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

D6.3

Life cycle assessment of hemicellulose-based products

This project has received funding from the Bio-based Industries Joint Undertaking (JU) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 887226. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Bio-based Industries Consortium.

Document Information

Grant Agreement No	887226	**Acronym**	BioSPRINT
Full Title	Life cycle assessment of hemicellulose-based products		
Start Date	M1, June 1st, 2020	**Duration**	48 months
Project URL	http://www.biosprint-project.eu/		
Deliverable	D6.3 Life cycle assessment of hemicellulose-based products		
Work Package	WP 6 - Integrated Lifecycle Sustainability Assessment (ILCSA)		
Contractual due date	M45, February 29th, 2024	**Actual submission date**	M45, February 26th, 2024
Nature	Report	**Dissemination Level**	PUBLIC, PU
Lead Beneficiary	IFEU gGmbH, Wilckensstr. 3, 69120 Heidelberg, https://www.ifeu.de/en/		
Responsible Author	Nils Rettenmaier, IFEU gGmbH, nils.rettenmaier@ifeu.de, Phone +49 6221 4767-24		
Contributions from	Sonja Haertlé, Heiko Keller, Guido Reinhardt (all IFEU)		

Disclaimer

This deliverable has been prepared in the context of the funded project BioSPRINT in accordance with the grant agreement No 887226 (European Union's Horizon 2020 research and innovation programme).

The views expressed in this BioSPRINT Deliverable D6.3 "Life cycle assessment of HMC-based products" are the sole responsibility of the author and do not necessarily reflect the views of the Bio Based Industries Joint Undertaking. The Bio Based Industries Joint Undertaking is not responsible for any use that may be made of the information contained therein.

The author does not accept any liability for any direct or indirect damage resulting from the use of this Deliverable to its content or parts of it.

The results achieved, conclusions made, and recommendations given by the author should not be interpreted as a political or legal signal that the European Commission or any other political or legal institution intends to take a given action.

Copyright message

© BioSPRINT Consortium, 2020-2024. This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both. Reproduction is authorised provided the source is acknowledged.

Refer to this deliverable as: "BioSPRINT – D6.3 (2024), Deliverable D6.3 – Life cycle assessment of hemicellulose-based products".

Table of contents

1 Executive summary....9
2 Introduction....10
2.1 Mapping project's outputs....11
3 Definitions and settings....12
3.1 Common definitions and settings for the ILCSA....12
3.1.1 Goal definition....12
3.1.2 Scope definition....12
3.2 Specific definitions and settings for life cycle assessment (LCA)....15
3.2.1 Introduction to LCA methodology....15
3.2.2 Settings for Life Cycle Inventory (LCI)....16
3.2.3 Settings for Life Cycle Impact Assessment (LCIA)....17
4 Analysed systems....20
4.1 Intensified BioSPRINT concepts vs. non-intensified biorefinery concepts....20
4.2 Intensified BioSPRINT concepts vs. fossil reference system....21
4.3 Biorefinery capacity....22
4.4 Life cycle stages....23
4.5 Co-products....27
4.6 Wastewater treatment....27
4.7 Electricity, heating and cooling....27
4.8 Infrastructure, direct emissions and transport....28
4.9 Fossil reference products....28
4.10 Scenarios....28
5 Results: Environmental impacts....30
5.1 BioSPRINT furans vs. furans from non-intensified biorefinery concepts....30
5.1.1 Evaluation of functional unit....30
5.1.2 Base case....31
5.1.3 Heat from co-generation....36
5.1.4 Renewable electricity....37
5.1.5 Excursus: Mixed hemicellulose and cellulose stream....37
5.2 BioSPRINT end products vs. fossil reference products....39
5.2.1 Previous use of HMC stream....39
5.2.2 BioSPRINT product portfolio: PU foam and wood laminate binder....40
5.2.3 Comparison of BioSPRINT furans to conventional equivalents....43
6 Key findings, conclusions and recommendations....45
6.1 Key findings....45
6.2 Conclusions....46
6.3 Recommendations....47
Acknowledgement....49
References....50

List of figures

Figure 1: Flow diagram of lignocellulosic biomass use for polymer applications and BioSPRINT's field of activity. 10

Figure 2: System boundaries for the LCA in BioSPRINT. 13

Figure 3: Phases of an LCA [ISO 2006a; b]. 15

Figure 4: Exemplary illustration of methodological approaches for co-product handling. 16

Figure 5: Simplified process flow diagram comparing the intensified BioSPRINT concepts (left) and the non-intensified biorefinery concepts (right). 21

Figure 6: Simplified process flow diagram comparing the intensified BioSPRINT concepts (left) and the fossil reference system (right). 22

Figure 7: Simplified process flow diagram comparing the previous use of the HMC / black liquor stream for biomethane provision with the fossil reference system providing methane in case the HMC / black liquor stream is used by the BioSPRINT system. 24

Figure 8: Mass of furans in relation to mass of sugars in the HMC (UPM), black liquor (FhG) and mixed HMC/cellulose streams (concept C). 31

Figure 9: Environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT concepts (green bars) and the non-intensified biorefinery concepts (grey bars) for typical technology development (scenario 1b, Ib). System boundary: cradle-to-gate. 31

Figure 10: Non-renewable energy use of furans produced from UPM's HMC stream via the intensified BioSPRINT concept (green bars) and the non-intensified biorefinery concept (grey bars) for conservative, typical and optimistic technology development (scenarios 1a-c, Ia,b) as well as the resulting ranges. System boundary: cradle-to-gate. 32

Figure 11: Ranges of environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT concepts (green bars, scenarios 1a-c) and the non-intensified biorefinery concepts (grey bars, scenarios Ia,b). System boundary: cradle-to-gate. 33

Figure 12: Environmental impacts of furans produced from different HMC / black liquor streams via the typical intensified BioSPRINT concepts and the typical non-intensified biorefinery concepts for the impact categories 'climate change' and 'acidification', broken down by life cycle stages. System boundary: cradle-to-gate. 34

Figure 13: Environmental impacts of furans produced from different HMC / black liquor streams via the typical intensified BioSPRINT concepts and the typical non-intensified biorefinery concepts for the impact categories 'climate change' and 'acidification', broken down by energy and material inputs. System boundary: cradle-to-gate. 35

Figure 14: Ranges of environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT biorefinery concepts (scenarios 2a-c) and the non-intensified biorefinery concepts (scenarios IIa,b), using heat from co-generation. System boundary: cradle-to-gate. 36

Figure 15: Ranges of environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT biorefinery concepts (scenarios 3a-c) and the non-intensified biorefinery concepts (scenarios IIIa,b), using renewable electricity from PV systems in both cases. System boundary: cradle-to-gate. 37

Figure 16: Range of environmental impacts of furans produced from a mixed HMC/cellulose stream via the intensified BioSPRINT concept B (scenarios 1a-c) and the non-intensified biorefinery concept (scenarios Ia,b). System boundary: cradle-to-gate. 38

Figure 17: Impact of furans produced via different typical intensified BioSPRINT concepts in 'climate change' if implemented in at a new or an existing biorefinery (scenarios 1b, 5b). System boundary: cradle-to-gate..... 39

Figure 18: Environmental impacts of the PU foam and wood laminate binder produced via the intensified BioSPRINT concept compared to the fossil reference system. 40

Figure 19: Materials used for BioSPRINT and fossil reference products PU foam (left) and wood laminate binder (right). 41

Figure 20: Environmental impacts of BioSPRINT and fossil reference products PU foam (left) and wood laminate binder (right) for the impact categories 'climate change' and 'acidification'. 42

Figure 21: Environmental impact (impact category 'climate change') of furans produced via different intensified BioSPRINT concepts for various scenarios compared to the environmental impact of potential fossil equivalents. 43

List of tables

Table 1: Adherence to BioSPRINT's GA Deliverable & Tasks Descriptions 11

Table 2: Comparison of the allocation factors calculated based on the mass of valuable substances in the respective streams or based on the dry mass of the respective streams for the BioSPRINT and the reference biorefinery concept. 17

Table 3: Overview of investigated and included midpoint impact categories. 18

Table 4: Resource demand and emissions per capita in the EU 28 in 2010 for relevant environmental indicators. 19

Table 5: Production volume for the different pre-treatments based on a 225 kt/a biorefinery. 22

Table 6: Main differences in the upstream purification and concentration for intensified and non-intensified biorefinery concepts. 25

Table 7: Main differences in the catalytic conversion for intensified and non-intensified biorefinery concepts. 25

Table 8: Main differences in the downstream processing for intensified and non-intensified biorefinery concepts. 26

Table 9: Main differences in product formulation and application of BioSPRINT and fossil products. 28

Table 10: Overview of analysed intensified BioSPRINT scenarios (arabic numerals) and non-intensified reference biorefinery scenarios (roman numerals). 29

Abbreviations used

Abbreviation / Terms	Description
ACR	Agitated Cell Reactor
Fraunhofer CBP	Fraunhofer Center for Chemical-Biotechnological Processes
CNSL	Cashew nut shell liquid
CO	Confidential
D	Deliverable
FhG	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
GHG	Greenhouse gas(es)
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
LCA	Life cycle assessment
LCI	Life cycle inventory
LCT	Life cycle thinking
MIBK	Methyl isobutyl ketone
PI	Process intensification
PU	Polyurethane
PV	Solar power
R & D	Research and development
SDR	Spinning Disc Reactor
TEA	Techno-Economic-Assessment
TRL	Technology readiness level
UPM	UPM-Kymmene Oyj

1 Executive summary

In order to replace fossil raw materials such as crude oil or natural gas, the products made from them should be based on renewable carbon sources in the future. 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. These novel bio-based products are substitutes for fossil-based polyurethane (PU) foam and wood laminate binder. The aim of the present Life Cycle Assessment (LCA) study is to i) evaluate the potential environmental benefits of the innovative processes and ii) compare the environmental impact of the hemicellulose-based products with that of their conventional/fossil equivalents.

These issues were analysed using hemicellulose streams obtained from two different biorefinery pre-treatments. These were UPM's pulping process and Fraunhofer CBP's ethanol organosolv pulping process. In addition, in the form of an excursus, the first question was analysed for a mixed hemicellulose and cellulose stream from a steam explosion pulping process. Process intensification was also applied to one of the pre-treatment processes, namely the organosolv process itself, while the other two pulping processes remained unchanged. From the investigated hemicellulose-rich streams, the furans 5-(hydroxymethyl)furfural (5-HMF) and furfural were co-produced in the project using innovative, intensified processes. A bio-based wood laminate binder was developed from 5-HMF and a PU foam from furfural.

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. It can be seen that, overall, the innovative, intensified processes show no or only minor advantages over the non-intensified reference processes from an environmental point of view. Significant advantages of the BioSPRINT concept are only achieved by improvements in the ethanol organosolv pre-treatment under certain boundary conditions. Savings in one process step are offset by increased emissions and resource use in a subsequent process step.

To compare the hemicellulose-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 comparison shows that the bio-based product portfolio studied in BioSPRINT has no environmental advantage over the fossil-based product portfolio. Other bio-based products made from the furans 5-HMF and furfural, which replace fossil products, may have the potential to reduce the environmental impact in exceptional cases and with great effort. However, this does not happen automatically in every case (e.g., just because biomass is a renewable resource), but depends on four factors that 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.

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

Deliverable Keywords: LCA; life cycle assessment; environmental

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 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') project, therefore, investigated innovative processes for the optimised production of novel bio-based products from hemicellulose. 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.

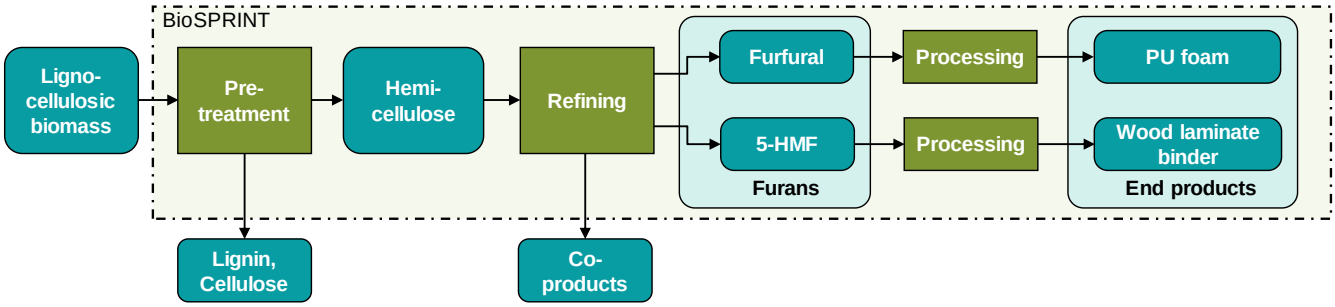


Figure 1: Flow diagram of lignocellulosic biomass use for polymer applications and BioSPRINT's field of activity.

However, it is unclear how the BioSPRINT concept compares from an environmental 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 environmental benefits of the innovative processes and to compare the environmental impact of the hemicellulose-based products with their conventional/fossil equivalents.

This environmental Life Cycle Assessment (LCA) study is part of an Integrated Life Cycle Sustainability Assessment (ILCSA), which also includes techno-economic, social and safety aspects. Chapter 3 describes the definitions and settings both for the ILCSA and the LCA 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 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 6.

2.1 Mapping project's outputs

Purpose of this section is to map BioSPRINT's Grant Agreement 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

BioSPRINT Task		Respective Document Chapters	Justification
Task 6.2 – Environmental Life Cycle Assessment (LCA)	This task will evaluate the environmental impacts associated with the targeted BioSPRINT products in comparison to all selected reference products and address the environmental aspects and potential environmental impacts (e.g. use of resources, environmental consequences of emissions) of the products/ processes. A wide range of impact categories will be covered (e.g. climate change, ozone depletion, acidification, eutrophication and resource depletion), providing a comprehensive picture of the environmental implications. The assessment includes the product's entire life cycle from raw material acquisition through production, use, end-of life treatment, recycling and final disposal. Screening LCAs following the guidelines of ISO 14040/14044 on product life cycle assessment will be carried out. Moreover, EN 16760 (Bio-based products – LCA) as well as the ILCD handbook will be considered.	Chapter 3 Chapter 4 Chapter 5 Chapter 6	Chapter 3 describes the definitions and settings of a LCA following the guidelines of ISO 14040/14044 on product life cycle assessment. Impact categories covered are described. Chapter 4 describes the entire life cycle of the analysed systems from raw material acquisition through production, use, end-of life treatment and final disposal following the guidelines of ISO 14040/14044. Recycling was not applicable to the analysed product/process system. Chapter 5 gives the results of the screening LCA for the BioSPRINT intermediates furfural and 5-HMF and the BioSPRINT products PU foam and wood laminate binder for a wide range of impact categories. The intermediates and products are compared to selected reference products. Chapter 6 summarises key findings and conclusions and gives recommendations to stakeholders following the guidelines of ISO 14040/14044.
BioSPRINT Deliverable			
D6.3 Life cycle assessment of hemicellulose-based products The deliverable provides the final results of the environmental assessment carried out at T6.2.			

3 Definitions and settings

3.1 Common definitions and settings for the ILCSA

The present environmental Life Cycle Assessment (LCA) of hemicellulose-based products is embedded in an Integrated Life Cycle Sustainability Assessment (ILCSA). 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. This section summarises the LCA-relevant parts of the common goal and scope of the ILCSA and highlights diverging definitions.

3.1.1 Goal definition

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 HMC use according to the BioSPRINT biorefinery concept contribute to a more sustainable supply of the targeted products?**

The goal of this report is to answer this question from an environmental perspective. Addressing the main question, consequently, leads to the following **sub-questions** relevant to the LCA:

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

2. **Sub-questions:**
   - 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?

