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Insights from the Sustainability Monitoring Tool SUMINISTRO Applied to a Case Study System of Prospective Wood-Based Industry Networks in Central Germany

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Abstract: Bioeconomy regions are a young concept representing emerging amalgamation points for the implementation of cross-sectoral value-added chains. When sustainable bioeconomy strategies are rolled out, their proof-of-concept implies that industrial R&D activities should lead to impact decoupling and that the valorization of locally available lignocellulosic biomass has to contribute to an increase in added value. Furthermore, regional co-benefits for society and a positive influence on local environmental and socioeconomic conditions are major factors. The fulfillment of these strategic goals would be a milestone achievement when progressing from the blueprint development and the road-mapping stage towards socially accepted and sustainable wood-based bioeconomy strategies. For regional industrial and science stakeholders who run pilot facilities for process upscaling and for energy and material flow integration, this requires well-orchestrated integrative processes, which go beyond conventional "Life Cycle Management" approaches. It is obvious that assessing and monitoring such integrative systems will have to account for different stakeholder perspectives and for detailed technology deployment and resource conversion scenarios. Applying a sustainability index methodology in a case study region must include an evaluation of the whole supply chain and the process networks associated with the characteristic products of the evaluated region. To date, no such integrative assessment methods exist in the literature. Therefore, the aim of this paper is to lay out, on the basis of a practical example in the case study region of Central Germany, an assessment of the sustainability level of wood-based bioeconomy networks by applying the Sustainability Monitoring Tool -SUMINISTRO"- to examine regional bio-based industry networks.

Keywords: bioeconomy regions; innovation clusters; sustainability indicators; multi-criteria decision analysis; industrial symbiosis

1. Introduction

The German bioeconomy strategy aims to realize sustainable and innovative conversion and utilization of biomass resources to produce sufficient and high-quality food and feed, as well as high-value-added products. The driving motivations behind the goal of achieving a sustainable bioeconomy are related to simultaneously guaranteeing resource conservation, low carbon intensity (i.e., fossil decoupling) and food security [1,2]. In the case of the wood-based bioeconomy, the various envisaged advantages over agricultural resource mobilization, such as lower land-use intensity, less pesticide use and less distortion of food markets, are not without their own set of intertwined trade-offs.

In a practical sense, the sectoral coupling between the wood and chemical industry value chains offers an array of effective and synergetic options to implement process and product innovations in order to minimize environmental impacts and generate social benefits; however, in a general sense, it does not lead per se to impact decoupling and resource use efficiency.

In particular, the following hotspot areas are facing increasing innovation pressures and/or are causing novel resource mobilization challenges:

(1) Production of new bio-based materials may require an increased manufacturing intensity, and expansion of production capacities for these materials may lead to an increased demand for regional fresh wood resources;
(2) Rising final energy demands for fossil-based process energy supplies in the wood manufacturing sector [3] and competition for wood-based energy carriers may require more energy-efficient processes or innovations in fuel substitution;
(3) Additional capacities may increase the competition between material and energy-related use of available woody biomass resources and thus set strong constraints on the implementation and optimization of waste-wood cascading systems [4];
(4) The varying degrees of industrial symbiosis among value-added industrial networks may have their own trade-offs in impact mitigation and resource substitution [5].

To successfully address the most effective leverage points in innovation management for sectoral coupling and in the implementation of sustainable and resource-efficient conversion processes, a coordinated response by the various stakeholders involved is required [6–8]. Therefore, to help promote and support such integrated innovation management activities, the bundling of competencies of wood and chemical industry stakeholders for setting up value-added clusters within bioeconomy regions has been proposed [2,9–11].

Besides the formal cooperation within cluster activities, the concept of bioeconomy regions is also increasingly used to connect and bundle forces of administrative entities, e.g., offices of economic development and regional managers; industrial initiatives of the chemical, biotechnology, and wood industry; and research institutes for launching and aligning R&D activities, spin-off projects, and shared demonstration platforms for initiating bioeconomy strategies [12–19].

In both cases, in more formal and in more spontaneous cooperation networks, accompanying research groups and consultants can support added-value clusters and coordinated industrial R&D activities by developing and applying case-specific Life Cycle Management (LCM) tools for benchmarking the directionality towards more sustainable (future) production systems.

In this sense, the presented sustainability monitoring tool is a contribution to the emerging field of LCM tools that provide decision support and strategy assessment of regional sustainability [20–24]. This study showcases the operationalization of an LCM tool in a case study system of future regional bioeconomy production networks.

In the following sections, the general concept of bioeconomy regions and the specificities of the case study system within the region of Central Germany are described in order to introduce why and how sustainability metrics were aggregated to examine future wood-based production networks and their associated scenarios.

1.1. Definition of the Terms and Function of A Wood-Based Bioeconomy Region

From a techno-economic industrial value chain perspective, the assessment methodology has to frame system boundaries to determine whether a particular set of proposed industrial conversion processes and sectoral coupling options for establishing bio-based production systems can contribute to more sustainable regional industrial development.

From a regional socio-ecological perspective, the framing of this assessment cannot be detached from technological and socioeconomic enabling factors, the biophysical state of managed (forest) ecosystems, and the regional biomass availability of the particular region.

A wood-based bioeconomy region, which represents the scale of aggregation for multi-criteria assessments in this study, refers to a region that is smaller than the national level and in which different wood-based, chemical, and biotechnology industries, which rely on a supply of limited biomass from the same timber stocks, cooperate in strategic alliances to plan and operate competitive and sustainable bio-based production platforms.

On the other hand, traditionally, regional wood resources are used by individual companies for the production of heat, power, materials, and chemicals. These strategic alliances can help to facilitate the implementation of synergetic production lines, e.g., through the vertical and horizontal integration of supply and conversion chains. Here, this definition of a bioeconomy region is used to provide the core concept of the accompanying sustainability assessment and of the sustainable management of regional wood resources as a basis for discourse along a tangible set of decision-making alternatives among different regional wood-based industries within cluster networks. One effective way that these bioeconomy regions are being established around the world is through the strategic alliance of newly launched biotechnology and chemical industry clusters with already-existing regional forest value chains and clusters to form regional bioeconomy networks [9,16–18,25,26]. In their aim for sustainable regional development, the ambition levels of these regional bioeconomy networks can vary depending on the incremental optimization of process integration and optimization principles in product design, e.g., circular design and cascading principles [5,7,27,28].

The assessment of these incremental optimization options for the sustainability profiles of these future bio-based industry networks and their emerging regional bio-based product portfolios encompasses (i) options for the production-integrated reduction of impacts and (ii) options for product-integrated resource efficiency and environmental protection.

In terms of options for production-integrated impact mitigation, LCA scenarios for regional cascading systems, the integration of thermal process energy cascades, and the substitution of realizing adhesive and resins were integrated into the final assessment scenarios of the bio-based networks. In terms of product-integrated environmental protection, the effects of including Design For Recyclability principles and region-specific product innovations are integrated into the collection and aggregation of sustainability indicators from individual product life-cycle inventories.

1.2. Conceptual Framework of the Sustainability Monitoring Tool

A monitoring tool that tracks the sustainability of bio-based production networks within a bioeconomy region should not only monitor the degree to which impact decoupling could potentially be achieved by bio-based process chains when substituting fossil-based resources and innovating new product options but also capture the social implications and benefits for regional organizations that result from the intensification of biomass resource use.

For this purpose, conventional monitoring and assessment tools such as Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and social Life Cycle Assessment (sLCA) are integrated into a multi-criteria analysis approach to advance towards a more holistic assessment of regional production systems and their associated environmental, social, and economic impacts, effects and benefits against global endpoints and references [23,29,30].

The framework SUMINISTRO (Sustainability Monitoring Index for assessing regional bio-based industry networks) was developed [31,32] in a joint project for accompanying research to support R&D activities in the sustainable use of beechwood resources for the production of chemicals, engineered wood products, and composites in the Leading-Edge Cluster BioEconomy (SCBE) (see acknowledgments) [10,33].

Potential future wood-based products that were developed, optimized, tested, and scaled up within the different demonstration projects associated with the SCBE [10,34] served as a basis for specifying and assessing energy and material flow scenarios of potential future biorefinery platforms and integrated bio-based industry networks [5,35,36].

In this study, the developed SUMINISTRO framework was used to aggregate the sustainability metrics and assessment results that were obtained from individual assessment steps, as performed by [35–38].

The framework of SUMINISTRO covers all three sustainability dimensions in order to integrate sustainability metrics from conventional life-cycle approaches (e.g., inventory and impact categories) [5,23,34,35], as well as socioeconomic criteria, which were developed in the RESPONSA framework for social Life Cycle Assessment [29].

The methodological procedure is demonstrated by using a practical example of industrial activities within a specific case study region of Central Germany (please refer to Figure 1 and to Section 1.3).

A system boundary was set to evaluate wood-based production systems within the boundaries of the studied bioeconomy region [5], [16] and includes organizations and process chains for biomass provision from regional forest ecosystems and various conversion and treatment process routes, such as fractionation and fermentation processes, along the production chains to the final product use phases.

The sustainability assessment also considered three future scenarios with varying degrees of industrial symbiosis among the bioeconomy network (please refer to Section 3.2) [5].

Such a Multi-Criteria Decision Analysis (MCDA) approach is considered to be valuable for supporting the decisions of both R&D managers and industrial stakeholders within regional bio-based networks to develop more efficient production technologies, but it can also help in the systemic analysis of future options for industrial symbiosis.

A major strength of this approach, besides the detailed regional resolution of process metrics and material flow scenarios, is the application as an ex post monitoring tool for evaluating the recent progress and deficits in the regional development of bioeconomy systems, as well as an ex ante assessment of future production systems and industrial bioeconomy blueprints.

Considering the innovative character of the regional case study system and the very early efforts in progressing towards a bioeconomy region in Central Germany, it is evident that the assessment in this study examined bioeconomy networks from an ex ante perspective. In essence, the aim of this paper is to demonstrate the application of a sustainability index methodology—the SUMINISTRO framework (Figure 2), which applies a set of 55 calibrated sustainability indicators—for the assessment of three different scenarios involving existing and future wood-based value-added networks within a future bioeconomy region in Central Germany.

1.3. Background Information on the Case Study Region of Central Germany

The area of Central Germany was identified to bundle several enabling factors that are valuable for constructing a growth core in biorefinery research around the refinery sites of Leuna [39,40] and crucial for establishing cluster cooperation between companies of the wood panel production, woodworking, and chemical industries [41,42].

Geographically, the study area is located in the federal states of Saxony, Saxony-Anhalt, and Thuringia (please refer to Figure 1). A special focus is directed towards the respective districts in which the locations of large enterprises and small and medium-sized enterprises (SMEs) from the leading-edge cluster are located [43].

