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LCA FOR AGRICULTURE PRACTICES AND BIOBASED INDUSTRIAL PRODUCTS

Applying an iterative prospective LCA approach to emerging wood-based technologies: three German case studies

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Abstract

Purpose The innovative utilization of hardwood as a future material resource can contribute to a wood-based bioeconomy. Many hardwood-based products are still at the developmental stage, so it is crucial to assess and improve their environmental performance now. Given the lack of knowledge about future conditions, and accounting for potential changes in emerging technologies at an industrial scale, mean that many parameters must be considered.

Methods A stepwise approach for prospective LCA has been refined, resulting in two LCA iterations. In the first iteration, a preliminary prospective LCA was conducted to understand the emerging technology, using an uncertainty analysis to identify the most influential parameters. The results were incorporated in the second LCA iteration, the final prospective LCA, to develop future scenarios based on the identified parameters. The approach is applied to three case studies that cover the range of technological readiness levels (TRL) from laboratory to pilot and industrial scale. The first case study is a lignin-based phenol–formaldehyde (LPF) adhesive (TRL 4). The second case study is a hardwood glued-laminated (glulam) load-bearing beam (TRL 7). The third case study is a cellulose-based viscose fiber for clothing (TRL 9).

Results and discussion Numerous parameters were narrowed down to a few parameters important for the scenarios; from 25 to 4 in the LPF adhesive case study, from 5 to 2 in the glulam case study, and from 24 parameters to 3 in the viscose fiber case study. The LCIA scenario results for climate change showed differences based on the effects of the important scenario-related parameters, such as the total energy demand or the renewable energy share in foreground and background systems. The LCIA scenario results for land use depend on the amount of wood input and the size of the allocation factor, which was also shown in the local sensitivity analyses. Their variation significantly affected the land use, while having a negligible effect on the other impact categories.

Conclusions and recommendations The prospective LCIA results for climate change depend mostly on the energy demand for the manufacture of emerging hardwood-based products. The effects of a high energy demand cannot be compensated for by inputting a higher share of renewable energy production, neither for on-site production nor in the electricity mix. To reduce the climate change impacts, it is crucial to reduce the overall energy demand of the product system. The results for land use are not robust against variations of the allocation factors. Local sensitivity analyses of different allocation methods are recommended. Overall, the inclusion of an uncertainty analysis in the first iteration of the prospective LCA can reduce complexity for the scenario development, especially when the emerging technology to be evaluated presents with a high number of uncertain parameters.

Keywords Prospective life cycle assessment · Future scenarios · Uncertainty analysis · Emerging hardwood-based products · Ex ante LCA · Wood-based bioeconomy · Glulam · Viscose · Adhesive

1 Introduction

The climate crisis has affected German forests through higher temperatures and less precipitation, lowering tree resistance. This is especially noticeable in softwood monocultures like spruce, which are vulnerable to insect and storm damage. In order to stabilize the forests, a 40-year

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restructuring program (BMEL 2021) aimed to increase the proportion of hardwood species available for utilization. Currently, most of the hardwood in Germany is used for energy production. The European and national bioeconomy strategies support the utilization of renewable materials to substitute fossil-based ones (BMBF and BMEL 2020; European Commission, Directorate-General Research and Innovation 2018). In comparison to softwood, hardwood is generally supplied in smaller-sized pieces, lower quality, and higher density. Its processing requires different tools and its products are, at present, only used for low-value applications. As a result, hardwood-based products are currently being developed and opportunities for their market diffusion are being evaluated.

Life cycle assessments during the development phase of emerging technologies can support improvements in the design and manufacturing of products toward lower environmental impacts. An LCA framework regarding the potential environmental impact of emerging technologies can be referred to as prospective (Arvidsson et al. 2018; Thonemann et al. 2020), ex ante (Buyle et al. 2019; Cucurachi et al. 2018; van der Giesen et al. 2020), anticipatory (Wender et al. 2014), or future-oriented (Olsen et al. 2018). Such a framework needs to take two aspects into account: (a) the product system under study is still being developed and should be assessed on an industrial scale and (b) the surrounding conditions of a product system under study change over time, which can influence the physical performance and thus its environmental impact (referred to as "future conditions"). Langkau et al. (2023) aimed at developing a stepwise approach to prospective LCA in order to handle these challenges.

Several attributional LCA studies have been conducted for emerging hardwood application in product systems, e.g., cellulose or lignin to ethylene and other polymers (e.g., Falano et al. 2014; Patel et al. 2018; van Uytvanck et al. 2017). However, the product systems were assessed under current conditions, even though their implementation into the market, and hence their environmental impacts, will occur in the future under potentially different circumstances. Only a few environmental assessment studies for wood-based product systems have applied future-oriented perspectives to an LCA (Aryapratama and Janssen 2017; Hesser 2015; Hesser et al. 2017; Mair-Bauernfeind et al. 2020). However, these studies did not examine potential differences between product systems entering markets today or in the future.

The goal of this study was to apply a prospective LCA to three emerging technology case studies about hardwood-based products in Germany in order to identify scenarios and requirements for modeling emerging hardwood-based product systems. The following research questions were posed:

1. Which aspects have to be considered in order to define the scope and the system of different emerging hardwood-based products in a prospective LCA?
2. Which parameters are relevant in the inventory modeling for a prospective LCA of hardwood-based products?
3. What are the future environmental impacts of the case studies and how do uncertainties affect the life cycle impact assessment (LCIA) results?
4. Which recommendations can be derived for conducting a prospective LCA of emerging hardwood-based products?

2 Prospective LCA approach

Several published studies address the differences and challenges inherent in a prospective LCA, resulting in various recommendations and approaches (e.g., Arvidsson et al. 2018; Buyle et al. 2019; Thonemann et al. 2020; Tsoy et al. 2020). The prospective approach described in this paper was developed using techniques outlined in two recent studies: the stepwise approach for scenario-based inventory modeling for prospective LCA, by Langkau et al. (2023), and the development of a guideline for bio-based emerging technologies, by Cucurachi et al. (2022). Conducting an LCA is an iterative process. Iterations can be done within one LCA phase or at a certain step in the phase. The approach developed here (Fig. 1) suggests two iterations of all LCA phases, including different additional steps. This results in two prospective LCAs: (i) a preliminary prospective LCA, with the goal of understanding the potential dynamics of modeling the emerging technology, and (ii) the final prospective LCA that includes future scenarios. The preliminary prospective LCA serves to explore the emerging technology (Fig. 1, Step 1.1), including preliminary flow charts and the effects of potential future conditions (Steps 1.2–1.3). The LCA modeling uses current data to identify important parameters (Steps 1.4–1.6). The final, prospective LCA incorporates these parameters in the results (Steps 2.1–2.5) and interpretation (Step 2.6). The following sub-sections outline the individual steps in the approach, explaining those that are novel in greater detail.

2.1 Preliminary prospective LCA

2.1.1 Goal definition

The main goal of the preliminary prospective LCA was to define the emerging technology systematically. In particular, it was important to constrain the various potential factors that may influence the future product system. Identifying whether the variation in an LCI parameter affects the LCIA

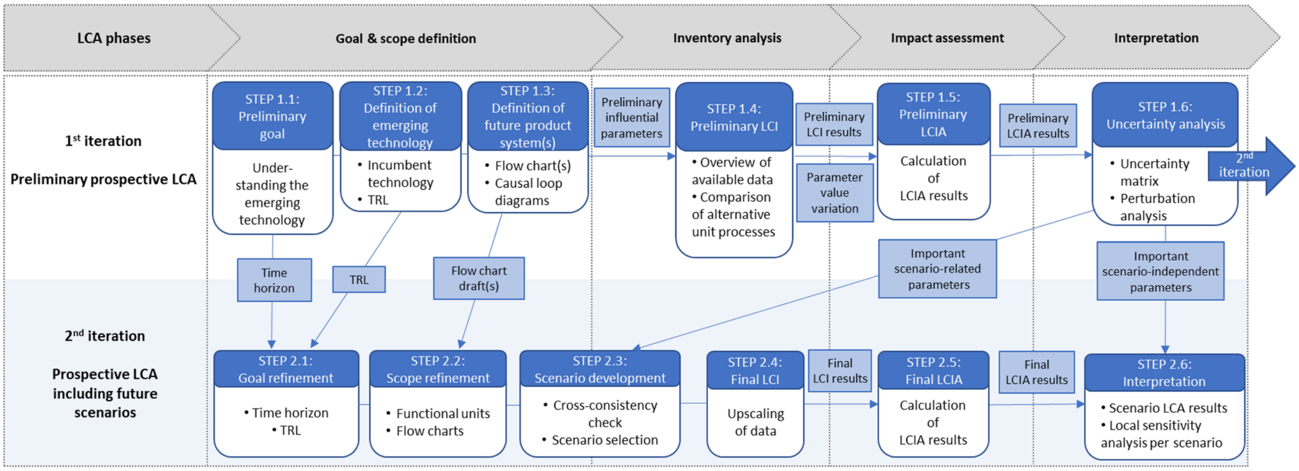


Fig. 1 Illustration of the prospective LCA approach. Fine blue arrows represent the flow of information between the LCA iterations and steps. A linear flow of information following the steps is given. Influential parameters: qualitatively identified parameters, including parameters external to LCA, that might have varying values in the future. Scenario-related parameters: uncertain parameters because of an unknown future that describe future scenarios; scenario-independent parameters: uncertain parameters because of other reasons than the future development that can affect all future scenarios

results or has a negligible impact allowed the identification of important parameters. Thus, the first LCA iteration enabled the selection of parameters that are relevant to upscaling and scenario development in the second, final LCA.

2.1.2 Definition of emerging technology

In the goal and scope phase, the technological development status of the emerging technology should be given as a technological readiness level (TRL) to facilitate comparison and understand the status of data collection (Arvidsson et al. 2018; Buyle et al. 2019; Thonemann et al. 2020; Tsoy et al. 2020). van der Giesen et al. (2020) also recommend identifying the incumbent technology that could be replaced by emerging technology with the same function in the future. The prospective LCA should be conducted using the same TRL as the incumbent technology. If the application of the technology is unclear and allows for various functions, it is recommended that the study should consider more than one functional unit (Buyle et al. 2019; Thonemann et al. 2020).

A preliminary TRL was identified for each case study using the TRL scale by the European Association of Research and Technology Organisations (EARTO 2014), including information from expert interviews, and information from published studies about the emerging technology. The same sources were used to identify one or several functional units of the emerging technology as well as the respective incumbent technology.

2.1.3 Definition of future product system

Collaboration with different experts involved in the development of the technology enables a good understanding of it (Tsoy et al. 2020; van der Giesen et al. 2020). A draft of an LCA flow chart served as a basis for discussion and input from product system experts, which was revised and improved with each interview. In some case studies, this resulted in several alternative flow charts, all covering the same scope. Langkau et al. (2023) developed a method that connects flow charts with a causal loop diagram (CLD) to identify influential parameters for inventory modeling. The CLD is a visualization of the effects of the parameters in the context of the LCA (external parameters, e.g., national bioeconomy strategies) and parameters within the LCA (internal parameters, e.g., the share of renewables in an electricity mix). Langkau et al. (2023) proposed the use of a systematic checklist to support the identification of external parameters. In this paper, the flow charts and CLD were already used in the goal and scope phase to understand the emerging technology system when engaging with the experts. The inclusion of this knowledge in the goal and scope phase was necessary to be able to define the TRL, the functional unit, and the scope of the product system. The step was also repeated in the phase of inventory analysis to include more data estimations by experts along the life cycle of the emerging technology. An example of a thorough visualization of connecting a flow chart with a CLD can be found in Cucurachi et al. (2022).

2.1.4 Preliminary LCI

In the inventory analysis phase, the status and quality of current information from both the literature and manufacturers are collated. An overview of available preliminary LCI models was created. When more than one unit process was available for a production process, the differences were analyzed. This resulted in potential variations of parameter values for the LCI flows.

2.1.5 Preliminary LCIA

When the data collection phase was completed, preliminary LCIA results with the current data were calculated using the Activity Browser (Steubing et al. 2020). The impact assessment was conducted with the widely used LCIA method ReCiPe 2008 (Goedkoop et al. 2013). The results served as the basis for the uncertainty analysis used to identify the important parameters, which were used to develop but also to limit the number of scenarios.

2.1.6 Uncertainty analysis

According to the literature, the main difference between prospective LCA and standard LCAs can be seen in the level of uncertainty (Arvidsson et al. 2018; van der Giesen et al. 2020). Therefore, an uncertainty analysis is essential to enable correct interpretation of the results. However, historic production data for the inventory analysis is often missing, so several production paths need to be generated to represent the manufacturing phase in a prospective LCA (Thonemann et al. 2020). The results of the preliminary prospective LCA were based on the collected data without upscaling or modeling of different production paths for the product system. The preliminary results are a preparatory step for the identification of the parameters important to the scenario development. The LCAs consist of various parameters that determine the input and the output amounts.