3.1.2 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 3.1.1).

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, concept B is applied to a mixed HMC/cellulose stream based on a steam explosion pre-treatment of residual wheat straw **(concept C)**.

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

Both ILCSA and LCA studies require delineating the investigated product system and its overall function(s). The main system boundary chosen within BioSPRINT comprises a cradle-to-grave analysis, which allows us to consider all relevant process steps from resource extraction (e.g., the biomass production) up to the end of life of the derived end products (e.g., 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 answers the relevant questions (see cradle-to-grave boundary in Figure 2). Deviating from the definition of the ILCSA, only the process steps up to the production of the furans are considered to compare the impact of the BioSPRINT concept with the reference biorefinery concept. 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-gate system boundary in Figure 2). The provision of lignocellulosic biomass does not involve any process intensification as well, but is considered because different amounts of raw material may be necessary due to differing yields of the biorefinery concepts. The end-of-life emissions of auxiliary materials are also considered.

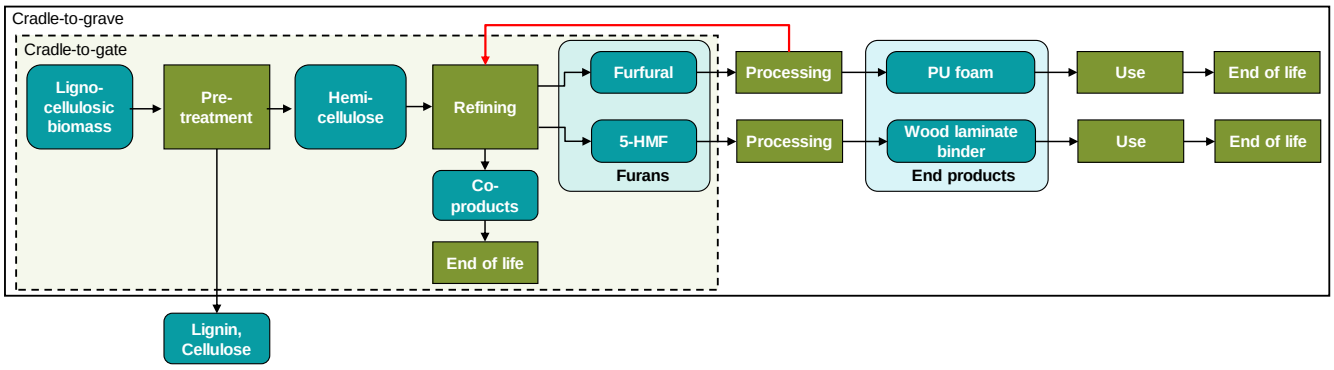


Figure 2: System boundaries for the LCA in BioSPRINT.

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 (see Figure 2, red arrow). 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).

Technical reference

The LCA, as defined for the ILCSA, evaluates scenarios representing a potentially mature technology ('n^{th} plant', technology readiness level TRL 9) based on R & D work of the project, expert knowledge and, where necessary, literature sources. As the R & D 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 wheat straw water content of 10%wt.

Timeframe

The choice of an adequate timeframe for the ILCSA includes the consideration of various technological and regulatory constraints. For a mature full-scale production, a timeframe such as 2030 seems realistic. Thus, important background data, such as Life Cycle Inventory (LCI) data for electricity generation, represent the year 2030.

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, where available.

3.2 Specific definitions and settings for life cycle assessment (LCA)

Life cycle assessment (LCA) is based on international standards such as [ISO 2006a; b] and the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012]. Within the BioSPRINT project, a screening LCA study is carried out that largely follows these standards and guidelines. Specific settings, methodological choices and deviations from these standards and guidelines are described in detail below.

3.2.1 Introduction to LCA methodology

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

- Goal and scope definition (see Section 3.1.1 and 3.1.2)
- Inventory analysis (see Section 3.2.2),
- Impact assessment (see Section 3.2.3), and
- Interpretation (see Chapter 4.10).

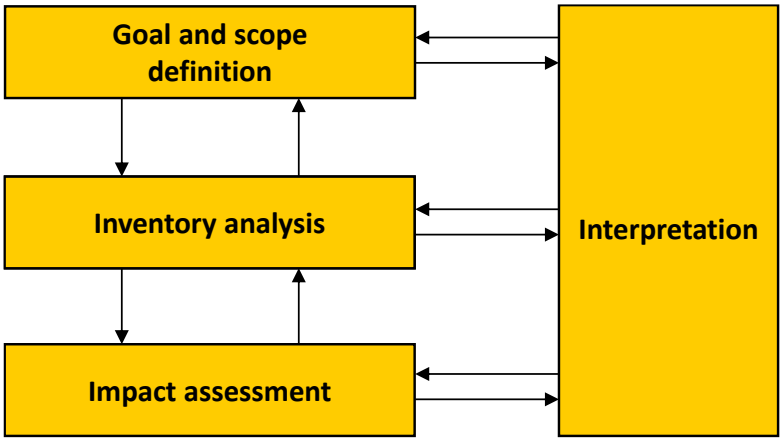


Figure 3: Phases of an LCA [ISO 2006a; b].

ISO standards 14040 and 14044 provide the indispensable framework for LCA. This framework, however, leaves the individual LCA analyst with a range of choices that can affect the legitimacy of the results of an LCA study. While flexibility is essential to respond to the wide variety of questions addressed, further guidance is needed to support consistency and quality assurance.

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

While the ILCD Handbook contains specifications for *any* product (good or service), standards have also been developed that contain specific provisions for selected impact categories (e.g. ISO 14046 on Water Footprint or ISO 14067 on Carbon Footprint of products) or selected product categories such as such as construction products (EN 15804), biofuels and bioliquids for energy applications (EN 16214) or bio-based products (EN 16760). This study, therefore, also takes into account EN 16760 on LCA for bio-based products [CEN 2015].

3.2.2 Settings for Life Cycle Inventory (LCI)

Data sources

Primary data on mass and energy balances from biomass to the production of polyols and resins were provided by project partner Maturus Optimi B.V., who carried out process simulations and collected input data from all technology-developing partners in the BioSPRINT project. Data on the process steps from these commercial intermediate products to the end products as well as the composition of fossil reference products, were obtained from project partners Prefere Resins Holding GmbH and AEP Polymers SRL. Data on the infrastructure of the foreground system were provided by project partner Maturus Optimi B.V. Secondary data for background processes were taken from IFEU's internal database [IFEU 2024], from the ecoinvent database [ecoinvent database] and, where necessary, from literature. If not indicated otherwise, data were provided by project partners.

Attributional vs. consequential modelling

Sustainability assessment can follow a consequential or attributional approach, which has implications for the methodological approach regarding co-products, indirect effects, etc., especially in LCA. Consequential modelling is more extensive and 'aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy' according to the ILCD Handbook [JRC-IES 2010]. Consequential modelling is recommended for decision contexts where influential impacts are expected to occur at the meso/macro-level [JRC-IES 2010]. This is the case for the BioSPRINT systems. Therefore, a consequential modelling approach is applied in this assessment.

Co-products handling

As explained in Section 3.1.2, the system boundary includes all products and co-products. Thus, the environmental impacts of multi-output systems must be partitioned between all (co-)products. The general alternatives concerning this procedure of co-product handling are exemplarily illustrated in Figure 4. System expansion (substitution) is applied wherever possible, which, according to the ISO standards for LCA [ISO 2006a; b], is preferred over allocation: the impacts of a multi-output system are reduced by credits given for avoided burdens associated with the reference products that are replaced by the products of the multi-output system.

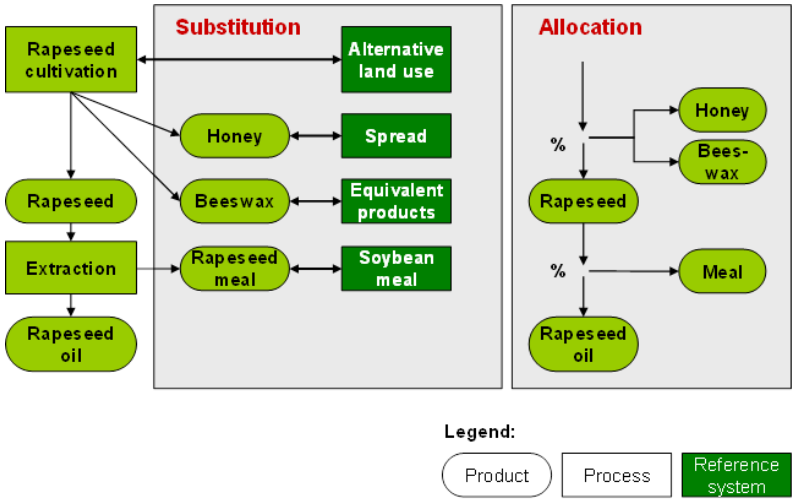


Figure 4: Exemplary illustration of methodological approaches for co-product handling.

To evaluate the impact of the hemicellulose stream, allocation is used to partition the environmental impacts of the biomass between the lignin, the cellulose and the hemicellulose streams. Allocation should preferably be based on a physical relationship (dry matter, energy content, etc.) or – where this is not possible – in proportion to the economic value of the products. No economic data are available for the respective streams. Thus, the

allocation factor (AF) corresponds to the mass of the individual valuable substances, m_i, in the HMC stream in relation to the total dry mass of valuable substances, compare Equation (1). The valuable substances i are the C5 and C6 sugars in the HMC stream, lignin in the lignin-rich stream and cellulose in the cellulose-rich stream.

$$AF = \frac{\left[m_{\text{C5 sugars}} + m_{\text{C6 sugars}}\right]_{\text{HMC stream}}}{\left[m_{\text{C5 sugars}} + m_{\text{C6 sugars}}\right]_{\text{HMC stream}} + \left[m_{\text{lignin}}\right]_{\text{lignin stream}} + \left[m_{\text{cellulose}}\right]_{\text{cellulose stream}}} \quad (1)$$

Another possibility would have been to use the dry mass of the respective streams, including ash or other impurities. The resulting allocation factors for both approaches are shown in Table 2. They differ by < 5% for both UPM and concept C and by ~ 20% for FhG, which affects the overall LCA result for FhG by a maximum of 5%.

Table 2: Comparison of the allocation factors calculated based on the mass of valuable substances in the respective streams or based on the dry mass of the respective streams for the BioSPRINT and the reference biorefinery concept.

Method	Life cycle stage	UPM	FhG	Concept C
Valuable substances	Biomass provision, pre-treatment	0.31	0.19	0.62
	Upstream purification	1.00	0.45	1.00
Dry matter	Biomass provision, pre-treatment	0.29	0.15	0.60
	Upstream purification	1.00	0.45	1.00

Biogenic carbon

There are two possible sources of carbon dioxide (CO_2) emissions: recently formed, mainly biogenic carbon stocks and fossil carbon stocks. In the case of biogenic carbon contained in the assessed bio-based products, the amount of CO_2 released to the atmosphere over the entire life cycle equals the amount of CO_2 recently absorbed by the plants during growth (short carbon cycle). Such short carbon cycles do not affect atmospheric CO_2 concentrations. CO_2 uptake and emissions are, therefore, not displayed in the result graphs for simplicity but are included in the LCA model. Fossil carbon, which can also be present in (partly) bio-based products, is accounted for and displayed explicitly in the result graphs.

3.2.3 Settings for Life Cycle Impact Assessment (LCIA)

According to ISO standard 14040 [ISO 2006a], Life Cycle Impact Assessment (LCIA) includes the mandatory steps of classification and characterisation and the optional steps of normalisation and weighting. Classification and characterisation depend on the selected impact categories and LCIA methods. Regarding the optional elements, only the normalisation step is applied within the BioSPRINT project. The corresponding specifications of these LCIA elements are described in the following sections.

Impact categories and LCIA methods

All main environmental issues related to the BioSPRINT value chains should be comprehensively covered within the impact categories of the screening LCA. Furthermore, the impact categories must be consistent with the goal of the study and the intended applications of the results. Potential environmental impacts can be analysed at midpoint or at endpoint level. For environmental assessments within technology development projects such as BioSPRINT, the midpoint level is considered to be more appropriate than the endpoint level because the impacts are analysed in a more differentiated way and the results are more accurate.

All midpoint indicators listed in Table 3 were investigated in a first analysis.

Table 3: Overview of investigated and included midpoint impact categories.

Midpoint impact category	LCIA method	Included
Non-renewable energy use	[Borken et al. 1999; VDI (Association of German Engineers) 2012]	✓
Climate change	[IPCC 2021]	✓
Acidification	[CML 2016]	✓
Eutrophication, terrestrial	[CML 2016]	✓
Eutrophication, freshwater	[CML 2016]	(✓)
Particulate matter formation	[de Leeuw 2002]	✓
Ozone depletion	[Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010]	(✓)
Photochemical ozone formation (photo smog)	[van Zelm et al. 2008]	✗
Land use (distance-to-nature-potential)	[Fehrenbach et al. 2019]	✓
Phosphate rock use	[Reinhardt et al. 2019]	(✓)

The type of biomass used to produce the furans significantly determines the impact categories 'freshwater eutrophication', 'ozone depletion' and 'phosphate rock use'. These impact categories are, therefore, only evaluated in the case of furans made from straw. For furans made from beech wood, the resulting inhabitant equivalents per tonne of furans in these three impact categories are less than 1%, 2% and 10%, respectively, of the inhabitant equivalents in the impact category showing the highest impacts. The impact category 'photochemical ozone formation' is excluded from further analysis in all cases since i) the resulting inhabitant equivalents per tonne of furans is less than 10% of the inhabitant equivalents in the impact category showing the highest impacts and ii) data quality is insufficient to assess differences between systems or scenarios. The impact category 'ionising radiation' is considered irrelevant for the BioSPRINT value chains and thus completely excluded from this study. Furthermore, the impact category 'toxicity' is excluded due to insufficient LCI data quality for the reference year 2030. However, specific human health issues are covered by the category particulate matter formation.

The chosen LCIA methods essentially follow the recommendations of [Detzel et al. 2016].

Normalisation

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

In the BioSPRINT project, the value chains are characterised for Europe. Therefore, resource demand and emissions per capita in the European region are chosen as references for normalisation. The latest available data from [Fehrenbach et al. 2019; Goedkoop et al. 2014; Reinhardt et al. 2019; Sala et al. 2015] is used. These values refer to the year 2010 and the EU-28 countries. The resulting inhabitant equivalents can be converted to non-normalised values by the resource demand and emissions per capita listed in Table 4.

Table 4: Resource demand and emissions per capita in the EU 28 in 2010 for relevant environmental indicators.

Environmental indicator	Resource demand and emissions per capita		Source
Non-renewable energy use	34	MJ / (inhabitant · year)	[Sala et al. 2015]
Climate change	9.2	t CO_2 equivalent / (inhabitant · year)	[Sala et al. 2015]
Acidification	35	kg SO_2 equivalent / (inhabitant · year)	[Sala et al. 2015]
Eutrophication, terrestrial	5.5	kg PO_4 equivalent / (inhabitant · year)	[Sala et al. 2015]
Eutrophication, freshwater	6.9	kg PO_4 equivalent / (inhabitant · year)	[Sala et al. 2015]
Particulate matter	28	kg PM2.5 equivalent / (inhabitant · year)	[Sala et al. 2015]
Ozone depletion	0.056	kg CFC-11 equivalent / (inhabitant · year)	[Sala et al. 2015]
Photochemical ozone formation	57	kg NMVOC equivalent / (inhabitant · year)	[Goedkoop et al. 2014]
Land use	0.24	ha artificial land equivalent / inhabitant	[Fehrenbach et al. 2019]
Phosphate rock use	23	kg phosphate rock use equivalent / (inhabitant · year)	[Reinhardt et al. 2019]

Weighting

Weighting uses numerical factors based on value choices to compare and sometimes aggregate indicator results that are not physically comparable. Weighting is not applied in this study.

