polyols and resins to answer this question (see **cradle-to-polyols/resins** system boundary in Figure 3). For similar reasons, the SEA and the process safety assessment only consider the process steps ‘refining’ and ‘polymerisation’ excluding the supply chains of energy and materials. The product safety assessment, on the other hand, evaluates the safety of polyols and resins, the novel bio-based products investigated in BioSPRINT.

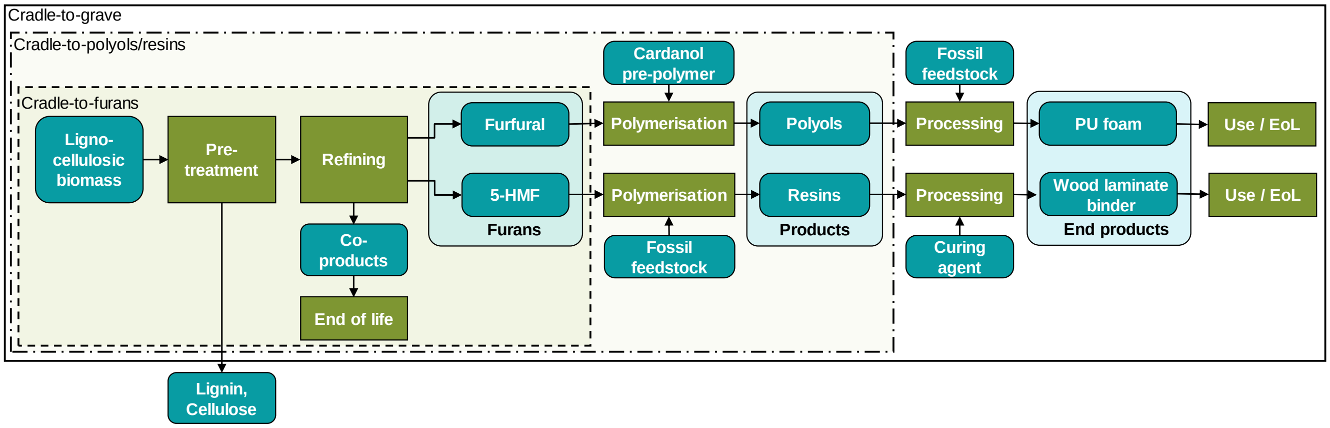

Figure 3: System boundaries for the LCA in BioSPRINT.

In order to compare the impact of the intensified BioSPRINT concept with the non-intensified reference biorefinery concept, only the process steps up to the production of the furans are considered in all contributing studies. The reason for this is that the subsequent process steps do not involve any process intensification and the downstream inputs mask the effects of the intensification (see **cradle-to-furans** system boundary in Figure 3). The production of lignocellulosic biomass is considered in detail in the LCA and as a black box together with the pre-treatment in the TEA, as different amounts of raw material may be required due to differing yields of the biorefinery concepts. In addition, the LCA and TEA take into account end-of-life emissions and disposal costs of auxiliary materials. The supply chains for energy, raw materials, and auxiliary materials are excluded in the SEA and the process safety assessment, as data availability and quality would not allow differences between the concepts to be identified.

These three different system boundaries need to be taken into account when interpreting the results of the ILCSA.

Functional units

The functional unit depends on the question to be answered. For a fair comparison between the BioSPRINT concept and the theoretically modelled reference biorefinery concept, the mass of the furans (sum of furfural and 5-HMF) is the appropriate functional unit. This takes into account the different yields of the concepts and gives equal weight to 5-HMF and furfural. Both substances have a similar carbon content (57% vs. 62%), a similar chemical structure and, therefore, a comparable substitution potential for fossil products.

While all 5-HMF produced in the biorefinery is used to make the end product, some furfural is recycled back from the PU foam processing into the refining process. The proportion of the recycled furfural is lower in the BioSPRINT concept than in the reference concept. To account for this difference, the functional unit ‘1 tonne of usable furans’ is used. This is calculated from the mass of furans after refining minus the mass of furfural recycled back to the refining from the end product processing. It should be noted that the co-location of polyol production and biomass pre-treatment at the same site, and thus the possibility to recycle furfural, is a deliberate setting within the BioSPRINT project. This possibility might not be given if the concept was implemented in reality and it could well be the case that furfural and 5-HMF are transported to specialised resin formulators or PU producers located elsewhere. However, the amount of recycling is an estimate for the quality of the furans.

For the comparison with the fossil system, a functional unit is defined for each end product: ‘1 tonne of wood laminate binder’ assuming the same binding properties (mass equivalence) and ‘1 m^3 of PU foam’ with the same properties for decorative applications (volume equivalence) for the LCA. The functional unit for the TEA, SEA and process safety assessment is ‘1 tonne of polyols and resins’. For comparability, the results of the LCA are related to ‘1 tonne of polyols and resins’ without changing the functional unit.

Technical reference

The ILCSA evaluates scenarios representing a potentially mature technology (‘nth plant’, technology readiness level TRL 9) based on research and development work of the project, expert knowledge and, where necessary, literature sources. As the research and development work in BioSPRINT is carried out at a lower TRL, an extrapolation of the corresponding data to an appropriate industrial scale has been performed by process simulation.

The process simulation is based on a biorefinery capacity of 225 kilotonnes per year (kt/yr) of dry-weight feedstock input. The set capacity is inspired by commercial-scale lignocellulosic ethanol plants, which are typically designed to process 250 kt/yr wheat straw, taking into account a water content of 10%wt.

Timeframe

The choice of an adequate timeframe for the ILCSA includes the consideration of various technological and regulatory constraints. The earliest realistic date for a mature industrial-scale production appears to be 2030. Thus, important background data, such as Life Cycle Inventory (LCI) data for electricity generation, refer to the year 2030. However, due to data availability, some background data, such as prices in the TEA, refer to 2023.

Geographical coverage

The geographical scope of the ILCSA is the European Union. This means that LCI data with appropriate geographical coverage are selected from relevant databases, if available. For the assessment of the biorefinery in the TEA, Germany was chosen as an example.

3.3 Specific definitions and settings for the ILCSA

The integrated sustainability assessment in BioSPRINT 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.

3.3.1 General approach

There are two general options to integrate a multitude of indicators in 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 number of options and indicators, this requires a structured approach. This approach is followed in this study. This section describes the methodology used for the structured comparison and presentation of decision options based on a multi-criteria analysis.

3.3.2 Collection of indicators and results

Indicators and results for all scenarios are provided by the parallel assessments addressing one single sustainability perspective each [Crnomarkovic & Eijkenboom 2024; Eijkenboom & Crnomarkovic 2024; Kekkonen et al. 2023; Rettenmaier et al. 2024]. They are collected in overview tables. In some cases, indicators are selected or aggregated by the authors of the respective contributing studies 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
- 5 quantitative economic indicators
- 2 qualitative technological indicators, each subdivided into 4 life cycle stages
- 4 qualitative social indicators
- 5 qualitative process safety indicators
- 1 qualitative product safety indicator

No further adjustments are made except for rescaling quantitative data to a common basis if necessary. Thus, all specific settings, methodological choices including underlying estimates, and data sources apply unchanged as documented in the respective reports.

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly. Dark and light green boxes represent overall advantageous results. Orange and red boxes represent overall disadvantages. 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 performance of a scenario. Results are collected for all assessed main scenarios. Additional results, such as from sensitivity analyses based on dedicated scenarios, are used to contextualise the results and taken into account for the overall conclusions (Section 7.1) and recommendations (Section 7.2).

3.3.3 Additional indicators

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

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. As this goal is not met by the analysed concepts of the BioSPRINT project, it is impossible to define an indicator on how efficiently the goal is reached. Moreover, 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]. Consequently, this additional indicator is not determined for the BioSPRINT concepts.

3.3.4 Benchmarking

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

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

A subsequent categorisation of the benchmarking results reflects the robustness of advantages or disadvantages over the benchmark. For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question of 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 considered not substantially different if the difference in a particular indicator is below a threshold of 10% of the absolute result of the benchmark scenario. This approach differs from that of Keller et al. [2015], which takes into account both the range between the best and worst results of all scenarios and the uncertainty of the results. As only a very small number of scenarios (that are meaningfully comparable) were evaluated in most of the contributing studies and no reliable estimate of uncertainty is available, the approach proposed by Keller et al. [2015] cannot be applied. For all qualitative indicators, rating of differences is done analogously but without applying minimum differences.

3.3.5 Overall comparison

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

4 Analysed systems

In a biorefinery, the pre-treatment of lignocellulosic biomass, such as wood or straw, aims to extract cellulose and recover the non-cellulosic components lignin and hemicellulose hydrolysate (HMC). The compositions of the resulting streams depend on the type of biomass and the used pre-treatment technology. Therefore, the BioSPRINT project developed two biorefinery concepts with intensified process steps to upgrade HMC streams to furans and further to novel bio-based products. The concepts differ in the upstream purification step.

- **Concept A:** suitable for streams containing large amounts of lignin in a solvent (e.g., ethanol), applied to a black liquor stream based on an organosolv pre-treatment of beech wood **(FhG)**
- **Concept B:** suitable for HMC streams with low lignin content, applied to a HMC stream based on UPM's pre-treatment of hardwood **(UPM)**

As an excursus, the process intensification measures used in concept B are applied to a mixed HMC/cellulose stream based on a steam explosion pre-treatment of residual wheat straw **(concept C)**.

UPM and FhG use the HMC stream of existing or newly built biorefineries and increase the portfolio of chemicals and products made in the biorefinery. For concept C, HMC and cellulose are used to make furans and chemical ingredients for PU foams and wood laminate binders.

To answer the sub-questions raised in Section 3.2.1, these **process-intensified BioSPRINT concepts** are compared with

a) **non-intensified biorefinery concepts** (see Section 4.1, relevant life cycle stages in Section 4.1: 'biomass provision' to 'downstream processing').
b) a **fossil reference system** (see Section 4.2, relevant life cycle stages in Section 4.1: 'biomass provision' to 'polymerisation and product formulation).

It should be noted that the term 'non-intensified' does not mean unambitious: the non-intensified biorefinery concepts do comprise state-of-the-art processes, some of which could be considered (partly) intensified.

4.1 Intensified BioSPRINT concepts vs. non-intensified biorefinery concepts

A cradle-to-grave analysis of the end products obtained from the intensified BioSPRINT concepts and non-intensified biorefinery concepts (reference) would not reveal any differences between the two systems, since the upgrading step from HMC to furans contributes very little to the life cycle environmental impacts of the chosen product system. Thus, this comparison is limited to a cradle-to-gate analysis from biomass provision to furan production (see also Figure 3 on p. 15). Figure 4 shows the life cycle stages and the co-products for this **cradle-to-furans** analysis.