The parameters were ranked according to their effect on the LCIA results and their uncertainty. Rosenbaum et al. (2018) illustrated the ranking as a plot, combining the level of uncertainty and the level of potential perturbation of results (Fig. 2). In this study, important parameters are defined as those parameters with the highest level in both criteria, since they have the highest potential to change the LCIA results. The possibly important parameters either have a high uncertainty but a low influence on the LCIA results, or have a potentially high influence on the results but a low uncertainty. Parameters are termed negligible when they are neither uncertain nor change the LCIA results.

At first, parameters subject to uncertainty were identified by systematically identifying uncertainties using the uncertainty matrix by Walker et al. (2003). The matrix consists

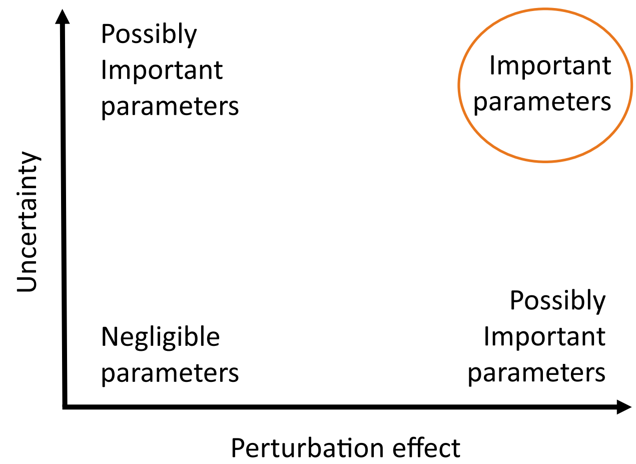


Fig. 2 Ranking of parameters by combining their uncertainty and their effect on the LCIA results based on Rosenbaum et al. (2018, p. 301). Orange circle around important parameters indicates which parameters are analyzed further

of different characterizing dimensions, such as *the location of uncertainty* or the *degree of uncertainty*. The dimensions were then used to filter those uncertainties that relate to one parameter, since only the individual effect of one parameter can be analyzed in the perturbation analysis. Additionally, the analysis of the uncertainty matrix showed that only some of the parameters are uncertain because the future is unknown. Other parameters are uncertain for other reasons, such as the choice of allocation method, or mismatches in the mass balance. This uncertainty persists whether the LCA is prospective or retrospective and thus can be said to affect the LCA independently of future scenarios. Based on this analysis, we differentiated the uncertain parameters into *scenario-related* and *scenario-independent* parameters, and used only the first to develop the future scenarios (Sect. 2.2.3).

The second part of the uncertainty analysis was a perturbation analysis to separate those parameters that barely or do not affect the LCIA results from the rest of the uncertain parameters. The effect of an altered parameter value is set according to the change of the LCIA results it causes, and normalized by both the initial value of the parameter and the initial LCIA result, using the following formula based on Rosenbaum et al. (2018):

$$S_{x_i} = \frac{\Delta y / y_0}{\Delta x / x_0}$$

S = normalized sensitivity coefficient

x_i = changed parameter value

Δy = difference between LCIA result before (initial) and after

y_0 = initial LCIA result
Δx= difference between parameter value before (initial) and after
x_0 = initial parameter value

The change in the initial parameter values can be absolute or relative, resulting in different effects. The kind of change depends on the model and the parameters themselves (Borgonovo 2017). In this study, the parameter values were changed according to the identified uncertainty. The sensitivity coefficient was considered high (and the parameter important) if the sensitivity value was greater than 0.3, and very high if it was greater than 0.5 (Owisianak et al. 2018).

2.2 Prospective LCA including future scenarios

2.2.1 Goal refinement

The original goal of the prospective LCA was revised at this stage based on insights from the preliminary prospective LCA. The feasibility of conducting the prospective LCA was considered in the context of the results from the preliminary LCA, such as confirming whether data could be upscaled or was available for the specified time horizon. Additionally, the prospective LCA settings identified in the goal and the definition of the emerging technology (e.g., TRL or incumbent technology) were finalized using the knowledge gained about the emerging technology in the first LCA iteration.

2.2.2 Scope refinement

In the scope definition of the emerging technologies, the flow charts and functional units discussed with experts were checked and, where possible, more information added. The flow charts were refined, balancing the need for detail and data availability based on the information gained from the first LCA iteration.

2.2.3 Scenario development

One highly recommended method for inventory modeling in prospective LCAs is to use scenarios that reflect different possible futures (Arvidsson et al. 2018; Buyle et al. 2019; Thonemann et al. 2020; Tsoy et al. 2020; van der Giesen et al. 2020; Langkau et al. 2023). Scenarios are defined as “a set of aspects describing a specific situation at a specified time” (Bisinella et al. 2021). Weidema et al. (2004) described different kinds of scenario types in the context of LCA application. Aspects describing a scenario consist mainly of parameters that may vary depending on how the future develops.

The influential parameters were identified in the CLDs and in the uncertainty matrix. The identified parameters were analyzed, resulting in the identification of the important scenario-related parameters. The development of the scenarios was based on a cross-consistency assessment and scenario selection method developed by Langkau et al. (2023). In the cross-consistency assessment, a plausibility check evaluates whether parameters can be combined within the same scenario. In this study, the combination of parameters was rated in numbers. Positive numbers (1 to 3) show that parameters can be combined. The higher the number, the better they fit together. The negative number − 1 shows that parameters cannot appear together within one scenario. A zero indicates the parameters are independent, meaning that there is no connection between them. The final scenarios for the prospective LCIA calculation were selected based on the following three criteria: (i) high diversity, (ii) high consistency of parameters (Spielmann et al. 2005; Langkau et al. 2022), and (iii) smallest number of possible scenarios in total. Descriptions were developed to frame each scenario in a plausible context.

2.2.4 Final LCI

Expert interviews or panels can serve as a method of generating foreground data, or to upscale data to an established product system for the life cycle inventory (LCI) (Arvidsson et al. 2018; van der Giesen et al. 2020). Upscaling data is often necessary to account for material and energy flows that differ according to production size. Additionally, changes in future conditions need to be considered as they influence the environmental impact of the product system under study. Foreground and background systems are affected by, for example, a different electricity mix composition. The choice of upscaling methods depends on the TRL and available resources of the LCA practitioner. A decision support diagram can be found in Tsoy et al. (2020). The LCI data used in the present study had already been upscaled by the respective authors, who mostly used simulation software (e.g., Culbertson et al. 2016; Arias et al. 2020; Nitzsche et al. 2021).

Additionally, a modified version of the ecoinvent database (Wernet et al. 2016) was used for the background data. The generation of electricity was changed by Mendoza Beltran et al. (2020) based on shared socioeconomic pathways (SSPs) representing two scenarios. The modelled scenarios describe the SSP2 baseline (baseline scenario leading to about 6.5 W/m^2 warming and a corresponding temperature increase of about 4 °C by 2100 with no stringent climate policy implemented), and the SSP2-RCP2.6 scenario with stringent climate policy to keep global temperature below 2 °C until 2100 (leading to 2.6 W/m^2 warming). The modified background database was then updated to the ecoinvent database version 3.7.1 (cutoff system model). Using the superstructure approach (Steubing and Koning 2021), it was converted to a single background database and a scenario difference file. This procedure facilitated the modeling of foreground data against different background scenarios with time steps in five-yearly increments from 2020 to 2060.

2.2.5 Final LCIA

The scenario LCIA results were calculated using the Activity Browser and the LCIA method ReCiPe 2008 as used in the preliminary prospective LCA (Sect. 2.1.5). The selection of environmental categories is reported in Sect. 3.5.

2.2.6 Interpretation

The LCIA results of the developed scenarios were compared and the effects generated by the scenario-related parameters analyzed. However, the scenario-independent parameters also affected the LCIA results of each scenario, for example, the choice of allocation method, or site-specific data differences for process water utilization. The effects of scenario-independent parameters were analyzed using a local sensitivity analysis (Rosenbaum et al. 2018) for each LCIA scenario result. The parameter values were set to minimum and maximum to test if and how LCIA scenario results were affected by alterations within the value range. Based on the magnitude of the LCIA result variation, the robustness of the final LCIA result could be tested.

3 Putting the iterative prospective LCA approach into practice

3.1 Description of the selected case studies

Experts identified three emerging products from different promising fields of hardwood utilization within workshops organized for the research project LauBiOek (FNR 2022) in 2020 and 2021. The goal of the research project is the development of a decision matrix for the future use of hardwoods. The selected case studies are (1) lignin-based phenol–formaldehyde (LPF) adhesive as an example of a bulk chemical derived from wood, (2) glued-laminated (glulam) load-bearing beam from solid wood, and (3) viscose fibers for clothing textiles derived from wood-based pulp. These three products not only represent each field of utilization, but are also representative of different stages of product development (Fig. 3). While solid hardwood products and

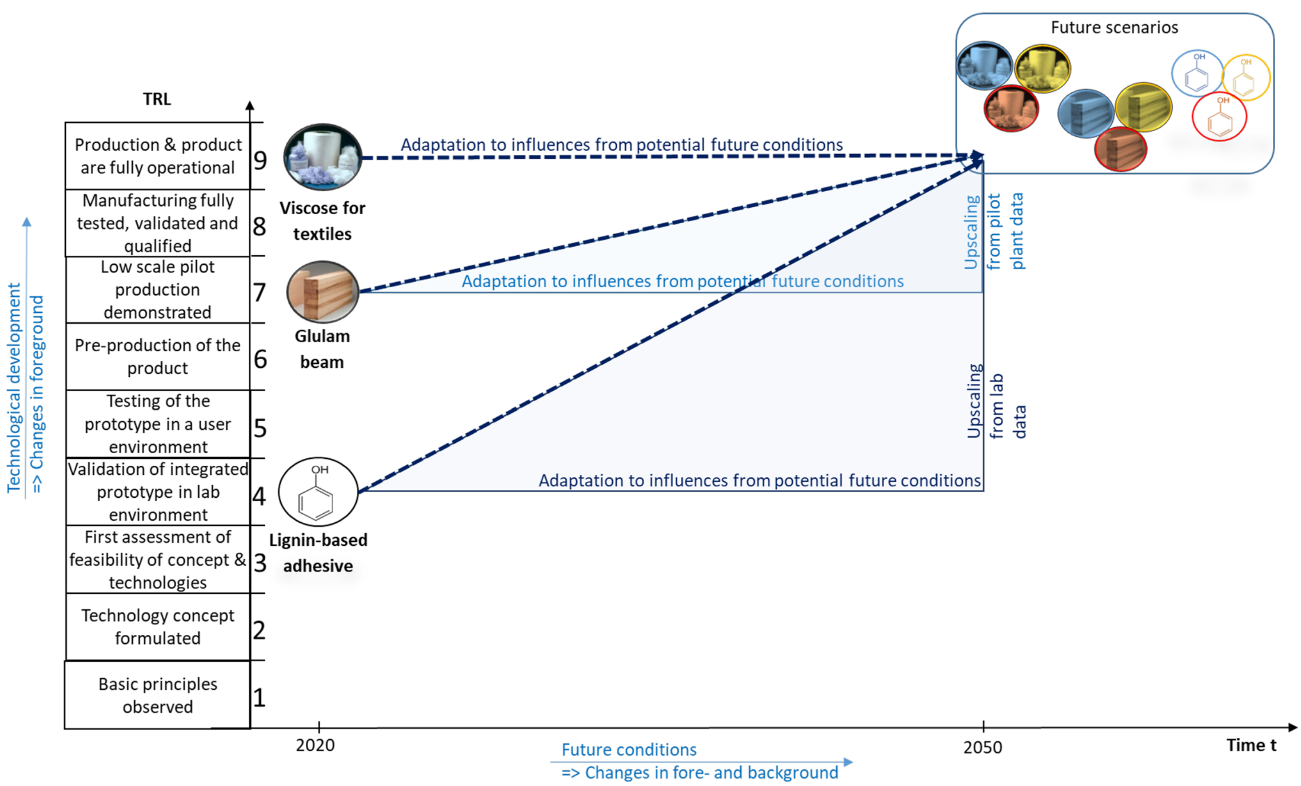


Fig. 3 Illustration of prospective LCA application to the three case studies. The differently colored pictures represent different future scenarios of the upscaled product systems under study. TRL scale from EARTO (2014); figure based on Thonemann et al. (2020); photos © Ralf Rosin, Wood Research Munich (HFM)

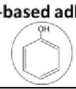
textiles are already at the production stage, bulk chemicals (here lignin-based phenol) are still only manufactured on a laboratory scale (Table 1).