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)**.

To answer the sub-questions raised in Section 3.1.1, these **process-intensified BioSPRINT concepts** are compared with

a) **non-intensified biorefinery concepts** (see Section 4.1, relevant life cycle stages in Section 4.4: 'biomass provision' to 'downstream processing').
b) a **fossil reference system** (see Section 4.2, relevant life cycle stages in Section 4.4: '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 2). Figure 5 shows the life cycle stages and the co-products for this cradle-to-gate analysis.

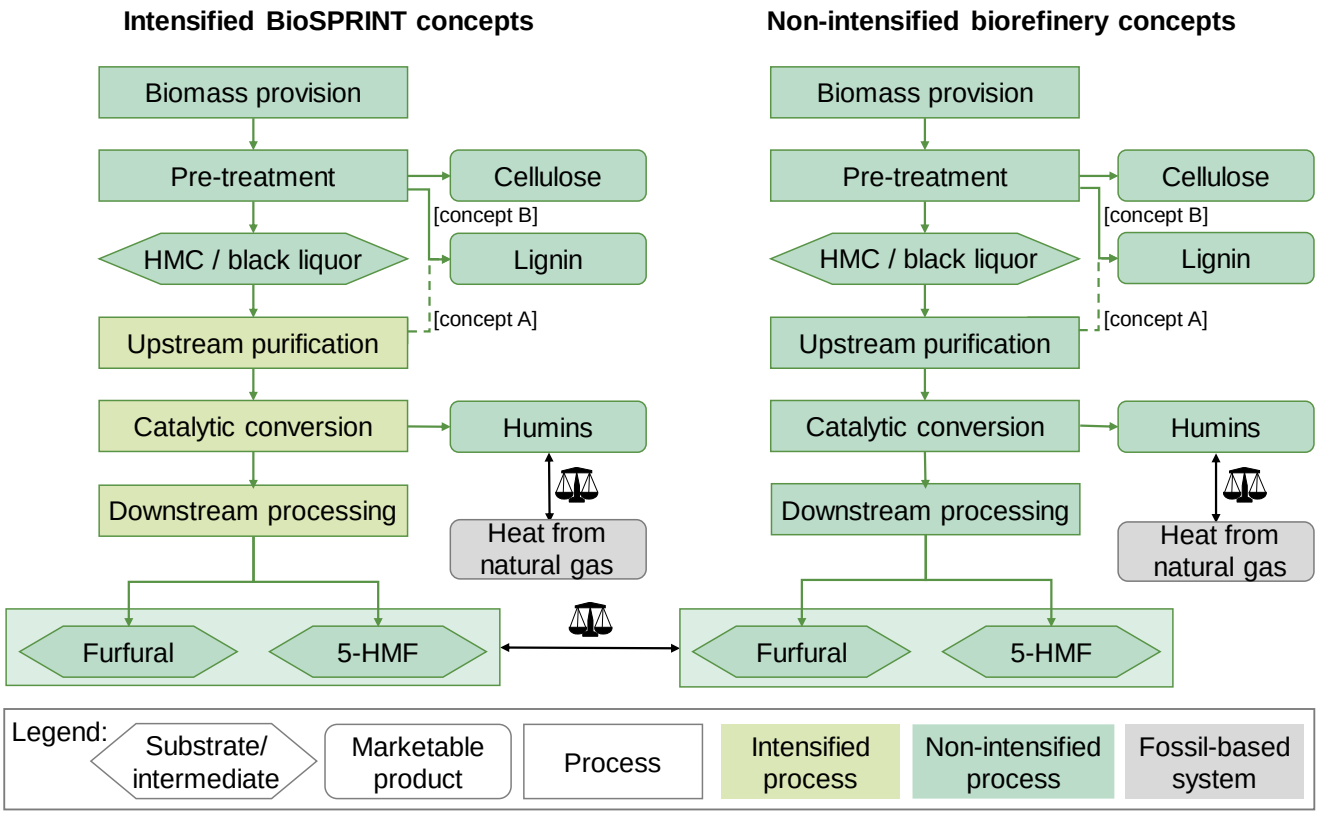


Figure 5: Simplified process flow diagram comparing the intensified BioSPRINT concepts (left) and the non-intensified biorefinery concepts (right).

4.2 Intensified BioSPRINT concepts vs. fossil reference system

The comparison of the BioSPRINT concepts with the fossil reference system is performed as a cradle-to-grave analysis from biomass provision to end product manufacture (see also Figure 2). Figure 6 shows the life cycle stages and the co-products for this cradle-to-grave analysis. 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 volume in the case of PU foam (assuming equal decorative function).

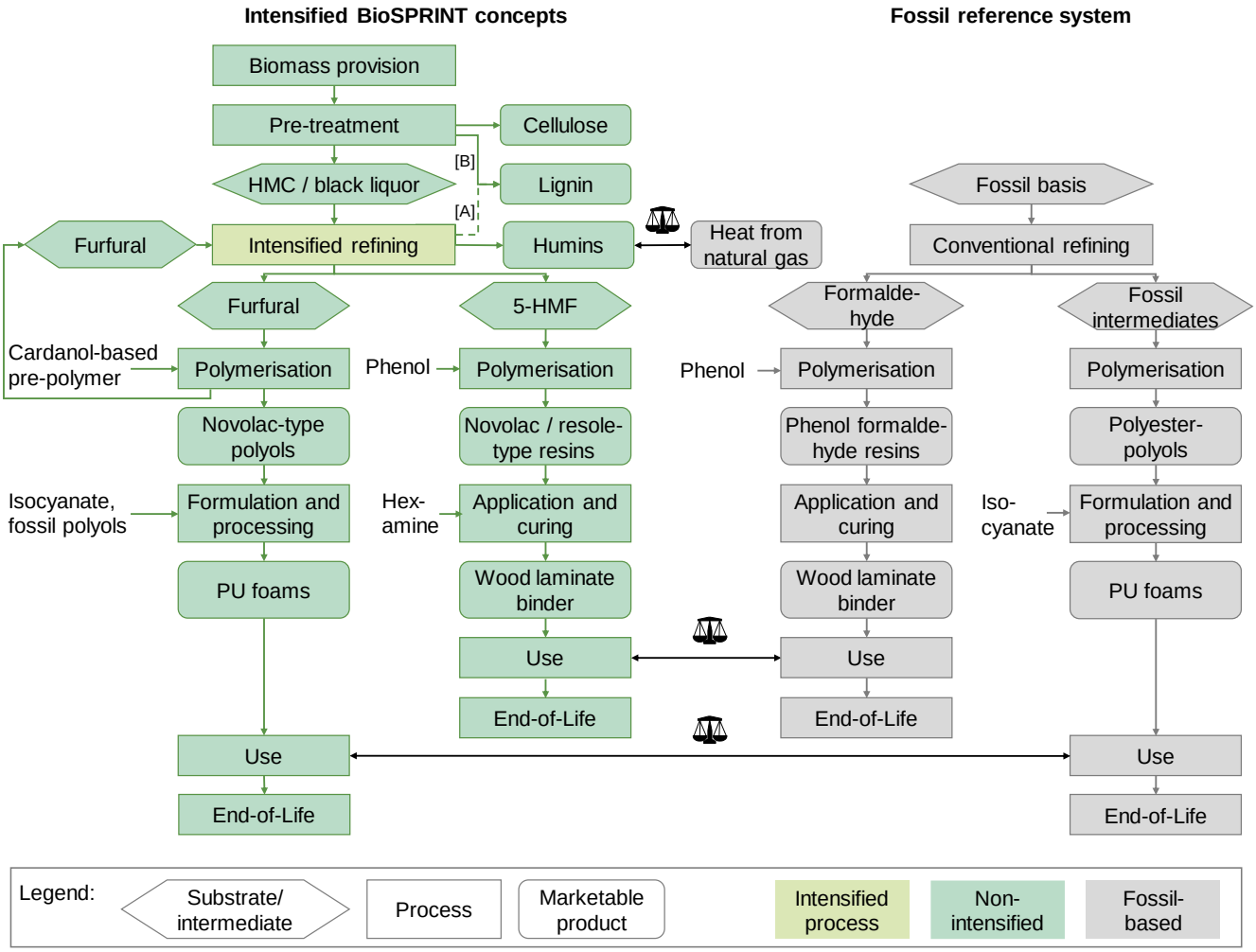


Figure 6: Simplified process flow diagram comparing the intensified BioSPRINT concepts (left) and the fossil reference system (right).

4.3 Biorefinery capacity

A biorefinery capacity of 225 kilotonnes per year (kt/yr) of dry weight feedstock input was chosen (see also Section 3.1.2). Table 5 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 5: 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

Biomass provision

Both FhG's and UPM's pre-treatment use hardwood. Exemplarily, we consider 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, we consider state-of-the-art technology for harvesting, transportation and chipping and no previous use of the biomass resource. Data on harvesting, transportation and comminution are based on IFEU's internal database [IFEU 2024]. 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

We 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 hemicellulose (HMC), cellulose and lignin. The resulting streams differ in composition. The pre-treatment is identical for the intensified and non-intensified biorefinery concept.

1. In FhG's ethanol organosolv pre-treatment, beech wood is boiled in a water-ethanol mixture containing sulphuric acid to dissolve lignin and HMC. The undissolved cellulose is separated. The remaining HMC stream contains large amounts of lignin and residual ethanol (black liquor). Fraunhofer CBP provided data on the non-intensified pre-treatment to Maturus Optimi B.V. for process simulation purposes.
2. In UPM's pre-treatment, hardwood is fractionated into HMC, cellulose fibres and lignin.
3. In the steam explosion pre-treatment, the lignocellulosic biomass is exposed to steam at elevated temperature and pressure, which dissolves the HMC. Enzymes are added to hydrolyse the cellulose and hemicellulose into more soluble monomeric sugars. The lignin is separated by filtration, leaving a stream containing both C5 sugars from HMC and C6 sugars from cellulose.

Maturus Optimi B.V. derived data for the latter two pre-treatments from the literature. The process simulation models thus have a more significant uncertainty than the model for FhG's pre-treatment.

The HMC and black liquor streams, respectively, are subsequently upgraded by either the non-intensified biorefinery concepts or the intensified BioSPRINT concepts. As the focus of BioSPRINT is entirely on the valorisation of the HMC/black liquor stream, we allocate the environmental impacts of the pre-treatment between the outputs of the pre-treatment. These are: cellulose and black liquor stream for FhG, cellulose, lignin and HMC stream for UPM, and cellulose and C5/C6 stream for concept C. The mass of valuable substances in the respective streams related to the overall mass of valuable substances is used as the allocation factor (compare Section 3.2.2, 'Co-products handling').

For the comparison between the intensified BioSPRINT concepts and the non-intensified biorefinery concepts, we set that a new biorefinery would be built in both cases, i.e., that the biomass (and thus the HMC / black liquor streams obtained from its fractionation) would be previously unused. For the comparison with the fossil reference system, we consider two different scenarios: either a new biorefinery is built or the HMC / black liquor stream of 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, we consider 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). Hence, Figure 7 displays this additional comparison.

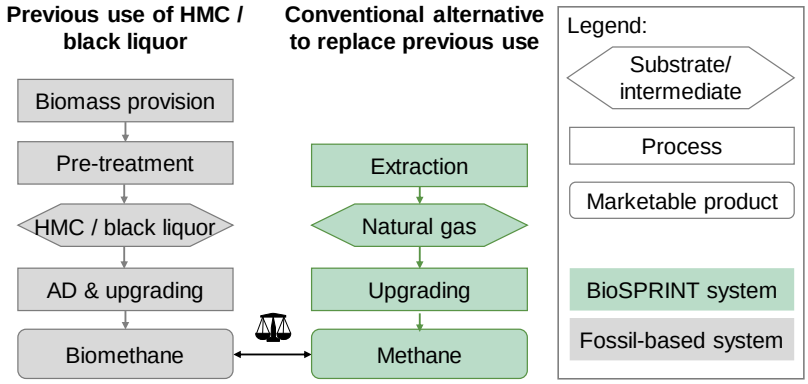


Figure 7: Simplified process flow diagram comparing the previous use of the HMC / black liquor stream for biomethane provision with the fossil reference system providing methane in case the HMC / black liquor stream is used by the BioSPRINT system.

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. We partition the environmental burdens of all process steps prior to / upstream of) lignin separation and ethanol recovery between a) a potential lignin production process and b) the HMC conversion process (i.e., BioSPRINT). The dry mass of valuable substances in the respective streams is used as the allocation factor (for further details see Section 3.2.2).

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

Table 6: 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 Disk 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 significant amounts of sulphuric acid. 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 7.

Table 7: 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 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
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 8.

Table 8: 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 and product formulation

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 final product formulations are described below. For the end-of-life of both products, state-of-the-art waste incineration is set. 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 systems.

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. Cardanol is distilled from cashew nut shell liquid (CNSL) and increases the bio-based content of the polyol to about 97%. No primary data are available for cardanol production. Therefore, a consequential approach is taken to model the environmental impact of cardanol. Approximately 15% of the PU foam consists of cardanol, resulting in a cardanol input of 60 kt/yr to 90 kt/yr to produce PU foam from the furfural of one biorefinery. To produce this amount of cardanol, the shells of 140 kt/yr to 220 kt/yr cashew nuts are required [Rwahwire et al. 2019; TechnoServe 2020]. This represents around 5% of the world market (2021). Given the enormous amount of cardanol used, a most optimistic scenario would be that additional cardanol is produced but the world harvest of cashew nut is not increased due to this production; and cashew nut shells are considered to be a true waste. We estimated that per kg of cardanol, 3 MJ of heat from natural gas is required for extraction and purification [Puente 2018].

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. We used polyether polyols as a model substance. The polyols react with polymeric methylene diphenyl diisocyanates. A combination of amine and metal-based catalysts is used, while the utilized additives are: flame-retardants and surfactants. We chose a conservative approach and modelled these as monoethanolamine and fossil non-ionic surfactants. Their impact is very low, so the approximation is justified.

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.

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. We modelled hexamine (hexamethylenetetramine) based on its production from formaldehyde and ammonia [Eller et al. 2000]. The mixing and curing steps are included in the modelling.

4.5 Co-products

As part of the biorefinery processes, humins are formed and considered as co-products. Humins can be used as bioenergy source, as feedstock for gasification or as bio-based building block (design of nanocomposites for different applications, e.g. fine chemicals) [García-Velásquez & van der Meer 2023; Ouyang et al. 2023]. Furthermore, they can be used as soil improvers. For the present study, we considered the replacement of heat from natural gas by burning the humins. The net calorific value of the humins is set to the net calorific value of carbohydrates (17 MJ/kg [Harms 2012]). In the non-intensified and intensified refinery concept, similar amounts of humins are produced. The humins stream also contains lignin, whose net calorific value is slightly higher (approx. 25 MJ/kg [Harms 2012]). This is taken into account in the assessment.

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. Therefore, we considered 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 with an emission factor of 254 g CO_2/kWh [IFEU 2024] is set. In a sensitivity analysis (scenarios 3 and III), solar power (PV) with an emission factor of 82 g CO_2/kWh [IFEU 2024] 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. This applies for example to the co-product humins which are used as a bioenergy source for heat generation, (partly) replacing heat from natural gas (see Section 4.5). 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.