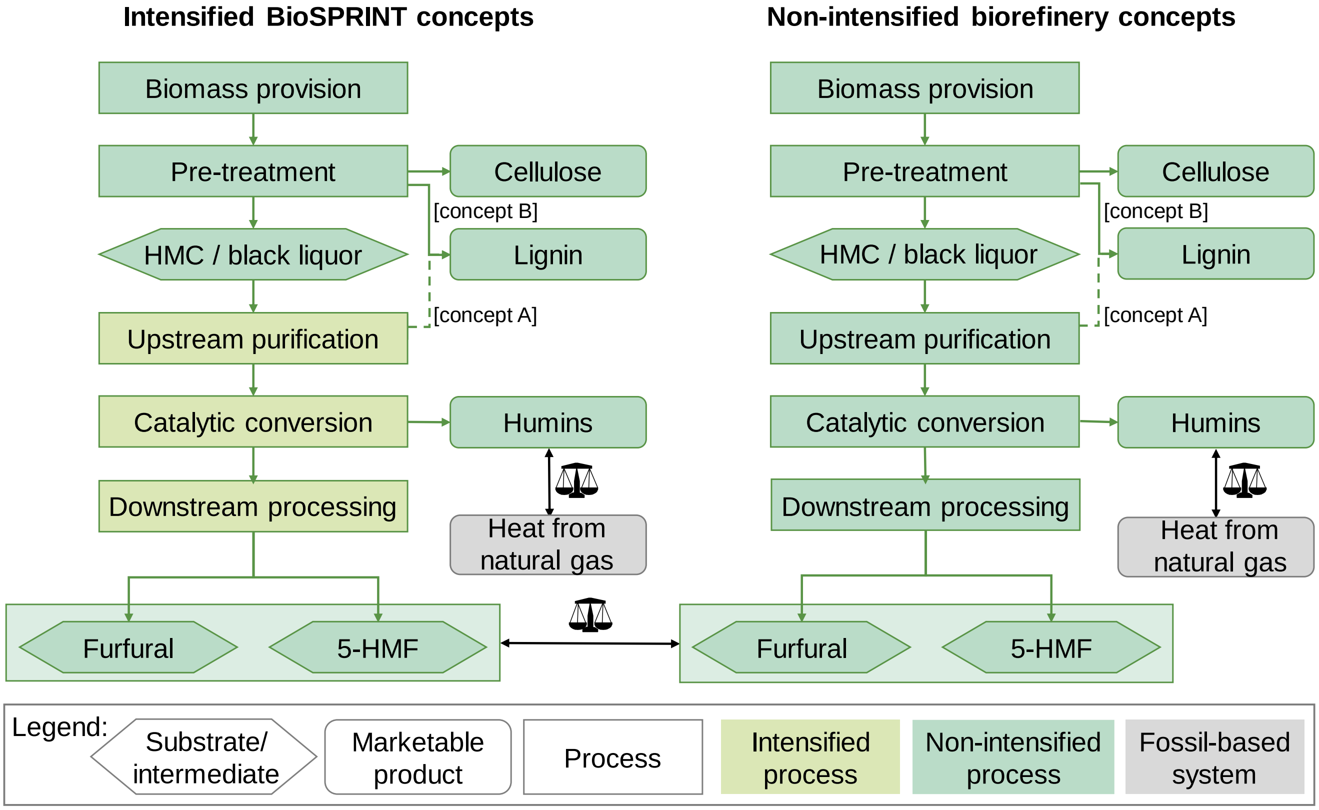

Figure 4: Simplified process flow diagram comparing the intensified BioSPRINT concepts (left) and the non-intensified biorefinery concepts (right).

4.2 Intensified BioSPRINT concepts vs. fossil reference system

The comparison of the BioSPRINT concepts with the fossil reference system was intended to be performed as a **cradle-to-grave** analysis from biomass provision to end product manufacture (see also Figure 3 on p. 15). For various reasons, it was however only applied in the LCA (see ‘System boundaries’ in Section 3.2.2). Figure 5 shows the life cycle stages and the co-products for this system boundary. The following sections describe the life cycle stages and the co-products in detail. The functional equivalence of the two systems is based on mass in the case of wood laminate binder (assuming equal binding function) and on volume in the case of PU foam (assuming equal decorative function).

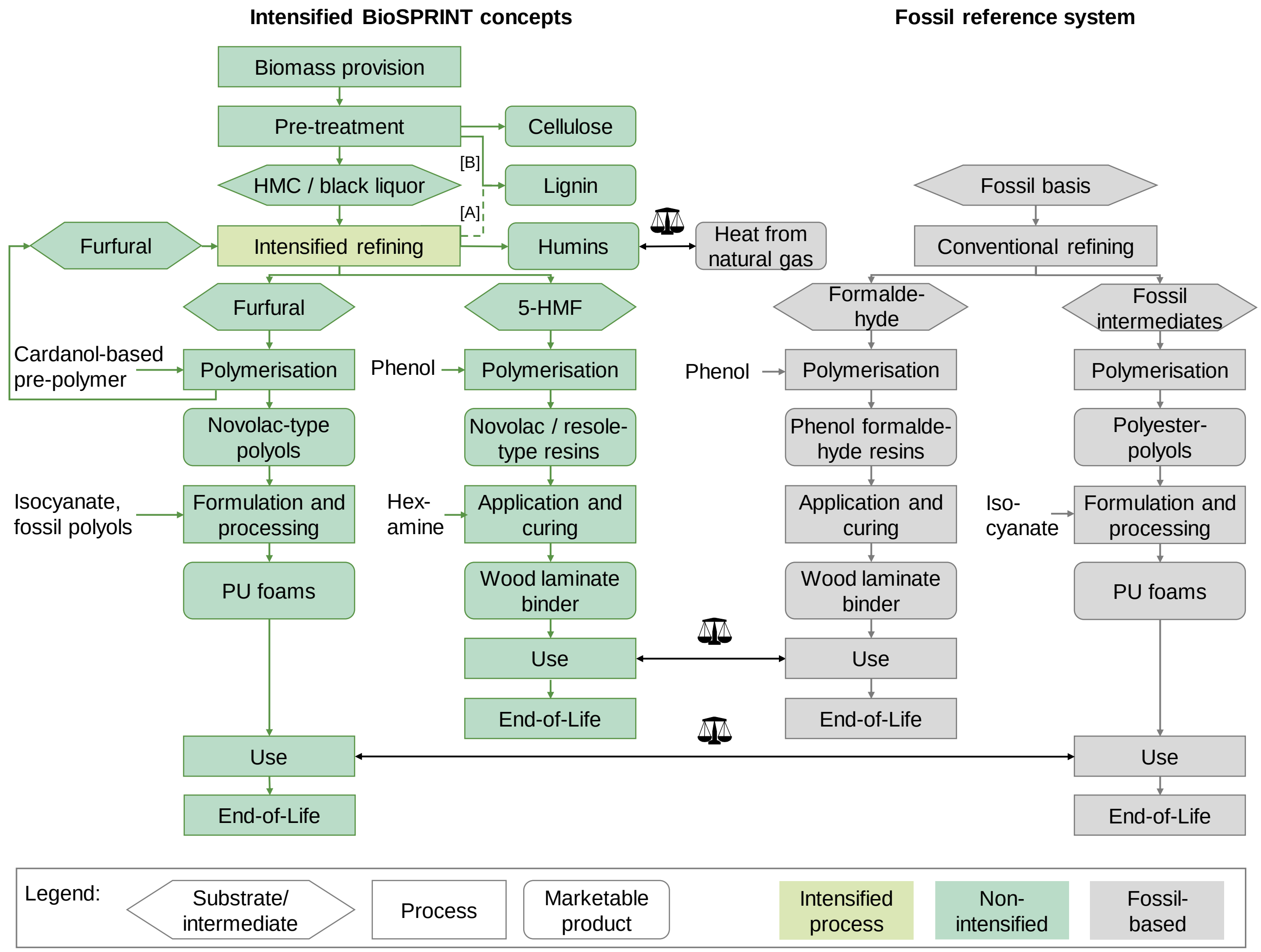

Figure 5: Simplified process flow diagram comparing the intensified BioSPRINT concepts (left) and the fossil reference system (right).

4.3 Biorefinery capacity

A biorefinery capacity of 225 kilotonnes per year (kt/yr) of dry weight feedstock input was chosen (see also Section 3.2.2). Table 2 summarises the resulting production volumes for furans, PU foams and wood laminate binder. The different composition of the HMC and black liquor streams in terms of C5 to C6 ratio results in different ratios of furfural to 5-HMF and, therefore, different ratios of PU foam to wood laminate binder.

Table 2: Production volume for the different pre-treatments based on a 225 kt/a biorefinery.

	UPM	FhG	Concept C
C5/C6 sugars (dry matter) [kt/yr]	66	32	130
Furans [kt/yr]	35	17	78
thereof furfural [kt/yr]	20	15	22
thereof 5-HMF [kt/yr]	15	2	56
Polyols (incl. cardanol) [kt/yr]	100	76	110
PU foams [kt/yr]	546	415	599
Wood laminate binder [kt/yr]	27	3	103

4.4 Life cycle stages

Table 3 provides an overview of the life cycle stages covered by each analysis. Due to different objectives and data availability, the analyses differ in terms of the life cycle stages modelled in detail. For example, a detailed TEA and SEA of the life cycle stage 'pre-treatment' for UPM and concept C was not possible due to a lack of data. Therefore, the HMC and, for equal treatment, the black liquor stream were considered as inputs to the system, treating the upstream life cycle stages as a black box. Product formulation and end-of-life were not included in the TEA, SEA and process safety assessment as these steps were not analysed in the BioSPRINT project and a comparison with fossil equivalents was already possible at the intermediate product level (polyols and wood laminate binders without hardener). The product safety assessment only covered the end products and did not consider other life cycle stages.

Table 3: Overview of the life cycle stages covered by the contributing studies.

	LCA	TEA	SEA	Process safety	Product safety
Biomass provision	✓	(✓)	(✓)	×	×
Pre-treatment	✓	(✓)	(✓)	×	×
Upstream purification and concentration	✓	✓	✓	✓	×
Catalytic conversion	✓	✓	✓	✓	×
Downstream processing	✓	✓	✓	✓	×
Polymerisation	✓	✓	✓	✓	×
Product formulation	✓	×	×	×	✓
End of life	✓	×	×	×	×

A detailed description of all life cycle stages can be found in D6.3. Here, only a brief summary of the respective stages is given.

Biomass provision

Both FhG's and UPM's pre-treatment use hardwood. Exemplarily for different wood qualities, the LCA considers beech stem wood as obtained from forest thinning operations. Concept C uses residual wheat straw as biomass feedstock. For both beech wood and straw provision, the LCA considers state-of-the-art technology for harvesting, transportation and chipping and no previous use of the biomass resource. The resource use and emissions per t biomass for the biomass provision are set the same for both intensified and non-intensified systems.

Pre-treatment

LCA, TEA, SEA and process safety assessment consider three different biomass pre-treatments: an organosolv pulping (FhG), UPM's pre-treatment and a steam explosion pre-treatment (concept C). All three pre-treatments fractionate the lignocellulosic biomass into monomeric and oligomeric HMC, cellulose and lignin. The resulting streams differ in composition. There are: cellulose and black liquor streams for FhG, cellulose, lignin and HMC streams for UPM, and cellulose and C5/C6 stream for concept C. The pre-treatment is identical for both the intensified and non-intensified biorefinery concepts.

The LCA considers two different scenarios for the pre-treatment: i) A new biorefinery would be built, i.e., the biomass (and thus the HMC / black liquor streams obtained from its fractionation) would be previously unused. ii) An existing biomass pre-treatment facility is diverted towards BioSPRINT. In the latter case, we need to take into account that the HMC stream is currently not a waste stream, but that this stream is likely to be already valorised. Exemplarily, the LCA considers a hypothetical previous use of the HMC stream for biomethane provision via anaerobic digestion (AD) and biogas upgrading. If the HMC stream was used for the production of furans, it would no longer be available for the previous use (biomethane), which under the current and near-future economic framework would most likely be replaced by conventional/fossil sources (natural gas).