The first case study considers phenol–formaldehyde (PF) resins or adhesives. They are used in a variety of products, from wood resin systems (e.g., plywood or oriented strand boards) to automotive parts. The components, phenol and formaldehyde, are mostly fossil-based, the production of which can release toxic emissions and is therefore regulated. For this reason, less problematic chemicals are being looked for, especially from bio-based resources, such as lignin (van Nieuwenhove et al. 2020). The wood industry has recently started using commercial LPF adhesives, in which most of the phenol (up to 80%) is substituted with softwood-based lignin (Karthäuser et al. 2021). Lignin is a highly complex macromolecule, with variable types and numbers of reactive functional groups. Its composition differs depending on tree species, forest management, and even the geographic location of the tree (Jardim et al. 2020). The functional groups of hardwood lignin differ from those of softwood and the use of hardwood-based lignin in PF adhesives is currently being discussed in the literature (Karthäuser et al. 2021; van Nieuwenhove et al. 2020). However, there is a pilot plant in Leuna, Germany, that uses beech as a resource and several studies on the production of LPF adhesives have been published that rely on data from that pilot plant (Lettner et al. 2018; Nitzsche et al. 2016, 2021; Rößiger et al. 2017).

The second case study examines glulam timber from hardwood, which is currently produced by a few manufacturers in Europe, but not regularly in Germany. Hardwood is more complex to process and is more susceptible to moisture damage. Therefore, the processing of stem wood and standards for the approval of building products still focus on the softwood tree species spruce and pine (Merz et al. 2021). The use of glulam from hardwood in construction is only permitted for beech, oak, and chestnut in limited sizes (Schäpel 2012, 2019). An example of the use of laminated beech wood in construction is the annex building of the Bavarian State Institute of Forestry on the Research Campus Freising-Weihenstephan near Munich (see Weber-Blaschke and Muys 2020).

The third case study looks at the use of viscose fibers derived from hardwood-based cellulose in textiles. The production chain is well established and already uses hardwoods, such as beech and eucalyptus, as a feedstock (Shen et al. 2010). Viscose is the second biggest natural fiber on

Table 1 Overview of the units used for the case studies

	Case study 1 **Lignin-based adhesive** 	Case study 2 **Glulam beam** 	Case study 3 **Viscose for textiles** 
Current TRL	4	7	9
Assortments of wood	Industrial wood	High quality stem wood	Industrial as well as low quality and small dimensional stem wood
Material composition	Purified lignin	Glue-laminated solid wood	Cellulose fibers
Utilization	Chemical sector – component in adhesive	Building sector – beam for load-bearing	Textile sector – fabric for clothing
Status in Germany	Not produced: Neither in Germany nor based on hardwood	Case studies with first applications e.g., building of Bavarian State Institute of Forestry, no regular production	Production within Germany
Functional unit(s)	1 kg of LPF adhesive with equivalent properties and function to phenol-formaldehyde adhesive (100 % solids)	• 1 m^3 of glulam (u = 12 %) • 5 m glulam beam of low strength beech assortments holding constant roof pressure of 1 N/mm for 50 years • 40 m glulam beam of high strength beech assortments holding constant roof pressure of 1 N/mm for 50 years	1 kg of viscose fiber (u = 11 %)

u moisture content

the world market, after cotton (Textile Exchange 2020). Therefore, the product system of producing viscose fibers from hardwood is already at a mature production level today. According to expert interview partners, the process has reached its technical optimum, but is subject to constant adjustment in order to meet the changing requirements for emissions reduction.

3.2 Goal and scope

The goal of the case studies' LCAs is to evaluate the potential future environmental impacts of the implementation of emerging product systems at industrial scales. A process-based attributional LCA (Schrijvers et al. 2020) was chosen as the modeling approach because different production paths of the product systems were compared with one another. A time frame of 30 years, up to 2050, was chosen, because the product implementation in the markets will be driven by the implementation of a bioeconomy, supported by a lack of softwood availability and a growing harvest potential of hardwood in Germany in 2050 (Bauhus et al. 2021). The scope of the studies ranges from cradle to gate with outputs of end (adhesive, glulam beam) or intermediate (viscose fibers, glulam) products at the factory gate.

3.2.1 System definitions of emerging technology and future production paths

Presently, when wood is separated into its macro-compounds, cellulose is the main output. It is usually extracted using the kraft (sulfate) pulping process, the by-product of which is black liquor, containing all the other macro-compounds, e.g., lignin, of the wood. The black liquor is generally burned as an energy supply for the pulping process (Suhr et al. 2015). If the aim is to produce lignin or other wood-based components, processes for the extraction of such from the black liquor are currently integrated into the kraft pulping process (van Nieuwenhove et al. 2020). Theoretically, 16 to 24% of hardwood is composed of lignin macromolecules, but the extraction process only isolates 5% (Jääskeläinen et al. 2017).

Conventional PF adhesives currently partially substitute phenol with extracted lignin. This production path combines the post-kraft pulping extraction of lignin (Fig. 4, process B) with adhesive production (Fig. 4, process Z). This was selected as a possible combination from all possible production pathways for lignin-based PF adhesives, illustrated in Fig. 4. However, in contrast to the monomer phenol, the extracted lignin is a macromolecule containing bound phenolic monomers. These monomers have to be isolated

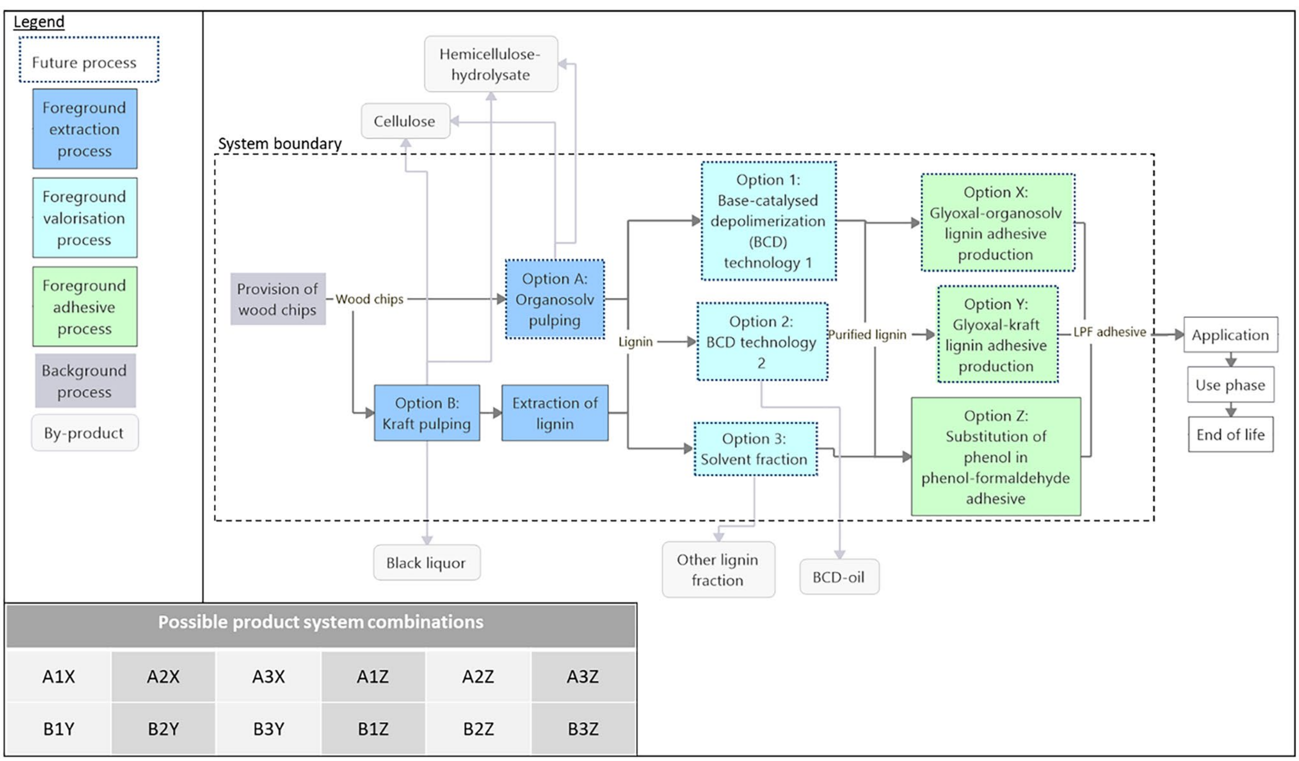


Fig. 4 Flow chart showing all considered production pathways for lignin. The possible future combinations of the production processes are in the lower left corner of the figure. Processes that are highlighted with dark blue dotted lines have currently not reached the final technological maturity level but are assumed to be established by 2050 at the latest

in order to substitute fossil-based phenol with lignin (Liu et al. 2020). In the future, a higher percentage of lignin (ca 16%) will be directly separated in wood pulping through organosolv technology (Nitzsche et al. 2016; Zeilerbauer et al. 2021). In organosolv pulping, there is no black liquor generated that can be burned to cover the energy demand of the process. An external energy source has to be used for electricity and for heat.

Valorization methods for the fragmentation of the extracted lignin into its different monomers have acquired the status of emerging technologies with proven concepts (Liu et al. 2020). However, not all parts of the original lignin can be used to replace the phenol. Using base-catalyzed depolymerization technology 1, two types of lignin fragments are produced: BCD-oligomer and oil (Rößiger et al. 2017). The BCD-oligomers are used in PF adhesives and can substitute up to around 80% of the phenol (Solt et al. 2018). BCD technology 2 was developed to isolate only BCD-oligomers without any other by-product. In general, future production of LPF adhesives (Fig. 4) cannot be established without a valorization step (Liu et al. 2020).

Additionally, in order to substitute fossil-based phenol, attempts have been made to replace the other main adhesive component, formaldehyde, with glyoxal (van Nieuwenhove et al. 2020). This resulted in two new adhesive production formulas for PF adhesives using lignin and glyoxal as the main ingredients (Arias et al. 2020). The composition of the adhesive depends on the quality of lignin, which in turn depends on which pulping technology is used, resulting in the development of two separate formulas.

In Germany, only glulam from softwood is produced today (Rüter and Diedrichs 2012). However, switching to hardwood as a resource for glulam cannot be done without process changes. High-speed steel cutting tools have to be replaced with a different more durable material, such as tungsten carbide. Additionally, pressing the sawn boards takes more force and time, which usually requires more energy in comparison to softwood processing. These two main differences were identified while collecting primary data from a hardwood glulam manufacturer in Europe. In the assessed glulam production (Fig. 5), the heat demand is covered by burning bark and most of the wood residues from the manufacturing process. A portion of the wood residues is used for pellet production or sold to particleboard manufacturers. Other manufacturers buy the sawn timber directly. Variations due to production design and conditions can occur but could not be taken into consideration, since only one production site was available for data collection (Fig. 5).

Hardwood glulam as a construction element is currently being used in the same way as softwood glulam. In production terms, the TRL 7 glulam case study does not have to be scaled up, whereas it does for its application in construction. Hardwood has a higher strength than softwood. Thus, load-bearing of hardwood can have smaller crosscuts and require less material input (Merz et al. 2021). A change in dimensioning of hardwood glulam construction elements in comparison to softwood glulam was assumed for the foreground system in the future. For this to happen, certain changes have to occur in construction regulations, such as fire protection standards and standards for hardwood glulam beams. The probable lack of softwood in the future and the availability of hardwood, together with the incentive to build with wood, could push a change in regulations altogether (Supporting information (SI) S2 Step 1.3).