There are many different systems for supplying cooling water (25 °C) and chilled water (6 °C): vapour compression chillers, cooling towers or free cooling. As the method used and the ambient conditions are unknown, an average value of 0.15 kWh electricity per kWh of cooling/chilling demand is set in the typical scenarios (1b and Ib). In the optimistic and conservative scenarios, the electricity demand per kWh of cooling/chilling demand is reduced to 0.05 kWh (1c) and or increased to 0.25°kWh (1a and Ia), respectively.

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 qualitatively in the final analysis since i) no data is available for the biomass pre-treatment, ii) data on concrete, structural steel and piping depends 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 9 summarises the differences between the BioSPRINT products and the fossil reference products.

Table 9: 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

As the R&D work in BioSPRINT is carried out at a low technology readiness level (TRL 3-5), an extrapolation of the corresponding data to an appropriate industrial scale (TRL 9) has been performed as part of the process simulation work. The introduced uncertainty is tackled by supplementing the analysis of the ‘typical’ scenario by a ‘conservative’ and an ‘optimistic’ scenario. The heat demand used for the base case already includes a 5% reduction compared to the process simulation carried out in this project, as a heat network analysis revealed

potential savings of up to 10%. In an optimistic scenario, the heat demand is reduced by 10% compared to the process simulations. The conservative scenario includes no further heat integration. Moreover, the electricity demand for cooling is varied for the different scenarios. Also, different heat supply scenarios are investigated.

All investigated scenarios are applied to the hemicellulose-rich streams of concepts A, B and C. The respective settings are summarised in Table 10. Information on heat and cooling demand can be found in Section 4.7.

Table 10: Overview of analysed intensified BioSPRINT scenarios (arabic numerals) and non-intensified reference biorefinery scenarios (roman numerals).

	Scenario name	Description
1a	BioSPRINT base case, conservative	• Heat and cooling demand as obtained from process simulation • Conservative values for electricity demand for cooling
1b	BioSPRINT base case, typical	• 5% savings in heat and cooling demand compared to process simulation accounting for further heat integration • Typical values for electricity demand for cooling
1c	BioSPRINT base case, optimistic	• 10% savings in heat and cooling demand compared to process simulation accounting for further heat integration • Optimistic values for electricity demand for cooling
2	BioSPRINT temperature-dependent heat supply	BioSPRINT base case conservative/typical/optimistic scenario, but: • Steam is provided by extracting steam from the steam turbine of a combined cycle power plant. The forgone electricity is used to assess the impact of the steam. High-temperature steam thus has a greater impact on the environment than low-temperature steam.
3	BioSPRINT solar power	BioSPRINT base case conservative/typical/optimistic scenario, but: • Electricity is provided by solar power plants
4	BioSPRINT with previous use of HMC stream (existing biorefinery) – biomethane	BioSPRINT base case conservative/typical/optimistic scenario, but: • HMC stream is used to supply biomethane if BioSPRINT was not introduced, see Section 4.4 'Upstream purification' and Figure 7
Ia	Reference biorefinery base case, conservative	• 10% less furans produced compared to reference biorefinery base case, typical (Ib) due to increased degradation in the catalytic conversion • Sugars are instead converted into humins • Decreased heat demand of furfural and 5-HMF separation
Ib	Reference biorefinery base case, typical	• Heat and cooling demand as obtained from process simulation • Typical values for electricity demand for cooling
II	Reference biorefinery temperature-dependent heat supply	Reference biorefinery base case conservative/typical scenario, but: • Steam is provided by extracting steam from the steam turbine of a combined cycle power plant. The forgone electricity is used to assess the impact of the steam. High-temperature steam thus has a greater impact on the environment than low-temperature steam.
III	Reference biorefinery, solar power	Reference biorefinery base case conservative/typical scenario, but: • Electricity is provided by solar power plants

5 Results: Environmental impacts

This chapter presents the results answering the guiding questions defined in Section 3.1.1.

First, we compare the environmental impacts of furans obtained from the intensified BioSPRINT biorefinery concepts with furans obtained from theoretically modelled non-intensified biorefinery concepts. After analysing the functional unit, we contrast the two concepts for the UPM and FhG streams for five environmental impact categories (Section 5.1.2). We perform sensitivity analyses to define the range of the results (Sections 5.1.3 and 5.1.4). Subsequently, we analyse the environmental impacts of furans obtained from applying the BioSPRINT concept to a mixed hemicellulose and cellulose stream in an excursus (Section 5.1.5).

Secondly, we compare the environmental impacts of the hemicellulose-based products with those of the fossil reference products. This includes investigating the impact of a previous use of the hemicellulose-rich streams (Section 5.2.1). After examining the BioSPRINT product portfolio (Section 5.2.2), we investigate the potential of hemicellulose-based products exemplarily for the environmental impact category 'climate change' (Section 5.2.3).

5.1 BioSPRINT furans vs. furans from non-intensified biorefinery concepts

The BioSPRINT concepts are compared with reference biorefinery concepts using a cradle-to-gate analysis (see Section 3.1.2 'System boundaries') according to the life cycle stages and comparisons are shown in Figure 5. The functional unit chosen is explained in Section 3.1.2 'Functional unit'. Allocation factors used for the life cycle stages 'biomass provision' and 'pre-extraction' and, in the case of the FhG stream, also for 'upstream purification' (of the hemicellulose-rich stream) are listed in Section 3.2.2 'Co-products handling'.

5.1.1 Evaluation of functional unit

The functional unit for the following comparison is '1 tonne usable furans' (see Section 3.1.2 'functional unit'). To analyse the reliability of this choice, Figure 8 illustrates the mass of the furans 5-HMF and furfural in relation to the mass of sugars in the HMC stream (UPM) and black liquor stream (FhG), respectively. As explained in Section 3.1.2 'functional unit', furfural is recycled from the polyol production back to the downstream processing of the biorefinery. Therefore, furfural is divided into usable furfural and recycled furfural. For UPM, the usable mass (green bar in Figure 8 without the shaded part of the bar) is identical in the intensified and non-intensified biorefinery concepts and differs only slightly for FhG and concept C. Process intensification leads to a slight increase or stagnation in the 5-HMF yield and at the same time to a significant decrease in the furfural yield combined with a decrease in the amount of furfural recycled. Although the conversion in the reactor increases, the increased purification of the HMC stream in the intensified BioSPRINT concept results in greater losses when considering the total production. However, an unpurified stream will likely lead to faster degradation of sugars and furans in the reactor. This will also increase reactor fouling. In this sense, it must be considered that the furan production rates calculated for the non-intensified biorefinery are likely to be overestimated and may even be lower than those of intensified biorefineries. As the mass of usable furans is used as the functional unit in the following comparisons, this uncertainty is taken into account.

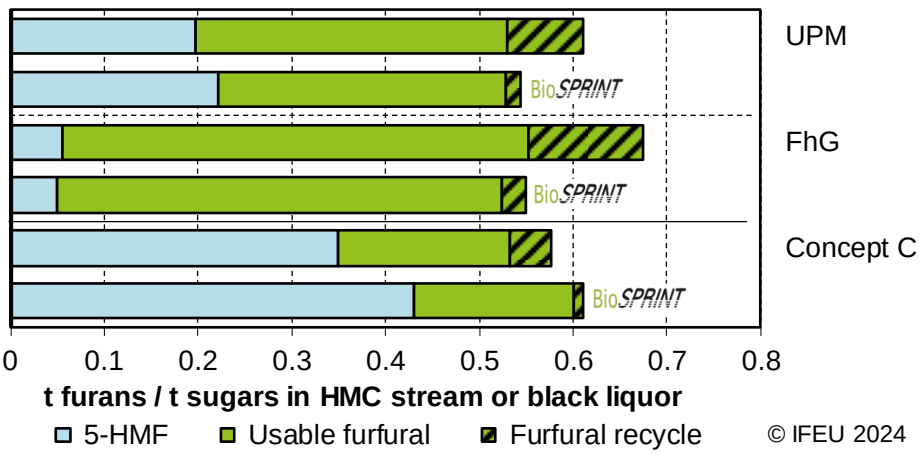


Figure 8: Mass of furans in relation to mass of sugars in the HMC (UPM), black liquor (FhG) and mixed HMC/cellulose streams (concept C).

5.1.2 Base case

The aim of this section is to give a first indication of how the intensified BioSPRINT concepts compare to state-of-the-art non-intensified biorefinery concepts and to answer the question of which unit processes determine the results and what potential there is for optimisation.

Typical scenario

Figure 9 compares the net environmental impacts of furans from the BioSPRINT concepts with those of furans from the reference biorefinery concepts (base case typical, scenarios 1b and Ib) for selected environmental impact categories. All environmental impacts are normalised by the resource use and emissions per capita (EU 28, reference year 2010) to inhabitant equivalents (compare section 3.2.3 'normalisation'). The 'typical' base case is based on data modelled by the project partners including a 5% reduction in heating and cooling demand that is realistically achievable through further improved heat integration for the intensified biorefinery concept (compare Section 4.10). The methods and systems used are detailed in Chapters 3 and 4.

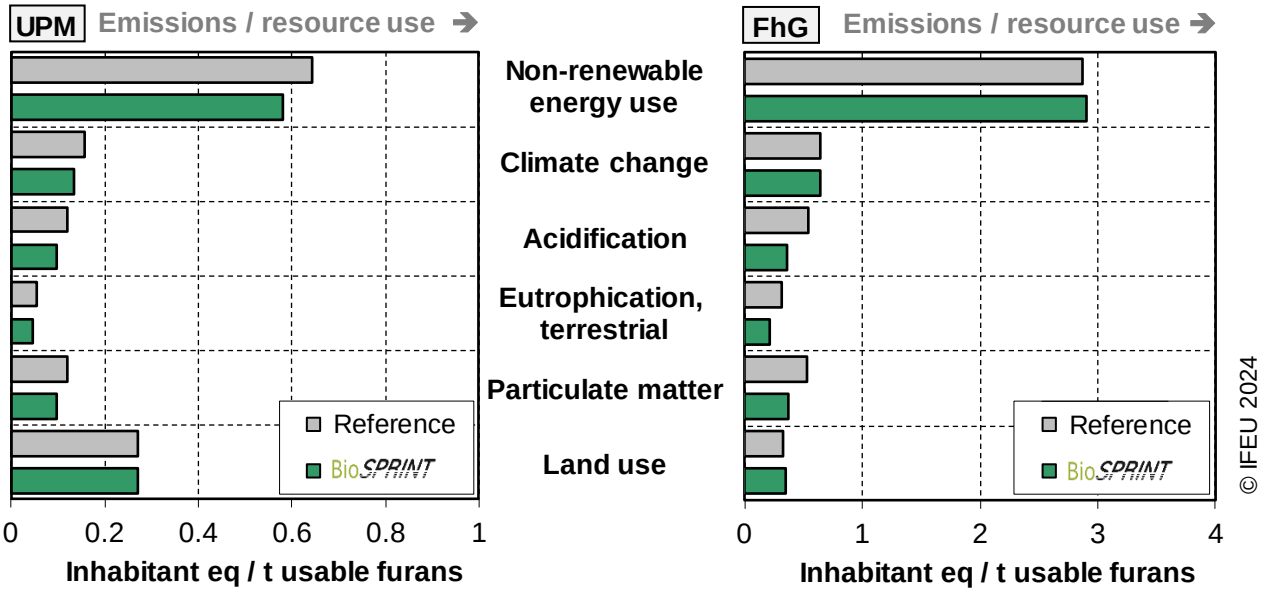


Figure 9: Environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT concepts (green bars) and the non-intensified biorefinery concepts (grey bars) for typical technology development (scenario 1b, Ib). System boundary: cradle-to-gate.

For UPM's HMC stream, the intensified BioSPRINT concept for the production of furans shows invariability or advantages compared to the theoretically modelled non-intensified biorefinery concept (reference). Significant advantages are observed in the environmental impact categories 'energy use', 'climate change', 'acidification' and 'particulate matter'. For FhG's black liquor stream, a slight disadvantage is observed in the category 'energy use' while significant advantages are shown for the categories 'acidification', 'terrestrial eutrophication' and 'particulate matter' for the intensified BioSPRINT concept. The environmental impacts of furans from FhG's concepts (both non-intensified and intensified) are larger than those of furans from UPM's stream due to the more energy-intensive ethanol organosolv pulping process (FhG). At the same time, the savings achieved through process intensification (compared to the reference biorefinery concepts) are larger for FhG than for UPM.

Technology development scenarios

To account for the uncertainty incurred due to the extrapolation of data obtained at low technology readiness level (TRL 3-5) to industrial scale (TRL 9), optimistic, typical and conservative scenarios for the BioSPRINT base case concept are compared with typical and conservative scenarios for the reference biorefinery. While the BioSPRINT base case scenarios differ in the efficiency of the cooling supply and the extent of additional heat integration, the reference base case scenarios differ in the efficiency of the cooling supply and the sugar yield (see also Table 10 in Section 4.10, scenarios 1a-c and Ia,b). These parameters were identified as having the greatest impact and uncertainty. No optimistic case was identified for the reference biorefinery. The uncertainty in sugar yield is due to a possibly increased sugar degradation in the reactor due to an insufficiently purified input stream.

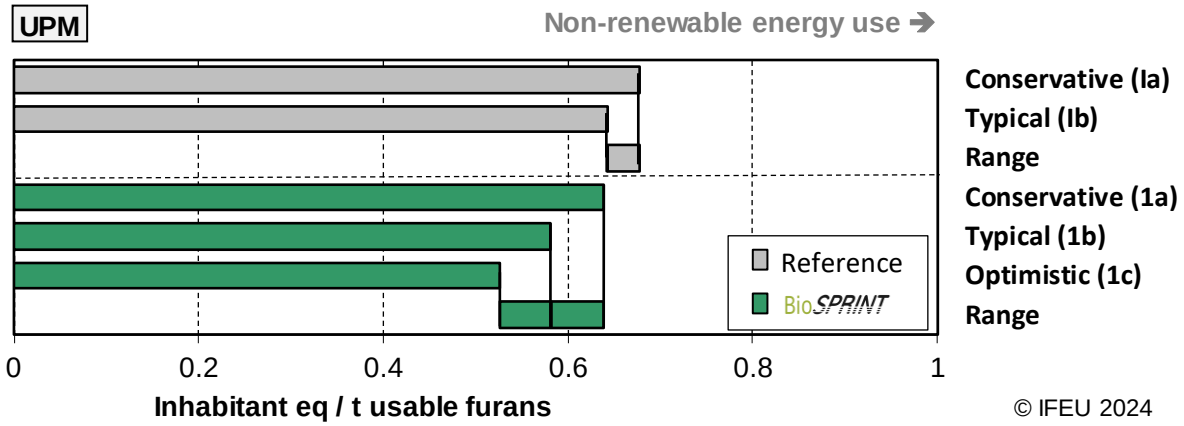


Figure 10: Non-renewable energy use of furans produced from UPM's HMC stream via the intensified BioSPRINT concept (green bars) and the non-intensified biorefinery concept (grey bars) for conservative, typical and optimistic technology development (scenarios 1a-c, Ia,b) as well as the resulting ranges. System boundary: cradle-to-gate.

Figure 11 shows the range of cradle-to-gate emissions and resource use of furans produced with the intensified BioSPRINT concept in comparison to furans produced with the non-intensified biorefinery concept (reference).