Upstream purification and concentration

The process steps summarised as upstream purification differ for concept A and concept B.

In concept A, applied to FhG, the upstream purification aims to separate lignin and ethanol from the black liquor to obtain an HMC stream and to concentrate it. In the case of the intensified BioSPRINT concept, the HMC stream is additionally purified by nanofiltration and diafiltration to remove impurities such as organic acids, salts, extractives and some lignin residues. The separation of lignin is carried out with different reactor technologies depending on the concept. The concentration step and the separation of ethanol are optimised by using improved mechanical vapour recompression for evaporation.

In concept B, applied to UPM, as well as in concept C, the upstream purification aims to concentrate the HMC stream. In the intensified BioSPRINT concept, the HMC stream is purified by nanofiltration and diafiltration prior to concentration.

Table 4 lists the different technologies applied for upstream purification of the intensified BioSPRINT and non-intensified biorefinery concepts, respectively.

Table 4: Main differences in the upstream purification and concentration for intensified and non-intensified biorefinery concepts.

	Intensified BioSPRINT concepts	**Non-intensified biorefinery concepts**
Concept A (FhG)	Lignin precipitation and ethanol evaporation with a cascade of spinning disc reactors (SDR) Improved mechanical vapour recompression (MVR) and heat integration for ethanol recovery Purification with nanofiltration and diafiltration	Lignin precipitation and ethanol evaporation with a falling film evaporator Heat integration and mechanical vapour recompression (MVR) for ethanol recovery No further purification
Concept B (UPM) and concept C	Purification with nanofiltration and diafiltration Concentration by evaporation with mechanical vapour recompression (MVR)	No purification Concentration by evaporation

Catalytic conversion

During catalytic conversion, a large proportion of the monomeric and oligomeric C5 and C6 sugars in the HMC stream are converted into the furans 5-HMF and furfural. Some of the furans polymerise and form humins. These processes are catalysed by sulphuric acid. Moreover, the catalytic conversion includes the separation of the humins and part of the separation of the furans from the unreacted sugars and other impurities. Wastewater is obtained that contains considerable amounts of sulphuric acid (up to 270 g/L). A partially purified aqueous phase containing furans and unconverted sugars and, in the case of the intensified BioSPRINT concepts, an organic phase containing furans are sent to the downstream processing unit. The main differences between the intensified BioSPRINT and non-intensified biorefinery concepts are listed in Table 5.

Table 5: Main differences in the catalytic conversion for intensified and non-intensified biorefinery concepts.

Intensified BioSPRINT concepts	Non-intensified biorefinery concepts
Bi-phasic reaction in agitated cell reactor (ACR) using a mixture of water and the organic solvent methyl isobutyl ketone (MIBK)	Single-phase reaction in plug flow reactor with static mixing elements
Improved heat exchanger for heat recovery upstream and downstream of the reactor	Heat recovery upstream and downstream of the reactor with shell and tube heat exchanger
Part of separation of furans and non-reacted sugars included in ACR	Separation of furans and non-reacted sugars by diafiltration with nanofiltration membrane
Separation of aqueous and organic phase with hydrocyclone	Not applicable
Separation of humins by microfiltration	Separation of humins by microfiltration and ultrafiltration

Downstream processing

In the downstream processing, the furans in the aqueous phase are completely separated from unreacted sugars and remaining impurities by liquid-liquid extraction with the organic solvent methyl isobutyl ketone (MIBK). The MIBK is recovered by distillation. The furans are separated into furfural and 5-HMF which are passed to the polymerisation stage. The differences between the intensified and the non-intensified biorefinery concept are listed in Table 6.

Table 6: Main differences in the downstream processing for intensified and non-intensified biorefinery concepts.

Intensified BioSPRINT concepts	Non-intensified biorefinery concepts
Liquid-liquid extraction applied to aqueous stream of catalytic conversion	Liquid-liquid extraction applied to complete output stream of catalytic conversion
Aqueous output of extraction unit is recycled to upstream purification	Aqueous output of extraction unit is wastewater containing relevant amounts of sulphuric and organic acids
Recovered MIBK is recycled to catalytic conversion and liquid-liquid extraction	Recovered MIBK is recycled to liquid-liquid extraction

Polymerisation

For both intensified and non-intensified routes of each biorefinery concept, furfural is processed into novolac-type polyols and 5-HMF is processed to novolac / resole resins. No process intensification was implemented in the process steps for the production of the end products from furfural or 5-HMF.

The biorefinery products and the end product formulations are described below.

Novolac-type polyols from furfural

The aldehyde furfural is used to produce novolac-type polyols. These polyols are the condensation products of an aldehyde and a phenolic compound. The reaction is supported by an acid catalyst. The phenolic compound used in this study is a pre-polymer based on cardanol produced from cashew nut shell liquid.

Novolac / resole-type resins from 5-HMF

5-HMF and a small amount of water are polymerised with phenol to produce novolac / resole-type resins. The reaction is catalysed by a base.

Product formulation

End product application: High-density structural foams

The novolac-type polyols can be used together with fossil polyols and conventional isocyanate to produce pour-in-place high-density structural polyurethane (PU) foams, which can be used to produce various protective and decorative elements for interior and exterior surfaces, such as faux wood and faux stone panels, realistic props for the entertainment industry, etc. PU foam-based thermal insulation panels would also be an interesting application, which would however require further R&D work beyond this project for verification. Given the low OH value compared to polyols traditionally used for insulation panels and the reactivity of the novolac polyol, high-density structural foams were chosen as the most appropriate type of application for the LCA and ILCSA.

The fossil polyols used in the formulation are Mannich and polyether polyols at variable ratios depending upon the type of formulation. The polyols react with polymeric methylene diphenyl diisocyanates. A combination of amine and metal-based catalysts is used, while the utilised additives are: flame-retardants and surfactants.

End product application: Binder for panels

The novolac / resole-type resin is used as a binder for wood laminates. The 5-HMF based material must first be heated to a viscous state. Furthermore, a hardener (hexamine) has to be added.

End of life

For the end-of-life of both products, state-of-the-art waste incineration is set in the LCA. Apart from biogenic CO_2, direct emissions from waste incineration are not modelled since they strongly depend on the specific waste incineration plant and are, moreover, comparable for both the fossil and the BioSPRINT system.

4.5 Co-products

As part of the biorefinery processes, humins are formed and considered as co-products. For the LCA, the replacement of heat from natural gas by burning the humins was considered. In the non-intensified and intensified refinery concept, similar amounts of humins are produced. The TEA considers lignin and ethanol as co-products of the upstream purification in case of the ethanol-organosolv pre-treatment.

4.6 Wastewater treatment

All biorefinery concepts yield wastewater. Most wastewater is acidic due to its content of sulphuric acid and various organic acids such as acetic acid, formic acid or levulinic acid. The LCA therefore considers pre-treatment with calcium hydroxide to raise the pH value, followed by treatment in a standard wastewater treatment plant. The organic load of the wastewater is low, so biogas production is not considered.

4.7 Electricity, heating and cooling

The BioSPRINT processes require electricity, heat and cooling. Regarding the electricity for the processes in the foreground system (biomass provision, pre-treatment, BioSPRINT processes, product formulation), an EU grid mix for 2030 is set. In a sensitivity analysis (scenarios 3 and III), solar power (PV) is set instead.

The required heat is provided by steam at different pressure levels. In the base case (scenarios 1a-c and Ia,b), steam is provided by a natural gas-fired steam boiler whose efficiency is independent of the pressure level. Moreover, all co-products of the life cycle stages ‘upstream purification and concentration’ to ‘polymerisation and product formulation’ are considered for energy recovery. As the process intensification aims at reducing the temperature level of the processes, the sensitivity analysis ‘temperature-dependent heat supply’ (scenarios 2 and II) is performed, where steam is provided by a combined cycle gas turbine with process steam extraction at different pressure levels. The forgone electricity from natural gas due to steam extraction is set as a reference for the respective environmental impact.

For cooling/chilling, the LCA sets an average electricity demand with a bandwidth in the optimistic and conservative scenarios.

4.8 Infrastructure, direct emissions and transport

The infrastructure of the background system is included in the analysis, i.e., the production facilities necessary to manufacture inputs such as MIBK or ethanol. The infrastructure of the foreground system was evaluated but only included for the indicator ‘climate change’ in the final analysis. It needs to be noted that these values are only a rough indicator of what could be the influence of including the infrastructure in the analysis since i) no data is available for the biomass pre-treatment, ii) data on concrete, structural steel and piping depend on the actual location of the plant to be built (i.e., site-specific conditions) and iii) the weight of the equipment is partially unknown.

No direct emissions to air from a plant according to the intensified BioSPRINT concepts or the non-intensified biorefinery concepts are taken into account since no data is available.

Transport of the biomass is included in the analysis. The transport of intermediates or products is excluded from the study since it is comparable for all analysed systems and has a negligible overall impact.

4.9 Fossil reference products

The formulation of the fossil reference products was provided by project partners. The bio-based PU foams are replacing fossil-based commercial PU foams with identical volume. The resin replaces functionally equivalent fossil-based phenol formaldehyde resins on a mass basis. Table 7 summarises the differences between the BioSPRINT products and the fossil reference products.

Table 7: Main differences in product formulation and application of BioSPRINT and fossil products.

	BioSPRINT products	**Fossil reference products**
PU foams	Contains bio-based ingredients: novolac-type polyols based on furfural and cardanol based on cashew nut shell liquid.	Contains only fossil ingredients.
Wood laminate binder	Based on novolac / resole-type resins made from 5-HMF, water and phenol (fossil) Heating of viscous resin prior to application and addition of curing agent hexamine (fossil) necessary.	Based on phenol formaldehyde resins made from formaldehyde, water and phenol No heating prior to application and no addition of curing agent necessary.

4.10 Scenarios

All contributing studies consider three different pre-treatments and the corresponding upstream purification concepts. These are UPM, FhG and concept C. For each of these three concepts, an intensified BioSPRINT biorefinery concept is compared to i) a non-intensified reference concept and ii) a fossil reference system.

Beyond this, the **LCA** investigated different scenarios as sensitivity analysis of which the scenarios included in Table 8 are considered in the ILCSA analysis. These scenarios include a variation of heat and electricity supply. The respective settings are summarised in [Rettenmaier et al. 2024].

Table 8: Overview of analysed intensified BioSPRINT scenarios (arabic numerals) and non-intensified reference biorefinery scenarios (roman numerals) for the LCA.

	Scenario name
1b	BioSPRINT base case, typical
2	BioSPRINT temperature-dependent heat supply
3	BioSPRINT solar power
Ib	Reference biorefinery base case, typical
II	Reference biorefinery temperature-dependent heat supply
III	Reference biorefinery, solar power

The **TEA** investigated products from the three different pre-treatments. Results are supplemented with sensitivity analyses for the indicators ‘internal rate of return’ (IRR) and ‘net present value’ (NPV) by varying different costs for feedstock, product, investment, etc.

The SEA distinguishes between UPM and FhG on the one hand (‘add-on’ to an existing biorefinery) and concept C on the other hand (‘stand-alone’ biorefinery). No sensitivity analyses were performed due to the high level of the assessment.