The following company locations, most of them members or former members of the SCBE, represent, for example, major industrial activities in bio-based production in the context of the Leading-Edge Cluster BioEconomy: the production of wood fiber insulation boards from the company HOMATHERM GmbH in Berga (Mansfeld/Südharz); the production of solid construction wood (KVH) in the sawmill of ante-holz GmbH & Co. KG in Rottleberode (Mansfeld/Südharz); demonstration plants for biomass digestion from Fraunhofer CBP, the production of isobutene by Global Bioenergies GmbH and the production of polylactic acid from Uhde Inventa-Fischer GmbH in Leuna (Saalekreis);

as well as the production of veneer lumber (FSH/LVL) from Pollmeier Massivholz GmbH & Co. KG in Creutzburg (Wartburgkreis) [10,33,42–44].

Furthermore, the fossil-based production capacities for bulk chemicals and polymer products, which are manufactured in established industrial parks, such as the cracker and polymer production plants in Böhlen, Schkopau, and Leuna [19,45–47], may build the foundation for more integrated hybrid refineries and future eco-industrial parks [43].

From the economic profiles of the region, it can be observed that the more densely populated regions in the cluster region of Central Thuringia and Western Saxony are economically stronger if, for example, the low municipal debt, the comparatively high wages in the industry, and the positive developments in income tax and household incomes are compared.

In contrast, in the less densely populated areas of Anhalt-Bitterfeld and Halle-Wittenberg, municipal indebtedness and the share of ALG II benefits per inhabitant are significantly higher, and average household incomes are lower. In terms of natural areas, however, the areas with moderate to weak economic indicators are characterized by a high proportion of forest and agricultural areas [43,48].

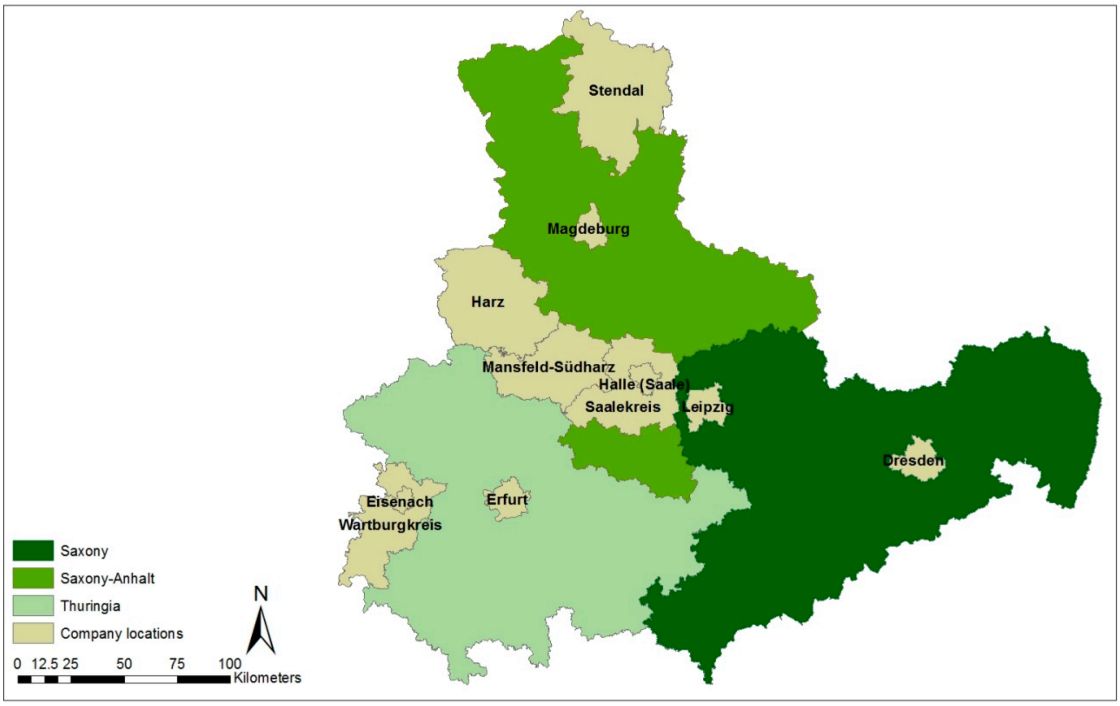


Figure 1. Administrative boundaries and production locations in the case study region defined in [43] and adapted from Verwaltungsgebiete 1:2 500 000 © GeoBasis-DE / BKG 2017 available under the License “dl-de/by-2-0”.

2. Materials and Methods

2.1. Aim of This Work

The aim of this work is to explore the methodological and strategic insights that were derived by applying the presented sustainability monitoring system SUMINISTRO to bioeconomy regions as an operational LCM tool for evaluating the sustainability of a case study system of existing and optional future added-value networks within a wood-based bioeconomy region in Central Germany.

The conceptual framework, which structures the aggregation methodologies of the sustainability monitoring tool, encompasses three different perspectives (please refer to Figure 2).

(1) From the operational perspective, the energy and material flow model has to specify technical, environmental, and energy-related parameters, and it has to quantify the existing and future

energy and resource flows, product flows, and energy and conversion losses associated with the industrial metabolism of the bioeconomy region.

(2) From the normative perspective, all relevant sustainability and efficiency goals that can be derived from societal and individual stakeholders and stakeholder groups need to be transformed into a quantifiable set of sustainability indicators.

(3) From the perspective of monitoring metrics, the accuracy of the aggregation procedure has to be ensured by calibrating case-specific evaluation functions and specifying the defined indicators according to the life-cycle metrics aggregated from material flow analysis, environmental LCA, and sLCA.

From these three methodological perspectives, three research questions were investigated in order to deliver a fully operational sustainability monitoring system.

(i) Concerning the modeling of the material flow system of the bioeconomy region: How can the multi-output production system of the bioeconomy region be broken into a basket of bio-based products, and which future scenarios for a blueprint of energy and material flow integration can be applied to this multi-output production system in order to reflect future increased ambition levels in mitigating environmental impacts?

(ii) Concerning the sets of sustainability indicators: Which sets of sustainability indicators for the sustainable management, conversion, and product manufacturing of wood resources in bioeconomy regions can be identified by reviewing the literature and consulting regional stakeholders?

(iii) Concerning the aggregation of the evaluation metrics: How can these indicator sets and evaluation values be aggregated within an indicator-based Multi-Criteria Assessment tool, and how can these indicators be applied in the assessment of an energy and material flow model as a case study system that represents bio-based production networks within a bioeconomy region?

An overview of the specific focus areas and more detailed research questions are provided in Table 1.

Table 1. Focus of the sustainability indicator systems and research questions for the regional case study system.

	Research Questions
General Focus • General structure of the regional forestry industries and forest resource supply chains • Upscaling of regional capacities for innovative conversion processes • Health and safety issues related to regional working conditions • Product responsibility for proposed product innovations	• Concerning the material flow system: How the multi-output production system of the bioeconomy region can be broken into a basket of bio-based products, and which future scenarios for a blueprint of energy and material flow integration can be applied to this multi-output production system in order to reflect future increased ambition levels in mitigating environmental impacts
Perspective: Sustainability indicators **Focus areas**: • Efficiency indicators and decoupling indicators • Indicators for sustainable biomass supply • Socioeconomic benefits	• Concerning the sets of sustainability indicators: Which indicators for sustainable management of wood resources in bioeconomy regions can be identified from literature review and from consulting regional stakeholders
Perspective: Assessment tool **Focus areas**: • Energy and Material Flow-based Indicators • Energy and Material Flow Model of a case study region • Aggregation of sustainability metrics along the value chains	• Concerning the aggregation of the evaluation metrics: i. How can these indicator sets and evaluation values be aggregated within an indicator-based Multi Criteria Assessment tool? ii. How can these indicators be applied in the assessment of an energy and material flow model as a case study system representing bio-based production networks within a bioeconomy region?

In order to understand the overall aim of the sustainability indicator system, the following definitions of the logical dependencies between sustainability goals, indicators, and sub-indices are introduced.

- A sustainability goal aims to define the direction for the performance evaluation of specific indicator values (maximum or minimum), e.g., maximizing resource use efficiency.
- A sub-goal refers to a particular part of resource efficiency, e.g., increasing the biomass conversion efficiency or water use efficiency. Indicator sets are then used to break down the sub-goals into quantifiable values, which can be compared with reference values to construct scoring values.
- The defined sub-indices break down the indicator sets even further in order to allow for calibrating scoring values and reference values for specific unit process modules, e.g., the biomass conversion efficiency of biorefinery processes or the material use efficiency of sawmill processes.

2.2. Methods and Procedures for Calibrating the Sustainability Monitoring Tool

The framework of SUMINISTRO was broken down into a series of six tasks and procedures in order to aggregate the monitoring metrics for specifying the sustainability of wood-based industry networks within bioeconomy regions (Figure 2 and Figure S1 in the Supplementary Materials).

In more detail, the following procedure, which comprised six tasks carried out sequentially, was developed and applied to the case study system of Central Germany:

(1) Identifying a regional basket of wood-based products To establish a robust basis for the functional units of the case study system, the identification of products was conducted in close cooperation with science and industrial partners in the Leading-Edge Cluster BioEconomy [32,42,44].
(2) Defining fossil-based and coniferous wood-based reference product systems By establishing the functional units in Task 1, the equality of benefits for benchmarking against fossil-based reference systems was also defined. By applying the sLCA framework RESPONSA, a procedure for identifying reference sectors was established [38].
(3) Deriving sustainability goals and defining a sustainability goal system The assessment of sustainable regional development and of biomass utilization pathways is not a new field per se; therefore, the sustainability goals were defined by reviewing the literature (refer to Section 3.3) and exchanging novel findings with A. Siebert [29].
(4) Adapting indicator sets for monitoring sustainability goals to suit regional conditions and stakeholder priorities The goal and indicator system was adapted to meet specific stakeholder priorities derived from stakeholder interviews [37], amended with indices useful for wood-based value chains and revised in cooperation with the cluster management of the Leading-Edge Cluster BioEconomy (refer to Section 3.4).
(5) Allocating life-cycle inventories and impacts associated with production volumes of individual value chains The allocation of impacts and the scenarios for fuel substitution inventories were evaluated in further studies and served as an input for the three scenarios also assessed in this manuscript [5].
(6) Scoring and calibration of evaluation functions For each of the technical-environmental, socioeconomic, and economic indicators, a specific evaluation function or scoring technique was calibrated (please see Supplementary Materials and Sections 3.5 and 3.6).

The six tasks were subsequently ordered and integrated, as presented in Figure 2.

The regional basket-of-products represents regional process chains and the associated material flow scenarios and balances. Therefore, the first task was carried out to include all relevant and promising innovative product options produced in the process chains of the bioeconomy region in the assessment. The process scalability and the maturity of the product innovations were decisive criteria in determining which products to include in the material flow scenario of the product basket (please refer to the Preselection Matrix in the Supplementary Materials).