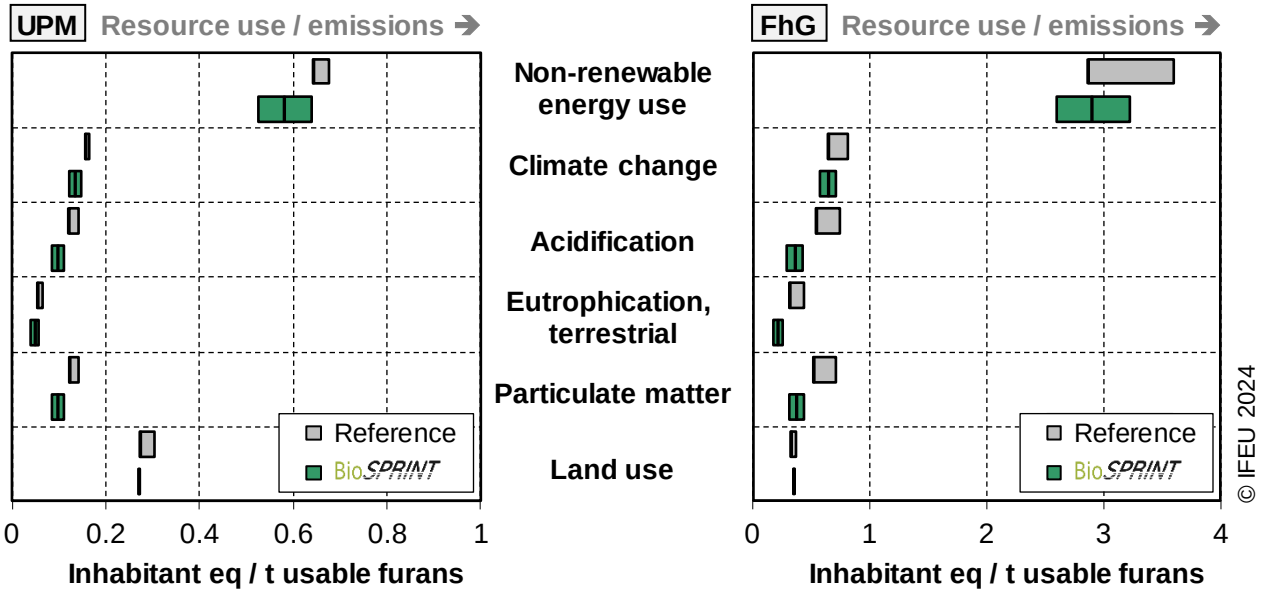


Figure 11: Ranges of environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT concepts (green bars, scenarios 1a-c) and the non-intensified biorefinery concepts (grey bars, scenarios Ia,b). System boundary: cradle-to-gate.

For both UPM and FhG, the trends observed for the typical base case scenario can be confirmed and summarised as follows: For both concepts, the intensified BioSPRINT concept shows slightly less environmental impacts compared to the non-intensified biorefinery concept (reference).

Key findings:

- The intensified BioSPRINT concept is slightly advantageous compared to the non-intensified biorefinery concept from an environmental point of view.

Life cycle stages and optimisation potential

In order to assess the dominating life cycle stages and the optimisation potential, Figure 12 breaks down the environmental impact category 'climate change' of the typical scenario (net results already shown in Figure 9) by life cycle stages. A description of each life cycle stage can be found in Section 4.4.

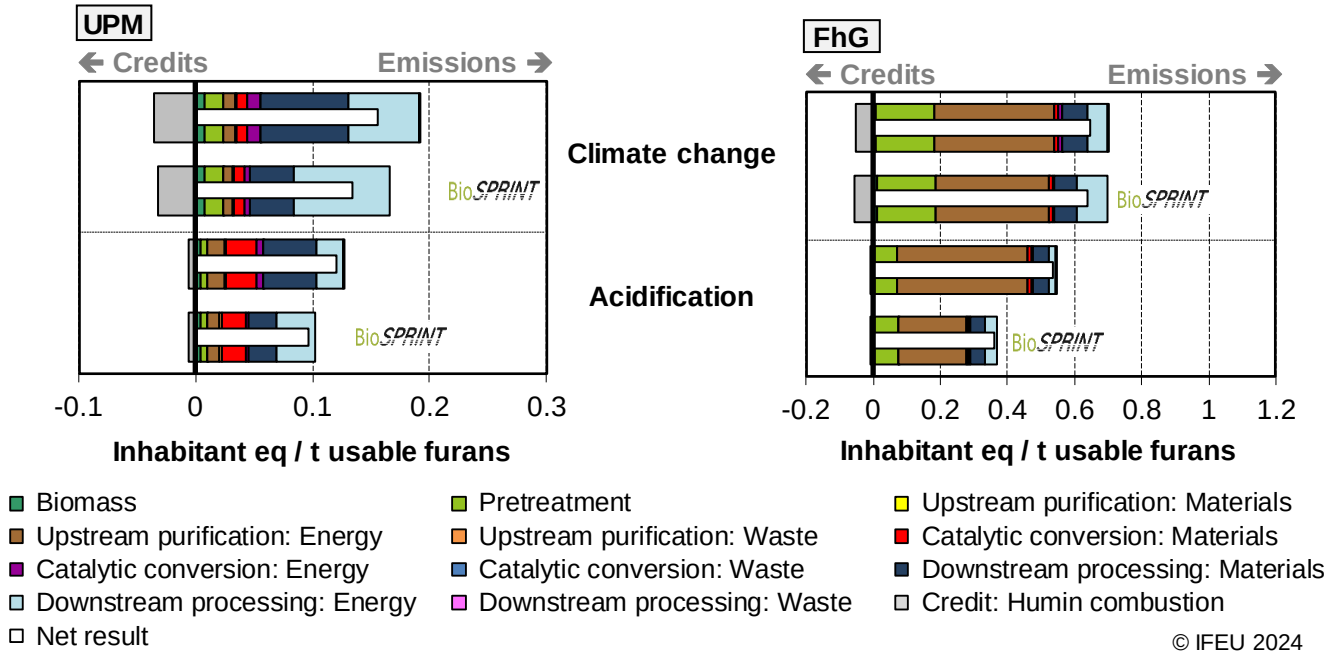


Figure 12: Environmental impacts of furans produced from different HMC / black liquor streams via the typical intensified BioSPRINT concepts and the typical non-intensified biorefinery concepts for the impact categories 'climate change' and 'acidification', broken down by life cycle stages. System boundary: cradle-to-gate.

For UPM, the most important life cycle stage is 'downstream processing'. Both material and energy required for these processes dominate the overall balance in all environmental impact categories. While the impacts of the 'catalytic conversion' are reduced by intensification, the impacts in the 'downstream processing' increase. This increase is larger than the reduction in the 'catalytic conversion', leading to a net increase in emissions.

For FhG, the biomass pre-treatment/fractionation and the upstream purification, i.e., the ethanol organosolv pulping process, dominate the overall impacts of the produced furans. Similar to UPM, emissions for the catalytic conversion are reduced, while emissions for the downstream processing are increased by intensification. In addition, emissions for the upstream purification can be significantly reduced through the process intensification investigated in BioSPRINT, leading to an overall improvement in the impact category 'acidification'.

In the following, the differences between the processes are evaluated in order to identify optimisation potentials:

- *Upstream purification: Energy* (FhG only): The improved ethanol recovery and the change of the reactor technology result in a higher heat demand but significantly lower cooling and electricity demand for the intensified BioSPRINT concept, which leads to lower net emissions for the intensified BioSPRINT concept.
- *Catalytic conversion:* The intensified BioSPRINT concept requires less material and energy. The material input with the highest impact on 'climate change' is $Ca(OH)_2$ for effluent neutralisation. The intensified biorefinery requires less $Ca(OH)_2$ because less H_2SO_4 is used as a catalyst. In addition, the intensified biorefinery has a lower heating and cooling demand due to enhanced heat transfer through an improved heat exchanger for the heat recovery upstream and downstream of the reactor. The use of the ACR in combination with a biphasic reaction system slightly increases the furan yield compared to a reference reaction on a reactor-only basis. However, this advantage is outweighed by the increased sugar loss in the upstream purification, so this improvement is not reflected in the overall balance.

- *Downstream processing: Materials and Energy:* The intensified BioSPRINT concept requires less material but significantly more energy in the downstream processing. Due to the biphasic reaction in the catalytic conversion, more MIBK is required. As a result, more thermal energy is used to separate the furans from the MIBK. For UPM, however, the loss of MIBK, and thus the required make-up, is reduced by using a decanter to recover MIBK from the wastewater. Further optimisation may be achieved by reducing the amount of MIBK or the energy consumption of the separation column. Reducing the latter would be possible through further heat integration, by supplying part of the heat to the column at lower temperatures. Due to the complex interactions with other process parameters, the environmental and economic feasibility of both measures must be carefully analysed.

To evaluate further optimisation potentials, the emissions and savings of the base case scenarios are broken down by different energy and material inputs used across all life cycle stages in Figure 13.

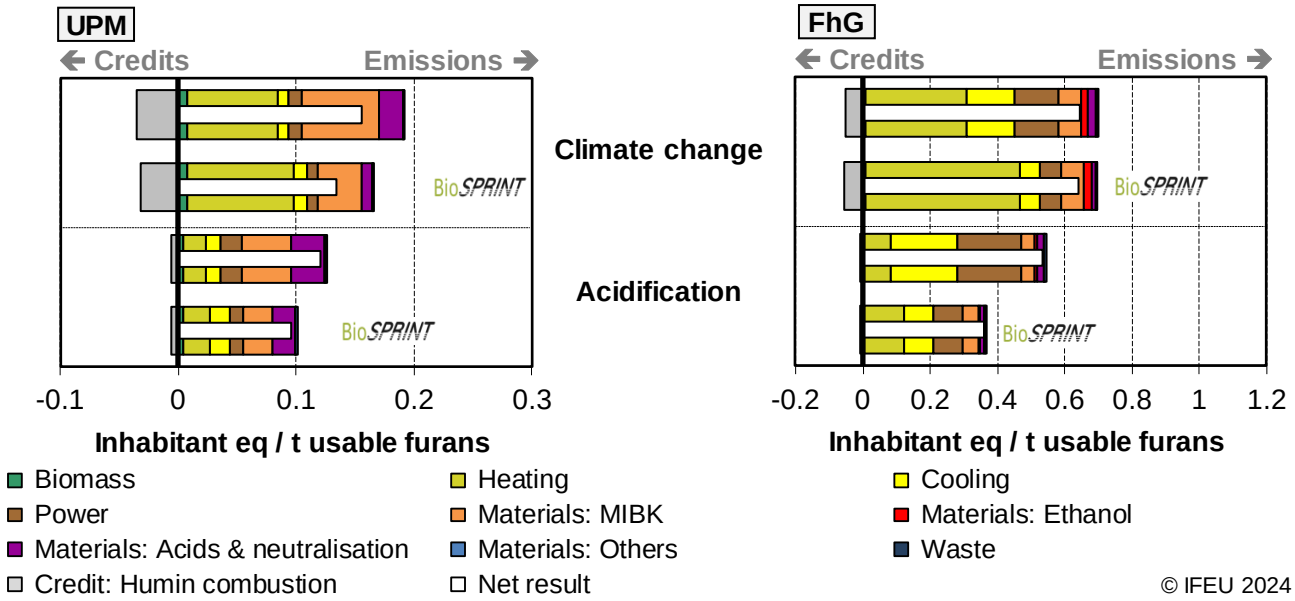


Figure 13: Environmental impacts of furans produced from different HMC / black liquor streams via the typical intensified BioSPRINT concepts and the typical non-intensified biorefinery concepts for the impact categories 'climate change' and 'acidification', broken down by energy and material inputs. System boundary: cradle-to-gate.

- For UPM, emissions from heat provision as well as the provision and end-of-life of MIBK dominate the impact category 'climate change'. The impact category 'acidification' is further dominated by emissions related to the provision of sulphuric acid and its neutralisation. A reduction in the use of MIBK would also lead to a reduction in heat demand, as explained above. A further potential for reducing the impact of MIBK would be the use of renewable MIBK, e.g., from biomass [GreenBiologics 2014] or from captured CO_2 [Duckett 2021]. The impact related to heat demand could be reduced by electrifying the process or by using sustainably available biomass residues.
- For FhG, the energy demand is the most significant contributor to the overall environmental impact. Heat provision from electricity or biomass as well as the use of renewable electricity would be beneficial.

Key findings:

- The dominant life cycle stages are 'downstream processing' for UPM and the ethanol organosolv pulping process ('pre-treatment' and 'upstream purification') for FhG.
- Differences between the biorefinery concepts exist mainly in the material and energy input in the life cycle stages 'catalytic conversion' and 'downstream processing'.
- Large optimisation potentials for the intensified biorefinery concept are identified in terms of the solvent MIBK, heat provision and power provision.

5.1.3 Heat from co-generation

Since the heat demand is identified to be one of the most important contributors to the overall environmental impact of the produced furans and since the BioSPRINT concept included the use of better heat exchangers, we investigate the influence of implementing the two concepts in a setting with a steam turbine providing both steam and electricity (co-generation). In such a setting, a better heat exchanger could lead to a temperature reduction of the steam providing the heat. The amount of electricity which cannot be produced due to the provision of steam depends on the steam temperature and so do the environmental impacts associated with the provision of heat. Details are described in Section 4.7 and Section 4.10. Figure 14 shows the range (conservative, typical and optimistic cases) of cradle-to-gate emissions and resource demands of furans produced with the intensified BioSPRINT concept in comparison to the non-intensified biorefinery concept (reference) when *both* concepts are implemented with steam turbine providing both steam and electricity.

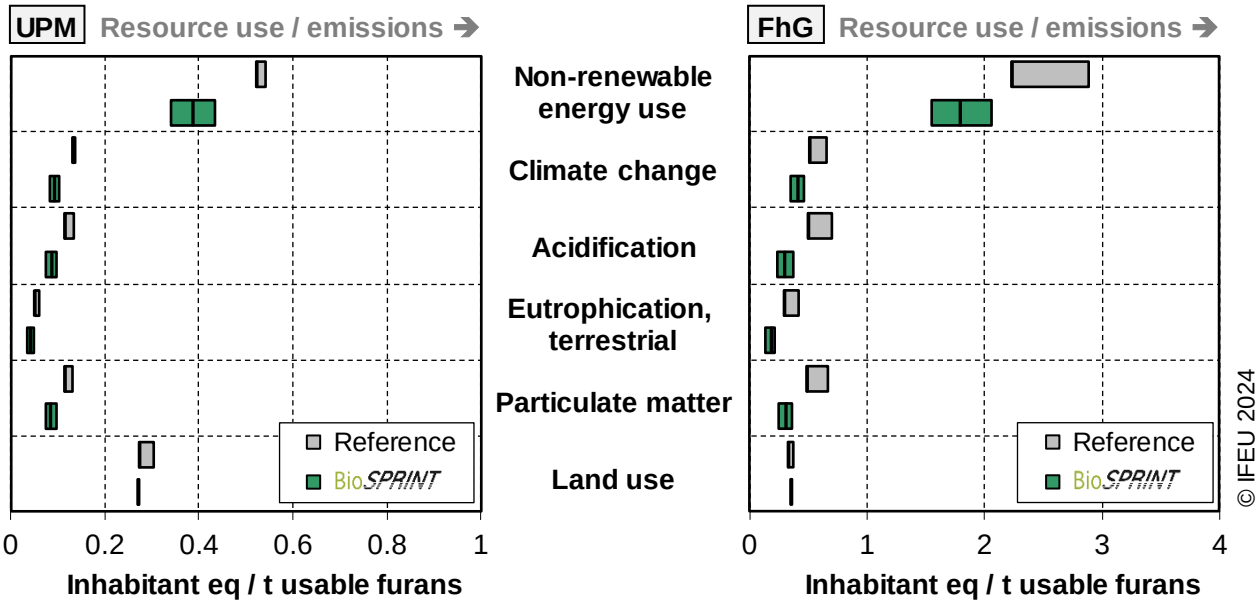


Figure 14: Ranges of environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT biorefinery concepts (scenarios 2a-c) and the non-intensified biorefinery concepts (scenarios IIa,b), using heat from co-generation. System boundary: cradle-to-gate.