Viscose production requires cellulose with specific fiber characteristics and a special sulfite (dissolving) pulping technique (Suhr et al. 2015). Other established pulping technologies cannot achieve sufficient fiber quality for textile production. Technically, cellulose for viscose can

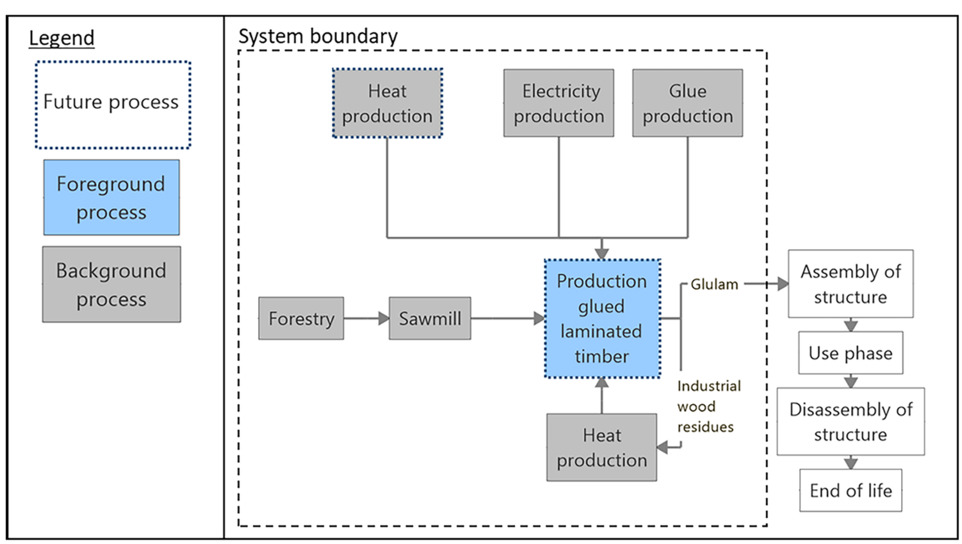


Fig. 5 Flow chart of hardwood glulam based on primary data from one production site in Europe. Processes that are highlighted with dark blue dotted lines are assumed to change until 2050

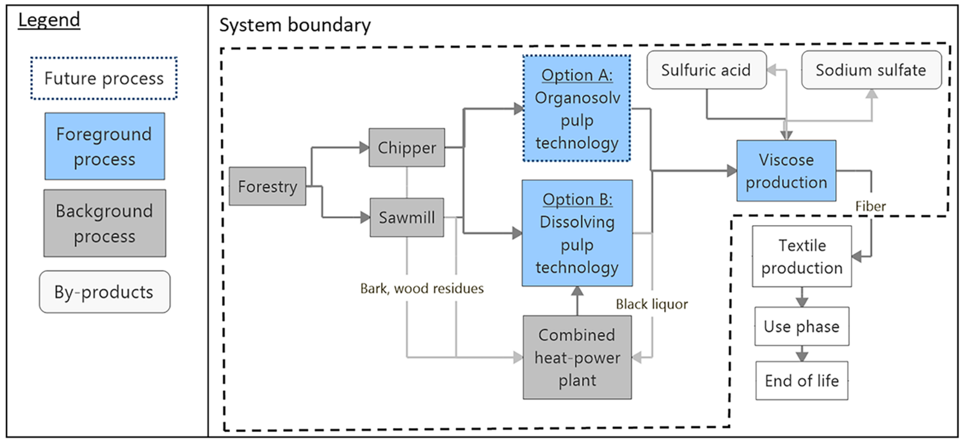


Fig. 6 Flow chart of current and future viscose fiber production. Processes that are highlighted with dark blue dotted lines have currently not reached the final technological maturity level but it is assumed they will be established by 2050 at the latest

be produced using organosolv as an emerging pulping technology (Fig. 6). Since current manufacturers of viscose in Germany buy the pulp on the market, it is assumed that a new provider of pulp could enter the German market in the future. This could be, for example, a biorefinery specialized in the commercialization of wood-based components as intermediate products for high-quality production (Nitzsche et al. 2021). In such a biorefinery, the by-products lignin and hemicellulose are also used for material applications and not for energy production because organosolv pulping produces purer outputs than other pulping technologies. Additionally, the viscose process itself is being constantly improved in order to keep up with stricter emission regulations in the future (SI S3 Step 1.3).

3.2.2 Functional unit

In the case of LPF adhesives, a fossil-based phenol is replaced by a lignin-based one. Functionally, LPF adhesives have the same properties and characteristics as the conventional PF adhesive (Karthäuser et al. 2021; Younesi-Kordkheili and Pizzi 2020). Consequently, the LPF adhesives are assumed to be applied in the same way as the ones today. Some are already being used in wood-based materials such as plywood (Stora Enso Oyj 2020; UPM Biochemicals 2022). The functional unit (FU), 1 kg LPF adhesive, was modelled on a 100% solid basis in order to compare different LPF adhesive formulas with one another (Table 1).

There is no representative load-bearing beam as they are all dimensioned specifically to meet the individual requirements of each construction application. Therefore, an FU of 1 m^3 glulam with a moisture content (u) of 12% was chosen as an intermediate product. This sort of FU is typically used for building elements because the exact function in a building is often not known in advance (Sahoo et al. 2019). This can also be observed in building materials databases, such as the oekobaudat (BMWSB 2022), that serve to compare buildings with the same function but using different materials. In the building context, different material properties lead to differences in the amount of material input. Projects have to be assessed on a case-by-case basis because the comparison of structural elements of different materials depends on the exact static requirements (Himes and Busby 2020). Therefore, two additional functional units were defined for the glulam case study to cover the potential modification of smaller crosscuts if standards change in the future (Table 1). The material reduction depends on the required length and pressure on the glulam load-bearing beam as well as on available hardwood assortments. Two examples representing both extremes were chosen: a short beam (5 m length) of low-strength hardwood lumber for buildings, such as residential houses, and a long beam (40 m length) of high-strength hardwood lumber for industrial buildings. Both examples represent possible future changes in the construction sector (SI S2 Step 2.2a).

Viscose fibers can be utilized to produce clothing and other technical fibers with certain property requirements (Kehlheim Fibres 2022). Experts claim (Hermanutz and Schuster, personal communications, 2021) that each fiber has a specific optimal area of application, and cannot be replaced with a different fiber. For example, clothing for firefighters requires a specific fiber performance. However, the exact function of fibers in everyday clothing is assumed to be negligible. Equivalent clothing made of 100% viscose, polyester, or cotton can be easily found today. Some LCA studies have considered fiber-level comparisons (Muthu 2015; Shen et al. 2010). An FU of 1 kg viscose fiber, with a moisture content of 11%, was chosen as a feasible comparison. No additional new insights between the production of textiles today and future viscose products were identified that might justify a broader LCA scope.

3.2.3 Handling of multi-functionality

Physical allocation was applied for all processes in the production of LPF adhesives with several valuable outputs (multi-output). In organosolv pulping and separating wood into its components, the actual output in mass from all products and the material losses were known. For kraft pulping, the actual output is not given, except for the cellulose output, since the rest is mostly burned to produce heat and electricity in this process step. From this “rest,” 5% lignin can be extracted for material utilization (SI S1 Step 2.2). The energy produced and used for the internal energy demand of the pulping is allocated with respect to the energy output of each product. Mass allocation was chosen over economic allocation, since the final product utilization of the wood-based components is not known, and prices can range significantly. For example, the price of lignin can range from 200 €/t (Moretti et al. 2021) to 2180 €/t (Nitzsche et al. 2021), depending on the lignin quality. These prices are based on economic calculations of the production costs at present. The future prices may differ from this due to shifts in demand for lignin or effects of production scale but the direction and quantity of the shift cannot be estimated. A high-value production for all wood-based components would lead to little price differences between them, which would then again result in allocation close to mass relations.

The solid wood material process is allocated economically, since prices between industrial wood residues and sawn products differ greatly at present (SI S2 Step 2.2b). Wood residues are mostly used internally for energy production and some are sold commercially for pellet manufacture. Prices of the primary and secondary products, sawn wood and glulam, are usually ten to a hundred times higher than prices for wood residues.

During the production of viscose fabric from cellulose fibers, both sulfuric and sodium sulfate are generated as by-products. Both are unrelated to the main material input (cellulose) and thus also to the viscose produced. For this reason, an economic allocation is chosen for this process step. The price relationship of these products is assumed to be constant in the future because viscose production is well established. The handling of the multi-outputs from the wood pulping was handled methodologically, like wood pulping in the LPF case study (SI S3 Step 2.2).

3.3 Inventory analysis

Access to primary data about LPF adhesives was not granted. Instead, published data in the public domain was sourced and inputted for each production process in the LPF adhesives value chain (SI S1 Step 1.4). All available data was already upscaled by the authors using simulation software such as AspenPlus. At the time of data collection, the primary lab and pilot data had not been published (SI S1 Step 2.4b–g). Exceptionally, the kraft pulping process is documented in the EU BAT (best available technique) reference documents, based on data from several European pulp mills (Suhr et al. 2015). These are also known as BREFs (SI S1 Step 2.4a). The current production and process-oriented research about LPF adhesives are focused on phenolic monomers from softwood feedstock. According to Liu et al. (2020) and Lourençon et al. (2020), hardwood-based lignin serves also as a substitute for phenolic monomers in PF adhesives. Their studies did not account for any differences in the processing of hardwood-based lignin. Therefore, the data remained unaltered despite the shift to hardwood feedstock.

A successful collaboration was initiated with a European glulam manufacturer, who provided valuable additional information about the process differences between hard- and softwoods. Currently, German glulam manufacturers only process softwood. Before the primary data from hardwood manufacturing was available, a proxy data set was used to represent an industrial production of hardwood glulam (SI S2 Step 1.4). The proxy data set was an adapted data set of originally generic data from 21 softwood glulam manufacturers in Germany. The comparison of the two LCI data sets highlighted that some of the input flows for the adapted data set had been underestimated by 25% to over 2000% percent (SI S2 Step 2.4). The biggest difference was found for the cutting tools, which are made from a different material (tungsten carbide instead of high-speed steel) and the wear was much higher than estimated. The primary data set was a much better representation of hardwood glulam production than the adapted proxy. The input flows differed due to the utilization of hardwood instead of softwood and not due to variability in manufacturing of the same product. For the utilization of the glulam as a beam in construction applications, the dimensioning of the beam was applied based on expert estimations and statics rules.

No primary data was made available by the viscose fiber manufacturers. However, recent data had been included in a published environmental assessment report (Schreiner 2020). Additionally, historic data collected more than 20 years ago from another company was available in the ecoinvent database (SI S3 Step 1.4). The established dissolving pulp process was also documented in the BAT documentation by the EU (Suhr et al. 2015). In contrast, for the emerging organosolv pulping process, upscaled data has been published by three different research projects (Bello et al. 2018; Nitzsche et al. 2016, 2021). All these data sets were upscaled using simulation software. The biggest difference between them is the input of ethanol as an auxiliary material for the separation of the wood components. Bello et al. (2018) set the amount of ethanol to around 8.13 kg/kg dried pulp (SI S3 Step 2.4b). Nitzsche et al. (2021) reported an input of around 0.022 kg/kg dried pulp. In contrast, Nitzsche et al. (2016) argued that the biorefinery product is ethanol, so they gave no input of ethanol. However, the recovery of a chemical is never 100% efficient. The high input amount reported by Bello et al. (2018) is assumed to be an absolute input of ethanol without considering the recovery of ethanol in the process. Hence, the data set published by Nitzsche et al. (2021) was selected as representative for the organosolv pulping process.

3.4 Scenario development

Environmental standards and technological developments in the field of wood pulping technologies are external drivers for the product systems of LPF adhesives and viscose fibers. Both product systems include mostly recovery processes of chemicals. As such, environmental standards for these product systems are aimed at reducing the emissions from the production sites, and simultaneously act as a driver for technological development of more environmentally friendly procedures. The bioeconomy strategy is an external factor, influencing the foreground system of all product systems. The mobilization of renewable biomass as a resource (BMBF and BMEL 2020) could be interpreted as prioritizing high-value production of biomass, replacing the current practice of burning wood residues by processing them into products. All three drivers are illustrated in the respective CLDs (SI S1–3 Step 1.3) and considered as a basis for developing the scenarios (Table 2).

The background system of the case studies is influenced by future electricity production, which was defined using the superstructure by Steubing and Koning (2021). The superstructure includes two different scenario models of energy electricity production in Germany for 2050. Other background process changes, such as transportation or heat production, can affect the case studies as well. Sacchi et al. (2022) suggested that further work will be able to account for such changes. The background assumptions are quite similar across the three case studies. One assumption is that the energy production is focused on fast growth of renewable energy production technology, resulting in a higher share in the electricity mix, and heat production from biomass, solar, or a heat pump if possible. Another assumption is that wood becomes such a valuable resource in the future that it is sold for material utilization and not used for energy production in the product system.

The selection process resulted in five scenarios for LPF adhesives (Table 2). Many parameters were identified to describe the LPF adhesive scenario (SI S1 Step 2.3a + b). In order to distinguish them clearly, the descriptions of each scenario are more detailed (Table 2). One scenario was selected assuming lignin is used in addition (by-product) to pulp as the main product of the existing pulping processes (*Kraft LPF as by-product 2050*). The lignin is sold to be processed in a new adhesive production facility, producing the new adhesive formula from lignin-based phenolic monomers and glyoxal. In the other four scenarios, a new biorefinery for the production and integrated processing of all wood components is assumed. In two of the four scenarios, the integrated processing of lignin to adhesive follows a new adhesive formula (*Kraft and Organosolv LPF new formula 2050*). The remaining two scenarios assume a further processing of lignin to substitute phenol in the conventional production of a PF adhesive (*Kraft and Organosolv LPF phenol substitution 2050*). The valorization of lignin via BCD technology 1 was combined with the phenol substitution process because the BCD-oligomer can replace a higher share of the phenol in PF adhesives. The pulping processes were selected according to their compatibility with the adhesive production processes (Fig. 4). A comparison to a status-quo scenario 2020 was not made because of the currently low TRL of the product system.