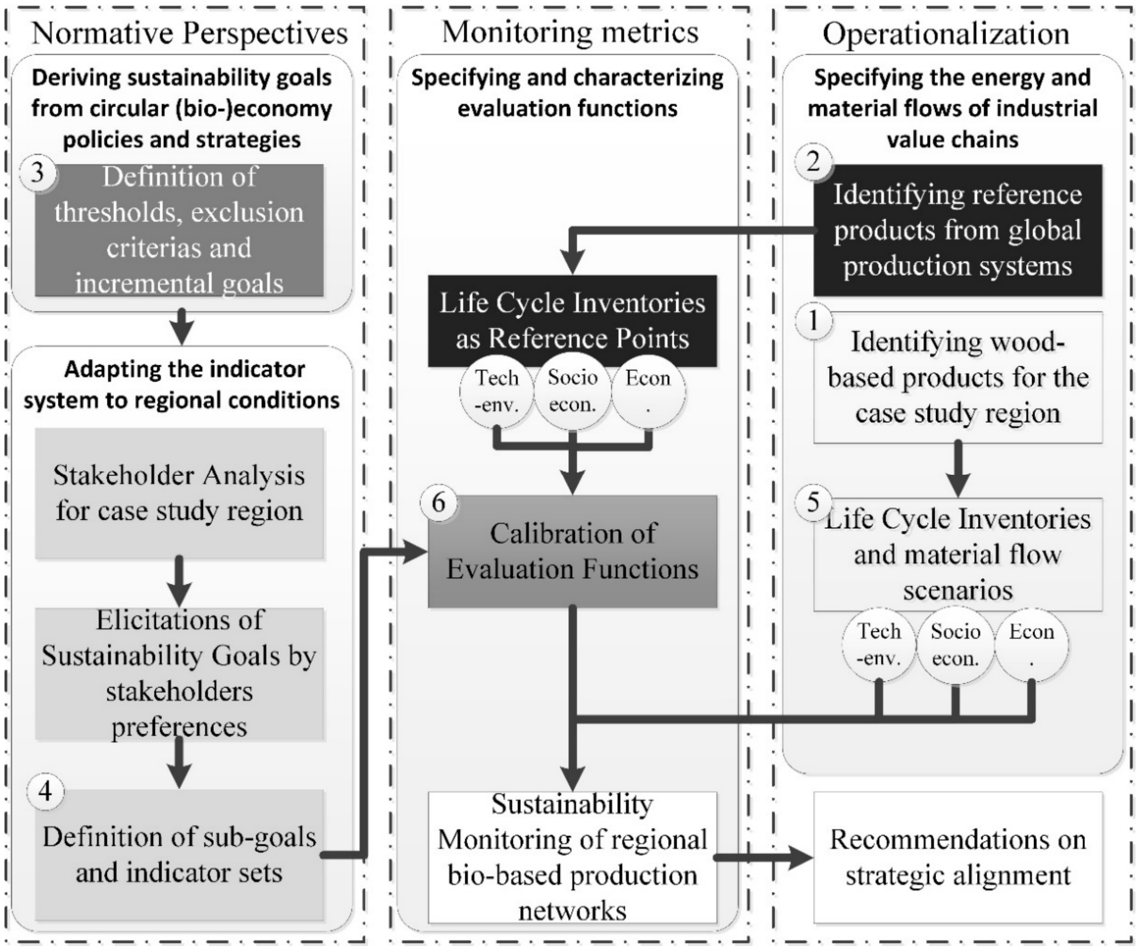


Figure 2. Conceptual framework and tasks for calibrating the Sustainability Monitoring tool (adapted from [23]).

Product innovations need to have a Technology Readiness Level (TRL) or maturity level of at least 7–9, and they also need to have a market potential that exceeds a production capacity of 1 kiloton per annum. The reference system represents global process chains of comparable non-bio-based products and their associated impacts and sustainability benefits and deficits. Therefore, the second task for defining a reference system with equal benefits was carried out to collect representative, robust, and accepted inventory data for benchmarking, scoring, and evaluation functions. Only if the functions, properties, and future potentials of the innovative bio-based products appear to be equal can the assessment evaluate whether the bio-based products can outcompete the fossil-based products by offering a higher sustainability level for all selected assessment metrics.

The sustainability goal system is the overarching procedure for structuring the sustainability assessment and the underlying indicator calibration, weighting, and characterization procedures. Therefore, the third task was carried out to compile, evaluate, and adapt internationally accepted sustainability goals and criteria applied in the monitoring of sustainable bioeconomy strategies, as well as applied in the assessment of wood-based value chain systems. The literature review focused on assessment studies and frameworks that cover forest management and/or innovative conversion processes for the material use of beechwood resources and/or socially responsible and equitable working conditions and product responsibility, e.g., recycling-friendly design. This helped to identify a list of sustainability priorities that are useful in wood-based bioeconomy regions and, in particular, in the evaluated case study region.

The fourth task was carried out with a bottom-up approach through the organization of workshop sessions and stakeholder interviews to validate the identified management goals [37]. The results of the workshop and interviews were also used to assign weights to the resulting goal system while considering the stakeholder-specific perceptions of the chances and threats triggered by bioeconomy strategies in their fields, e.g., administrative constraints, nature and resource protection issues, and innovation management. Furthermore, stakeholders from industry were contacted to perform individual selections and elicitation of potential sustainability goals for bioeconomy regions [49].

The fifth task was conducted to ensure the consistent aggregation of sustainability metrics along value-added chains. For this purpose, allocation factors had to be computed on the basis of annual production capacities (please refer to Supplementary Materials) at a given point in time in order to allocate the impacts, emissions, and benefits according to the contribution of the individual or integrated production chains. To allocate the organizations' contributions to the final product within the sLCA, activity variables such as mass, working hours, or value added were applied.

The sixth task for defining the evaluation functions involved the application of the multi-attribute utility theory (MAUT), as well as the ideal and reference point approaches to developing appropriate scoring techniques [50,51]. The reference values for calibrating the attributes and evaluation criteria were compiled from LCA databases such as Gabi and Ecoinvent; from publicly available environmental product declaration; from Eurostat databases on business statistics for criteria such as industrial value creation; as well as from data provided by the Institute of Employment Research.

In the following sections, the materials and data obtained by applying the six tasks and the underlying basic assumptions, methods, and data to the case study system are compiled and explained.

3. Results

3.1. Results of Task 1 and Task 2: Identification of A Wood-Based Product Basket Representing the Case Study System and A Reference Basket Representing Global Reference Products

To identify a basket of wood-based products that is representative of the innovation system of the bioeconomy region of Central Germany, all relevant topic areas of the Leading-Edge Cluster BioEconomy were screened to establish mature product innovations and cooperations of the accompanying research with the help of the material scientists and process engineers who test these product innovations [10,31,34,36,42,44]. The result of this procedure was that for the regional basket-of-products, three product groups, namely, (1) engineered wood products, panel boards, and composites; (2) polymer and resin products; and (3) energy carriers were identified to be representative of the innovation system of the bioeconomy region. These products were included in all further assessments because these exact or similar product and process innovations were developed and evaluated within the case study region by partner research institutions and industrial stakeholders [10,34,35], and they were identified as exemplary case study products in the preselection procedure. To define reference products, the equality of benefits for products with the same product properties was evaluated. Table 2 presents the shares of the products within the product basket in terms of their annual production volumes. The bioeconomy region's products were quantified on the basis of a model biorefinery concept with an input capacity of 400,000 tonnes (in absolute dry matter) of wood chips and the regionally most probable capacities for engineered wood products. The absolute figures are presented in the Supplementary Materials in Table S1.

Table 2. Shares of characteristic production capacities for the case study of the wood-based bioeconomy region.

Product Group	Wood-based Products	Product Applications	Share of Product with in the Basket
Engineered wood products (EWP), panel boards, and composite materials	Cross-laminated timber (CLT) Laminated veneer lumber (LVL) Glulam timber Wood fiber insulation boards (WFIB) Fiber-reinforced composites (FRIC)	Load-bearing walls Beams Stanchions Insulation boards Construction materials and interior designs	20% *w/w* out of which the individual product shares are the following: CLT: 14.1 % *w/w* LVL: 4.1 % *w/w* WFIB: 0.9 % *w/w* FRIC: 0.9 % *w/w*
Polymer products and bio-based resins and foams	Expanded Poly lactic acid (E-PLA) Premium Lignin for foams and resins (PRL)	Platform chemicals	32% *w/w* out of which the individual product shares are the following: E-PLA: 22.5 % *w/w* PRL: 9.5 % *w/w*
(Solid) energy carriers	Hydrolysis lignin (HEL) Biomethane (BM) Wood chips Sawmill byproducts (SMBP), bark residues	Solid biofuels Heat and Power	48% *w/w* out of which the individual product shares are the following: HEL: 39 % *w/w* BM: 7.5 % *w/w*

3.2. Results for Task 5: Scenarios for Integration of Material and Energy Flows within the Industrial Production Network

The basket of bio-based products, as presented in Table 2, can be produced in value-added networks that rely on different levels and options for the integration of residue flows from cross-sectoral cooperation partners, for heat recovery, and for waste recovery infrastructures. Furthermore, the levels of resource decoupling and fuel substitution can vary and can be implemented with a higher ambition level when aiming to substitute natural gas in process energy provisioning. In order to reflect these different levels of systems integration, three scenarios that were previously developed in an earlier study in the *Journal of Industrial Ecology* [5,51] were further used in this MCDA assessment study, as well. The order of magnitude of the material flows in the regional production system is also presented in Figures S2 and S3 in the Supplementary Materials. Figure 3 presents the three scenarios in a generalized scheme of wood-based industry networks.

Scenario 1 (baseline): The bioeconomy region is getting in shape.

A lignocellulosic biorefinery plant that produces bio-based polymers, lignin intermediates, and energy carriers is launching its operation; wood-based feedstocks and bio-based chemicals are shared across industrial parks, and capacities for engineered wood products are expanded. Energy utility infrastructures for producing heat, steam, and electricity are not shared, however, and the energy supply relies, to a large extent, on natural gas (80%). Furthermore, the production of bio-based resins and adhesives is only able to substitute 10% of the regional demand [5,51].

Scenario 2: The bioeconomy region integrates thermal cascades.

Production pathways are starting to become integrated; for example, the requirements for the process energy of plants in different industrial parks in the wood-based bioeconomy region are met by the energy cascading of nonrecyclable waste wood and sawmill by-products. This circular supply chain integration ensures the full decoupling of the regional process heat supply from natural gas by substitution with solid bioenergy carriers. This scenario assumes that 85% of fuels are provided by energy cascading from bioenergy and biomaterials facilities. A refiner plant to supply beechwood-based fibers to two different parks is run jointly by panel and composite manufacturers. However, bio-based production still replaces only 10% of the regional demand for resins and adhesives [5,51].

Scenario 3: The bioeconomy region becomes fully bio-based.

Industrial parks are fully integrating energy-cascading options and coupled-use schemes into their industrial networks for the production of bio-based materials (please refer to Figure 3). The demand for fossil-based resins and adhesives is completely substituted by lignin-based resins, and the industrial demands for fuel are fully met by non-recyclable wood-based resources [5,51].