The **process safety assessment** takes into account the UPM and FhG pre-treatments. After consultation with the authors of this assessment, the results for UPM can largely be transferred to concept C. No sensitivity analyses were performed due to the high level of the assessment.

Since the **product safety assessment** was carried out at the level of polyols and resins for which no difference due to different pre-treatments was known at the time the analysis was carried out, no distinction is made between pre-treatments.

5 Summaries of contributing studies

5.1 Summary: life cycle assessment

To assess the potential environmental benefits of the innovative processes, the intensified BioSPRINT concept developed in the project was compared with a theoretically modelled, non-intensified biorefinery concept based on state-of-the-art technologies. The process intensification measures investigated in BioSPRINT to improve the production of furans from HMC-containing streams certainly lead to environmental improvements for individual processes, such as the catalytic conversion, but are inherently associated with additional environmental burdens for other processes. In the end, this leads to similar results for both the (intensified) BioSPRINT concept and a theoretically modelled, non-intensified biorefinery concept (reference). As part of the project, the organosolv pre-treatment has been improved to such an extent that it has clear advantages over the non-intensified biorefinery concept (reference). The full potential of this improvement can be exploited particularly in combined heat and power generation.

To compare the HMC-based products with their conventional/fossil equivalents, the entire life cycle from biomass extraction to end-of-life was modelled and compared with the life cycle of the same product portfolio made purely from fossil resources. The furans 5-HMF and furfural that replace fossil equivalents have the potential to reduce the environmental impact of conventional products. However, this does not occur automatically in every case (just because biomass is used as a renewable resource), but depends on four factors, which must be favourable at the same time.

- Minimum environmental impact associated with the furans (including indirect impacts)
- Maximum environmental impact of the substituted conventional/fossil intermediate
- A substitution ratio (mass of furans : mass of conventional/fossil equivalent intermediate) as close as possible to 1 : 1. This can be achieved by the most complete conversion of the furans to furan-based products and an improved functionality of the furan-based product compared to its conventional/fossil equivalent.
- Minimum environmental impact associated with the conversion of furans to furan-based products.

Moreover, the environmental impacts of other ingredients also need to be considered.

For the reasons given above, a case-by-case assessment is essential.

A case-by-case analysis is absolutely necessary for the reasons mentioned above. Even though the BioSPRINT product system with the end products PU foam and wood laminate binder does not show advantages over the fossil reference system due to the poor substitution ratio, HMC-based products certainly have the potential to achieve environmental advantages over their conventional/fossil equivalents.

5.2 Summary: technological assessment

The techno-economic viability of the process-intensified biorefineries at the projected large industrial scale is investigated. In particular, the economic viability of the commercial-scale process-intensified biorefineries was evaluated for the production of furans from the HMC streams obtained from the three biorefinery cases, FhG, UPM and concept C. Furthermore, the economic outcomes of the process-intensified biorefineries are compared with their non-intensified references. Capital expenditures (CAPEX), production cost and financial indicators (net present value, NPV, and internal rate of return, IRR) are assessed for the respective biorefinery concepts.

The CAPEX analysis shows that process intensification can be beneficial to lowering capital cost intensity in the FhG biorefinery by implementing spinning disc reactor (SDR) technology for lignin precipitation and ethanol recovery. On the other hand, in UPM and concept C biorefineries, process intensification based on a biphasic reaction system and rotating tubular reactor (RTR) technology increases capital expenditure compared to their non-intensified references. The increase in capital costs is mainly due to increased equipment sizes in the process-intensified biorefineries' catalytic conversion and downstream processing sections. By replacing monophasic with biphasic reaction technology in the process intensified biorefineries, the volumetric flows of the process streams almost doubled in the catalytic conversion and downstream processing section, causing an increase in sizes and costs of the major equipment such as reactor and distillation columns.

The production cost analysis shows that UPM and concept C non-intensified and process-intensified biorefineries make furans at comparable prices. Due to higher investment costs, the UPM process-intensified biorefinery makes furans at a slightly higher cost than the non-intensified reference. On the other hand, concept C process intensified biorefinery shows better economic performance compared to the non-intensified biorefinery, mainly due to better raw material utilisation and higher furan yields in the biphasic reactor, thus demonstrating the benefits of implementing process intensification methods and technology in biorefineries. The production cost of FhG biorefineries is dominated by significant contributions of side product credits from ethanol and lignin and the black liquor stream costs. However, excluding these cost contributions, the analysis shows that the utilities' cost contribution in FhG process-intensified biorefinery is significantly lower compared to the non-intensified reference. A significant cut in energy cost is achieved by replacing a conventional technology to precipitate and recover lignin and ethanol in a falling film evaporator with a process-intensified method based on SDR technology.

A financial assessment of the three process-intensified biorefinery cases shows that the base cases of UPM and concept C are not financially viable as the calculated NPV and IRR values are negative or close to zero. The FhG biorefinery project, on the other hand, demonstrates economic viability as NPV and IRR values are positive for the considered base case. NPV and IRR sensitivity analysis for the three biorefineries indicate that the feedstock cost, namely HMC and black liquor stream, and the product pricing play a critical role in the project's financial viability. Small changes in these costs or prices determine whether BioSPRINT's process-intensified biorefinery concepts become economically feasible.

5.3 Summary: socio-economic assessment

A high-level socio-economic assessment was carried out to evaluate how the implementation of the new biorefinery based on process intensification methods could affect the European economy and society. Three questions on the impact of a BioSPRINT biorefinery on job creation, workers' profiles, local development and value added were answered. The questions were:

- how does the intensified biorefinery compare to the non-intensified biorefinery,
- are there differences between the BioSPRINT concept as an 'add-on' to an existing biorefinery (UPM, FhG) and a 'stand-alone' concept (concept C), and
- what are the effects of the intensified BioSPRINT biorefinery concept compared to fossil refineries.

The information and data used for the analysis and discussion were sourced from the public literature and the research work carried out as a part of the BioSPRINT project. Only the foreground system without the supply chain was considered.

The results of the analysis indicate that the BioSPRINT process intensified biorefinery does not show any advantages or disadvantages compared to a biorefinery based on non-intensified or conventional methods and process equipment in terms of socio-economic impact indicators: job creation, workers profile, local development and value added. Similarly, when comparing the BioSPRINT concept as an 'add-on' to the existing biorefinery with a 'stand-alone' concept, no differences were observed in the socio-economic impact indicators. However, the analysis shows a trend towards a positive impact of the BioSPRINT concept compared to the fossil reference system. In particular, the BioSPRINT biorefinery is likely to positively impact job creation, workers' profiles and skill levels, and local development, but mainly in rural regions. On the other hand, no advantages or disadvantages are expected in terms of value added compared to the fossil reference.

5.4 Summary: process safety assessment

Process safety is an important aspect of ensuring the sustainability of chemicals. By evaluating process safety, possible improvements in operational and occupational safety aspects related to the production of chemicals can be identified, especially in the BioSPRINT project, the biorefinery operation. For this purpose, the non-intensified and intensified biorefinery concepts were analysed for different pre-treatments. In addition, the bio-based and fossil refinery routes were compared.

The level of detail of the scenarios analysed was not sufficient for a hazard and operability (HAZOP) study. Instead, a HAZOP-like assessment was carried out, bringing together the expertise of the project consortium through various interviews and workshops to identify the hazards of the different biorefinery scenarios and provide a risk assessment for each hazard. During the risk assessment process, reliability and consistency were sought by jointly discussing the probability and consequence scales used in the risk assessment and by discussing the results of the risk assessment with the consortium. In both the hazard identification and the risk assessment, it was recognised as a challenge that the biorefinery scenarios did not exist at industrial scale and the assessment was based on the available information extrapolated to industrial scale from the process simulation models and qualitative information shared by the BioSPRINT experts. Therefore, the results presented for the process safety assessment are not detailed enough to be used as a basis for the design of an industrial-scale process, which would require a detailed process safety assessment. It is also important to note that the assessment for the fossil refining route was only considered at a coarser level based on literature references.

For biorefineries, the highest risks were in the category ‘chemical and physical properties of the materials used’. A rough comparison was made between the non-intensified, intensified and fossil routes. When comparing the biorefinery scenarios, there are only minor differences in favour of the intensified biorefinery in the categories ‘temperature at different process stages’ and ‘complexity of process control’. Compared to the fossil route, the non-intensified and intensified biorefinery concepts analysed were safer than the fossil route.

5.5 Summary: product safety assessment

The product safety assessment addresses the safety of newly developed products as well as their regulatory compliance with the REACH Regulation (EC 1907/2006). The product safety assessment was performed for ten novel bio-based Mannich and novolac polyols and two resins for wood laminate binders. The analysis was performed *in silico* using dedicated software tools to predict four different endpoints selected as appropriate toxicity indicators to describe the novel bio-based products developed in BioSPRINT: acute oral toxicity, carcinogenicity, mutagenicity and bioconcentration factor. The products were then categorised according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) classification criteria for oral exposure. The regulatory compliance of polyols and resins was performed following the ECHA guidance for monomers and polymers [ECHA 2023]. Chromatographic methods were used to determine whether the substance meets the criteria to be considered as a polymer and thus exempted from the REACH registration process.

The results of the toxicity prediction show that most of the products developed in BioSPRINT do not pose serious toxicity problems. Most of the products fall into category IV (moderate to low toxicity) of the GHS classification criteria. Some polyols are even classified either in category V (relatively low toxicity) or not at all (they are essentially ‘non-toxic’). Of the twelve products assessed, only one polyol and the two resins analysed appear to be potentially carcinogenic, none of them mutagenic. Regarding the ecotoxicological aspect, the highest predicted bioconcentration factor of the resins is well below the REACH Regulation threshold to be considered bioaccumulative. In terms of compliance, both the novolac polyols and the phenol-5-hydroxymethylfurfural (PHMF) resin appear to meet the REACH criteria to be considered as polymers. However, the vast majority of Mannich polyols do not meet the criteria.

6 Results and discussion: integrated sustainability assessment

The integrated sustainability assessment combines and links the results of the parallel assessments addressing one single sustainability aspect each in order to obtain an integrated view of the implications for sustainability associated with the BioSPRINT concepts. The different sustainability perspectives (such as environmental, economic, social, and safety) are compared and differences are identified. This chapter is subdivided to answer the sub-questions raised in Section 3.2.1. Section 6.1 compares the intensified BioSPRINT biorefinery concepts with the conventional, non-intensified biorefinery concepts. It discusses which unit processes significantly influence the results, the potential for optimization, the influence of a possible transition in the economy, and the barriers and limitations to industrial-scale implementation. Section 6.2 contrasts the intensified BioSPRINT biorefinery concepts with conventional (fossil) ways of providing the same product portfolio.

6.1 Intensified BioSPRINT concepts vs. non-intensified biorefinery concepts

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

6.1.1 Selection of sustainability perspectives, scenarios and indicators

In order to compare the intensified BioSPRINT concepts with the non-intensified biorefinery concepts, only the life cycle stages from the cradle to the production of furans are considered, as the subsequent life cycle stages do not differ between the different concepts. Therefore, the product safety analysis, which only deals with product-related aspects at the level of polyols or resins, is excluded from this part of the analysis.