For both UPM and FhG, the intensified BioSPRINT concepts show clear advantages over the non-intensified biorefinery concepts (reference) in all impact categories. This is due to the fact that the intensified concepts need steam at a lower temperature level due to improved heat exchangers. The lower temperature results in advantages in the temperature-dependent evaluation of the heat.

Key findings:

- For UPM and FhG, the intensified BioSPRINT concepts show clear advantages over the non-intensified biorefinery concepts if co-generated heat is used.
- In case the temperature of the steam used influences the related emissions, improved heat exchangers can lead to large benefits.

5.1.4 Renewable electricity

In the future, electricity and thus heat and materials can hopefully be produced with an even smaller environmental impact than projected for the year 2030. To calculate the environmental burdens of the biorefinery concepts for the year 2050 or 2070 would go beyond the scope of this work. However, in Figure 15 we exemplarily show the environmental impacts of furans from the intensified BioSPRINT concepts compared to those of furans from the non-intensified biorefinery concepts (reference), when *both* concepts use solar power from PV systems for pumping, compressing and cooling.

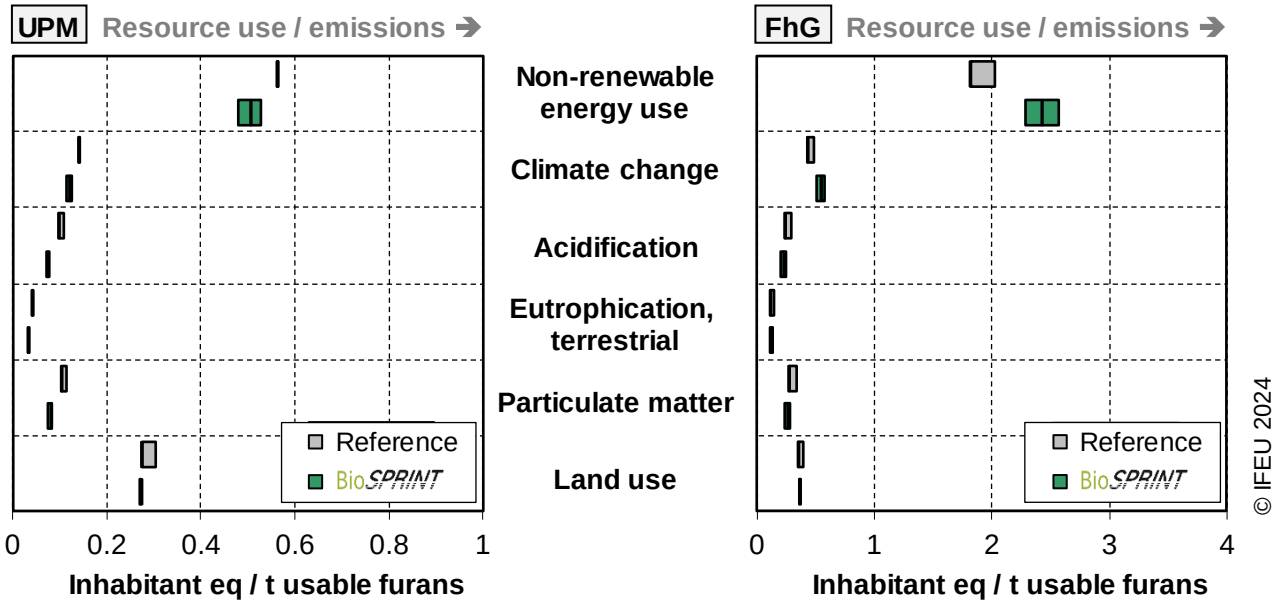


Figure 15: Ranges of environmental impacts of furans produced from different HMC / black liquor streams via the intensified BioSPRINT biorefinery concepts (scenarios 3a-c) and the non-intensified biorefinery concepts (scenarios IIIa,b), using renewable electricity from PV systems in both cases. System boundary: cradle-to-gate.

In case of UPM, the result pattern showing advantages for the intensified BioSPRINT concept over the non-intensified biorefinery concept (reference) also prevails in case of an electricity mix with lower environmental impacts, such as solar power, however slightly diminished. For FhG, on the contrary, the non-intensified biorefinery concept shows comparable or even lower environmental impacts compared to the intensified BioSPRINT concept. This is due to the larger electricity demand of the non-intensified biorefinery concept whose contribution to the overall impacts is reduced by using renewable electricity with lower environmental burdens.

Key findings:

- Whether the intensified BioSPRINT concept is advantageous over the non-intensified biorefinery concept in the future depends on the environmental burdens of the electricity, the heat and the materials.

5.1.5 Excursus: Mixed hemicellulose and cellulose stream

In this excursus, the BioSPRINT concept B is also applied to a stream from a steam explosion pre-treatment, which contains both hemicellulose and cellulose (concept C). Its content of C6 sugars is significantly higher compared to the hemicellulose streams from UPM and FhG. This results in a furan product stream containing a significantly higher proportion of 5-HMF than the product streams from UPM and FhG (compare Figure 8). Moreover, the steam explosion pre-treatment is based on wheat straw as biomass feedstock instead of beech wood. Thus, the impact categories ‘freshwater eutrophication’, ‘ozone depletion’, and ‘phosphate rock use’ are

included in the evaluation. The operating conditions of all process steps are adapted to the changed ratio of C5 to C6 sugars.

Figure 16 shows the comparison of the range of the environmental impacts of the BioSPRINT concept (base case scenario, 1a-c) with the reference biorefinery concept per tonne of usable furans for the base case scenario (Ia,b).

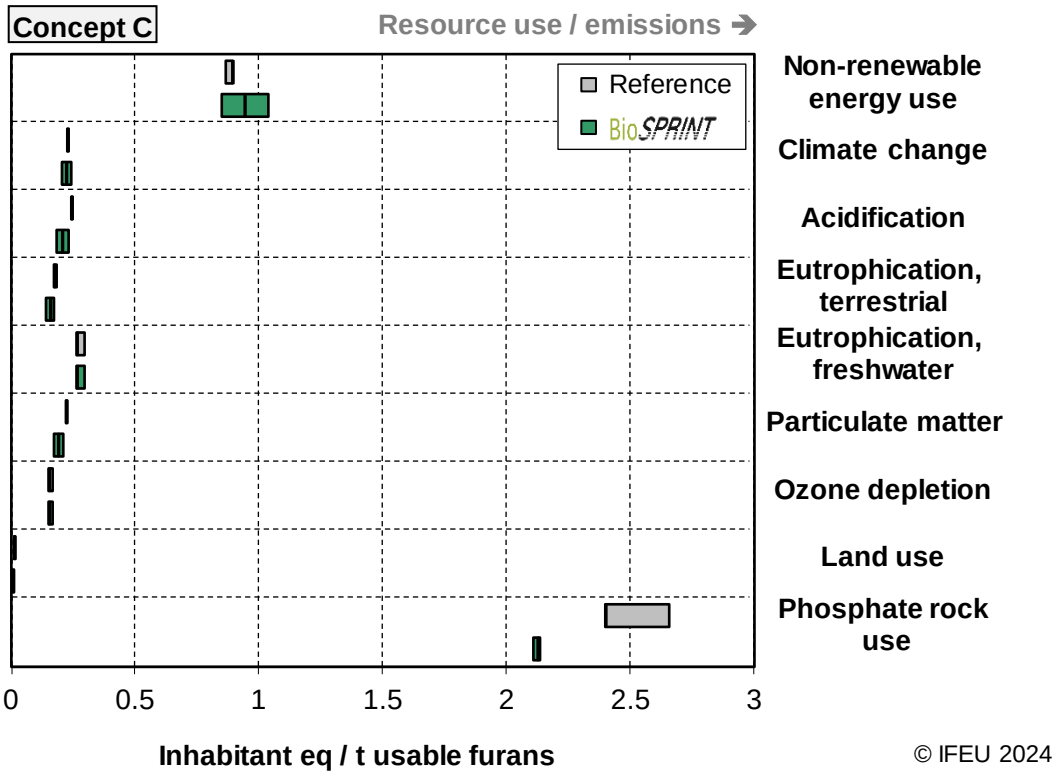


Figure 16: Range of environmental impacts of furans produced from a mixed HMC/cellulose stream via the intensified BioSPRINT concept B (scenarios 1a-c) and the non-intensified biorefinery concept (scenarios Ia,b). System boundary: cradle-to-gate.

When applying the BioSPRINT process intensification measures to concept C, there is no clear advantage for the intensified BioSPRINT concept over the non-intensified biorefinery concept (reference) in any of the analysed impact categories but phosphate rock use. Phosphate rock use directly scales with biomass input. Due to the better yield in case of concept C (compare Figure 8), the intensified BioSPRINT concept needs less wheat straw than the non-intensified biorefinery concept. The disadvantages of the intensified BioSPRINT concept are particularly visible for concept C in the impact categories 'energy use' and 'climate change'. This is due to the disproportionately high energy requirements for the downstream processing. A higher proportion of 5-HMF from the C6 fraction increases the amount of MIBK required to recover the furans compared to intensified processing of an HMC stream. This increases the energy requirement for the distillation of furans and MIBK.

Key findings:

- In case of a mixed hemicellulose and cellulose stream, the intensified BioSPRINT concept for the production of furans is comparable to the theoretically modelled, non-intensified biorefinery concept from an environmental point of view.

5.2 BioSPRINT end products vs. fossil reference products

In order to assess how the innovative, hemicellulose-based products produced via the intensified BioSPRINT concepts compare to their fossil-based equivalents, the entire product system is analysed from cradle-to-grave (see Figure 2 and Figure 6). First, the impact of possible previous use of the HMC streams is investigated (Section 5.2.1). This gives possible ranges for the environmental impacts of the furans (Section 5.2.1). These impacts are used in a second step to analyse the whole system from cradle to grave (Section 5.2.2). Since no conclusions can be drawn from this analysis for the wood laminate binder, the sub-systems 'PU foam' and 'wood laminate binder' are analysed separately (Section 5.2.2). Finally, the environmental impacts of the furans are compared with the environmental impacts of potential fossil equivalent products (Section5.2.3).

5.2.1 Previous use of HMC stream

In addition to the analyses carried out in Section 5.1 considering the building of a new biorefinery, the comparison with fossil reference products must take into account that the HMC stream is not a waste stream, but is already being valorised (see Section 4.2 and Figure 7) in existing biorefineries. For example, HMC stream could be used to generate energy in a biogas plant. If the HMC stream is used to produce furans, it is no longer available for the previous use, which in the worst case would have to be 'conventional' again. Therefore, Figure 17 considers the carbon footprint for the production of furans, taking into account the foregone environmental benefits of the previous use.

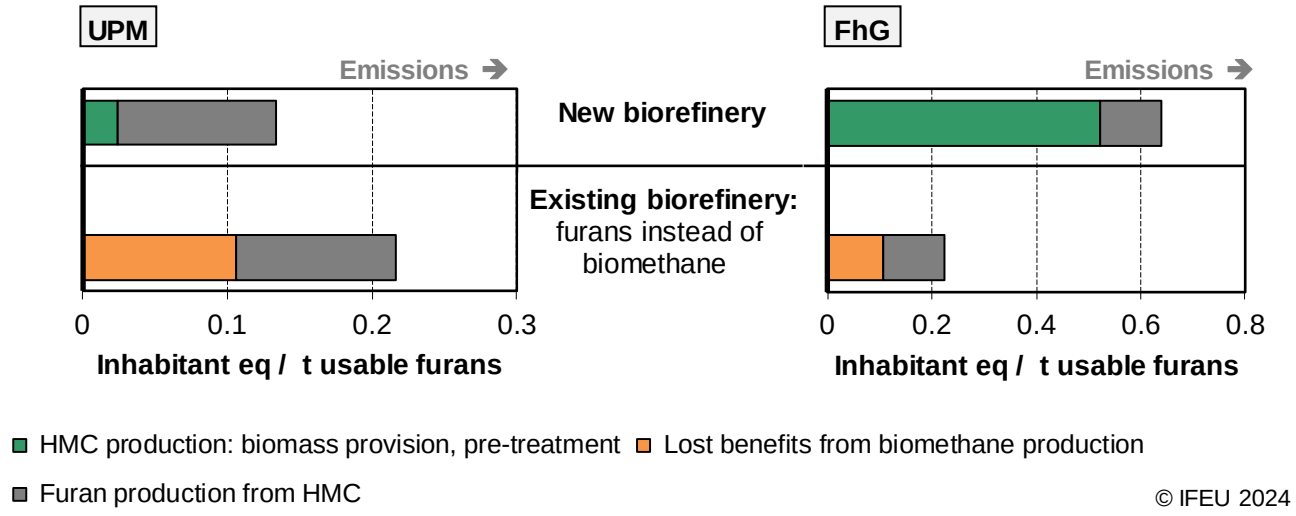


Figure 17: Impact of furans produced via different typical intensified BioSPRINT concepts in 'climate change' if implemented in a new or an existing biorefinery (scenarios 1b, 5b). System boundary: cradle-to-gate.

When taking into account a previous use for other purposes, the use of UPM's HMC stream from an existing biorefinery for furan production results in a higher carbon footprint than if the biomass (and thus the HMC stream) had not been used (new biorefinery), as the previous use can no longer lead to emission savings in case of implementing the BioSPRINT concept. The emissions of producing the HMC stream in the organosolv pulping process (FhG) are so high that its use for biomethane would make no sense. Therefore, the calculated carbon footprint is lower if a previous use is taken into account. For both UPM and FhG, the carbon footprint is similar (~0.2 inhabitant eq. per tonne of furans) when produced from a previously used HMC stream.

Key findings:

- The cradle-to-gate carbon footprint of the furans produced with the intensified BioSPRINT concept depends on whether the HMC stream is part of the portfolio of a new biorefinery or the previously otherwise valorised stream of an existing biorefinery.

5.2.2 BioSPRINT product portfolio: PU foam and wood laminate binder

Environmental impacts

The BioSPRINT and the fossil product system yield the same volume of PU foam and mass of wood laminate binder (see definition of functional units in Section 3.1.2). The mass of C5 and C6 sugars in the HMC stream is chosen as a reference value for the graphical display. Other reference values could be used but would lead to the same conclusions.

To gain an initial insight, a base case with favourably low emissions for the intensified BioSPRINT concept is compared with the fossil reference system in Figure 18. To model the furans, furans produced by UPM's pre-treatment (concept B, scenario 1b (compare Table 10)) are set. The most favourable approach is also chosen for cardanol, i.e., only emissions and resource use for processing cardanol from cashew nuts are considered.