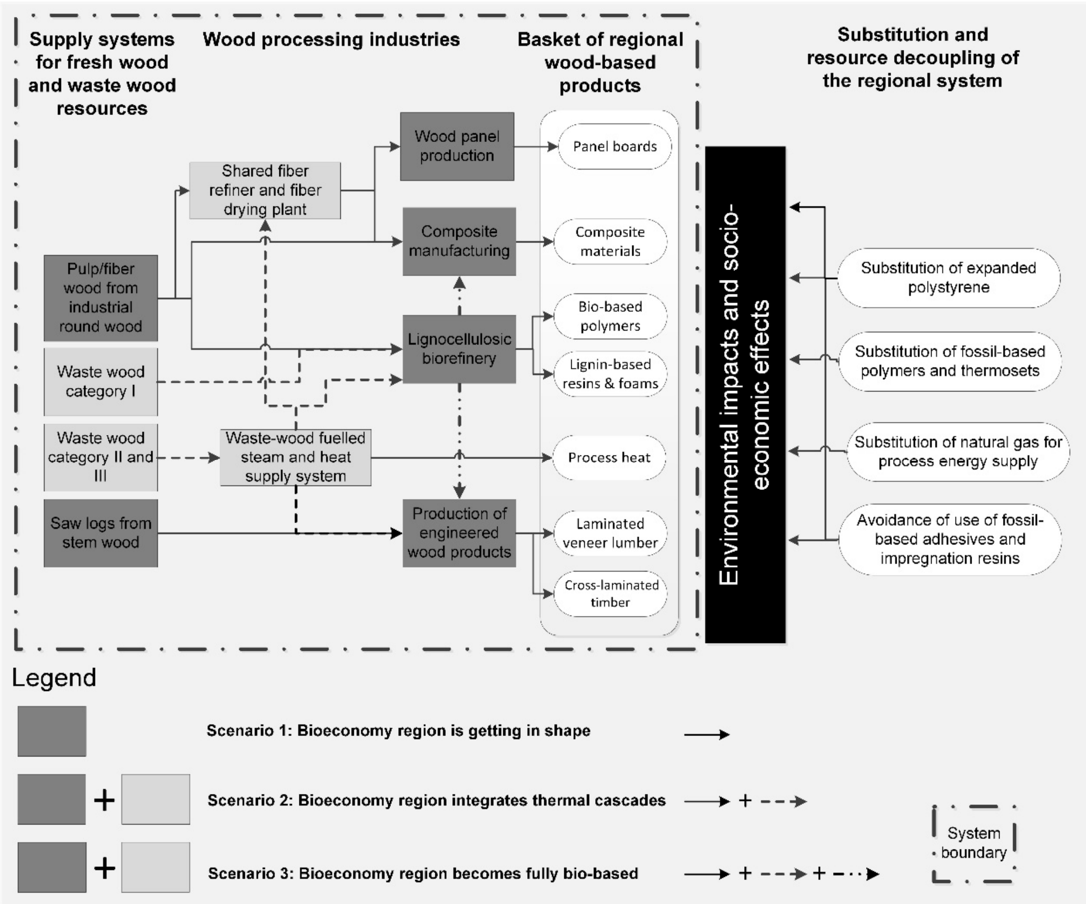


Figure 3. Substitution pathways in the wood-based production networks for the three scenarios.

3.3. *Results of Task 3: Deriving A Sustainability Goals System from A Review of Assessment Frameworks Assessing Circular (Bio-) Economy Strategies and Policies*

A broad set of sustainability criteria for potential bioeconomy regions, bio-based value chains, and process technologies was established and advanced in the past five years by different institutions [24,25,52–55]. Therefore, the aim of the literature review step was to identify suitable sustainability criteria that could support the identification of sustainability indicators that would be suitable for assessing wood production chains within the context of a bioeconomy region. As the case study region is located in Germany, the literature reviewed was mostly from European and German studies. An overview of the most comprehensive studies, as well as their associated relevant sustainability criteria, are provided in Table 3.

In order to pre-structure the identification and adaption of regionalized criteria, they were analyzed and discussed with regard to the question of which criteria would best suit the requirements for the assessment of wood-based production chains in Central Germany.

The scope of the different assessment frameworks covers a broad range of spatial scales, with some EU projects focused on the national level using national statistics, some focused merely on technology assessment, and others on the sustainable supply of biomass, while others assessed regional strategies or the sustainability of production chains.

In general, most of the reviewed studies implemented between 20 and 35 sustainability criteria, effectively using a "triple bottom line" approach (i.e., environmental, social, and economic dimensions) and focusing strongly on environmental aspects. However, the scope of the SUMINISTRO monitoring system is broader than those used in most of the projects outlined in Table 3, and it is not fully matched by any of those in the previously conducted projects. However, similar proposals and frameworks had broadly and commonly applied aspects, goals, and criteria of sustainability assessments that might be transferrable or that prove to be robust evaluation criteria. The SUMINISTRO tool aims to include, for example, greater socioeconomic criteria and indicators related to societies' decoupling of fossil-based products and indicators for assessing the efficient secondary raw material use and material flow integrations.

To date, in a number of these studies (Table 3), many of these indicators were not included, or the indicators that were used were not specific enough to account for more detailed strategic interventions in the cross-sectoral material flow architectures. Therefore, to set up an appropriate goal system and indicator sets for the management of regional resources and regional planning, it is particularly important to further specify inventory data and regional impacts that are neglected or considered with a low regional resolution within global, pan-European, or national assessment frameworks.

Table 3. Review of the sustainability criteria applicable to the assessment of bioeconomy regions [56].

Selected Impacts and Sustainability Metrics	Reference Number [a]						
	1	2	3	4	5	6	7
Technical and Environmental Criteria							
Biomass availability	x	x	x	x	x	x	x
Resource use efficiency	x		x		x		x
Energy efficiency	x		x		x		
Land use efficiency	x	x	x		x		
Cascading factors		x	x		x	x	x
Waste avoidance and minimization	x	x	x		x		x
Water use efficiency	x	x	x			x	x
Self-sufficiency of energy supply		x	x	x	x		x
Decoupling from use of fossil resources	x	x	x			x	x
Eco-design and Circular economy					x		
Renewable power and heat		x	x	x			x
Avoidance of persistent, toxic, and bioaccumulating substances		x			x		x
Decarbonization of the industry		x	x				x
Organizational and Socioeconomic Criteria							
Cluster and regional networking					x	x	x
Competitive products		x		x	x	x	x
R&D employment		x	x	x	x		
Employment of qualified/unskilled workers		x			x		
Average/Fair Income of employees		x					
Rate of formation of small and medium-sized enterprises (SMEs) and of start-up companies						x	
Creation of added value	x	x	x	x		x	
Public health and safety of workers							

[a] Legend: 1: Adler et al. 2015; 2: SAT BBE 2015; 3: S2BIOM Fritzsche and Iriarte 2015; 4: MCPFE 2002; 5: Geibler et al. 2010; 6: BERST 2014; 7: ToSia 2010.

3.4. Results for Task 4: Definition of Goals and Indicators Adapted to Suit Sustainability Priorities of Stakeholders from Central Germany

Most of the sustainability criteria identified from the literature do not exhibit an adequate regional resolution or practical requirements for precisely describing the sustainability performances of regional supply and conversion chains.

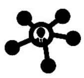
In the next task, the sustainability criteria were broken down into quantifiable indicator sets that were capable of being related to the functional units as either a direct indicator value or a qualitative score.

To characterize and specify these indicator sets and scores, Task 4 was therefore subdivided into four separate steps:

I. Identify sustainability goals for the regional wood-based bioeconomy system by breaking down sustainability goals compiled from interviews with local stakeholders and clustering them along the system compartments of the bioeconomy region;
II. Describe and quantify the underlying sustainability assessment rules and sustainability indicators along the value-added chains;
III. Define the evaluation functions and scoring techniques for calibrating the indicator values in the three future scenarios of value-added networks and the baskets of assessed products;
IV. Integrate the evaluation functions and indicator values from the sLCA framework developed by A. Siebert into the web-based evaluation platform of the monitoring tool [31,32,37,38].

The local stakeholders who were identified in a stakeholder analysis for the region of Central Germany and who were interviewed following a guiding question catalogue of semi-structured interviews are compiled in the list in Table 4. In the case study for Central Germany, the sustainability goal system and the sub-goals were adapted to the local context by interviewing the stakeholders as presented in Table 4. Within the semi-structured interviews the individual interview partners stressed different sustainability issues. Their replies on sustainability issues are clustered in Figure 4.

Table 4. Local stakeholders identified in stakeholder analysis to participate in semi-structured interviews and in a survey on sustainability goals for cluster members only.

Stakeholder Category		Interview Partners	Explanation
	Working health and safety and workers' rights	Industriegewerkschaft Bau Agrar Umwelt (IG B.A.U.) Sozialversicherung für Landwirtschaft, Forsten, Gartenbau (SVLFG)	Labor union representing workers in the German forestry industries Employer's liability insurance association in Germany
	Cluster management and cluster companies	Members of Cluster management of Leading-Edge Cluster BioEconomy in Central Germany Companies within the Cluster	The BioEconomy e.V. is supported by a team for Cluster management to steer the activities of the Leading-Edge Cluster BioEconomy
	Local government bodies	State Ministry for Science and Arts State Ministry for Science and Economy Regional planning organization	Department of State Government Department of State Government Organization for regional planning
	Societal groups, NGOs, and Academia	Friends of the Earth Germany (BUND) Forest Stewardship Council (FSC) Programme for the Endorsement of Forest Certification Schemes (PEFC) State forest organization Nordwestdeutsche Forstliche Versuchsanstalt	Association for environmental protection and nature conservation German branches of certification organization for sustainable forest management Forest organization owned by the government Research institute for forest owners, forest companies and politics from several federal states

Finally, the sustainability goals were aligned along the value-added chains (please refer to Figure 5) and were subsumed under the following three overarching sustainability goals (please refer to Figure 5 and to Tables 5 and 6):

(1) the maintenance of the resource base, which encompasses efficient resource mobilization and sustainable ecosystem management, as presented in Table 6;
(2) the increase in resource productivity, which encompasses efficient process operation and optimized added-value creation, as presented in Table 5; and
(3) the maximization of regional co-benefits and the minimization of impacts, which encompasses emission reductions, end-of-life management options, worker health, and safety and regional added-value creation, as published by Siebert et al. [37,38].