Various environmental, economic, social and safety aspects relevant to sustainability have been analysed in parallel assessments that form the basis of this integrated sustainability assessment (for summaries see Sections 5.1 -5.4). The performance of the assessed BioSPRINT scenarios and the conventional reference systems with respect to all these aspects is quantified or qualitatively rated based on various indicators. The suitability and scientific validity of the indicators were verified in each of the parallel assessments. Table 9 provides an overview of the sustainability indicators considered in this analysis.

For the comparison of the (intensified) BioSPRINT concepts with the non-intensified concepts, the indicators of the life cycle assessment (LCA) are taken directly. The indicator ‘climate change including infrastructure’ is added to illustrate the impact of taking infrastructure into account. This indicator extends the 'climate change' analysis to include a rough estimate of the impact of infrastructure for the life cycle stages 'upstream cleaning' to 'downstream processing' based on available data.

From the economic assessment, the indicators are taken directly, with the exception of the indicators ‘product gross cost’ and ‘side product credits’. These indicators are excluded from the analysis because a direct comparison of the results for these indicators for BioSPRINT concepts and non-intensive concepts does not provide meaningful results. Only when analysed together as ‘product costs’, a comparison is possible.

From the technological assessment, only indicators for the relevant life cycle stages are included in the analysis. From the socio-economic assessment (SEA) and the process safety assessment, all indicators are taken directly.

No additional indicators are considered.

Table 9: Overview of sustainability indicators selected for the integrated assessment.

Impact category	**Short description**
Environmental life cycle assessment (LCA)	
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 including infrastructure	Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases including release of greenhouse gases related to the infrastructure of the foreground system.
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, freshwater	Input of excess nutrients into freshwater ecosystems directly or indirectly via input into soils and erosion or gaseous emissions (e.g., phosphorous, keyword ‘algal bloom’).
Particulate matter	Damage to human health due to air pollutants, such as fine, primary particles and secondary particles (mainly from nitrogen oxides, ammonia and sulphur dioxide, key-word ‘London smog’).
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword ‘ozone hole’).
Land use	Occupation of land at varying degrees of human influence on a natural area [Fehrenbach et al. 2019].
Phosphate rock use	Demand of phosphate rock [Reinhardt et al. 2019].
Economic assessment	
Capital investment (CAPEX)	IBL investment for new BioSPRINT facilities
Operating cost	Ongoing costs for BioSPRINT production (sum of variable costs and fixed cost, excluding depreciation cost, desired return on invest and side product credits)
Product cost	Net product cost including depreciation, return on invest (ROI = 12%) and side product credits
Net present value (NPV)	The value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. Discount rate: assuming weighted average cost of capital (WACC) of 12%. Assuming CAPEX, products and raw materials cost annual escalation of 2% and plant labour and utilities escalation of 1%.
Internal rate of return (IRR)	Discount rate that makes the NPV equal to zero.
Technological assessment	
Technical maturity	Technical maturity of involved processes. Distinguishes between proven (+) and not proven (-) at relevant commercial scale.
Scale-up issues	Likelihood of challenges that have to be resolved for up-scaling of the BioSPRINT process.
Socio-economic assessment (SEA)	
Job creation	Number of direct or indirect jobs possibly created across the supply chain. Indicator for employment.
Worker profile (skill level)	Type of jobs created, e.g., skill level of workers. Indicator for occupation/education.
Location development	Extent to which the development of the region or province surrounding the production site is affected, for instance through the creation of employment in other sectors and the improvement of the quality of life of local or regional communities. Indicator for economic growth.
Added value	Economic value created by products and their contribution to GDP. Indicator for economic growth.
Process safety assessment	
Chemical and physical properties of materials used	Risk of exposure through leakage and sampling. Takes into account the amounts of chemicals in the process.
Pressure in different process phases	Risks due to high pressure.
Temperature in different process phases	Risks due to high temperature.
Complexity of process control	Risks due to malfunctions of the equipment, moving mechanical parts and recycling of streams to earlier phases of the process.
Activities needed for maintenance and monitoring	Risks due to activities needed for maintenance and monitoring.

As the TEA, SEA and process safety assessment only differentiate between the three concepts (FhG, UPM and concept C) and do not consider further sub-scenarios, the main analysis is carried out by means of the base case scenarios of the LCA (Ib, 1b), which are similar to the scenarios investigated in the other assessments. Further analysis of the sub-scenarios of the LCA is provided to analyse the influence of a possible transition in the economy, the influence of boundary conditions, and the influence of the uncertainty due to the necessary scale-up to industrial scale.

6.1.2 Comparison of main scenarios for all sustainability perspectives

In order to compare the intensified BioSPRINT concepts with the non-intensified reference concepts, two aspects need to be considered i) how large is the improvement or deterioration due to the implementation of intensification measures compared to the uncertainty of the result for a specific indicator and ii) what is the relevance of this indicator. For this purpose, Table 10 shows the absolute results for each concept and the relative deviation between the intensified BioSPRINT concepts and non-intensified biorefinery concepts.

Table 10: Benchmarking table for the comparison of intensified BioSPRINT concepts to non-intensified biorefinery concepts for the pre-treatments of UPM, FhG and concept C. The unit IE / t refers to inhabitant equivalents per tonne of furans.

System boundary: cradle to furans			Scenario:	**UPM**			**FhG**			**Concept C**		
	Indicator		Unit	non-intensified (Ib)	intensified (1b)	intensified vs. non-intensified	non-intensified (Ib)	intensified (1b)	intensified vs. non-intensified	non-intensified (Ib)	intensified (1b)	intensified vs. non-intensified
Environment	Non-renewable energy use		IE / t	0.64	0.58	-10%	2.87	2.90	1%	0.89	0.94	5%
	Climate change		IE / t	0.16	0.13	-14%	0.65	0.64	-1%	0.23	0.22	-2%
	Climate change incl. infrastructure		IE / t	0.17	0.18	1%	0.74	0.75	2%	0.24	0.27	10%
	Acidification		IE / t	0.12	0.10	-20%	0.54	0.36	-33%	0.24	0.21	-14%
	Eutrophication, terrestrial		IE / t	0.05	0.05	-13%	0.32	0.21	-33%	0.17	0.16	-10%
	Eutrophication, freshwater		IE / t	0.00	0.00	0%	0.00	0.00	0%	0.27	0.24	-12%
	Particulate matter		IE / t	0.12	0.10	-20%	0.52	0.37	-29%	0.22	0.19	-14%
	Ozone depletion		IE / t	0.01	0.01	-2%	0.11	0.07	-40%	0.15	0.14	-10%
	Land use		IE / t	0.27	0.27	-1%	0.33	0.35	6%	0.01	0.01	-39%
	Phosphate rock use		IE / t	0.03	0.02	-15%	0.25	0.12	-51%	2.40	2.12	-12%
Economy	Capital investment		EUR / t	1672	2440	46%	9251	8053	-13%	1189	1858	56%
	Operating cost		EUR / t	2497	2465	-1%	35245	36100	2%	2869	2625	-9%
	Product cost		EUR / t	2768	2874	4%	2082	1087	-48%	3061	2939	-4%
	Net present value (NPV)		k EUR	-80	-84.5	0	111.5	205.7	84%	-164.2	-61.8	+
	Internal rate of return (IRR)		%	-	-	0	22	33	50%	-	4	+
Technology	Technological maturity (state of development)	Upstream purification		N/A	N/A	N/A	+	-	--	N/A	N/A	N/A
		Concentration		+	+	0	+	+	0	+	+	0
		Catalytic conversion		-	-	0	-	-	0	-	-	0
		Downstream purification		+	+	0	+	+	0	+	+	0
	Scalability issues (technical / technological)	Upstream purification		N/A	N/A	N/A	+	-	--	N/A	N/A	N/A
		Concentration		+	+	0	+	+	0	+	+	0
		Catalytic conversion		0	-	-	0	-	-	0	-	-
		Downstream purification		+	+	0	+	+	0	+	+	0
Socio-economy	New biorefinery: Effect on community	Job creation		+	+	0	+	+	0	+	+	0
		Worker profile		+	+	0	+	+	0	+	+	0
		Location development		+	+	0	+	+	0	+	+	0
	Added value			0	0	0	0	0	0	0	0	0
Process safety	Chemical and physical properties of materials used			-	-	0	-	-	0	-	-	0
	Pressure in different process phases			+	+	0	+	+	0	+	+	0
	Temperature in different process phases			-	0	+	-	0	+	-	0	+
	Complexity of process control			-	0	+	-	0	+	-	0	+
	Activities needed for maintenance and monitoring			0	0	0	0	0	0	0	0	0

For comparability with the qualitative indicators, the relative deviation between quantitative indicators is categorised and the tables are coloured accordingly: Dark green boxes represent large overall improvements due to intensification measures that differ by more than 50% from the non-intensified reference concept. Light green boxes represent relevant overall improvements due to intensification measures that differ by more than 10%. Orange and red boxes represent overall deteriorations compared to the reference case of more than 10% and more than 50% respectively. Yellow boxes represent a minor improvement or deterioration. The same colour scheme is used to compare the qualitative indicators. An improvement of two levels on the quantitative scale is shown in dark green (++). Similarly, boxes are highlighted light green (+), yellow (0), orange (-) and red (--). The relevance of an indicator is discussed individually, also on the basis of the absolute results.

A *cross-comparison between the different pre-treatments* is only meaningful to a limited extent, both due to the fundamental differences between the pre-treatment technologies (and resulting fractions) and due to more uncertain data used for simulating the pre-treatments of UPM and concept C. The ethanol organosolv pre-treatment (FhG) tends to have higher impacts in most environmental impact categories and results in higher capital and operating costs. This is due to the more complex pre-treatment and upstream purification process compared to furans derived from UPM's pre-treatment and the steam explosion pre-treatment (concept C). The higher environmental impact is a result of higher heating, cooling and electricity demand of these two life cycle stages compared to UPM or concept C, especially for ethanol recovery. Capital costs are higher because the equipment for upstream purification is at the limit of feasibility, resulting in extreme prices for large-scale biorefineries. Operating costs are higher due to the higher cost of the black liquor stream, which contains ethanol and lignin in addition to HMC, compared to the pure HMC stream in UPM and concept C. On the other hand, high amounts of ethanol are recovered in the upstream purification, which in turn leads to high co-product credits and thus lower product costs, resulting in a positive NPV and IRR. The pricing of the ethanol and the black liquor stream considered in the economic model will significantly impact the production cost of furans and the financial viability of the FhG biorefinery project.

The results for furans from UPM's pre-treatment and the steam explosion pre-treatment (concept C) are similar owing to similar processing concepts. For the product costs, similar results are obtained, however, due to opposing effects: plant operation, ROI and depreciation are lower for concept C (due to the higher production volume), while HMC costs and utility costs are higher due to the more diluted HMC stream. The slightly higher environmental impact is due to the raw material used for pre-treatment (straw compared to hardwood) and the higher energy requirement is caused by the more diluted HMC stream. However, these differences are within the range of uncertainty due to the uncertain modelling of these two concepts.

For *UPM and concept C*, there is a tendency towards improvement through intensification measures from an environmental and process safety perspective. On the other hand, there are economic disadvantages and technological (scalability) issues. From a socio-economic point of view, the intensification measures are neutral (Table 11 and Table 12).

Table 11: Comparison of biorefinery concepts for UPM's pre-treatment. Categories for the deviation of the intensified concept from the non-intensified concept as obtained in Table 10 are highlighted. Main reasons for deterioration (-) or improvement (+) are given.