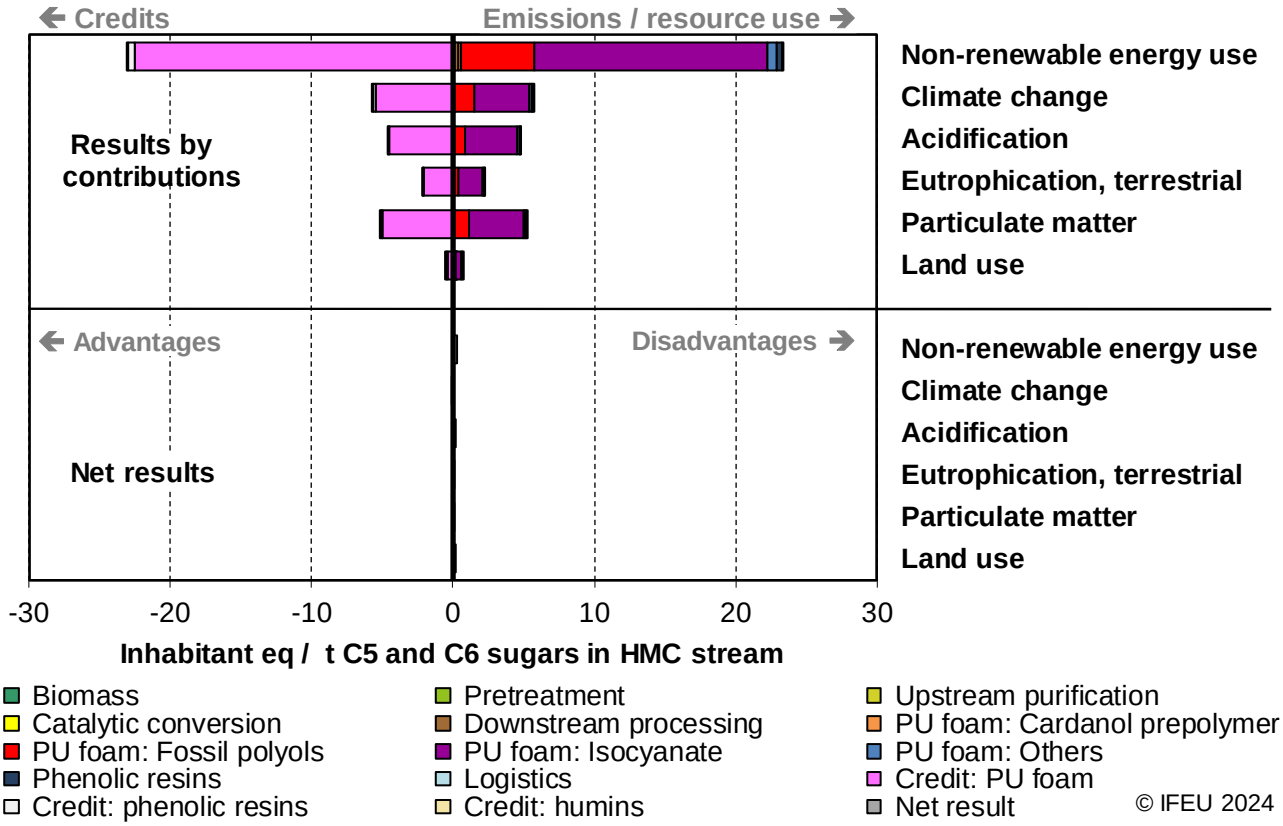


Figure 18: Environmental impacts of the PU foam and wood laminate binder produced via the intensified BioSPRINT concept compared to the fossil reference system.

The results in the individual impact categories are completely dominated by the expenditure for the non-hemicellulose components of the PU foam, while the contribution for the production of furans and phenolic resins plays a minor role. The result shown above is, therefore, highly dependent on the conditions under which the fossil components of the PU foam are produced.

Key findings:

- The expenditures of the fossil components of the PU foams dominate the cradle-to-grave balance of the BioSPRINT product system
- The impact of the furans on the overall cradle-to-grave balance is extremely low.

Product formulation

For the analysis of the BioSPRINT product system, the formulations of the PU foam and the wood laminate binder are compared with their fossil equivalents, firstly on a mass basis in Figure 19 and secondly in the impact categories 'climate change' and 'acidification' in Figure 20. All components except furfural, 5-HMF and cardanol are fossil-based since no suitable bio-based alternatives could be identified for these specific applications.

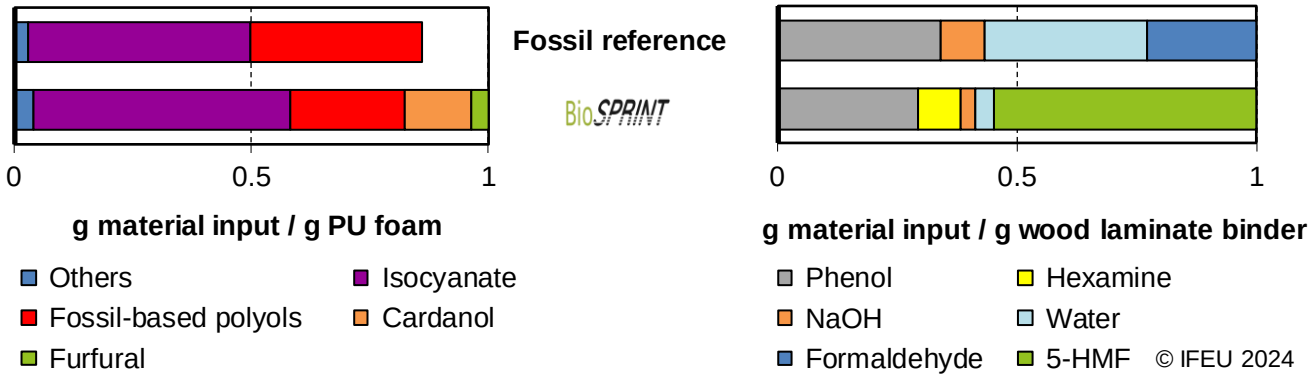


Figure 19: Materials used for BioSPRINT and fossil reference products PU foam (left) and wood laminate binder (right).

A comparison of the mass of material required to produce the same volume of PU foam shows that the use of biogenic components (furfural and cardanol) increases the density, i.e., significantly more material has to be used to obtain the same volume. This means that a large mass of bio-based cardanol and some furfural replace only a small mass of fossil-based polyols. The formulation of the BioSPRINT PU foam could be optimised to reduce the density by modifying the amount of material input, e.g. blowing agent. Moreover, a large part of the PU foam still is based on fossil resources, i.e. fossil-based polyols and isocyanate. To date, no bio-based isocyanates suitable for the production of rigid PU foams are available.

In bio-based wood laminate adhesives, the same mass of material inputs can be used as in fossil-based adhesives. However, the bio-based formulation tolerates a lower water content due to the lower reactivity of 5-HMF compared to formaldehyde and the lower general miscibility with water. Therefore, 5-HMF replaces formaldehyde and water. Moreover, hexamine is necessary to cure the bio-based binder, while the fossil-based binder is self-curing. Hexamine is produced from formaldehyde and ammonia.

To illustrate the resulting disadvantages for the bio-based BioSPRINT products, Figure 20 compares the emissions associated with the ingredients of PU foams and wood laminate binders with their fossil equivalents for the impact categories 'climate change' and 'acidification'. The emissions for manufacturing are in the same order of magnitude, even tend to be higher for the BioSPRINT product and are omitted in the graph. The impacts of the furans are represented by furans from a HMC stream from UPM's pre-treatment for scenario 1b.

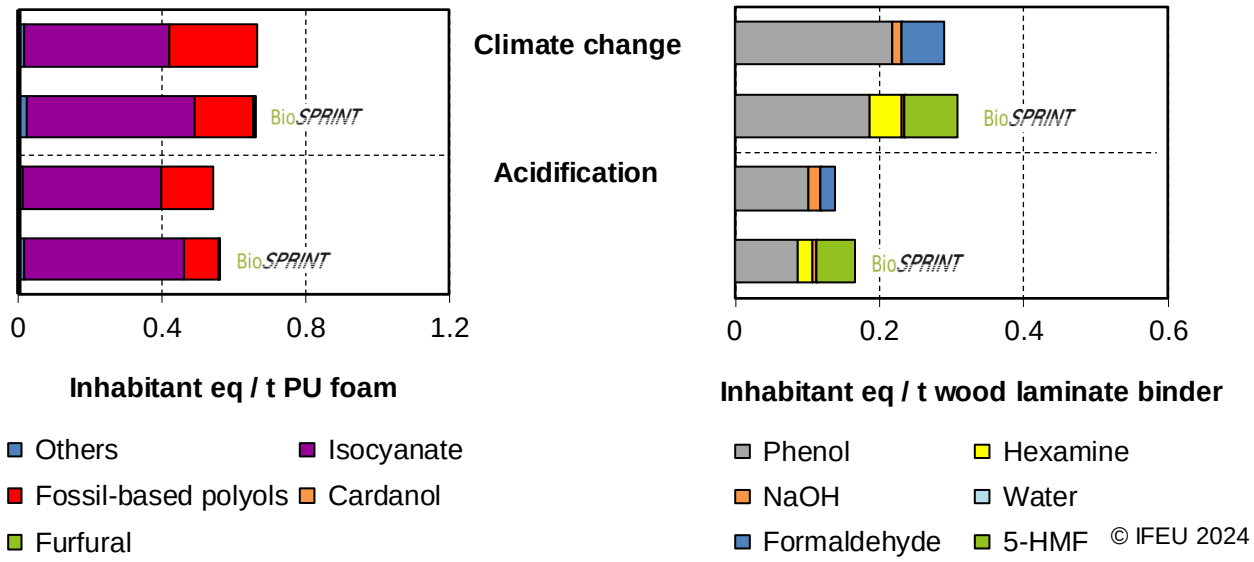


Figure 20: Environmental impacts of BioSPRINT and fossil reference products PU foam (left) and wood laminate binder (right) for the impact categories 'climate change' and 'acidification'.

For both product systems, the fossil product system is advantageous due to the net smaller environmental disadvantages. For the PU foam, this result is independent of the emissions of the furans, for the wood laminate binder, however, a reduction of the furans' impact could lead to advantages over the fossil reference system. Further optimisation potentials include reducing i) the isocyanate footprint, ii) the total material use per volume of PU foam and iii) the hexamine footprint for the wood laminate binder.

Key findings:

- The BioSPRINT PU foam has an extremely low furfural content and requires more biogenic material to replace a smaller amount of fossil material.
- In the wood laminate binder, 5-HMF replaces water and formaldehyde.
- The BioSPRINT product systems are not environmentally beneficial compared to fossil alternatives.

5.2.3 Comparison of BioSPRINT furans to conventional equivalents

As shown in the previous Section 5.2.2, the product system investigated in the BioSPRINT project is not expected to have any environmental benefits – at least no benefits that can be attributed to the processes investigated in BioSPRINT. Therefore, the potential of the furans produced in BioSPRINT has been analysed. For this purpose, the carbon footprints of the furans are compared with those of fossil-based chemicals that they could potentially replace. Formaldehyde and polyol are selected because the products invented in BioSPRINT aim to replace these chemicals. Additionally, terephthalic acid, a precursor of polyethylene terephthalate (PET) is included in the analysis. PET can be replaced by polyethylene furan-2,5-dicarboxylate (PEF), which is made from 2,5-furan-dicarboxylic acid (FDCA) and ethylene glycol. 2,5-FDCA can be synthesised from 5-HMF [de Jong et al. 2012].

In order to estimate a range for the carbon footprint of furans, the following scenarios (compare Table 10) are evaluated and compared in Figure 21:

- For new biorefineries:
  optimistic cases: 1c and 2c; typical cases: 1b and 2 b (bold in Figure 21); conservative cases 1a and 2a
- For existing biorefineries with previous use of HMC stream:
  scenarios 4a-c (shaded in Figure 21).

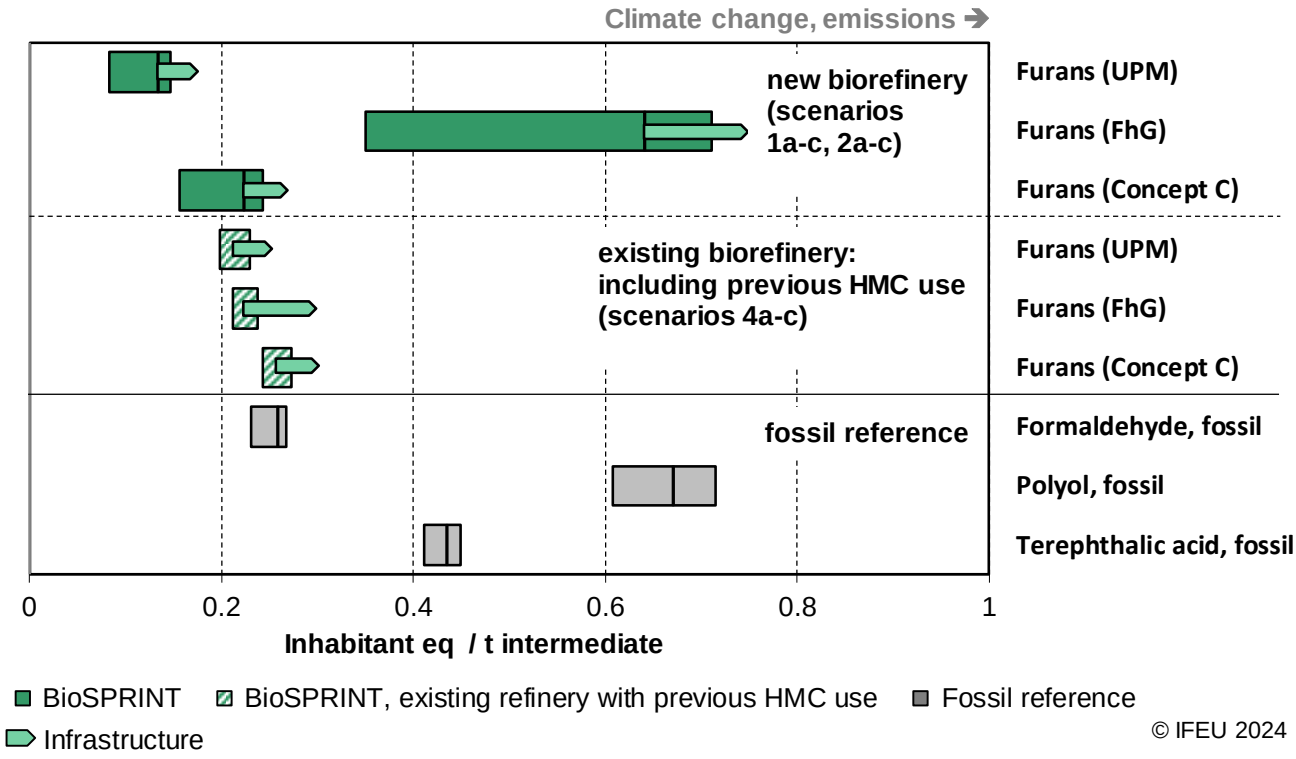


Figure 21: Environmental impact (impact category 'climate change') of furans produced via different intensified BioSPRINT concepts for various scenarios compared to the environmental impact of potential fossil equivalents.

The environmental impacts of the bio-based furans 5-HMF and furfural depend on the type of lignocellulosic pulping process (pre-treatment) used in the biorefinery and on whether the HMC stream has previously been used for other purposes (existing biorefinery): in the case UPM and concept C, the results for the impact category 'climate change' are in the range of 0.1 to 0.3 inhabitant equivalents per tonne of furan (1.0-2.5 kg CO_2 eq/kg), whereas in the case of ethanol organosolv pulping it is around 0.2 to 0.7 inhabitant equivalents per tonne of furan (2.0-6.5 kg CO_2 eq/kg), i.e. a factor of 2 higher due to very high energy requirement of this pre-treatment technology (ethanol recycle).

The furans 5-HMF and furfural (or derivatives thereof) can be used to replace a number of functionally equivalent conventional/fossil products whose carbon footprint (impact category 'climate change') ranges from about 0.2 inhabitant equivalents per tonne (2 kg CO_2 eq/kg, formaldehyde) to more than 0.7 inhabitant equivalents per tonne (6 kg CO_2 eq/kg, polyols).