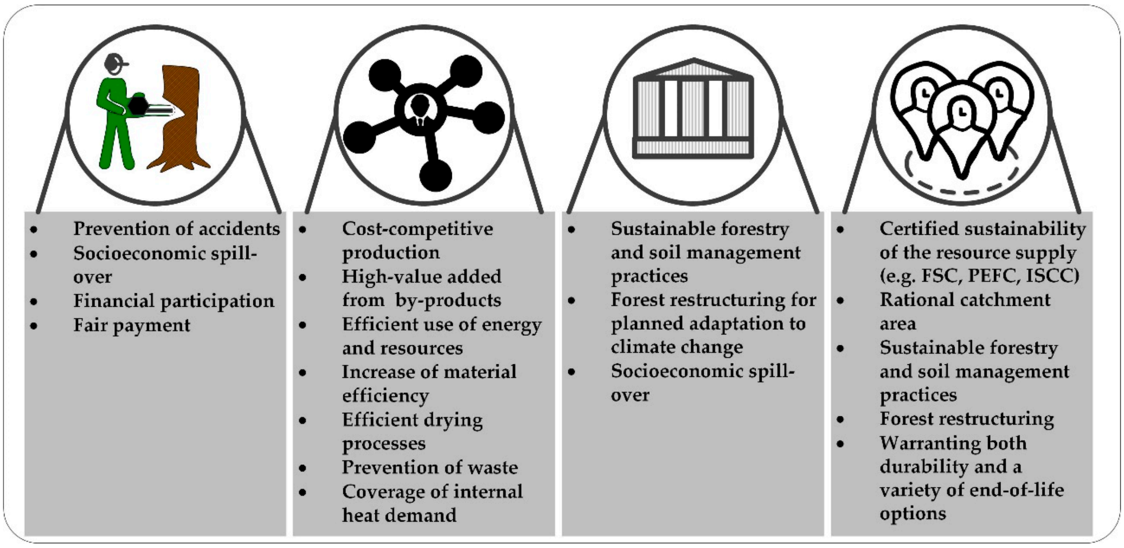


Figure 4. Sustainability issues stressed by interview partners and in member company surveys.

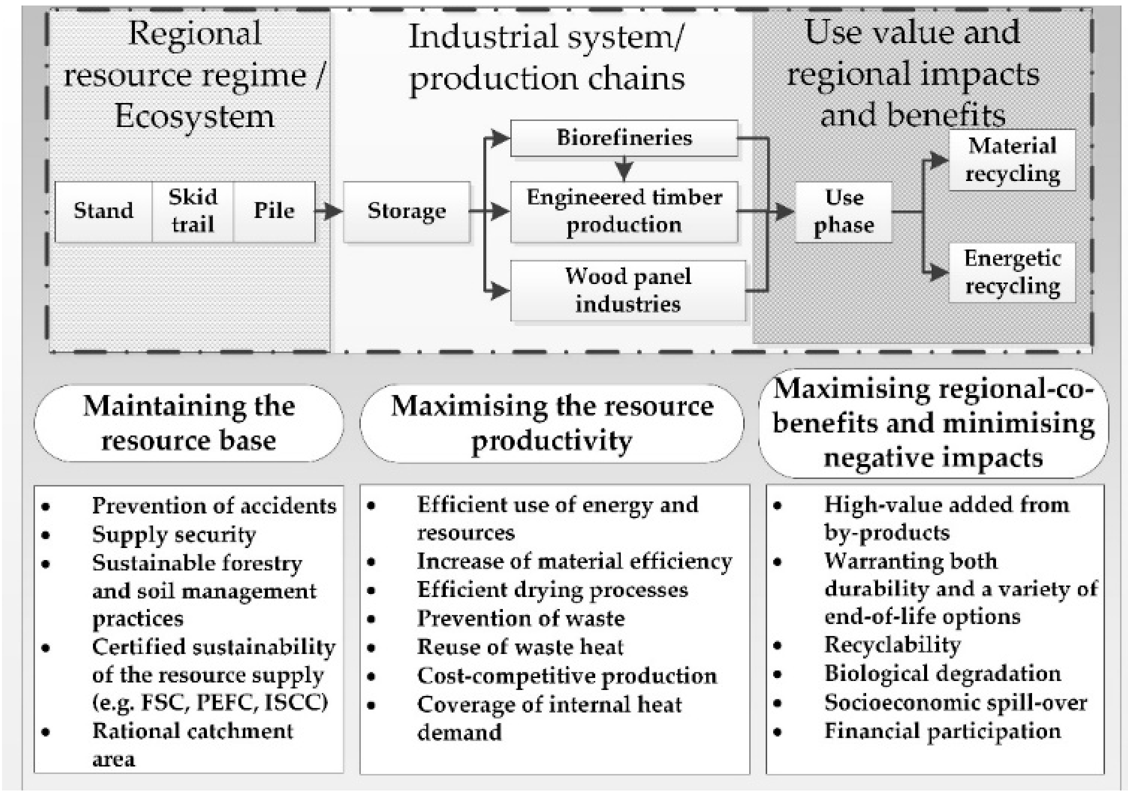


Figure 5. Aligning the sustainability goal system and the indicator sets along the value-added chains. The resulting sustainability goal system was then critically reviewed and validated in cooperation with the Cluster Management (CM) of the Leading-Edge Cluster BioEconomy.

As a result, Task 4 delivered a list of eligible indicators that were appropriate for monitoring the attainment degree of the overriding sustainability goals along the added-value chains (see Tables 5 and 6). The full procedure by which the sustainability goal system was operationalized with utility functions is presented in the Supplementary Materials, Tables S2–S11 and Table S13.

The goal system was adapted to (i) describe the system boundaries and system compartments of wood-based production systems, (ii) define regionally specific and globally valid sustainability goals, and (iii) identify specific and measurable indicators to assess the efficiency and sustainability of wood-based value chains in bioeconomy regions.

The approaches for deriving socioeconomic indicators and sustainability metrics correspond directly to the results presented in the articles "Social life cycle assessment indices and indicators to monitor the social implications of wood-based products" and "How not to compare apples and oranges: Generate context-specific performance reference points for a social life cycle assessment model" by Siebert et al. [37,38].

Table 5. Set of eligible indicators for monitoring resource productivity [56].

Category	**Index**			
Goal	**Sub-index**	**Indicator**	**Unit**	**Equation/Measure/Data Sources**
		Minimization of Water Use		
		Consumption of ground and surface water	m^3/t	Life-Cycle Inventories and Water Footprint data
		Maximization of the Efficiency in Use of Biomass Resources		
		Stoichiometric efficiency	% *w*/*w*	
		Flows of enthalpy	% E/E	Enthalpy of formation (products) compared to Enthalpy of formation
		Reduction of Fossil-Based Additives and Auxiliaries		
		More efficient use of resins and adhesives	% *w*/*w*	Life-Cycle Inventories for product specific resin dosing
		Substitution of fossil-based adhesives and resins	% *w*/*w*	Amount of fossil-based resins and adhesives substituted by alternatives
		Increase of Cascading Use of Bio-Based Secondary Raw Materials		
Maximization of the resource productivity		Reduction of waste in production chains	% *w*/*w*	
		Share of secondary raw materials in the input resources	% *w*/*w*	
		Reduction of the Cumulative Energy Demand		
		Increase of heat reuse and power generation from by-products	MJ/t	Inventory-based
		Reduction of steam and power demand	MJ/t	
		Reduction of Greenhouse Gas (GHG) Emissions		
		Carbon footprint for product basket	t $CO_{2\text{-eqv.}}$	Cumulated GHG emissions for entire production processes from cradle-to-gate
		Saved emissions	t $CO_{2\text{-eqv}}$.	Saved GHG emissions from gate-to-grave compared to substituted energy carriers and materials

GHG: Greenhouse Gas, MJ: Megajoule, *w*/*w*: Weight percentage.

Table 6. Set of eligible indicators for monitoring the sustainability of the resource base [56].

Category Goal	Index Sub-Index	Indicator	Unit	Equation/Measure/Data Sources
Maintaining the resource base	**Increase or Steady Extend of External Certification of Sustainable Forestry in the Catchment of the Wood Resources**			
		Fractions of input raw materials externally certified for their origin from sustainably managed forest catchments	% *w*/*w*	Questionnaire-based and inventory-based
	Maximization of the Recycled Share at the End of Product Life			
		Fraction of waste wood suitable for multi-stage cascade use	% *w*/*w*	Inventory- and scenario-based
		Fraction of polymers suitable for multi-stage cascade use	% *w*/*w*	Inventory- and scenario-based
	Increase of the Energy Self-Sufficiency of Utility Services such as Steam and Power			
		Cumulated heat and power produced from bark, wood chips, and other sawmill by products	kWh_{SS}/ kWh_{total}	Inventory-based
	Increase of the Share of Electricity from Renewable Sources in the Production Processes			
		Cumulated share of electricity provided from renewable sources in the overall electricity mix	kWh_{RE}/ kWh_{total}	
	Minimization of the Share of Imported Fossil-Resources			
		Cumulated share of fossil-resources (natural gas, resins, adhesives)	t/t Output	Inventory-based, cumulated consumption of non-renewable fossil resources

GHG: Greenhouse Gas, MJ: Megajoule, *w*/*w*: Weight percentage.

3.5. Results of Task 6: Calibration of Evaluation Functions

The scoring values for the definition of evaluation functions were clustered along the lower and upper boundaries of the current industry standards, the current best practices, and emerging next practice innovations (please refer to the seven selected examples of evaluation functions in Figures 6 and 7.

Both the qualitative specification of the lower and upper boundaries of the industry standards and the actual specification of quantitative reference values were compiled from product footprint results, e.g., Cumulative Energy Demand (CED) and Carbon Footprints (CFP), specified in other LCA studies [5,34,35,57,58]; from the energy demands and footprints compiled in benchmarking studies [59–64]; from Environmental Product Declarations (EPS) [65–67]; from the sLCA results of A. Siebert [29,37,38] and from the sources presented in Table S6 of the Supplementary Materials.

The scoring values range from 0 to 100 and thereby serve as normalization techniques adapted to the specific preconditions of each of the individual sustainability indicators. In essence, this ensures that all evaluation criteria are either assessed against quantitative reference values or are ranked according to qualitative scales.

In general, the simplest evaluation function requires at least four data points as reference values (x_{rv}) to be specified. When considering the whole set of 55 indicators that was specified, we found that it was necessary to specify between four and 13 reference values in order to compose a robust evaluation function for a single evaluation criterion.

The environmental and technical evaluation functions aggregate the different plateaus of performance that are typical of the different product groups and industrial standards in the chemical industry and the wood panel and woodworking industry.