	< -50%	**< -10%**	**Neutral**	**> 10%**	**> 50%**	**Main reason for deviation**
Environment		🟩	🟨			(+) reduction of MIBK in downstream processing
Economy			🟨	🟧	🟥	(-) RTR and bi-phasic system in catalytic conversion
Technology			🟨	🟧		(-) RTR in catalytic conversion
Socio-economy			🟨			-
Process safety		🟩	🟨			(+) RTR and heat integration in catalytic conversion

Table 12: Comparison of biorefinery concepts for the steam explosion pre-treatment (concept C). Categories for the deviation of the intensified concept from the non-intensified concept as obtained in Table 10 are highlighted. Main reasons for deterioration (-) or improvement (+) are given.

	< -50%	< -10%	Neutral	> 10%	> 50%	Main reason for deviation
Environment		🟩	🟨	🟧		(+) reduction of MIBK in downstream processing
Economy		🟩	🟨		🟥	(-) RTR and bi-phasic system in catalytic conversion (+) larger capacity than UPM
Technology			🟨	🟧		(-) RTR in catalytic conversion
Socio-economy			🟨			-
Process safety		🟩	🟨			(+) RTR and heat integration in catalytic conversion

Most environmental indicators show advantages for the intensified concepts. Only the indicators ‘climate change including infrastructure’ and ‘non-renewable energy use’ show disadvantageous results in the case of applying intensification measures. Although the impacts due to energy demand increase, especially in the downstream processing, the net impacts decrease slightly because of a reduction in solvent make-up (MIBK). When infrastructure is included in the analysis, i.e., in the indicator ‘climate change including infrastructure’, there is an overall increase in environmental impacts. This illustrates the limited benefits of the intensification measures, which can also turn into disadvantages depending on the system boundaries and framework conditions.

From an economic point of view, the intensified concepts require higher investment costs. This is due to the use of the biphasic system and applying the new and unproven rotating tube reactor (RTR) for the catalytic conversion. The RTR is the industrial-scale equivalent of the agitated cell reactor (ACR) investigated in the BioSPRINT project. The use of the biphasic system leads to larger flow volumes in the downstream processing, which makes the equipment larger and more expensive. The operating costs are slightly lower for the intensified concepts. This is in line with the results for the environmental indicators. While utility costs increase due to an increased energy demand, especially in the downstream processing, the costs of input materials decrease due to a more efficient use of MIBK. Product costs increase for UPM and decrease for concept C as a result of the intensification. Concept C performs better because the furan yield is higher due to the higher proportion of cellulose in the input stream and the capital costs are lower due to the larger plant size. For all concepts, the internal rate of return (IRR) is not defined or smaller than the weighted average cost of capital (WACC) of 12%, which means that the concepts are not economically viable.

Possible scalability issues of the RTR in the catalytic conversion are an additional technological barrier to the successful implementation of the intensified concepts. From the socio-economic point of view, the difference between the non-intensified and the intensified biorefinery concepts is minimal, as the value chains and input streams of the two concepts remain the same and similar product quantities are produced. The process safety of the intensified concept is estimated to be slightly better than that of the non-intensified concept due to the lower process temperature in the catalytic conversion, as a result of the improved heat transfer and the lower complexity of process control expected in the intensified catalytic reactor.

In summary, minor environmental benefits are offset by insignificant economic improvements and minor improvements in process safety. Due to the high uncertainty of the available data and the scarce results, the sustainability perspectives for these concepts should be reassessed once a higher TRL and more reliable figures for the entire biorefinery are available. To further improve the intensified concepts, the scale of the biorefinery should be optimised and the energy input in downstream processing should be minimised.

The comparison of the intensified concept with the non-intensified *FhG concept* (organosolv pre-treatment) shows that the intensification measures proposed in BioSPRINT can lead to significant improvements from an economic point of view and slight improvements from an environmental and process safety point of view. Technical and possibly technological constraints are more likely for the process-intensified concept (Table 13).

Table 13: Comparison of biorefinery concepts for FhG's pre-treatment. Categories for the deviation of the intensified concept from the non-intensified concept as obtained in Table 10 are highlighted. Main reasons for deterioration (-) or improvement (+) are given.

	< -50%	**< -10%**	**Neutral**	**> 10%**	**> 50%**	**Main reason for deviation**
Environment	🟩	🟩	🟨			(+) heat integration & SDR in upstream purification
Economy	🟩	🟩	🟨			(+) heat integration & SDR in upstream purification
Technology			🟨	🟧	🟥	(-) SDR in upstream purification, RTR in catalytic conversion
Socio-economy			🟨			-
Process safety		🟩	🟨			(+) RTR and heat integration in catalytic conversion

The economic improvements are mainly caused by improvements in the upstream purification: The falling film technology applied in FhG's non-intensified biorefinery requires large amounts of steam for ethanol recovery, which is provided by mechanical vapour recompression (MVR). This configuration results in an extremely high capital investment because of the uncommonly large equipment sizes. In comparison, the spinning disc reactor (SDR) technology of the process-intensified solution is more compact and efficient, and therefore less expensive. Although the use of the SDR in the upstream purification results in a higher heat demand, the cooling and power demand are significantly reduced. Therefore, the environmental impact of the intensified concept is slightly lower than that of the non-intensified concept. From a technological point of view, scalability problems could arise due to technological immaturity. This is particularly the case for the SDR in the upstream purification. Furthermore, other equipment such as evaporators, blowers, columns and recuperators of the upstream purification are reaching the limits of feasibility. In addition, similar to UPM and concept C, the need to scale up the rotating tube reactor (RTR) in the catalytic conversion, raises scalability issues. From a socio-economic point of view, there are no differences between the two concepts since the value chains are essentially the same and the overall contribution to the GDP is low. The process safety of the intensified concept is considered to be slightly better than the non-intensified concept due to the lower process temperature in the catalytic conversion, as result of the improved heat transfer, and the lower risk related to the complexity of control in the catalytic conversion.

The aim should therefore be to minimise the risks while maintaining the benefits. One option is to reduce the capacity of the biorefinery. This reduces the likelihood of scalability problems and should improve profitability. Another option would be to abandon the high-risk technology while retaining clearly beneficial intensification measures such as improved heat integration, purification methods and recycling of waste streams. In this case, however, the environmental and economic benefits would need to be assessed. However, as SDR technology in particular offers high economic and environmental savings, this technology should be further explored to address scalability issues. If these can be avoided, the intensified BioSPRINT concept is clearly advantageous.

Key findings:

- For UPM and concept C, the BioSPRINT concepts tend to be favourable from an environmental and process safety point of view but, like the non-intensified concepts, they are not economically viable.
- For FhG, the BioSPRINT concept is clearly advantageous if scalability issues can be mitigated.
- For all concepts, further research is needed to minimise the economic and technological risks and to further reduce environmental impact.

6.1.3 Comparison of environmental sub-scenarios

In the LCA, several sub-scenarios were exemplarily analysed to assess the influence of external boundary conditions and future developments, such as the possibility of heat supply from a combined heat and power plant and the availability of solar power (see Table 8). Basically, two questions can be answered from these analyses: i) are the intensification measures significant compared to improvements due to external developments and ii) are the external boundary conditions important for the intensified concepts? Therefore, Table 14 compares the non-intensified and intensified concepts with different boundary conditions against the base case scenario of the non-intensified reference biorefinery.

For visualisation, the relative deviation between quantitative indicators is categorised and the tables are coloured accordingly: Dark green boxes represent large overall improvements that differ by more than 50% from the non-intensified reference concept. Light green boxes represent relevant overall improvements that differ by more than 10%. Orange and red boxes represent overall deteriorations compared to the reference case of more than 10% and more than 50% respectively. Yellow boxes represent a minor improvement or deterioration.

Table 14: Benchmarking table for the comparison of different sub-scenarios of the concepts UPM, FhG and concept C from an environmental perspective. The unit IE / t refers to inhabitant equivalents per tonne of furans.

System boundary: cradle to furans		Scenario:	UPM non-intensified			UPM intensified		
	Indicator	Unit	base case (Ib)	heat supply (IIb vs. Ib)	solar power (IIIb vs. Ib)	base case (1b vs. Ib)	heat supply (2b vs. Ib)	solar power (3b vs. Ib)
Environment	Non-renewable energy use	IE / t	0.64	-19%	-13%	-10%	-40%	-22%
	Climate change	IE / t	0.16	-16%	-11%	-14%	-41%	-24%
	Acidification	IE / t	0.12	-6%	-19%	-20%	-30%	-38%
	Eutrophication, terrestrial	IE / t	0.05	-8%	-29%	-13%	-26%	-40%
	Eutrophication, freshwater	IE / t	0.00	0%	0%	0%	0%	0%
	Particulate matter	IE / t	0.12	-7%	-16%	-20%	-31%	-35%
	Ozone depletion	IE / t	0.01	-8%	-51%	-2%	-15%	-51%
	Land use	IE / t	0.27	0%	1%	-1%	-1%	0%
	Phosphate rock use	IE / t	0.03	-1%	13%	-15%	-16%	-2%

		Scenario:	FhG non-intensified			FhG intensified		
	Indicator	Unit	base case (Ib)	heat supply (IIb vs. Ib)	solar power (IIIb vs. Ib)	base case (1b vs. Ib)	heat supply (2b vs. Ib)	solar power (3b vs. Ib)
Environment	Non-renewable energy use	IE / t	2.87	-22%	-37%	1%	-38%	-16%
	Climate change	IE / t	0.65	-21%	-34%	-1%	-37%	-16%
	Acidification	IE / t	0.54	-7%	-56%	-33%	-45%	-59%
	Eutrophication, terrestrial	IE / t	0.32	-8%	-65%	-33%	-46%	-62%
	Eutrophication, freshwater	IE / t	0.00	0%	0%	0%	0%	0%
	Particulate matter	IE / t	0.52	-8%	-48%	-29%	-43%	-51%
	Ozone depletion	IE / t	0.11	-5%	-80%	-40%	-49%	-77%
	Land use	IE / t	0.33	0%	6%	6%	6%	9%
	Phosphate rock use	IE / t	0.25	0%	18%	-51%	-51%	-42%

		Scenario:	Concept C non-intensified			Concept C intensified		
	Indicator	Unit	base case (Ib)	heat supply (IIb vs. Ib)	solar power (IIIb vs. Ib)	base case (1b vs. Ib)	heat supply (2b vs. Ib)	solar power (3b vs. Ib)
Environment	Non-renewable energy use	IE / t	0.89	-11%	-20%	5%	-20%	-13%
	Climate change	IE / t	0.23	-10%	-16%	-2%	-24%	-17%
	Acidification	IE / t	0.24	-3%	-21%	-14%	-20%	-34%
	Eutrophication, terrestrial	IE / t	0.17	-2%	-20%	-10%	-15%	-29%
	Eutrophication, freshwater	IE / t	0.27	0%	0%	-12%	-12%	-12%
	Particulate matter	IE / t	0.22	-3%	-19%	-14%	-21%	-32%
	Ozone depletion	IE / t	0.15	-1%	-10%	-10%	-11%	-19%
	Land use	IE / t	0.01	-1%	33%	-39%	-40%	-8%
	Phosphate rock use	IE / t	2.40	0%	0%	-12%	-12%	-11%

Comparing all additional non-intensified scenarios (IIb, IIIb) and the intensified base case scenario (1b) with the non-intensified base case scenario (Ib), the benefits of intensification for UPM and concept C are similar to those if solar power is available for the electricity demand of the entire biorefinery instead of the EU electricity mix in 2030 in the non-intensified concept. For FhG, however, the savings from solar power are significantly higher than the benefits of intensification. Disadvantages in the environmental impact category 'phosphate rock use' should not be overinterpreted as the absolute impacts observed in this category are very small. The supply of heat from CHP plants does not bring comparable benefits. For the intensified base case scenario, solar energy can still provide significant benefits (scenario 3b). This shows that, from an environmental point of view, not only process intensification measures (that are aimed at reducing the amount of energy required) are necessary, but also measures that promote the provision of energy with the lowest possible environmental impact. These measures should not only be analysed from an environmental but also from the other perspectives of sustainability.