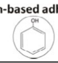
For the hardwood glulam production scenarios (SI S2 Step 2.3b), a few parameters were identified with high sensitivity and future changes for the foreground system. The two selected scenarios for glulam production (Table 2) differ in heat provision technology. In the glulam production itself, heat is only required to maintain a constant temperature to achieve a particular adhesive consistency (*Glulam 2050*). Therefore, fewer industrial wood residues are necessary for heat production, and an additional heat pump can compensate for any drops in room temperature. Instead, the surplus of industrial wood residues could be used for material applications, like plywood, or processed in a biorefinery (*Glulam 2050 + Bioeconomy*). Additionally, a scenario of current production was added to benchmark the future environmental impacts (*Glulam 2020*).

In addition to a scenario of status-quo conditions for viscose production in 2050 (*Diss Viscose 2050*), two more scenarios were selected (Table 2). In one of them, the current production of viscose can be optimized by 2050 from an environmental perspective, reducing emissions and increasing material efficiency where possible (*Diss optViscose 2050*). In the other one, pulp for viscose production is part of a new biorefinery using organosolv pulping to simultaneously create other high-value products, such as lignin (*Organosolv optViscose 2050*). A scenario of the current production was selected as a benchmark established viscose production (*Diss Viscose 2020*). The corresponding consistency check and parameter values for the scenarios can be found in the SI (S3 Step 2.3a + b).

3.5 Life cycle impact assessment

The impact assessment method used, ReCiPe 2008, includes a broad range of impact categories to cover the environmental

Table 2 Descriptions of selected scenarios for foreground and background data for 2050 of all case studies

Case study 1 Lignin-based adhesive 		Case study 2 Glulam beam 		Case study 3 Viscose for textiles 	
Description		**Description**		**Description**	
Foreground	**Background**	**Foreground**	**Background**	**Foreground**	**Background**
Kraft LPF as by-product (BP) 2050 (Fig.3, B3Y)		*Glulam 2050*		*Diss Viscose 2050*	
pulp remains main product (2% lignin output) + new PF formula with lower lignin content → surplus energy to lignin processing → pulp is sold for further processing	constant increase of renewable energy share in electricity mix since 2020 (status-quo conditions)	constant production conditions	status-quo conditions	constant production conditions	status-quo conditions
Kraft LPF of new formula (NF) 2050 (Fig.3, B3X)		*Glulam 2050 +Bioeconomy*		*Diss optViscose 2050*	
new production site with integrated processing lignin as by-product + new PF formula with lower lignin content + less surplus energy from kraft process → on-site energy demand with natural gas	Faster growing share of renewables in electricity mix (+RE)	by-products to material → room heat via heat pump	+RE	optimization of viscose process regarding environmental standards	+RE
Organosolv LPF of new formula (NF) 2050 (Fig.3, A3X)				*Organosolv optViscose 2050*	
new biorefinery for complete utilization of wood + new adhesive formula to substitute PF adhesive → wood-chips are chosen as energy supply	+RE			optimized organosolv pulp to viscose	+RE
Organosolv LPF with phenol substitution (PS) 2050 (Fig.3, A1Z)					
new biorefinery for complete utilization of wood + conventional adhesive production → maximal phenol substitution	status-quo conditions				
Kraft LPF with phenol substitution (PS) 2050 (Fig.3, BIZ)					
new production site with integrated processing lignin production only for adhesive → higher lignin content in conventional adhesive → maximal phenol substitution + no surplus energy from kraft process → on-site energy demand with natural gas	+RE				

For more details see the SI S1-3 Step 2.3b

RE renewable energy, *Diss* dissolving pulp, *opt* optimized

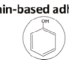
impacts possible in an LCA. The updated version for 2016 could not be used since the ecoinvent database v3.7.1 (Wernet et al. 2016) used for data modeling has not yet been updated with this method. The environmental impact categories "climate change" (represented by Global Warming (GW)) and "land use" (represented by Agricultural Land Occupation (ALO)) are discussed for each case study. Global warming is relevant since the main aim of utilizing bio-based materials is to reduce greenhouse gas emissions. Agricultural land occupation is selected as an impact category, since this category includes the area needed to grow wood in forests, which is the main material input of the three case studies. The results for the other impact categories can be found in the SI (S1 – 3 Step 2.6b). Additionally, the biogenic carbon is reported separately to the environmental impacts as "technical information" (SI S1 – 3 Step 2.6c). For wood products, the calculation of biogenic carbon follows the DIN EN 16449 (2014) standard. The biogenic carbon content is calculated based on the carbon content in the final product. It considers wood-specific characteristics such as moisture content, wood species, and non-wood materials (e.g., adhesive).

3.6 Interpretation of scenario results including sensitivities

3.6.1 Uncertainty analysis results

Table 3 lists the important scenario-related and scenario-independent parameters. The results for all parameters subject to uncertainty can be found in the SI (S1 – 3 Step 1.6). The scenario-related parameters were used to compare the scenarios with each other, whereas the scenario-independent parameters were analyzed with respect to their effect on the scenarios themselves. The variation of the phenol substitution rate is a scenario-related parameter because it depends on the technology that will be used for lignin valorization in the future. The input quantities of pulp and water into the viscose process are both scenario-related parameters. Here the reduction in quantities depends on the pressure exerted by environmental standards, resulting in a trend of emissions and waste reduction. In contrast, the wood chips input in organosolv pulp, the sawn wood input in glulam production, and the water input in kraft pulp are scenario-independent

Table 3 Overview of important parameters subject to uncertainties for all three case studies. The important parameters are characterized by a high sensitivity value of ≥ 0.3 in at least one environmental impact category. A higher value in several impact categories is indicated with a median ≥ 0.3. All parameter values are given per respective FU (cf. SI S1-3 Step 2.4)

	Case study 1 Lignin-based adhesive 			Case study 2 Glulam beam  © Ralf Rosin				Case study 3 Viscose for textiles  © Ralf Rosin			
Important scenario-related parameters											
LCI flow in system process	x_0	x_i	S	**LCI flow in system process**	x_0	x_i	S	**LCI flow in system process**	x_0	x_i	S
Purified lignin [%] from foreground in LPF adhesive production (phenol substitution rate)	50	70	M_S = 0.32	-	-	-	-	Pulp [kg] from foreground process in viscose production	1.03	1.025	S(ALO) = 0.71
								Water input [m³] in viscose production	0.06	0.042	M_S = 0.95
Important scenario-independent parameters											
LCI flow in system process	x_0	x_i	S	**LCI flow in system process**	x_0	x_i	S	**LCI flow in system process**	x_0	x_i	S
Allocation factor for lignin in organosolv & kraft pulping	0.466	0.393	S(ALO, WD, ME, TET)>0.3	Allocation factor in glulam production	0.99	0.96	M_S = 0.99	Allocation factor in dissolving pulping	0.5	0.4*	M_S = 0.7*
Market for hardwood chips, wet, measured as dry mass [kg] in organosolv pulping	1.29	2.5	S(ALO)= 0.33	Board, hardwood, raw, kiln drying to u=10% [m³] in glulam production	1.47	1.57	S(ALO) = 0.98	Allocation factor for cellulose in organosolv pulping	0.5	0.9	S(ALO, WD, ME, TETP)>0.3
Water input [m³] in kraft pulping	0.08	0.014	M_S = 0.99								

x_0 initial parameter value, x_i changed parameter value, S normalized sensitivity coefficient, M_S median of normalized sensitivity coefficient, *ALO* agricultural land occupation, *WD* water depletion, *ME* marine eutrophication, *TET* terrestrial ecotoxicity, sensitivity scale: very high > 0.5, high > 0.3, low < 0.3, very low < 0.1

*One of three examples for a possible change of the allocation factor. See the SI (S3 Step 1.6 & Step 2.6a) for all uncertainties affecting the allocation factor of cellulose

parameters because they depend on the manufacturing design. Although they use the same kinds of production technology, they can vary between production sites. Furthermore, the allocation factor is a scenario-independent parameter whose values depend on the choice of allocation method designated by the LCA practitioner.

Originally, the total number of parameters subject to uncertainties was 25 for LPF adhesives, 5 for glulam beam, and 24 for viscose (SI S1 – 3 Step 1.6). Using a cutoff criterion of having a sensitivity coefficient greater than 0.3 to identify important parameters, the number of uncertain parameters could be narrowed down to 4, 2, and 3 parameters, respectively.

3.6.2 LCIA results: lignin-based phenol adhesives

The projected scenarios that show the lowest overall environmental impacts in 2050 are *Organosolv* and the *Kraft LPF with phenol substitution (PS)*. This is because the determining process for the total impacts is the adhesive production process (SI S1 Step 2.6b). The substitution of phenol requires a lot less energy than the production of the new adhesive formula. The demand in energy and other ingredients is even higher when organosolv lignin is used in the new adhesive formula. This is one of the reasons for the higher environmental impacts of the *Organosolv LPF of new formula (NF) + RE* scenario when compared to the *Kraft LPF NF + RE* scenario (Fig. 7).

Other reasons for a higher impact in agricultural land occupation (ALO) of the *Organosolv LPF NF + RE* scenario are the high lignin content of the final adhesive and the high mass allocation factor for organosolv lignin. The *Kraft LPF NF + RE* scenario and *Kraft LPF as by-product (BP)* are similar in their ALO impact. The heat demand of the lignin processing is met by having additional recovered wood in the *Kraft LPF NF + RE* scenario, and the share of RE of the electricity mix is higher. Furthermore, the *Kraft LPF NF + RE* impact is higher than that of the *Kraft LPF PS + RE* scenario because the impacts from pulping are distributed between BCD-oligomers and oil in the valorization process (BCD technology 1; Fig. 4). The same is true for the *Organosolv LPF PS + RE* scenario. Nonetheless, the results for the ALO in the *Organosolv LPF PS + RE* scenario are significantly affected when the allocation method is changed from mass to economic. The scenarios including organosolv pulping show a linear change of impact in ALO when the allocation factor or the wood chips input amount is changed. In contrast, the change of the allocation factor for kraft lignin has smaller effects on the ALO. The effect of a change in the allocation factor is bigger for organosolv

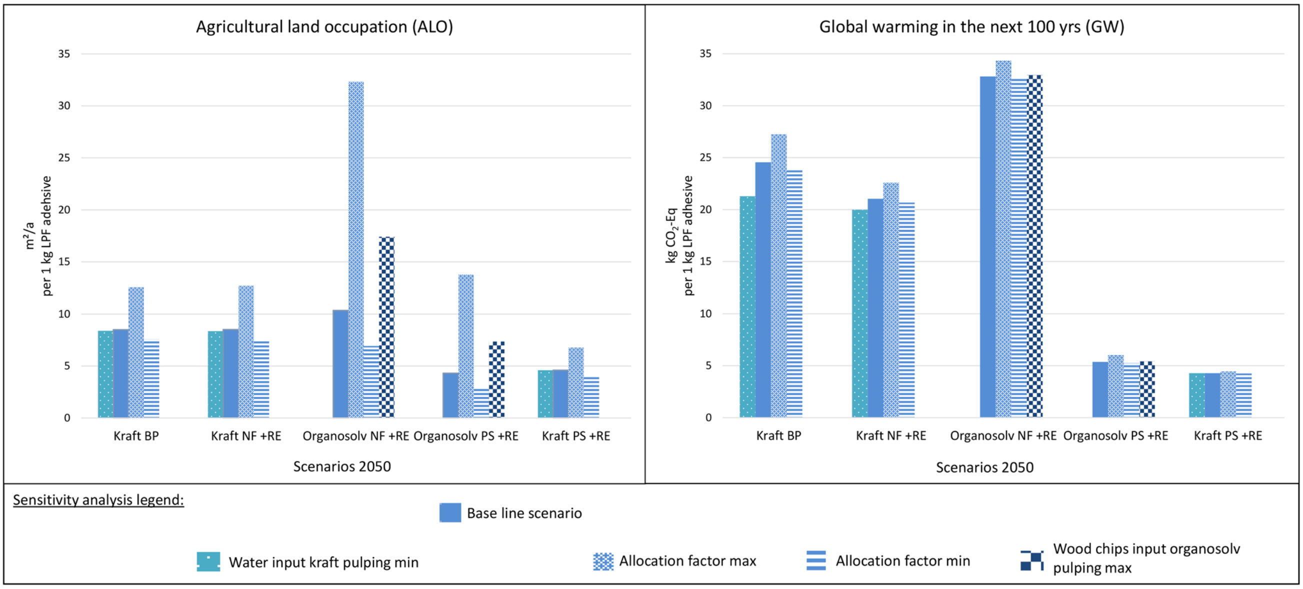


Fig. 7 Prospective LCIA results for 1 kg of LPF adhesive in 2050 represented by exemplary environmental impact categories. + RE indicates a faster grow of RE share in electricity mix in 2050. For results of other impact categories, see the SI (S1 Step 2.6b). For parameter values for sensitivity analysis, see the SI (S1 Step 2.6a). For scenario description, see Table 2

lignin in comparison to kraft lignin because the value change of the allocation factor of organosolv lignin is much bigger (SI S1 Step 2.2).