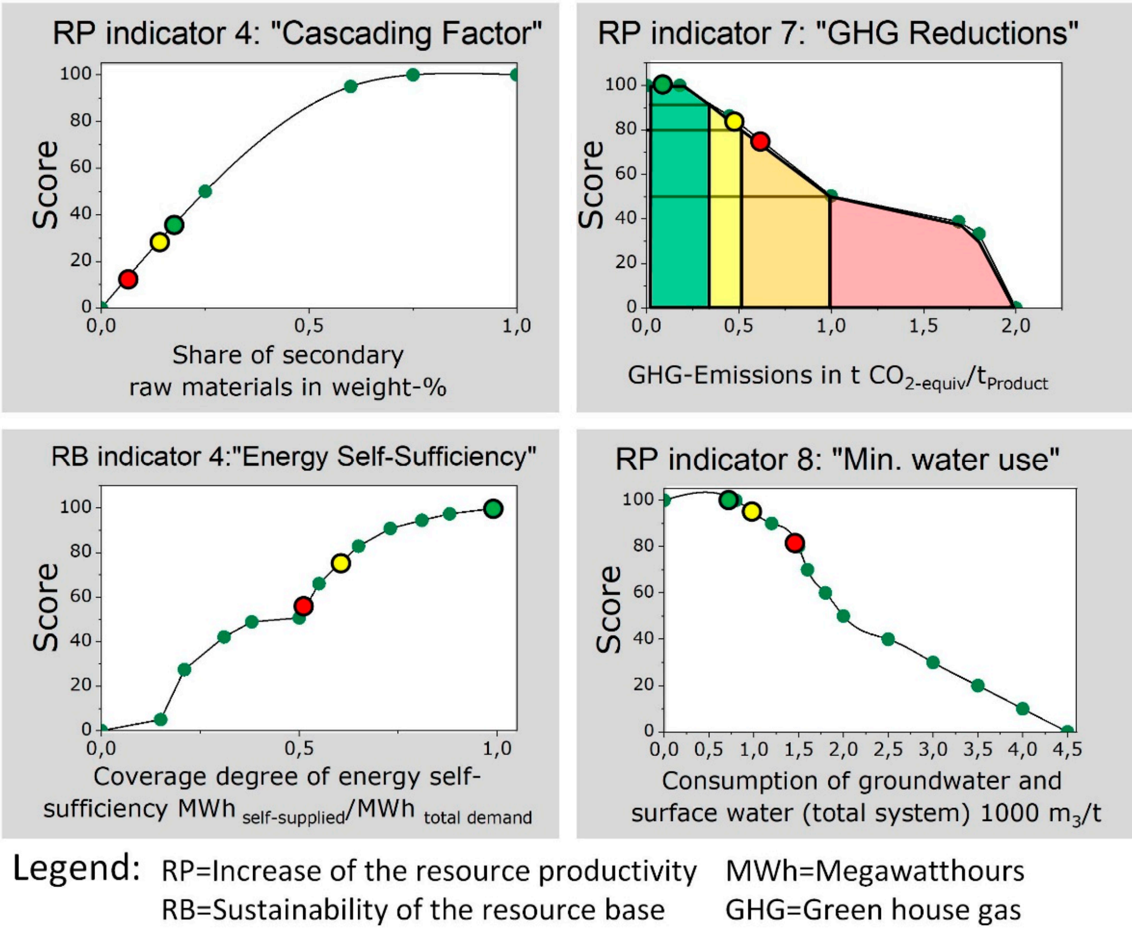


Figure 6. Calibrated functions for evaluating four exemplary technical and environmental indicators.

The scoring values on the y-axis are defined in the following manner:

- The lower-boundary plateau of the industry standard is scored with at least 50+, the industry's best practice is scored with 80+, and the next best practice development in the bioeconomy innovation system is scored for a performance plateau with above 80+.
- Every performance metric, e.g., resource use efficiency, renewable energy use, and energy self-supply, that falls below the industry standard is scored with <50 to 0.
- The ranges and steepness of the curves between the industries' standards and industries' best practices vary significantly and, therefore, require a higher fraction of reference values.
- For the product footprint (PF), e.g., water use and greenhouse gas (GHG) emission, the industry standard and industry's best practice are defined by the weighted average of the product footprints for the representative product groups produced within the sector associated with the production network assessed with the monitoring tool.

$$y(Score \geq 50) = x_{rv-PF-industry\ standard} \cdot \\ = \frac{m_{share\ of\ product\ 1} \times i_{Footprint\ Product\ 1} + m_{share\ of\ product\ n} \times i_{Footprint\ Product\ n}}{m_{total\ product\ basket\ Products\ 1....n}}. \tag{1}$$

For energy supply indicators and coverage degrees such as energy self-sufficiency and the ration of renewable energy in the supply mix the industry standard and industry's best practice were defined by using sector benchmarking results. The evaluation functions for individual added-value chains were compared with internal benchmarks such as the best performing product available on the market or best performing production systems running at an industrial scale.

For each of these plateaus and product groups, the monitoring tool incorporated the data available for the particular product's carbon footprint, for the particular efficiency criteria, e.g., available for polymer production processes in the chemical industry, for the sawing processes in the sawmill industry, for life-cycle inventories of wood products and for conversion efficiencies of bio-based plastics [59,60,62,68–70].

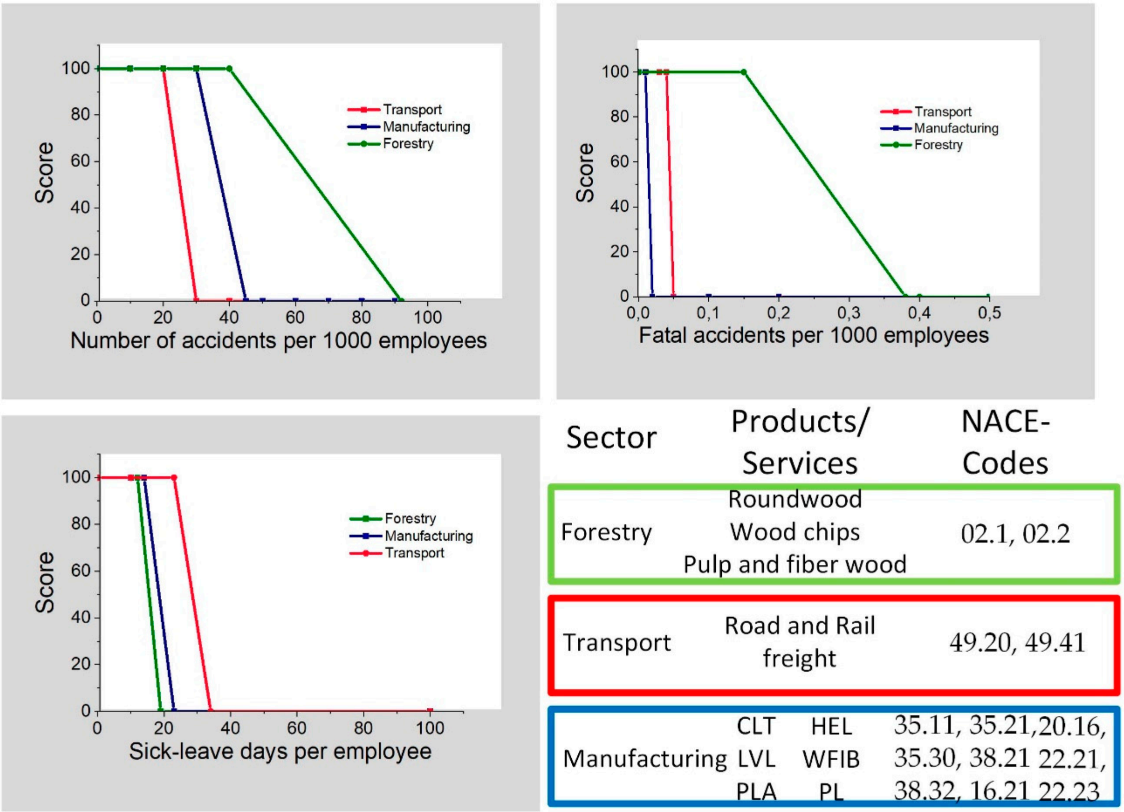


Figure 7. Evaluation functions for evaluating social indicators (Siebert 2017).

On the other hand, for aggregated evaluation functions, external benchmarks of global reference products, e.g., the carbon footprint of fossil-based counterparts, were also included to overcome indifferent plateaus when trying to aggregate the different sectors into one common baseline.

The full overview of the evaluation functions and the benchmarking results are provided in the Supplementary Materials in Tables S2–S13.

The functions for the evaluation of social indicators derived from the sLCA approach (Figure 7) basically rely on the same principle of allocating performance scores to each of the statistical reference data points. The anonymized reference data points were compiled from data from the Establishment Panel of the Institute for Employment Research (IAB), Federal Statistical Office. The socioeconomic indicators were characterized on the basis of the performance of reference organizations in the relevant economic sector (according to the NACE Codes for the classification of industry sectors) associated with the organizations under assessment (refer to Table 7). The indicator scores for the organizations were thus aggregated along the value chain [38].

Table 7. Integration of the social Life Cycle Assessment (sLCA) classification system into the product basket approach [56].

Products	Involved Industry Sectors	Associated NACE-Codes
• Molded plywood	Silviculture, Logging Transport, Manufacture of veneer sheets and wood-based panels	02.1, 02.2, 49.20, 49.41, 02.3, 16.21
• LVL	Silviculture, Logging Transport, Manufacture of veneer sheets and wood-based panels	02.1, 02.2, 49.20, 49.41, 02.3, 16.21
• CLT	Silviculture, Logging Transport, Manufacture of veneer sheets and wood-based panels	02.1, 02.2, 49.20, 49.41, 02.3, 16.21
• PLA • Lignin-based resins • Laminates and composites	Silviculture, Logging Transport, Manufacture of plastics in primary forms, Manufacture of plastics products, Manufacture of builders' ware of plastic	02.1, 02.2, 02.3, 2400, 49.20, 20.16, 22.21, 22.23
• Biomethane • Electricity from biogas • Hydrolysis-Lignin • Waste wood	Silviculture, Logging Transport, Manufacture of gas, steam, and air conditioning supply, waste treatment, and disposal, Recovery of sorted materials	02.1, 02.2, 49.20, 49.41, 35.11, 35.21, 35.30, 38.21, 38.32

3.6. Results of Task 5: Aggregating Social and Environmental Life-Cycle Inventories along the Indicator System

For each individual indicator short fact sheets defining the individual aggregation procedures of the indicator values along individual product systems were compiled [43]. Figure 8 provides some insight into four selected examples of these fact sheets and how they define the aggregation of the indicator values along the value-added networks for producing biorefinery products and for producing engineered wood products before aggregating them for the full basket of bio-based products. In Figure 8 these aggregation procedures are presented, considering Scenario 1 for the indicators (i) on the water footprint of the products, (ii) the share of sustainably certified forest resources, (iii) the biomass conversion efficiency, and (iv) the coverage degree in the self-supply of process energy. These procedures were then applied to individual value-added chains and value-added networks by calculating the weighted average of the value within the multi-output product system. The values for energy self-supply reflect the difference in the energy supply structures of the two value-added networks, e.g., steam provisioning for thermo-chemical processes such as fractionation and biotechnological processes such as lactic acid fermentation compared to wood manufacturing processes such as wood, fiber, and veneer drying. The energy self-supply in Scenario 1 stands in trade-off with biomass conversion efficiency for biorefinery products because in this Scenario energy carriers such as hydrolysis lignin are assumed to be exported out of the region. If a fraction of these energy carriers is used internally to further extend the energy self-supply, the coverage would rise, whereas the conversion efficiency might go down. Thus, finding material solutions for the valorization of a major share of hydrolysis lignin beside energetic use is paramount for optimized balancing of these indicators in the future such as implemented in the more advanced Scenarios 2 and 3.

The actual values of sustainability performance for each of the indicators were then weighted, accounting for the share of the respective product mass flows within the full basket-of-products. The weighted average for each indicator is presented as a non-normalized value in Table 8.