Key findings:

- In addition to process intensification measures, measures to reduce the impact of the energy inputs should be considered. These measures need to be analysed from all sustainability perspectives.

6.1.4 Economic sensitivity analyses

In the TEA, a sensitivity analysis was carried out for the indicators ‘net present value’ (NPV) and ‘internal rate of return’ (IRR) for the intensified biorefinery concepts by varying operating costs, raw material costs, utility costs, investments, the desired WACC, the product price and the wastewater price.

The results show that for UPM and concept C, the feedstock costs and the furan product price in particular have a strong influence on the project’s profitability. A reduction in raw material costs or an increase in the furan product price would lead to a (higher) profitability. In contrast, the FhG intensified biorefinery is economically viable in the base case (see Section 6.1.2). However, the results should be viewed with a certain degree of caution, as the added value of the co-products is significantly higher than that of the furans. Therefore, small changes in co-product credits and raw material costs have a major impact on the economic viability of the FhG intensified biorefinery.

Key findings:

- The economic viability of the biorefinery concepts is highly dependent on raw material costs, furan product price and, in case of FhG, on the co-product credits.

6.2 Intensified BioSPRINT concepts vs. fossil reference systems

This section discusses advantages and disadvantages that are expected to arise from the realisation of different BioSPRINT concepts to provide **polyols and resins** compared to corresponding conventional (fossil) concepts. None of the concepts scores best in all indicators and none of the concepts is advantageous from all sustainability perspectives. Therefore, no best solution can be identified on an entirely scientific basis, i.e., without value-based choices. The purpose of this comparison is to identify optimisation potentials, synergies and trade-offs to support further development.

6.2.1 Selection of sustainability perspectives, scenarios and indicators

In order to compare the intensified BioSPRINT concepts with the fossil refinery concepts, the life cycle phases from the cradle to the production of the polyols and resins are considered. If life cycle thinking (LCT) was applied consistently, the life cycle stages up to the end of life of these products should be taken into account. Unfortunately, the challenging data availability and the slightly deviating objectives of the contributing studies prevented a complete analysis of the life cycle, including the end-user products and end-of-life treatment. In addition, the direct impact of the non-intensified and intensified concepts investigated in BioSPRINT on the production of polyols and resins is low, as the formulation of the polyols contains only about 20% furans (see Table 2). In the end-user products, i.e., PU foams and wood laminate binders, the furan content is even lower.

Various environmental, economic, social and safety aspects relevant to sustainability have been analysed in parallel assessments that form the basis of this integrated sustainability assessment (for summaries see Sections 5.1 -5.5). The performance of the assessed BioSPRINT scenarios and the fossil reference system with respect to all these aspects is quantified or qualitatively rated based on various indicators. The suitability and scientific validity of the indicators were verified in each of the parallel assessments. Table 15 provides an overview of the sustainability indicators considered in this analysis.

For the comparison of the (intensified) BioSPRINT concepts with fossil reference system, the indicators of the life cycle assessment (LCA) are taken directly. The indicator ‘climate change including infrastructure’ is added to illustrate the impact of taking infrastructure into account. This indicator extends the 'climate change' analysis to include a rough estimate of the impact of infrastructure for the life cycle stages 'upstream cleaning' to 'downstream processing' based on available data. The results of the environmental assessment are compiled by taking into account the whole life cycle but relating the result to the products polyols and resins. Thus, effects like an increased input of other substances or the need for additional curing agents for renewable polyols and resins are taken into account. The results are relative results representing an advantage of the BioSPRINT concepts compared to the fossil concept if negative and a disadvantage if positive.

From the economic assessment, only indicators which indirectly allow for a comparison to a fossil product are included. These are ‘payback period’, ‘net present value’ and ‘internal rate of return’. These indicators include market prices of polyols (3,500 EUR/tonne) and novolac/resole resins (4,500 EUR/tonne) to reflect the current fossil counterparts.

For the technological assessment, no assessment of the fossil system was carried out by the partners. These indicators are thus excluded from the analysis. From the socio-economic assessment (SEA), the indicators are taken directly. From the process and product safety assessment, only indicators for which a comparison to the fossil reference system is possible are included.

No additional indicators are considered.

Table 15: Overview of sustainability indicators selected for the integrated assessment.

Impact category	**Short description**
Environmental life cycle assessment (LCA)	
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 including infrastructure	Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases including release of greenhouse gases related to the infrastructure of the foreground system.
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, freshwater	Input of excess nutrients into freshwater ecosystems directly or indirectly via input into soils and erosion or gaseous emissions (e.g., phosphorous, keyword ‘algal bloom’).
Particulate matter	Damage to human health due to air pollutants, such as fine, primary particles and secondary particles (mainly from NOX, NH3 and SO2, key-word ‘London smog’).
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword ‘ozone hole’).
Land use	Occupation of land at varying degrees of human influence on a natural area [Fehrenbach et al. 2019].
Phosphate rock use	Demand of phosphate rock [Reinhardt et al. 2019].
Economic assessment	
Net present value (NPV)	The value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. Discount rate: assuming weighted average cost of capital (WACC) of 12%. Assuming CAPEX, products and raw materials cost annual escalation of 2% and plant labour and utilities escalation of 1%.
Internal rate of return (IRR)	Discount rate that makes the NPV equal to zero.
Socio-economic assessment	
Job creation	Number of direct or indirect jobs possibly created across the supply chain. Indicator for employment.
Worker profile (skill level)	Type of jobs created, e.g., skill level of workers. Indicator for occupation/education.
Location development	Extent to which the development of the region or province surrounding the production site is affected, for instance through the creation of employment in other sectors and the improvement of the quality of life of local or regional communities. Indicator for economic growth.
Added value	Economic value created by products and their contribution to GDP. Indicator for economic growth.
Process safety assessment	
Chemical and physical properties of materials used	Risk of exposure through leakage and sampling. Takes into account the amounts of chemicals in the process.
Pressure in different process phases	Risks due to high pressure.
Temperature in different process phases	Risks due to high temperature.
Process safety assessment	
REACH compliance	Compliance to the ‘Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals’ [ECHA 2023] to protect human health and the environment.

As the TEA, SEA and safety assessment only differentiate between the three pre-treatments (UPM, FhG and concept C) and further sub-scenarios of the LCA do not lead to relevant differences in the results, the analysis is carried out on the basis of the base case scenarios of the LCA (Ib, 1b), which are similar to the scenarios investigated in the other assessments.

6.2.2 Comparison of main scenarios for all sustainability perspectives

In order to compare the bio-based concepts with the fossil concepts, Table 16 shows the results for each bio-based concept relative to a corresponding fossil concept. For the economic indicators, absolute results are shown as they characterise the likelihood of investing in a project independent if it is fossil or bio-based.

For comparability to qualitative indicators, quantitative indicators are categorised and the tables are coloured accordingly (Table 16): For environmental indicators, green boxes represent overall advantageous results, i.e., an improvement compared to a situation without BioSPRINT. Orange and red boxes represent overall disadvantages, i.e., a deterioration compared to a situation without BioSPRINT. Yellow boxes represent a minor sustainability impact (see Section 3.3.4 for further explanations). The economic indicators NPV and IRR are shown in green if they are positive, i.e., if the analysed concept is viable. Orange and red boxes would represent non-viable concepts. The same colour scheme is used to compare the qualitative indicators. An improvement compared to the fossil system of two levels on the quantitative scale is shown in dark green (++). Similarly, boxes are highlighted light green (+), yellow (0), orange (-) and red (--). The relevance of an indicator is discussed individually, also on the basis of the absolute results.

Table 16: Overview table for the comparison of biorefinery concepts (both intensified BioSPRINT concepts and non-intensified biorefinery concepts) with fossil concepts (relative values except for economic point of view). The unit IE / t refers to inhabitant equivalents per tonne of polyols and resins.

System boundary: cradle to polyols/resins		Scenario:	**UPM vs. fossil**		**FhG vs. fossil**		**Concept C vs. fossil**	
	Indicator	Unit	non-intensified	intensified	non-intensified	intensified	non-intensified	intensified
Environment	Non-renewable energy use	IE / t	1.78	1.64	2.42	2.45	1.52	1.28
	Climate change	IE / t	0.42	0.39	0.56	0.57	0.36	0.30
	Climate change incl. infrastructure	IE / t	0.43	0.40	0.58	0.59	0.37	0.32
	Acidification	IE / t	0.30	0.28	0.41	0.38	0.28	0.24
	Eutrophication, terrestrial	IE / t	0.13	0.12	0.20	0.18	0.15	0.13
	Eutrophication, freshwater	IE / t	0.00	0.00	0.00	0.00	0.09	0.09
	Particulate matter	IE / t	0.30	0.28	0.41	0.39	0.28	0.23
	Ozone depletion	IE / t	0.06	0.05	0.08	0.08	0.09	0.09
	Land use	IE / t	0.12	0.13	0.13	0.14	0.05	0.04
	Phosphate rock use	IE / t	-0.17	-0.16	-0.15	-0.17	0.67	0.70
Economy	Net present value (NPV)	k EUR	101.6	129.6	102.3	200.5	572.5	870
	Internal rate of return (IRR)	%	31	30	20	31	87	84
Socio-economy	New biorefinery: Effect on community	Job creation	+	+	+	+	+	+
		Worker profile	+	+	+	+	+	+
		Location development	+	+	+	+	+	+
		Added value	0	0	0	0	0	0
Process safety	Chemical and physical properties of materials used		+	+	+	+	+	+
	Pressure in different process phases		0	0	0	0	0	0
	Temperature in different process phases		+	++	+	++	+	++
Product safety	REACH Compliance		0	0	0	0	0	0

On the one hand, both the intensified BioSPRINT concepts and the non-intensified biorefinery concepts show overall environmental disadvantages compared to the fossil alternative. This is mainly due to the formulation of the end products and the environmental impact of the individual components. Two further limitations of the product system are not considered by the environmental indicators but reported by calculation: First, the polyols contain a significant amount of cardanol, which is produced from cashew nut shell liquid. Assuming that the whole furfural output of the biorefinery is used to produce polyols, an amount of shells corresponding to 140 kt/yr to 220 kt/yr cashew nuts is required. This corresponds to around 5% of the world market (2021). Second, the mass of PU foams produced from one biorefinery is in the order of magnitude of 700 kt/yr, approximately 0.3% of the world market for polyurethane (2022). Consequently, there won't be enough cardanol for bio-based polyurethane even if a significant growth in the cashew market is assumed. Moreover, research is needed to produce PU foams for other applications than decoration.