The impacts on global warming (GW) are higher for the *Kraft LPF BP scenario* in comparison to the *Kraft LPF NF + RE* scenario. In the *Kraft LPF BP* scenario, the energy is provided by recovered wood, whereas in the *Kraft LPF NF + RE*, the energy at the production site is provided by natural gas. Even so, the GW for *Kraft LPF NF + RE* is still lower because the pulping process is integrated into the lignin processing, leading to an overall lower energy demand. Additionally, the share of RE in the electricity mix is higher. The reduction effects from a lower water input in the kraft pulping are smaller in the *Kraft LPF NF + RE* scenario in comparison to the *Kraft LPF BP* scenario. The effect is further weakened by the higher share of RE in the electricity mix. In the *Kraft MP + RE* scenario, the reduction of the water input in kraft pulping has no effect at all because of the allocation in the valorization process, consequently lowering the overall effect of the kraft pulping process. The highest energy demand of the *Organosolv LPF NF + RE* scenario leads to the highest impacts for GW when compared to the other scenarios. Using natural gas to provide heat and electricity to the foreground system of organosolv pulping is the same as in the *Organosolv LPF PS + RE* scenario. The lower energy demand in the adhesive production of the *Organosolv LPF NF + RE* scenario leads to a lower GW impact. The GW results are quite robust against the alterations in the allocation factor of lignin from pulping and wood chips input to the organosolv pulping process because the GW results change only slightly and in the same way for all scenarios.

Lettner et al. (2018) also compared LPF adhesives made by a solvent fraction or BCD with one another. They used the same data sources for kraft pulping and lignin valorization. The GW impact results ranged between 1 and 5 kg CO_2-eq/kg LPF adhesive, depending on the valorization and amount of phenol substituted in the LPF adhesive. Here, the *Organosolv LPF PS + RE* scenario and the *Kraft LPF PS* scenario that include a direct substitution of phenol also have similar results in the upper range of 4 to 5 kg CO_2-eq/kg PF adhesive. In the study by Lettner et al. (2018), they applied a higher mass allocation to kraft lignin of 10.6%, and did not use the surplus energy of the kraft process in further lignin processing. Additionally, they assumed the production site to be in Sweden and increased the RE share for electricity production only for the electricity mix used in the foreground system. As a consequence, the GW impact decreased by 15%. In this study, a higher RE percentage in the electricity mix was also assumed, but the electricity mix was changed throughout the entire database because of the background database's superstructure. For the scenarios *Kraft LPF BP* and *Kraft LPF NF + RE*, the higher share of RE in the electricity mix led to a similar effect for the GW results.

Arias et al. (2020) assessed a new adhesive production based on lignin-based phenol, using glyoxal as a formaldehyde substitute. They identified adhesive production as having the highest contribution to the environmental impacts. This is in line with the results found in this study. However, the environmental impacts calculated by Arias et al. (2020)

with 8 kg CO_2-eq/kg kraft LPF adhesive and 15 kg CO_2-eq/kg organosolv LPF adhesive are lower than the results for the scenarios *Kraft LPF BP, Organosolv LPF NF*, and the *Kraft LPF NF* adhesive production with glyoxal in this study (20–35 kg CO_2-eq /kg LPF adhesive). This may be because Arias et al. (2020) did not consider lignin valorization in their analysis. Moretti et al. (2021) found that the utilization of biomass for energy production in the pulping process led to lower GHG emissions in comparison to fossil fuel. In this paper, it is shown that GHG emissions can also be reduced by including a higher share of RE in the electricity mix and integrating the pulping process into the adhesive production process. This can be seen when the results of scenarios *Kraft LPF BP* and *Kraft LPF NF + RE* are compared.

3.6.3 LCIA results: hardwood glulam beams

In the *Glulam 2020* scenario, the status-quo production of hardwood glulam mainly performs in a similar or worse way in all categories in comparison to the other two scenarios *Glulam 2050* and *Glulam 2050 + Bioeconomy*, with the exception of the impact caused by ionizing radiation (SI S2 Step 2.6b). The ALO impact results are the same for all scenarios (Fig. 8a). In the local sensitivity analysis, the allocation factor is proportionally reduced by the price change described in the SI (S2 Step 1.6). This reduces the ALO impacts assigned to glulam with respect to the status quo by 4%. Hence, even if the retailed wood residues are used for high-value applications in biorefineries (*Glulam 2050 + Bioeconomy*), the effect on the allocation factor remains small (SI S2 Step 2.6a). A further sensitivity analysis using a higher sawn wood input shows a linear increase of the ALO impact by 6%. The GW impacts for all scenarios lie between 400 and 550 kg CO_2-eq per 1 m^3 of glulam. Inputting an energy production with a higher RE share into the *Glulam 2050 + Bioeconomy* scenario reduces the GW impacts by 27% in comparison to current energy production mixes. Changes in the allocation factor and the sawn wood inputs hardly affect the GW impact results, which are consistent across all scenarios, indicating that the GW outcomes are robust.

Figure 8b depicts the impact of two possible applications for a beech glulam load-bearing beam, depending on the

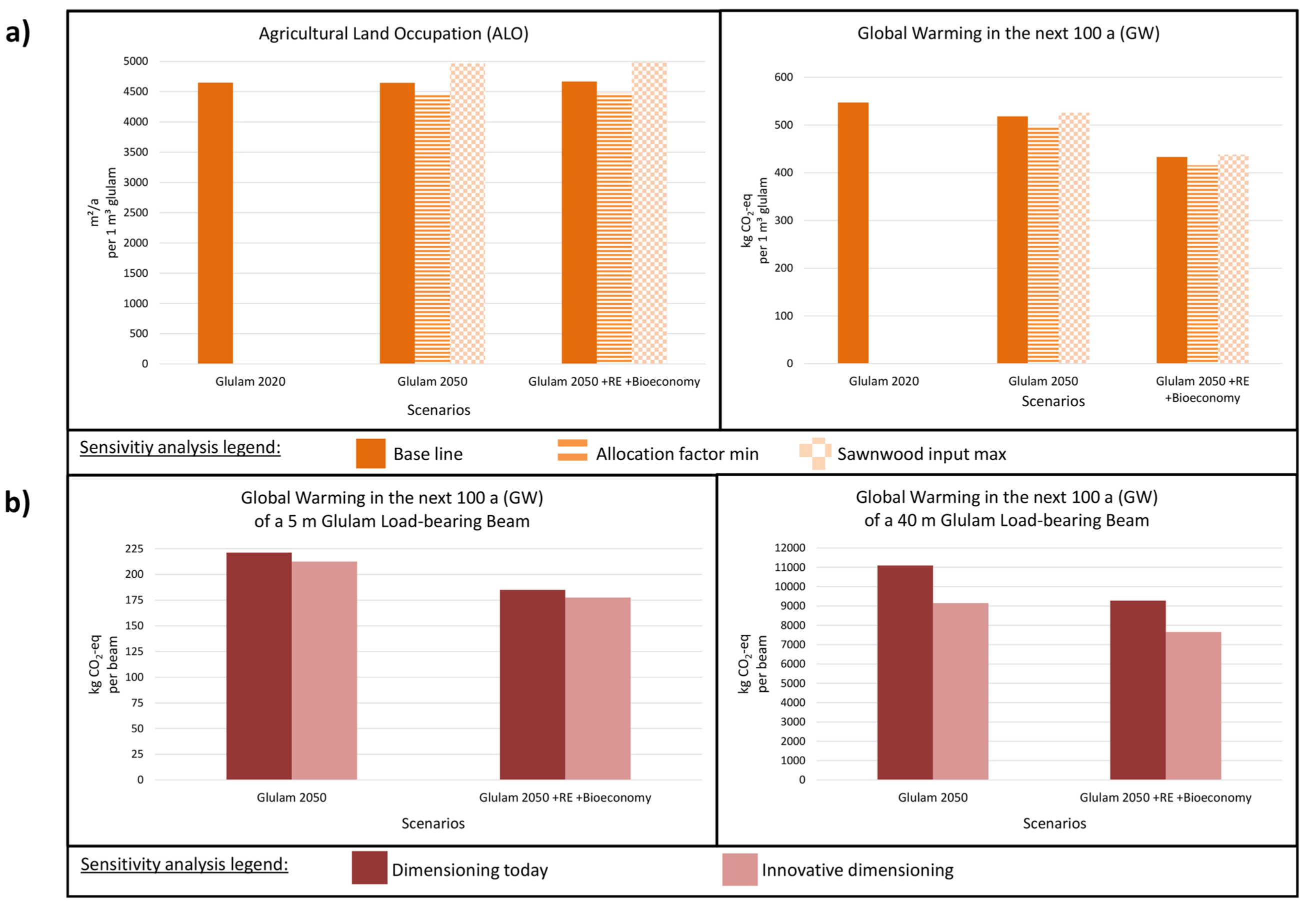


Fig. 8 **a** Prospective LCIA results for 1 m^3 glulam beam represented by exemplary environmental impact categories. + RE indicates a faster grow of RE share in electricity mix in 2050. For scenario description, see Table 2. **b** LCIA results for glulam beams of 40 m (volume of RF of 21.42 m^3/new dimension of 17.66 m^3) and 5 m length (volume of RF of 0.427 m^3/new dimension of 0.41 m^3), each beam bearing a constant pressure of 1 N/mm

wood quality available. High-quality beech glulam characterized by a high strength is suitable for larger dimension beams (40 m lengths) and, thus, can be produced using 18% less total material input than equivalent softwood glulam simply by using smaller crosscuts. A smaller 5 m beam constituted of lower-strength beech is more similar to softwood glulam, in terms of strength. In this case, we see only a 4% reduction in material input, using slightly smaller crosscut dimensions, in comparison to current softwood glulam beams. The environmental impacts of reducing the current dimensioning of 5 m and 40 m glulam load-bearing beams by 2050 are concomitantly reduced by 4% and 18% respectively.

Both future scenarios for 2050 predict reduced environmental impacts, implying an overall improvement. The greatest reduction of an environmental impact is through the rapid growth of the RE share in the electricity mix coupled with the amendment of standards to allow smaller crosscuts of hardwood glulam.

The LCIA results for the glulam beam cannot be compared to other LCIA results of glulam products, because there are no other studies that use this specific functional unit. However, there is an environmental product declaration (EPD; last updated in 2018) that refers to one cubic meter of hardwood glulam. The calculated GW impact of 561 kg CO_2-eq/m^3 glulam (Grupo Gámiz 2018) is quite similar to the GWP impact of 547 kg CO_2-eq/m^3, calculated in this paper for the status-quo production (*Glulam 2020*).

3.6.4 LCIA results: viscose fibers

A comparison of all scenarios shows an improvement mostly caused by a higher share of RE in the electricity mix (SI S3 Step 2.6b). Comparing the *Diss Viscose 2020* scenario with the future scenarios *Diss Viscose 2050* and *Diss optViscose 2050*, the environmental impacts are lower in the scenarios for 2050 (Fig. 9). For the *Diss Viscose 2050* scenario, a change in the electricity mix is responsible for the reduction in comparison to the *Diss Viscose 2020* scenario. In the scenarios *Diss optViscose 2050* and *Organosolv optViscose 2050*, the pulping technology is changed from dissolving to organosolv respectively. This led to an increase in all impact categories in the *Organosolv optViscose 2050* scenario because of the higher energy demand for organosolv pulping, and the greater amount of sodium hydroxide needed to bleach the organosolv pulp. For product systems focusing only on viscose production, a switch to organosolv pulping does not improve the environmental impact.

The allocation by mass for pulp resulted in similar factors for the two pulping technologies. In contrast, the change to economic allocation led to very different allocation factors for the organosolv and dissolving pulp (SI S3 Step 2.2). The effects of the change in allocation method, and therefore the factors, are highest for the ALO impact results. Increasing the sawn wood input in organosolv pulping mostly influences the LCIA results for the ALO. The variation of the parameter values of lignin and the sawn wood input for organosolv pulping has negligible effects on the GW results. A larger reduction of the GW is achieved by having a larger share of RE in the electricity mix for the *Diss optViscose 2050* scenario. Changing the emission reduction and material efficiency does not reduce the impacts as much as changing the RE share in the electricity mix does.