Whether and to what extent GHG emissions can be saved depends on the following factors:

- Carbon footprint of the bio-based furans (and thus indirectly on the type of lignocellulose pulping process as well as on the foregone environmental benefits of the previous use of the HMC stream, assuming that it is actually not being disposed of as waste).
- Carbon footprint of the substituted conventional/fossil equivalent product (including all changes in the product formulation).
- Substitution ratio (mass of furan: mass of conventional/fossil equivalent), taking into account any conversion steps that may be required to obtain a furan derivative with which functional equivalence to a conventional/fossil product can be established, e.g., conversion of furans into 2,5-FDCA as a substitute for terephthalic acid.
- Emissions and resource use associated with the conversion of furans into furan derivatives.

Thus, if *both* bio-based furans (5-HMF and furfural) can replace the respective fossil equivalent with a favourable substitution ratio, the furans and the process routes presented show a high potential for lowering environmental impacts, especially if the HMC stream is obtained from UPM's pre-treatment, no previous use needs to be considered and complex molecules such as polyols or terephthalic acid can be replaced. In this case, a substitution ratio (mass of furan : mass of conventional/fossil equivalent) *better* than 1 : 1 to 3 : 1 for formaldehyde, 2 : 1 to 5 : 1 for terephthalic acid and 3 : 1 to 9 : 1 for polyols is required to achieve environmental benefits in the impact category 'climate change'. The lower value needs to be achieved in case of a conservative scenario for furans but an optimistic scenario for the fossil equivalents.

Key findings:

Replacing fossil chemicals with bio-based furans can bring benefits in the environmental impact category 'climate change' if the following criteria are met:

- Low environmental impact associated with the furans
- Indirect effects caused by displacing the previous use of the HMC stream are avoided as far as possible
- Fossil-based chemicals with a high environmental impact are replaced
- The substitution ratio (mass of furan: mass of conventional/fossil equivalent intermediate) is as close to as possible 1 : 1.
- Both furfural and 5-HMF replace fossil-based chemicals
- Low emissions and resource use associated with the conversion of furans into furan-based products

6 Key findings, conclusions and recommendations

The aim of this screening LCA is to clarify to what extent and under which conditions the BioSPRINT concept can contribute to a more environmentally friendly utilisation of the hemicellulose stream from biorefineries. This main question has been subdivided into a number of sub-questions (see Section 3.1.1):

- How do the intensified BioSPRINT biorefinery concepts compare from an environmental perspective to
  a) the conventional non-intensified biorefinery concepts and to
  b) conventional (fossil) ways of providing an equivalent product portfolio?
- In both cases: which unit processes determine the results significantly and what are the optimisation potentials?

6.1 Key findings

The results of the screening life cycle assessment presented in Chapter 5 can be summarised as follows:

Environmental impacts of BioSPRINT concepts vs. reference biorefinery concepts

Intensified BioSPRINT concepts applied to hemicellulose/black liquor streams

- Furans produced from the *UPM hemicellulose stream* via the intensified BioSPRINT concept show comparable environmental impacts to furans produced via the theoretically modelled, non-intensified biorefinery concept (reference) in all cases studied. Savings in the catalytic conversion are offset by higher emissions and resource use for extraction (solvent and energy consumption).
- Furans produced from the *FhG black liquor stream* (organosolv pulping process) via the intensified BioSPRINT concept show small to significant advantages in the base case compared to furans produced via the non-intensified biorefinery concept. These savings are mainly due to lower energy requirements in the upstream purification (part of the organosolv pulping process). When temperature plays a role in the heat supply, for example, in combined heat and power generation, there are clear advantages in all environmental impacts compared to the reference concept. This is because the intensified BioSPRINT concept requires more heat but at a lower temperature level. This gives advantages in the temperature-dependent assessment of heat.
- For FhG and UPM, the recovery of MIBK was identified as the greatest potential for optimisation. This could be achieved by reducing the amount of solvent, improving the energy efficiency of the separation of furans from the solvent and downstream recovery of MIBK from the wastewater. The use of renewable MIBK, renewable electricity, and the electrification of the process or bioenergy provision from sustainably available biomass residues would further reduce the environmental impact of the furans.

Excursus: Intensified BioSPRINT concept applied to a mixed hemicellulose and cellulose stream

- The intensified BioSPRINT concept for the production of 5-HMF and furfural from a mixed hemicellulose and cellulose stream shows clear disadvantages in all impact categories investigated. This is due to the low energy savings in the catalytic conversion, which is offset by the enormous additional heat required for separation of furans and solvent. Thus, the biorefinery concepts need to be tuned to the sugar composition.

Environmental impacts of hemicellulose-based products vs. fossil reference products

BioSPRINT products

- With the product system selected in BioSPRINT, no environmental advantages can be achieved compared to the fossil reference system.
- As only a small amount of bio-based material (< 20%) is used in the BioSPRINT *PU foam*, and at the same time more material is required to fulfil the same function as the fossil equivalent, the BioSPRINT product formulation is not advantageous from an environmental point of view.

- In the BioSPRINT *wood laminate binder*, the hemicellulose-based material essentially replaces formaldehyde and water, which both have a low environmental impact. The BioSPRINT product formulation is, therefore, disadvantageous compared to fossil alternatives.
- The mass of decorative PU foams produced from the HMC stream of one biorefinery, processing 225,000 tonnes per year of dry biomass input, is in the order of magnitude of 700,000 tonnes per year, if all furfural was used for this product. It is questionable whether there is a market for this huge amount of decorative PU foams. For cardanol, more than 5% of the world cashew nut harvest (2021) would need to be processed.

Other furan-based products

- The environmental impacts of the bio-based furans 5-HMF and furfural depend on the type of lignocellulose pulping process (pre-treatment) used in the biorefinery: in the case of UPM's pre-treatment and steam explosion pre-treatment, the results for the environmental impact category 'climate change' are in the range of 1.0 to 2.5 kg CO_2 eq per kg of furans, whereas in the case of ethanol organosolv pulping the carbon footprint is between 2.0 and 6.5 kg CO_2 eq per kg of furans.
- The furans 5-HMF and furfural (or derivatives thereof) can be used to replace a number of fossil equivalent products whose carbon footprint (environmental impact category 'climate change') ranges from about 2 kg CO_2 eq/kg (formaldehyde) through about 4 kg CO_2 eq/kg (terephthalic acid) to more than 6 kg CO_2 eq/kg (polyols).
- Whether and to what extent GHG emissions can be saved depends on the following factors:
    - Carbon footprint of the bio-based furans (and thus indirectly on the type of lignocellulose pulping process as well as on the foregone environmental benefit of the previous use of the HMC stream)
    - Carbon footprint of the substituted conventional/fossil equivalent product(s)
    - Substitution ratio (mass of furan : mass of conventional/fossil equivalent intermediate)
    - Emissions and resource use associated with the conversion of furans into furan derivatives.
- Thus, if *both* bio-based furans (5-HMF and furfural) can replace the respective fossil equivalent with a favourable substitution ratio, the furans and the process routes presented show a high potential for lowering environmental impacts, especially if the HMC stream is obtained from UPM's pre-treatment, no previous use needs to be considered and complex molecules such as polyols or terephthalic acid can be replaced. In this case, a substitution ratio (mass of furan : mass of conventional/fossil equivalent) *better* than 1 : 1 to 3 : 1 for formaldehyde, 2 : 1 to 5 : 1 for terephthalic acid and 3 : 1 to 9 : 1 for polyols is required to achieve environmental benefits in the impact category 'climate change'. The lower value needs to be achieved in case of a conservative scenario for furans but an optimistic scenario for the fossil equivalents.

6.2 Conclusions

The following conclusions can be drawn on the basis of the key findings of the screening life cycle assessment:

Environmental impacts of intensified BioSPRINT concepts vs. non-intensified biorefinery concepts

- The process intensification measures investigated in BioSPRINT to improve the production of furans from hemicellulose-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 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.

Environmental impacts of hemicellulose-based products vs. fossil reference products

- 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.

- 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, hemicellulose-based products certainly have the potential to achieve environmental advantages over their conventional/fossil equivalents.

6.3 Recommendations

From these conclusions, the following recommendations can be derived for the target audiences defined in Section 3.1.1.

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

Before implementing the BioSPRINT concept

- Investigate ways to further minimise the net energy consumption and solvent loss, especially related to the recovery of MIBK which was identified as the greatest potential for optimisation.
- Since the co-product humins has not been specifically researched in BioSPRINT, an environmentally friendly use for this stream should be researched and developed.
- Establish an environmentally friendly product portfolio. LCA tools, together with further questions to be answered, can support this decision. Not only the environmental impact of a kilogramme of product should be assessed, but also the scale of the production. Questions such as whether there is a sustainable provision of the raw material, 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 a world in the year 2050 (i.e., after transformation towards a green, digital and resilient economy) should be considered. For example, instead of using the PU foams for decorative elements, it would be much more beneficial for the environment (and society) to further develop the PU foams for use in insulation panels (and thus positively contribute to the 'heat transition'). Such application needs to be competitive not only with fossil equivalents but also with bio-based alternatives, e.g., insulation boards made of wood foam.

To consider for other projects

- When evaluating the environmental aspects related to process intensification measures on a product basis, it is absolutely essential to consider the entire life cycle (of a product or product portfolio) and not just at the level of an individual process because the investigated process might have implications on other processes further downstream the value chain.

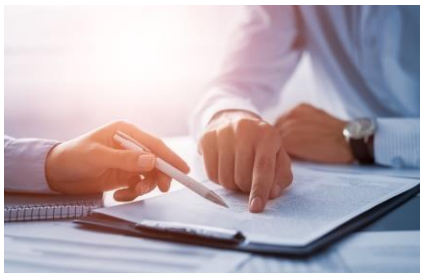
- Therefore, it is important to take a life cycle perspective already at an early stage of process development in order to avoid shifting of environmental burdens from one life cycle stage (process step) to another, from one geographic area to another and from one environmental medium (for example air quality) to another.
- LCA should be intertwined with process development, not necessarily to quantify the environmental impacts of products, but above all to identify bottlenecks and identify optimisation potentials (from an environmental perspective) *from early on*.
- Optimisation of the product system should be aimed at reducing environmental impacts. It is not enough to simply replace fossil-based products with bio-based ones; the respective environmental impacts and the ratio at which the products are replaced must be taken into account.



© elenanoeva / stock.adobe.con

To political decision makers and research funding agencies

- Continue the existing approach of carrying out life cycle analyses alongside projects in order to avoid well-intentioned but non-beneficial investments in supposedly green technologies and to be able to manage projects well.
- Take into account that replacing fossil-based products with bio-based products is not inherently beneficial to the environment; only a consideration of the entire life cycle up to an actually comparable end product, considering indirect effects, can provide a statement on this.



© REDPIXEL - stock.adobe.com

- 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 should be supported.
- Induce a societal discussion about essential products and develop biomass allocation plans at national and/or European level. Scarce biomass should be used as beneficially 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 implementation of the UN Sustainable Development Goals. In the long term, introduce mechanisms that put a price on environmental and social impacts.
- 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 use of biomass, as opposed to uses 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. Laws, taxes and tariffs should be adjusted in the same direction.
- 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.

Acknowledgement

This deliverable is part of the BioSPRINT project. This project has received funding from the Bio-Based Industries Joint Undertaking under the European Union Horizon 2020 research and innovation programme under grant agreement No 887226. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Bio Based Industries Consortium.

The authors would like to thank all BioSPRINT project partners sincerely for the provision of information and data, which forms the basis of this life cycle assessment, notably the mass and energy flow data provided to Task 6.3, and for the very constructive feedback to this report. Furthermore, we are grateful to Mladen Crnomarković and Marcel Eijkenboom for the close interaction and continuous valuable discussions in WP6 in particular on input data and project context.

References

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

CEN (2015): EN 16760:2015 Bio-based products - Life Cycle Assessment. European Committee for Standardization.

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

Detzel, A., Kauertz, B., Grahl, B., Heinisch, J. (2016): Prüfung und Aktualisierung der Ökobilanzen für Getränkeverpackungen. UBA-Texte Institut für Energie- und Umweltforschung Heidelberg (ifeu), Heidelberg, Germany. *https://www.umweltbundesamt.de/publikationen/pruefung-aktualisierung-der-oekobilanzen-fuer*.

Duckett, A. (2021): Biotech demonstrator will produce acetone from captured industrial emissions. *The Chemical Engineer*, Vol. 964.

ecoinvent (database): Ecoinvent database. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Eller, K., Henkes, E., Rossbacher, R., Höke, H. (2000): Amines, Aliphatic. In: *Ullmann's Encyclopedia of Industrial Chemistry*, John Wiley & Sons, Ltd.

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

García-Velásquez, C., van der Meer, Y. (2023): Mind the Pulp: Environmental and economic assessment of a sugar beet pulp biorefinery for biobased chemical production. *Waste Management*, Vol. 155, pp. 199–210.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. D., Struijs, J., van Zelm, R. (2014): Characterisation and normalisation factors, version 1.11. PRé Consultants, Radboud University Nijmegen, Leiden University, RIVM. *https://www.rivm.nl/dsresource?objectid=881acbe7-49d0-41b1-b432-f97e4b237504*.

GreenBiologics (2014): Renewa-ToneTM (Renewable Acetone). *http://www.chemwinfo.com/private_folder/Uploadfile2014December/Green_Ace_Datasheet.pdf* (last accessed: 11/16/2023).

Harms, H. (2012): Holzraffinerie - Chemische Verarbeitung von Holz. *Zuschnitt*, No.48, p. 9.

IFEU (2024): Continuously updated internal IFEU database. IFEU - Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany.

IPCC (2021): Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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

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

de Jong, E., Dam, M. A., Sipos, L., Gruter, G.-J. M. (2012): Furandicarboxylic Acid (FDCA), A Versatile Building Block for a Very Interesting Class of Polyesters. In: *Biobased Monomers, Polymers, and Materials*, ACS Symposium Series American Chemical Society. pp. 1–13.

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

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

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

Ouyang, W., Balu, A. M., ALOthman, Z. A., Wang, X., Wang, W., Luque, R. (2023): Valorisation of humins to high value-added products: Integrating biorefinery process towards a more sustainable future. *Current Opinion in Green and Sustainable Chemistry*, Vol. 39, p. 100717.

Puente, Á. (2018): Life cycle assessment CNSL-based derivatives. nova-Institut GmbH.

Ravishankara, A. R., Daniel, J. S., Portmann, R. W. (2009): Nitrous oxide (N2O): the dominant ozone-depleting substance emitted in the 21st century. *Science (New York)*, Vol. 326, No.5949, pp. 123–125.

Reinhardt, G., Rettenmaier, N., Vogt, R. (2019): Establishment of the indicator for the accounting of the resource "phosphate" in environmental assessments. ifeu papers ifeu - Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany. *www.ifeu.de/en/ifeu-papers*.

Rwahwire, S., Tomkova, B., Periyasamy, A. P., Kale, B. M. (2019): Green thermoset reinforced biocomposites. In: *Green Composites for Automotive Applications*, Elsevier. pp. 61–80.

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

TechnoServe (2020): Cashew shells: from waste to energy & profit. *https://www.technoserve.org/wp-content/uploads/2020/05/TechnoServe-Cashew-shells-for-energy.pdf* (last accessed: 11/15/2023).

VDI (Association of German Engineers) (2012): VDI Standard 4600: Cumulative energy demand - Terms, definitions, methods of calculation. VDI (Association of German Engineers) e.V. / Beuth Verlag GmbH, Düsseldorf / Berlin, Germany. *https://www.vdi.de/richtlinien/details/vdi-4600-kumulierter-energieaufwand-kea-begriffe-berechnungsmethoden*.

WMO (World Meteorological Organization) (2010): Scientific Assessment of Ozone Depletion: 2010. Global Ozone Research and Monitoring Project - Report No. 52. World Meteorological Organization, Geneva, Switzerland. *https://csl.noaa.gov/assessments/ozone/2010/*.

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