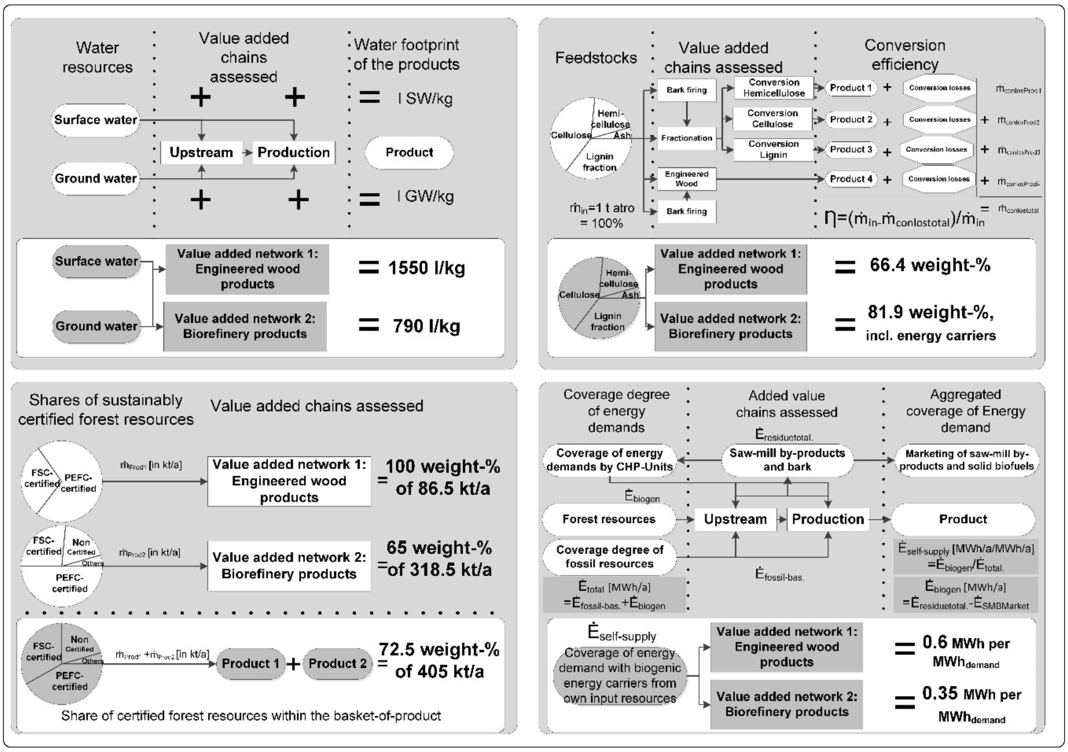


Figure 8. Aggregation of the indicator values in Scenario 1 for the water footprint, the biomass conversion efficiency, the share of certified forest resources, and the self-supply of process energy aggregated along the individual value-added networks.

Table 8. Non-normalized and weighted indicator sets for the basket-of-products in Scenario 1.

ID	Description of the Indicator	Unit	Benchmarking Ranges		Weighted Average
			Max.	Min.	
RP 1	Minimizing the consumption of fresh water	m^3/t	1383.15	739.0	**986.2**
RP 2	Increasing the biomass conversion efficiency	*w/w*	90.70	59.78	**78.8**
RP 3	Reduction of waste from fossil-based auxiliaries	*w/w*	0.07	0.02	**0.046**
RP 4	Cascading factor	*w/w*	1.33	1.00	**1.2**
RP 5	Reduction of cumulative energy consumption	MJ/t	58.18	23.49	**38.5**
RP 6	Maximizing land use efficiency (forest biomass, agroforestry, and agrarian biomass)	t saw logs/ha, t fiber/ha, t sugar/ha, t pulp/ha	14.13	4.90	**8.7**
RP 7	Reduction of GHG emissions	t CO_2-eqv./t	1.25	0.87	**1.035**
RP 8	Increase in material efficiency	U-Value, Tensile modulus	1.63	0.77	**1.1**
RP 9	Employment of highly qualified employees	% of total workforce	5.39	3.24	**4.0**
RP 10	Employment of marginally employed persons	% of total workforce	7.19	2.80	**6.2**
RP 11	Employment in research and development	% of total workforce	7.37	5.60	**6.3**
RB 1	Maximizing or Guaranteeing high standards of raw material provision	*w/w* [t Input certified, regional/t total input]	99.88	37.22	**74.0**
RB 2.1	Maximizing the recycled content at end-of-life		15.22	5.13	**9.8**
RB 2.2	Qualitative factor for multi-stage cascading	Extrusion and molding	0.84	0.76	**0.8**

Table 8. *Cont.*

ID	Description of the Indicator	Unit	Benchmarking Ranges		Weighted Average
			Max.	Min.	
RB 4	Maximizing the coverage degree of energy self-sufficiency	% [MWh $_{\text{Self-supply}}$/ MWh $_{\text{total demand}}$]	80.79	30.55	**43.1**
RB 5	Maximizing the share of renewable energy	%	65.92	38.46	**43.8**
RB 6	Proportion of imported fossil resources	%	78.09	45.45	**61.7**
RB 8	Adequate remuneration	Score from A. Siebert	7.57	4.64	**7.0**
RB 9	Minimizing the accident numbers	Score from A. Siebert	7.991	5.99	**7.0**
RB 11	Prevention of occupational diseases	Score from A. Siebert	6.807	4.00	**5.4**
RB 12	Minimizing the cases of illness	Score from A. Siebert	6.492	5.61	**5.9**
RB 13	Employees per 100 t moisture free wood (atro) processed into product output	MA/100 t atro	0.120	0.01	**0.035**
RB 14	Creation of training places	Score from A. Siebert	7.991	5.48	**7.0**
EB 3	Maximizing financial participation	Score from A. Siebert	4.889	1.20	**4.8**
EB 5	Improvement of working conditions	Score from A. Siebert	8.890	4.72	**6.2**
WS 1	Added-value creation (Distant second-best performer)	€/t	307.838	55.08	**233.4**
WS 2	Competitive production costs	€/t	483.638	736.4	**558.1**
WS 3	Potential for capacity expansion in the competition regime (input capacities)	Kilotons (kt)	2315.0	482.5	**632.663**

RP = all indicators under the sustainability goal: Maximizing the resource productivity. RB = all indicators under the sustainability goal: Maintaining the resource base. WS = all indicators under the sustainability goal: Maximizing added-value and Enhancing regional co-benefits.

3.7. Results of the Full Aggregation Procedure of the Monitoring Tool SUMINISTRO

The future value-added networks of the case study region were assessed by calibrating utility functions for 25 indices with 55 selected indicators for Scenario 1 (baseline): The bioeconomy region is getting into shape. In Figure 9, the results of the multi-criteria evaluation procedure for Scenario 1 are compared with the more ambitious future Scenarios 2 and 3. The absolute weighted indicator values for Scenario 1 are presented **in bold units** in Table 8. An overview of the normalized indicator values for all three scenarios is presented in Table S14 in the Supplementary Materials.

As normalization techniques, the MAUT theory, the ideal and reference point approach, and qualitative ranking approaches were applied. A comparative assessment of the Multi-Criteria Performance Scores was conducted for the three future scenarios, which specified and reflected the integration of regional wood-based added-value networks.

The results of the Multi-Criteria Sustainability Scores for Scenario 1 confirm the findings that adequate remuneration, a high level of energy self-sufficiency, a high level of efficiency in biomass conversion, a moderate aggregated carbon footprint for the presented basket-of-products, and acceptable land-use efficiency are already ensured by the baseline Scenario 1. In particular, the range of long-term durable engineered wood products and of durable products made from thermoplastic bio-based polymers will constitute a good starting point for fostering sustainable development of regional bioeconomy systems.

Considering the qualification of the workforce in the wood-based bioeconomy region, the shares of training and R&D positions will be enhanced over time from Scenario 1 to 3, compared with reference sectors, when more knowledge-intensive downstream processing is integrated into the value-added chains. Considering that the design innovations for more recycling-friendly products, the promised innovations in cascading use by increasing the shares of secondary raw materials, or better product recyclability are not yet observable in the upscaling of the suggested product innovations. However, without innovations already within the product design, the uptake of near infra-red (NIR) sorting technologies for PLA recovery in the recycling sector will support the bioeconomy region in increasing the recovery of secondary raw materials of wood-based polymers [27].

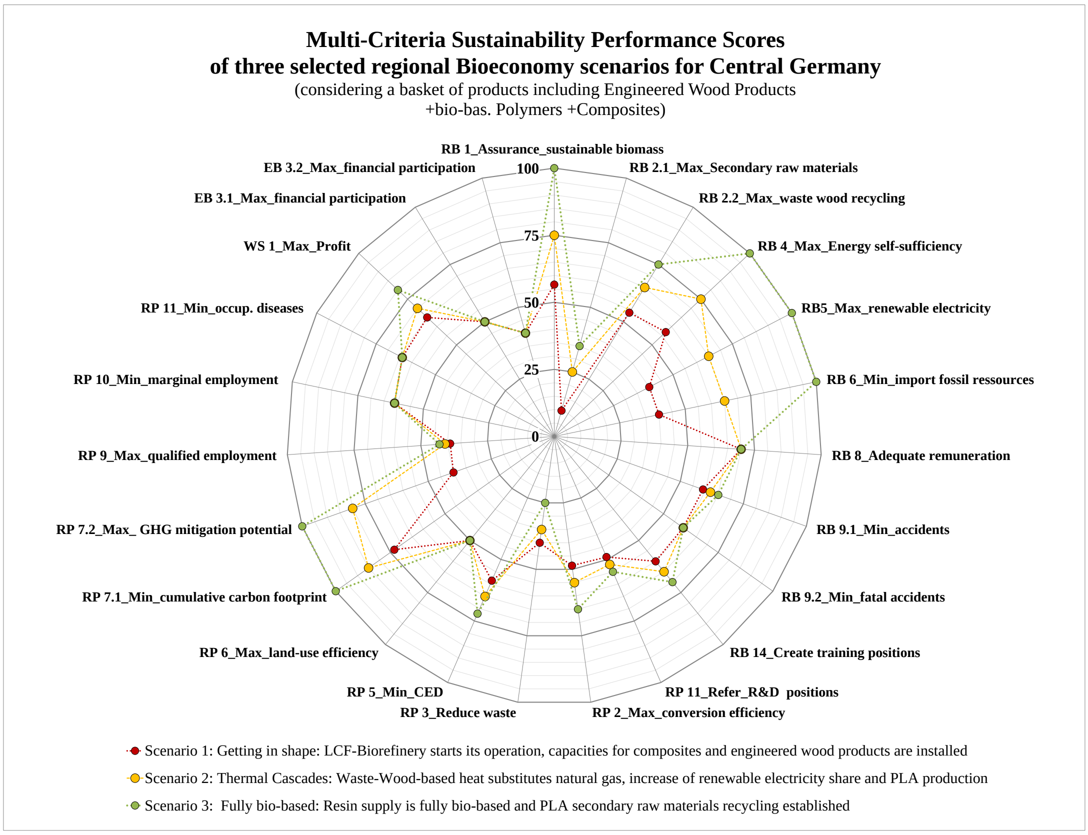


Figure 9. Multi-Criteria Sustainability Performance Scores of three selected regional wood-based bioeconomy scenarios for the case study region of Central Germany.