Only one study has been published about the environmental impact of viscose fibers. Shen et al. (2010) calculated the impacts for one ton of viscose fibers produced in Asia and Austria based on confidential data supplied by Lenzing AG. The scope of the study is the same as in this paper, but the multi-functionality was handled using system expansion

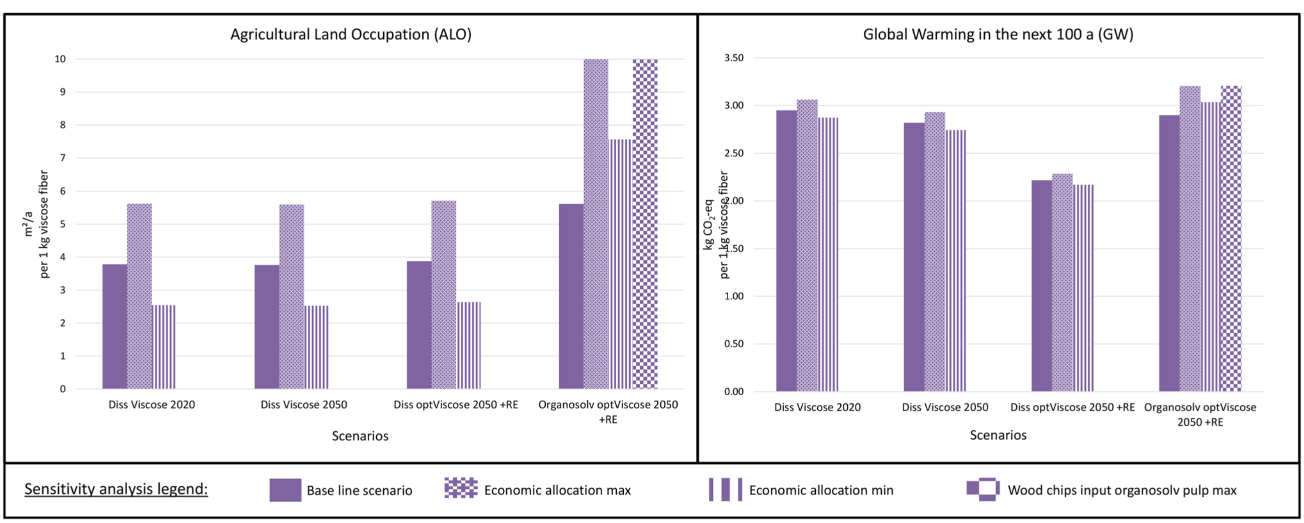


Fig. 9 Prospective LCIA results for the viscose study represented by exemplary environmental impact categories. For scenario description, see Table 2. + RE indicates a faster grow of RE share in the electricity mix of 2050

instead of allocation. The overall impacts assigned to the viscose fiber were 62%. However, the specific unit process allocations were not reported by Shen et al. (2010). In this study, the allocation to viscose fibers in the viscose process is 94%. Shen et al. (2010) integrated pulping into the viscose process rather than allocating them separately. When comparing the results calculated via the CML package of impact assessment methods to the results for viscose production in Germany today, the results for ALO impacts fall within the same magnitude range. The GW impacts of the previous study resulted in 2 kg CO_2-eq/kg viscose, which is very similar to the *Diss optViscose 2050* scenario of around 2.2 kg CO_2-eq/kg and the *Diss Viscose 2020* scenario of 3 kg CO_2-eq/kg.

4 Conclusions

Several challenges regarding scenario development and specific requirements were identified while conducting a prospective LCA of three emerging hardwood-based products in Germany. The first challenge in understanding and defining hardwood-based product systems was the collating of knowledge about the specific hardwood characteristics, such as strength and molecular structures, in comparison to the better-known softwood traits. An additional challenge is when the hardwood-based product is in an early stage of development. In this study, the LPF adhesives, with a low TRL (4), have several possible production paths, whereas the case studies with a higher TRL (glulam with TRL of 7, and viscose with a TRL of 9) have just one main production path. There is only one other option for the production process of wood pulping in the viscose product system, since it is aimed at a high-value utilization of the pulping by-products. The definition of the functional unit for hardwood-based products, especially in construction applications, should consider the differences in material properties between hardwood and softwood. Another challenge in understanding emerging wood-based products is the knowledge about the moisture content of the product along its life cycle. The mass or volume of wood can change depending on the moisture content of the material, which might not be known for the emerging intermediate and final wood-based products.

For the inventory modeling, the influential parameters for wood-based products were the bioeconomy strategies, the trend of the electricity mix transition, and the recovery systems, if the wood-based product was chemically processed. Analysis of those identified parameters showed that the important scenario-related parameters of wood-based products were the energy production technology used in the foreground system, the composition of the electricity mix, and the water utilization in the chemical processes.

The impact of wood utilization on land occupation between scenarios of the same product depends strongly on the size of the allocation factor of the wood-based material and the amount of wood in the final product. The highest lignin content in the LPF adhesive had the highest impact for land occupation in comparison to the other scenarios. Likewise, the LCIA results were strongly influenced by the chosen allocation method and factor within each scenario as well as by changes in the wood input flow. For example, the land occupation impacts were particularly affected by allocation factor variations in the wood-based materials, as well as the initial wood input. An exception was seen in material efficiencies that reduce the overall material use, as is the case for construction elements when the properties of the wood species are advantageous for a specific use. The calculation of specific applications for the glulam case study showed a reduction effect for all impact categories.

The climate change impacts of each scenario mostly differed depending on the share of RE in the electricity mix and the on-site energy production technology of the product manufacturers. Nonetheless, the LPF and viscose case studies showed that the impact on the GW of a high demand in energy for manufacturing cannot be compensated for by a high share of RE in energy production (heat and electricity). The results of the GW are quite robust regarding the allocation factor of all wood-based materials (lignin, cellulose, and solid wood). Only the effect of less water use in kraft pulping has a higher influence on the scenarios that include a smaller share of RE in the electricity mix.

Overall, the scope of the LCA in this paper included scenarios per single product system, and the LCIA results depended on the selection of allocation methods. Until now, wood pulping processes have been focused on one main output product: cellulose. Now that lignin can be used in high-value applications, the complete utilization of wood-based compounds has become interesting. The case of viscose production showed that the individual environmental impact for viscose increases when production switched to organosolv pulping. However, the organosolv pulping allows the highest output in lignin and, thus, enables a greater use of more low-quality hardwood for high-value applications. The next research step should look for a shift in material flows of hardwood in order to weigh the utilization of hardwood for material applications against its current energy use requirements. This could be considered when using a prospective consequential LCA approach to look at the overall utilization of available hardwood.

When conducting a prospective LCA of emerging hardwood-based products, an uncertainty analysis can be conducted as part of the interpretation phase of the preliminary prospective LCA (1st iteration). This helps to constrain the overall number of parameters by identifying the important scenario-related parameters. The important scenario-independent parameters are then handled in an extra step. Having fewer parameters reduced the complexity of the scenario development, which resulted in smaller, more manageable tables for the cross-consistency check and fewer potential scenarios to choose from. In conclusion, the authors recommend the inclusion of an uncertainty analysis when there is a high number of LCI flows that might change in the future, such as it is the case for the production of LPF adhesives and viscose fibers.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information file. The background data that support the findings of this study are available from ecoinvent but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available.

Declarations

Competing interests The authors declare no competing interests.

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References

Arias A, González-García S, González-Rodríguez S, Feijoo G, Moreira MT (2020) Cradle-to-gate life cycle assessment of bio-adhesives for the wood panel industry. A comparison with petrochemical alternatives. Sci Total Environ 738:140357. https://doi.org/10.1016/j.scitotenv.2020.140357

Arvidsson R, Tillman A-M, Sandén BA, Janssen M, Nordelöf A, Kushnir D, Molander S (2018) Environmental assessment of emerging technologies: recommendations for prospective LCA. J Ind Ecol 22:1286–1294. https://doi.org/10.1111/jiec.12690

Aryapratama R, Janssen M (2017) Prospective life cycle assessment of bio-based adipic acid production from forest residues. J Clean Prod 164:434–443. https://doi.org/10.1016/j.jclepro.2017.06.222

Bauhus J, Seeling U, Dieter M, Farwig N, Hafner A, Kätzel R, Kleinschmidt B, Lang F, Lindner M, Möhring B, Müller J, Niekisch M, Richter K, Schraml U (2021) Die Anpassung von Wäldern und Waldwirtschaft an den Klimawandel: Gutachten des Wissenschaftlichen Beirates für Waldpolitik Berlin

Bello S, Ríos C, Feijoo G, Moreira MT (2018) Comparative evaluation of lignocellulosic biorefinery scenarios under a life-cycle assessment approach. Biofuel Bioprod Biorefin 12:1047–1064. https://doi.org/10.1002/bbb.1921

Bisinella V, Christensen TH, Astrup TF (2021) Future scenarios and life cycle assessment: systematic review and recommendations. Int J Life Cycle Assess 26:2143–2170. https://doi.org/10.1007/s11367-021-01954-6

BMBF and BMEL (2020) National Bioeconomy Strategy, German Ministry of Education and Research (BMBF), German Ministry of Food and Agriculture (BMEL), Berlin, Germany. https://www.bmel.de/SharedDocs/Downloads/EN/Publications/national-bioeconomy-strategy.pdf?__blob=publicationFile&v=2. Accessed 11 Aug 2022

BMEL (2021) Waldbericht der Bundesregierung 2021, German Ministry of Food and Agriculture (BMEL), Bonn, Germany. https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/waldbericht2021.pdf?__blob=publicationFile&v=11. Accessed 9 Dec 2022

BMWSB (2022) ÖKOBAUDAT: Sustainable Construction Information Portal, German Ministry of Housing, Urban Development and Building (BMWSB), Berlin. https://www.oekobaudat.de/datenbank/browser-oekobaudat.html. Accessed 12 Dec 2022

Borgonovo E (2017) Sensitivity Analysis, vol 251. Springer International Publishing, Cham

Buyle M, Audenaert A, Billen P, Boonen K, van Passel S (2019) The future of ex-ante LCA? Lessons learned and practical recommendations. Sustainability 11. https://doi.org/10.3390/su11195456

Cucurachi S, Steubing B, Siebler F, Navarre N, Caldeira C, Sala S (2022) Prospective LCA methodology for novel and emerging technologies for BIO-based products - the PLANET BIO project, EUR 31215 EN, Publications Office of the European Union, Luxembourg. ISBN 978–92–76–56855–1. https://doi.org/10.2760/695092

Cucurachi S, van der Giesen C, Guinée J (2018) Ex-ante LCA of emerging technologies. Procedia CIRP 69:463–468. https://doi.org/10.1016/j.procir.2017.11.005

Culbertson C, Treasure T, Venditti R, Jameel H, Gonzalez R (2016) Life cycle assessment of lignin extraction in a softwood kraft pulp mill. Nord Pulp Paper Res J 1:30–40

DIN EN 16449 (2014) Wood and wood-based products: calculation of the biogenic carbon content of wood and conversion to carbon dioxide; German version EN 16449:2014 NHM; NaBau Berlin

EARTO (2014) The TRL scale as a research and innovation policy tool. EARTO Recommendations, Brussels, Belgium. https://www.earto.eu/wp-content/uploads/The_TRL_Scale_as_a_R_I_Policy_Tool_-_EARTO_Recommendations_-_Final.pdf. Accessed 31 Aug 2022

European Commission, Directorate-General Research and Innovation (2018) Review of the 2012 European Bioeconomy Strategy, Luxembourg. https://doi.org/10.2777/086770. Accessed 11 Aug 2022

Falano T, Jeswani HK, Azapagic A (2014) Assessing the environmental sustainability of ethanol from integrated biorefineries. Biotechnol J 9:753–765. https://doi.org/10.1002/biot.201300246

FNR (2022) Projektverzeichnis – Details, Verbundvorhaben: Entwicklung einer Entscheidungsmatrix für die zukünftige Laubholznutzung im Rahmen einer effizienten Bioökonomie; Teilvorhaben 2: Bewertung spezifischer Produktlinien innovativer Laubholznutzung im regionalen Kontext. - Akronym: LauBiOek, Project number: FKZ2218WK11B3, Agency for Renewable Resources (FNR), Gülzow-Prüzen, Germany. https://www.fnr.de/index.php?id=11150&fkz=2218WK11B3. Accessed 12 Dec 2022