On the other hand, the bio-based concepts are considered more favourable from a socio-economic and process safety perspective. The operation of biorefineries tends to create more jobs with a slightly higher skill level and promotes the development of rural areas. Moreover, the fossil processes used to produce polyols and resins are more likely to use hazardous chemicals. One of the fossil-based processes analysed also operates at a higher temperature.

From an economic perspective, the bio-based concepts have positive net present values (NPV) and high internal rate of returns (IRR), meaning that the project is highly profitable. A limitation of the economic analysis is that polyols and resins are typically produced in separate and dedicated multi-product plants, which are often not aligned with the business strategy of biorefineries.

In summary, bio-based concepts can be sustainable if the environmental drawbacks are addressed and the economic benefits can be transferred to the more realistic scenario of separate production of furans and polyols/resins. The LCA provides guidance on how to address the environmental drawbacks:

1) **Improve the formulation of the end products.** For example, improve the reactivity of 5-HMF to maximise the water content in the resin formulation. Reduce the total mass required to replace the fossil equivalent. Changing the density of the end product could play a role here.
2) **Reduce the environmental impact of the other ingredients of the end products.** Further research and development are needed to incorporate renewable alternatives to fossil-based ingredients in the bio-based end products. These renewable alternatives need to be sourced sustainably.
3) **Improve the application of the end products.** Ensure that the end product is applied in a way that contributes to the implementation of the UN Sustainable Development Goals. For example, PU foam can be applied as thermal insulation. Recycling and carbon storage options should also be considered.
4) **Improve the product portfolio.** It is possible that other furan-based products perform better than the product system investigated in BioSPRINT. To this end, the LCA developed four guidelines, which *must be favourable at the same time*.
    a. Minimum environmental impact associated with the furans (including indirect impacts)
    b. Maximum environmental impact of the substituted conventional/fossil intermediate
    c. A substitution ratio (mass of furans : mass of conventional/fossil equivalent intermediate) as close as possible to 1 : 1. This can be achieved by the most complete conversion of the furans to furan-based products and an improved functionality of the furan-based product compared to its conventional/fossil equivalent.
    d. Minimum environmental impact associated with the conversion of furans to furan-based products.

Of course, all these changes require a thorough analysis from all other sustainability perspectives. Such analyses based on life cycle thinking should accompany the development of new concepts from the outset.

Key findings:

- If the environmental drawbacks can be overcome and the economic viability can be transferred to a realistic production scenario, the bio-based concepts investigated in BioSPRINT for the production of furan-based products could become sustainable.

7 Conclusions and recommendations

The aim of this ILCSA is to clarify to what extent and under which conditions the BioSPRINT concept can contribute to a more sustainable utilisation of the hemicellulose (HMC) stream from biorefineries. This main question has been subdivided into a number of sub-questions (see Section 3.2.1). Section 7.1 aims at answering these questions by concluding the results discussed in Chapter 6. Building on this, Section 7.2 gives recommendations to the target audiences identified in Section 3.2.1.

7.1 Key findings and conclusions

Intensified BioSPRINT concepts vs. non-intensified biorefinery concepts

In principle, the differences between the intensified BioSPRINT concepts and the non-intensified biorefinery concepts are small. From an environmental point of view, similar savings could be achieved by simply using 100% renewable electricity (solar power) instead of a prospective EU electricity mix in 2030. A sensitivity analysis of the economic indicators shows a strong dependence of the result on the market prices of furans and co-products and the cost of the HMC or black liquor stream. The process safety differs in only a few risks and is based on a rough analysis as none of the concepts have been implemented yet. Regarding the socio-economic aspects, no differences were found. From a technological point of view, there are challenges associated with the intensified BioSPRINT concepts, but these can be overcome.

From an overall sustainability perspective, the intensified BioSPRINT concepts are favourable compared to the non-intensified biorefinery concepts in case of an ethanol-organosolv pre-treatment (FhG), if scalability issues can be mitigated. The process step with the greatest influence on the results is the pre-treatment, for which a spinning disc reactor (SDR) is used in the intensified BioSPRINT concept. This reduces the energy demand and the plant size, but involves risks for scale-up. Economic and environmental indicators point in the same direction, i.e., synergies can be leveraged here. The aim of this approach should be to minimise the risks while retaining the benefits. One option is to reduce the capacity of the biorefinery. This reduces the likelihood of scalability problems and should improve viability. Another option would be to do without high-risk technology while retaining the clearly beneficial intensification measures, such as improved heat integration, purification processes and recycling of waste streams. In this case, however, the environmental and economic benefits would have to be re-assessed. However, as SDR technology in particular offers high economic and environmental savings, this technology should be further investigated to address scalability issues. If these can be avoided, the intensified BioSPRINT concept is clearly advantageous.

For the other pre-treatments investigated (UPM, concept C), the BioSPRINT concepts are slightly advantageous from an environmental and process safety point of view. From an economic point of view, however, they are unlikely to be implemented. The process with the greatest influence on the results from an environmental and economic point of view is the treatment. Here the use of a two-phase reaction system is disadvantageous. From a technological and process safety point of view, the differences between the concepts lie in the catalytic conversion. Due to the high uncertainty of the available data and the sparse results, the sustainability dimensions for these concepts should be re-evaluated as soon as a higher TRL and reliable figures for the whole biorefinery are available. To further improve the intensified concepts, the scale of the biorefinery should be optimised and the energy input in downstream processing should be minimised.

Intensified BioSPRINT concepts vs. fossil reference systems

When bio-based concepts are compared with the equivalent fossil-based concepts for the production of polyols and resins, the bio-based concepts tend to be more sustainable from an economic, socio-economic and safety point of view. However, they are less sustainable from an environmental perspective. The environmental disadvantages need to be addressed by i) improving the formulation of the end products, ii) reducing the environmental impact of other end product ingredients (e.g. via renewable alternatives), iii) improving the application of the end products towards products helping to achieve the SDGs and iv) improving the product portfolio considering the environmental impacts of both bio-based products and replaced equivalents.

7.2 Recommendations

From the contributing studies and the overall picture of this ILCSA analysis, the following recommendations can be derived for the target audiences defined in Section 3.2.1.

To the scientific community and industry (process developers and refinery operators)

Before implementing the BioSPRINT concept

- *Pre-treatment processes for lignocellulosic biomass must be optimised* in terms of productivity and cost to produce HMC or black liquor streams.
- Investigate ways to minimise the *net energy consumption and solvent loss*. Especially the downstream processing and, in case of an ethanol organosolv pre-treatment, the pre-treatment and upstream purification require large amounts of energy.
- *Test the spinning disc reactor technology* on a large scale to improve the quality of the techno-economic assessment of the upstream purification, especially as this technology appears to be a sustainable alternative to the conventional technology used for lignin precipitation and of solvent recovery.
- Develop a sustainable use for the *co-product humins* which has not been specifically researched in BioSPRINT.
- Establish a sustainable *product portfolio*. LCA tools can support this decision. Not only should the impact per kilogramme of product be assessed, but also the scale of production. Questions such as whether the provision of raw materials is sustainable, what indirect effects may be associated with this provision, whether the product is recyclable with a low energy consumption, and whether the product is still compatible with the world in the year 2050 (i.e., after transformation towards a green, digital and resilient economy) should be considered.
- Optimise the *scale of the biorefineries* to mitigate technological challenges while preserving economic viability.
- The economic feasibility is highly dependent on the feedstock cost considered and the price of the products, namely furans. *Better estimates of these costs and prices* will improve the quality of the economic analysis and give a better picture of the project's economic viability.

To consider for other projects

- It is essential to *implement life cycle thinking (LCT)* already at an early stage of process development *for all sustainability perspectives* in order to consider the relevant aspects relating to a product during its entire life cycle.
- Instead of looking at just one stream of the biorefinery, as in BioSPRINT, the sustainability of the *biorefinery as a whole* should be assessed. Then, questions such as heat integration and the allocation of burdens to the main products (lignin, cellulose, hemicellulose) could be answered satisfactorily.
- Consider the lessons learned which are necessary to *establish a sustainable product portfolio* for biorefineries:
    - *Check the formulation of the end products.* Which molecules replace which equivalents? Which ingredients have the highest sustainability impacts? Are there optimisation potentials to reduce the amount of ingredients with high sustainability impacts? Is a sustainable supply of all ingredients possible at the desired production scale? Always take a holistic approach to the sustainability of each component.
    - *Check the application of the end products.* Ensure that the end product is applied in a way that contributes to the implementation of the UN Sustainable Development Goals. Recycling and carbon storage options should also be considered.
    - *Reduce the overall impacts of the product system.* It is not enough to simply replace fossil products with bio-based ones; the respective environmental impacts and the ratio at which the products are replaced must be taken into account.

- However, some sustainability perspectives such as process safety or socio-economic assessments are particularly *challenging when data is available only at a low TRL*. Data refinement is required throughout the development of a project.
- *Computational fluid dynamics (CFD)* modelling is recommended at an early stage of development to identify risks, limitations and opportunities associated with scaling up new and unproven technology to commercial scale.

To political decision-makers and research funding agencies

- Continue the existing approach of carrying out life cycle thinking-based analyses from *different sustainability perspectives* alongside projects in order to avoid bad investments in supposedly green technologies and to be able to manage projects well.
- Take into account that the substitution of fossil products by *bio-based products is not inherently sustainable*; only a consideration of the entire life cycle up to an actually comparable end product, considering indirect effects, can provide a statement on this. Moreover, the different perspectives on sustainability lead to different results, so a summary in the form of a discussion is necessary.
- *Fund relevant research projects* to establish sustainable overall concepts to support the further development of sustainable building blocks and integrated concepts for future biorefineries using underutilised lignocellulosic residues.
- Initiate a *societal debate* on essential products and develop biomass allocation plans at national and/or European level. Scarce biomass should be used as profitably as possible for the environment and society. As there is no appropriate price for the environmental and social impacts of resource scarcity, market mechanisms cannot replace these plans. In the short term, ensure that research projects focus on products that contribute to the achievement of the Sustainable Development Goals (SDGs). In the long term, introduce mechanisms that put a price on environmental and social impacts.
- 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.
- Underpin existing strategies, such as *bioeconomy strategies* at EU, member state and regional level, with a holistic biomass use concept that takes into account material and energetic biomass use. This is urgently needed in view of (i) the lack of alternatives for renewable/green carbon in the chemical sector, (ii) the foreseeable intensification of competition for biogenic residues and arable land with simultaneously limited potentials and (iii) the risk of potentially stranded investments in new technologies. Such plans can help to address and resolve trade-offs between nature conservation objectives, dedicated crop cultivation and other alternative uses.
- *Reduce one-sided incentives and support structures* that favour certain sectors, such as the use of biomass for energy. Otherwise, disincentives may be created that encourage inefficient uses of biomass, as opposed to use that could potentially deliver greater environmental and social benefits with the same amount of biomass. Appropriate criteria should be included in the subsidy guidelines. Subsidy schemes for biorefineries should be based on the actual environmental benefits achieved after an initial grace period for the introduction of the new technology. Legislation, taxes and tariffs should be adjusted in the same direction.
- *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 the costs of the transition. Attracting biorefineries to less privileged regions could be one potential measure where local biomass residue availability allows for it.

Many of the recommendations listed here cannot be implemented without considerable *financial and political resources*. All stakeholders should therefore work towards a consensus on an appropriate long-term strategy.

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