The sustainability assessment showed that potential trade-offs, e.g., between energy-intensive processing routes and the degree of coverage of process energy, and major potential for synergies could persist for a considerable amount of time when shared infrastructures for heat supply from bark residues, sawmill byproducts and waste wood are not realized. Conversely, the installation of waste-wood-fired cogeneration and boiler units and the shared use of process heat by these installations supplied, as represented by Scenarios 2 and 3, will support the meeting of an array of sustainability goals, particularly the goals for increasing energy self-sufficiency, mitigating GHG emissions, and minimizing the import of fossil fuels. Furthermore, the persistant dependence on fossil fuels in the logistics and supply of natural gas and resins will be difficult to solve when decoupling strategies are not incorporated into primary investment in planned capacity installations.

Both the weighted and aggregated single-score and non-weighted radar plot results of the applied normalization techniques for Scenario 1 showed that in almost all evaluation categories and for all sustainability criteria, the performance scores were below 60 and the overall score was approximately 55 out of an attainable score of 100.

When striving to attain the 55–45 scores missing for the best performance, a scenario comparison showed that this is only possible when further emission reductions, more intelligent logistics, enhanced thermal integration and cascading use, and a more consolidated employment strategy with the softwood processing industry sectors are rigorously rolled out in the implementation of more sustainable, regional Life Cycle Management strategies.

4. Discussion

This discussion section summarizes the achieved results of specifying the sustainability monitoring tool and reflects on the achieved novelties and benefits and possible shortcomings of the conducted methodology. By operationalizing the described specification procedures, the sustainability monitoring tool SUMINISTRO, in its finalized version, is capable of identifying and quantifying not only the priority areas in which good sustainability performance can be achieved, but also the priority areas in which deficits in regional sustainable development will persist or occur in the future (please refer to the benchmarking table in the Supplementary Materials and to Figure 9).

SUMINISTRO provides a fully operational and region-specific assessment platform that aggregates a broad set of well-established indicators (such as material intensity and resource productivity) and specifies upcoming indicator aspects associated with biomass use efficiency in the bioeconomy, as known from, for example, the concept of biomass utilization efficiency (BUE) [69], indicators for cascading [27,31], and socioeconomic indicators from the sLCA approach RESPONSA, as developed and applied in [29,37,38,71]. Considering the geographical scope, the monitoring tool is especially powerful in assessing local and super-regional integrated production systems within bioeconomy regions, which is different from many of the assessment frameworks developed in an international context [72]. By integrating the data from its own LCA studies conducted in cooperation with material scientists from the cluster networks [34] and the LCA data from research partners in biorefinery research [35], the MCDA tool brings light into the black box of industrial R&D activities, more in-depth than studies that focus on input-output analysis for comparative cluster benchmarking [73]. This allows for a precisely contextualized internal benchmarking and tracing of progress towards intraregional sustainable development, even though comparison of social and policy indicators [73,74] with other bioeconomy clusters, which rely on other biomass resources or on other biotechnologies [75], might be partially compromised by this approach. But for practical decision support we regard the strength of this regionalized MCDA approach in providing in-depth insights into the regional sustainability of industrial innovation systems for local stakeholders and local industrial R&D practitioners. Therefore, the major strength lies in the aggregation all along the regional bio-based value-added chains, from single-unit process modules up to full individual value-added chains, with even more aggregation towards the assessment of full scenarios for integration options of regional added-value networks. However, the approach is not directly used, for example, to assess whether regional production systems contribute to the meeting of Sustainable Development Goals [76,77], but the data can form a strong and valid database and aggregation point to further couple SDG-related and sLCA-related assessment studies with [71].

The integration of sLCA assessment approaches that derive their evaluation functions from sector-based benchmarking data and the aggregation of the multi-criteria assessment method is capable of assessing both individual value-added chains and more aggregated added-value networks [37,71]. The developed monitoring tool is quite specific to the German wood-based bioeconomy [10]. However, the indicator sets used for the assessment also allow for adapting the monitoring tool to bioeconomy valued-added chains that rely more on agricultural biomass.

As the major focus is on high regional resolution and decision support for lignocellulosic biorefinery clusters and the wood-based bioeconomy, possible shortcomings that fall out of the scope of the SUMINISTRO framework are the integration of marine biomass-based value chains more common in the Nordic bioeconomy [73] that could potentially emerge in the blue bioeconomy.

With its focus on regional scale indicators it can be seen as complementary both to multi-regional input-output (MRIO) approaches [78] as well as to more national or European assessment frameworks for bioeconomy monitoring [79].

5. Conclusions and Further Research Needed

This conclusion section reflects on the benefits and deficits identified in the regional case study system, identifies underlying causes, and provides recommendations for cluster practitioners regarding strategy readjustments that could help to overcome these deficits. Further research that should be conducted to support regional bioeconomy networks is also discussed.

The deficits identified for several aspects of efficient resource use and cascading options and their infrastructural and design-related causes should be considered as important leverage points when strategic alignment and future R&D in novel product development strategies are envisioned.

From the different assessment perspectives evaluated in the MCDA assessment tasks, several operational conclusions can be derived from the case study application and its meta-analysis. The findings and their meta-analyses are discussed in the following paragraphs according to the two major domains to which they belong: (i) the practical perspective for strategy alignment, and (ii) the perspective of future research for further tracing the impacts of bioeconomy strategies and concepts.

Regarding (i), the practical perspective for strategy alignment, we highlight the benefits, positive outlooks, and progress that can be expected from the expansion of future production systems:

- The marketing of engineered wood products is a safe start, with a robust market perspective and a strategically good outlook for the assessed region and beyond [80].
- The expansion of production capacities of around 90,000 to 160,000 t/a stays within the limits of European market growth potentials [80] and regional biome productivity potentials in a supply radius of around 150 km [81].
- The substitution of up to 20% of the total consumption of fossil-based resins, adhesives, and foams is technically possible and environmentally beneficial.
- The use of debarking residues and the installation of waste-wood-fired heat and power plants as thermal integration options for energy provision for wood-based value chains offer many opportunities for fully covering the energy demands of the regional bioeconomy network [5].
- From the environmental perspective, the integration of lignocellulosic biorefineries into wood-based value chains and the production of bio-based polymer products offer significant potential for the reduction of environmental impacts [5,36].
- Work safety will increase with higher mechanization in harvesting, increased automatization in production plants, and higher shares of employees in R&D and product design activities.
- The socioeconomic performance, in terms of remuneration and the specific numbers of R&D employees, is more preferable against the benchmarks of the chemical and biotechnology sector compared with those of traditional wood-based industry sectors.

Regarding (i), the practical perspective for strategy alignment, the negative impacts and emerging risks that can be expected when expanding future production systems while simultaneously increasing their dependency on adapting to climate risks in forest restructuring, need to be considered:

- The expansion of capacities for the production of engineered wood products (EWPs) above 160,000 t/a implies increased market saturation risks when considering overall market developments [80], as well as increased transport burdens and super-regional resource competition conflicts.
- The resource supply is especially dependent on the supply of higher breast-height-diameter assortments and on sustainably sourced materials. For these assortments, the desired qualities may face shortages, particularly when drought events and calamities further limit the supply of saw logs by increasing the amount of damaged wood in the short term [82], and forest regrowth patterns limit the availability in the long term [81]. Thus, the major consequence of adapting to drought events in long-term forest restructuring will be a switch to the selection of more drought-tolerant individuals [83] or the remodification of the mixture of tree species [84] in silviculture management.
- Besides the EWPs, the use, decommissioning, and recycling phases for long-term durable bio-based polymer products and thermosets also have a lot of uncertainties with regard to the use of flame retardants, stabilizers, and future end-of-life treatment options such as feedstock recycling [27].
- To date, improving the design for recyclability has not been promoted as a high priority, but is rather outweighed against wood modification measures for enhancing the durability of beechwood-based products [10,85].

- The large-scale substitution of commodity chemicals only on the basis of non-food biomass resources from beechwood is not an option when comparing regional production capacities of fossil-based chemicals of above 560,000 t/a of olefins, e.g., [19]. The mobilization of further feedstocks (e.g., from short rotation coppices) and the clear prioritization of bio-based polymer preferences (e.g., polymers selected on the basis of biomass conversion efficiencies) will therefore become necessary in the mid-term [69].
- The overall job creation potential is not increasing, and absolute figures are even dropping in conventional woodworking companies [86]. In the mid-term, it can be expected that a stable plateau can be obtained by increasing the utilization of beechwood resources, but advancements of the overall situation are more unlikely.

Regarding (ii), the perspective of future research needed, we suggest that the following findings be further addressed in future studies.

The tracing of future demand-driven market developments and cost competitiveness for the identified basket-of-products was not included in the assessment because the data aggregation procedure did not include data elicitation for (1) the full-cost accounting of production facilities and of future market prices for novel polymer products, and (2) estimating the willingness-to-pay for bio-based premiums. Future research should therefore focus on the development of databases and agent-based modeling approaches that support the exploration of future market potential and development trends in the uptake of bio-based products in the building sector, the plastic packaging industry, the automotive industry, the energy sector, and the fashion industry.

Supplementary Materials: The following supplementary materials are available online at http://www.mdpi.com/2071-1050/12/9/3896/s1 in a single file for the bundling of Figures S1–S3 and Tables S1–S14. Figure S1: Analytical and conceptual framework of the MCDA tool "SUMINISTRO", Figure S2: Sankey Chart representing the material flows for Scenario 1, Figure S3: Sankey Chart representing the material flows for Scenario 2, Table S1: Material and sectoral specifications of the assessed product basket, Table S2: Qualitative scale for Indicator RB 1 "Maximizing or Guaranteeing high standards of raw material provision", Table S3: Utility function for Indicator RB 4 "Increase of energy self-sufficiency", Table S4: Utility function for Indicator RP 4 "Cascading factor", Table S5: Qualitative scale for Indicator RP 5 "Reduction of cumulative energy consumption", Table S6: Utility function for Indicator RP 7 "Reduction of GHG emissions", Table S7: Utility function for Indicator RP 8 "Minimization of water use", Table S8: Utility function for Indicator RB 8 "Adequate remuneration", Table S9: Utility function for Indicator RB 9.1 "Minimizing the accident numbers", Table S10: Utility function for Indicator RB 9.2 "Minimizing the accident numbers", Table S11: Utility function for Indicator RB 11 "Prevention of occupational diseases", Table S12: Overview of the indicator benchmarking and the weighted average of the calibrated indicators for scenario 1 as non-normalized absolute figures, Table S13: Sources used in indicator benchmarking, Table S14: Normalized results for scenarios 1, 2 and 3 as presented in the radar plot in the results section.

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