Gámiz G (2018) Climate declaration for Vigam laminated beams and Perfigam laminated profiles: Declared unit 1 m^3. Álava, Spain

Goedkoop M, Heijungs R, Huijbregts MAJ, Schryver a de, Struijs J, van Zelm R (2013) ReCiPe 2008 - a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level: report I: characterisation. The Hague, Netherlands

Hesser F (2015) Environmental advantage by choice: Ex-ante LCA for a new Kraft pulp fibre reinforced polypropylene composite in comparison to reference materials. Compos B Eng 79:197–203. https://doi.org/10.1016/j.compositesb.2015.04.038

Hesser F, Wohner B, Meints T, Stern T, Windsperger A (2017) Integration of LCA in R&D by applying the concept of payback period: case study of a modified multilayer wood parquet. Int J Life Cycle Assess 22:307–316. https://doi.org/10.1007/s11367-016-1173-y

Himes A, Busby G (2020) Wood buildings as a climate solution. Developments in the Built Environment 4:100030. https://doi.org/10.1016/j.dibe.2020.100030

Jääskeläinen A-S, Willberg-Keyriläinen P, Liitiä T, Tamminen T (2017) Carbohydrate-free and highly solulable softwood kraft lignin fractions by aqueous acetone evaporation fractionation. Nord Pulp Paper Res J 4:485–492. https://doi.org/10.3183/npprj

Jardim JM, Hart PW, Lucia L, Jameel H (2020) Insights into the potential of hardwood kraft lignin to be a green platform material for emergence of the biorefinery. Polymers 12. https://doi.org/10.3390/polym12081795

Karthäuser J, Biziks V, Mai C, Militz H (2021) Lignin and lignin-derived compounds for wood applications-a review. Molecules 26:1–15. https://doi.org/10.3390/molecules26092533

Kehlheim Fibres (2022) Viscose fibres - functional and sustainable. https://kelheim-fibres.com/en/viscosefibres/applications/. Accessed 14 Jul 2022

Langkau S, Steubing B, Mutel C, Ajie M P, Erdmann L, Voglhuber-Slavinsky A, Janssen M (2023, submitted) A stepwise approach for scenario-based inventory modeling for prospective LCA (SIMPL). Int J Life Cycle Assess (under review)

Lettner M, Solt P, Rößiger B, Pufky-Heinrich D, Jääskeläinen A-S, Schwarzbauer P, Hesser F (2018) From wood to resin—identifying sustainability levers through hotspotting lignin valorisation pathways. Sustainability 10:2745. https://doi.org/10.3390/su10082745

Liu X, Bouxin FP, Fan J, Budarin VL, Hu C, Clark JH (2020) Recent advances in the catalytic depolymerization of lignin towards phenolic chemicals: a review. Chemsuschem 13:4296–4317. https://doi.org/10.1002/cssc.202001213

Lourençon TV, Alakurtti S, Virtanen T, Jääskeläinen A-S, Liitiä T, Hughes M, Magalhães WL, Muniz GI, Tamminen T (2020) Phenol-formaldehyde resins with suitable bonding strength synthesized from "less-reactive" hardwood lignin fractions. Holzforschung 74:175–183. https://doi.org/10.1515/hf-2018-0203

Mair-Bauernfeind C, Zimek M, Asada R, Bauernfeind D, Baumgartner RJ, Stern T (2020) Prospective sustainability assessment: the case of wood in automotive applications. Int J Life Cycle Assess 25:2027–2049. https://doi.org/10.1007/s11367-020-01803-y

Mendoza Beltran A, Cox B, Mutel C, Vuuren DP, Font Vivanco D, Deetman S, Edelenbosch OY, Guinée J, Tukker A (2020) When the background matters: using scenarios from integrated assessment models in prospective life cycle assessment. J Ind Ecol 24:64–79. https://doi.org/10.1111/jiec.12825

Merz K, Niemann A, Torno S (2021) Building with hardwood: innovation through an almost forgotten building material. DETAIL Praxis. Detail Business Information GmbH, Munich, Germany

Moretti C, Corona B, Hoefnagels R, Vural-Gürsel I, Gosselink R, Junginger M (2021) Review of life cycle assessments of lignin and derived products: lessons learned. Sci Total Environ 770. https://doi.org/10.1016/j.scitotenv.2020.144656

Muthu SS (ed) (2015) Handbook of life cycle assessment (LCA) of textiles and clothing. Woodhead Publishing series in textiles, Number 171. The Textile Institute; WP Woodhead Publishing; Elsevier, Amsterdam, a.o

Nitzsche R, Budzinski M, Gröngröft A (2016) Techno-economic assessment of a wood-based biorefinery concept for the production of polymer-grade ethylene, organosolv lignin and fuel. Bioresour Technol 200:928–939. https://doi.org/10.1016/j.biortech.2015.11.008

Nitzsche R, Gröngröft A, Köchermann J, Meisel K, Etzold H, Verges M, Leschinsky M, Bachmann J, Saake B, Torkler S, Patzsch K, Rößiger B, Pufky-Heinrich D, Unkelbach G (2021) Platform and fine chemicals from woody biomass: demonstration and assessment of a novel biorefinery. Biomass Convers Biorefin 11:2369–2385. https://doi.org/10.1007/s13399-020-00769-z

Olsen SI, Borup M, Andersen PD (2018) Future-oriented LCA. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 499–518

Owisianak M, Bjørn A, Hugge HB, Carvalho S, Jebahar M, Rasmussen J, White CM, Olsen SI (2018) Illustrative case study of four window alternatives. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 1059–1146

Patel MK, Bechu A, Villegas JD, Bergez-Lacoste M, Yeung K, Murphy R, Woods J, Mwabonje ON, Ni Y, Patel AD, Gallagher J, Bryant D (2018) Second-generation bio-based plastics are becoming a reality - Non-renewable energy and greenhouse gas (GHG) balance of succinic acid-based plastic end products made from lignocellulosic biomass. Biofuel Bioprod Biorefin 12:426–441. https://doi.org/10.1002/bbb.1849

Rosenbaum RK, Georgiadis S, Fantke P (2018) Uncertainty management and sensitivity analysis. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 271–321

Rößiger B, Röver R, Unkelbach G, Pufky-Heinrich D (2017) Production of bio-phenols for industrial application: scale-up of the base-catalyzed depolymerization of lignin. Green and Sustainable Chemistry 07:193–202. https://doi.org/10.4236/gsc.2017.73015

Rüter S, Diedrichs S (2012) Ökobilanz-Basisdaten für Bauprodukte aus Holz: Abschlussbericht. https://www.cipra.org/de/publikationen/5087. Accessed 12 Aug 2022

Sacchi R, Terlouw T, Siala K, Cirnaichner A, Bauer C, Cox B, Mutel C, Daioglou V, Luderer G (2022) PRospective EnvironMental Impact asSEment (PREMISE): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. Renew Sust Energ Rev 160:112311. https://doi.org/10.1016/j.rser.2022.112311

Sahoo K, Bergman R, Alanya-Rosenbaum S, Gu H, Liang S (2019) Life cycle assessment of forest-based products: a review. Sustainability 11:1–30. https://doi.org/10.3390/su11174722

Schäpel R (2012) Allgemeine bauaufsichtliche Zulassung: VIGAM Brettschichtholz aus Eiche Berlin

Schäpel R (2019) Allgemeine bauaufsichtliche Zulassung/Allgemeine Bauartgenehmigung: BS-Holz aus Buche und BS-Holz Buche-Hybridträger und zugehörige Bauarten Berlin

Schreiner T (2020) Umwelterklärung 2020, Kehlheim. https://kelheim-fibres.com/wp-content/uploads/2021/01/Umwelterkl%C3%A4rung-Final_EMAS.pdf. Accessed 12 Aug 2022

Schrijvers D, Loubet P, Sonnemann G (2020) Archetypes of goal and scope definitions for consistent allocation in LCA. Sustainability 12:5587. https://doi.org/10.3390/su12145587

Shen L, Worrell E, Patel MK (2010) Environmental impact assessment of man-made cellulose fibres. Resour Conserv Recycl 55:260–274. https://doi.org/10.1016/j.resconrec.2010.10.001

Solt P, Rößiger B, Konnerth J, van Herwijnen HWG (2018) Lignin phenol formaldehyde resoles using base-catalysed depolymerized kraft lignin. Polymers 10. https://doi.org/10.3390/polym10101162

Spielmann M, Scholz R, Tietje O, de Haan P (2005) Scenario modeling in prospective LCA of transport systems. Application of Formative Scenario Analysis (11 pp). Int J Life Cycle Assess 10:325–335. https://doi.org/10.1065/lca2004.10.188

Steubing B, de Koning D (2021) Making the use of scenarios in LCA easier: the superstructure approach. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-021-01974-2

Steubing B, Koning D de, Haas A, Mutel CL (2020) The Activity Browser — an open source LCA software building on top of the brightway framework. Software Impacts 3:100012. https://doi.org/10.1016/j.simpa.2019.100012

Stora Enso Oyj (2020) Lineo® kraft lignin: replacing fossil-based raw materials with Lineo® by Stora Enso. https://www.storaenso.com/en/products/lignin/lineo. Accessed 9 May 2022

Suhr M, Klein G, Kourti I, Rodrigo Gonzalo M, Giner Santonja G, Roudier S, Delgado Sancho L (2015) Best available techniques (BAT) reference document for the production of pulp, paper and board: Industrial Emissions Directive 2010/75/EU - Integrated Pollution Prevention and control, Luxembourg

Textile Exchange (2020) Preferred fiber and materials: Market Report 2020. https://www.chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Ftextileexchange.org%2Fwp-content%2Fuploads%2F2020%2F06%2FTextile-Exchange_Preferred-Fiber-Material-Market-Report_2020.pdf&clen=21746720&chunk=true. Accessed 24 Dec 2021

Thonemann N, Schulte A, Maga D (2020) How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. Sustainability 12:1192. https://doi.org/10.3390/su12031192

Tsoy N, Steubing B, van der Giesen C, Guinée J (2020) Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. Int J Life Cycle Assess 25:1680–1692. https://doi.org/10.1007/s11367-020-01796-8

UPM Biochemicals (2022) UPM BioPiva product family. https://www.upmbiochemicals.com/lignin-solutions/products/UPM-BioPiva-product-family/. Accessed 13 July 2022

van der Giesen C, Cucurachi S, Guinée J, Kramer GJ, Tukker A (2020) A critical view on the current application of LCA for new technologies and recommendations for improved practice. J Clean Prod 259. https://doi.org/10.1016/j.jclepro.2020.120904

van Nieuwenhove I, Renders T, Lauwaert J, de Roo T, de Clercq J, Verberckmoes A (2020) Biobased resins using lignin and glyoxal. ACS Sustainable Chem Eng 8:18789–18809. https://doi.org/10.1021/acssuschemeng.0c07227

van Uytvanck PP, Haire G, Marshall PJ, Dennis JS (2017) Impact on the polyester value chain of using p-xylene derived from biomass. ACS Sustain Chem Eng 5:4119–4126. https://doi.org/10.1021/acssuschemeng.7b00105

Walker WE, Harremoës P, Rotmans J, van der Sluijs JP, van Asselt M, Janssen P, Krayer von Krauss MP (2003) Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integr Assess 4:5–17. https://doi.org/10.1076/iaij.4.1.5.16466

Weber-Blaschke G, Muys B (2020) Bioeconomy - potentials for innovation and sustainability regarding wood utilisation and forest management. In: Krumm F, Schuck A, Rigling A (eds) How to balance forestry and biodiversity conservation? - A view across Europe. European Forest Institute, Birmensdorf, pp 88–107

Weidema BP, Ekvall T, Pesonen H-L, Rebitzer G, Sonnemann GW, Spielmann M (2004) Scenarios in life-cycle assessment. Society of Environmental Toxicology and Chemistry (SETAC), Pensacola FL, USA

Wender BA, Foley RW, Hottle TA, Sadowski J, Prado-Lopez V, Eisenberg DA, Laurin L, Seager TP (2014) Anticipatory life-cycle assessment for responsible research and innovation. J Responsible Innov 2:200–207. https://doi.org/10.1080/23299460.2014.920121

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Younesi-Kordkheili H, Pizzi A (2020) Improving the properties of urea-lignin-glyoxal resin as a wood adhesive by small addition of epoxy. Int J Adhes Adhes 102:102681. https://doi.org/10.1016/j.ijadhadh.2020.102681

Zeilerbauer L, Lindorfer J, Süss R, Kamm B (2021) Techno-economic and life-cycle assessment of a wood chips-based organosolv biorefinery concept for production of lignin monomers and oligomers by base-catalyzed depolymerization. Biofuel Bioprod Biorefin 2:370–388. https://doi.org/10.1002/bbb.2315

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