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A holistic life cycle sustainability assessment for bioeconomy regions

Linking regional assessments, stakeholders and global goals

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A Holistic Life Cycle Sustainability Assessment for Bioeconomy Regions

Linking Regional Assessments, Stakeholders and Global Goals

A DISSERTATION

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Dr. Ing.

Presented by

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Abstract: Since about 2015 the social, environmental and economic risks and chances of the bioeconomy and economy in general are becoming increasingly the subject of applied sustainability assessments. Under a bioeconomy, a variety of industrial metabolisms, strategies and visions on substituting fossil resources by renewables and hereto associated societal transformations is formulated, characterized as regional bioeconomy if most foreground activities take place in a specific region. Based on the life cycle assessment (LCA) methodology, further social and economic LCA approaches were developed in previous research whereby life cycle sustainability assessment (LCSA) aims to combine or integrate the evaluation of social, environmental and economic effects. In this early stage of rudimentary and combinatory LCSA development, the research questions of this work are to develop a transdisciplinary framework for integrated LCSA for regional stakeholders to assess ecological, economic and social sustainability in one harmonized method, as well as to implement, apply and validate it by two regional case studies.

Therefore, i) the understandings of sustainability and approaches of sustainability assessment in LCA are transdisciplinary reflected and developed, ii) a systemic framework of the important aspects of such assessments is structured by a series of stakeholder workshops, iii) the methods and indicators from existing LCA approaches as well as from bioeconomy monitoring systems are selected, identified and allocated to a sustainability concept of holistic and integrated LCSA (HILCSA), iv) databases for the life cycle inventory and methods for life cycle impact assessment are implemented in a software, as well as v) the model and method is applied and validated in two case studies on laminated veneer lumber production and production of biofuels in central Germany.

Based on previous research, the dissertation provides a theoretically well based and practically applicable framework for integrated life cycle sustainability assessment, an applicable indicator set for regional (product & territorial) bioeconomy assessment, an integration of life cycle impact assessment methods as well as their comprehensive interpretation. Thereby, LCSA is able to identify the contribution of regional bioeconomy product systems to 14 out of 17 Sustainable Development Goals in terms of planetary boundaries, a sustainable economy and societal needs. The presented results on material and energetic use cases of biomass show that integrated assessments are able to deliver a broad and comprehensive analysis of impacts to identify synergies, trade-offs and hot spots of regional bioeconomy. Compared to existing LCA and LCSA methodologies, the added value of the HILCSA methodology is its integrated and holistic character, which [1] allows consistent and comparable data on social, ecological, and economic indicators, [2] identifies synergies and trade-offs between different aspects and SDGs, [3] traces down impacts to regions in the fore-and background systems, [4] as well as allocates and aggregates them to the SDGs to make complexity communicable. Additionally, HILCSA takes social sciences and political economy into account from beginning to interpretation and discussion of results, relating to social, environmental, and economic impacts not only to technologies but also to societal, economic, and political questions.
Keywords: bioeconomy; sustainability; life cycle sustainability assessment; life cycle assessment

Curriculum Vitae

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Walther Zeug

Leipzig, 10. July, 2023

Declaration of Academic Integrity

I hereby declare that I have composed this dissertation myself and without inadmissible outside help, in particular without the help of a doctoral consultant (Promotionsberater). I have used no other sources and aids than those stated. I have indicated all text passages that are incorporated, verbatim or in substance, from published or unpublished writings. I have indicated all data or information that is based on oral communication. All material or services provided by other persons are indicated as such.

Walther Zeug

Leipzig, 10. July, 2023

List of Publications

This thesis is based on the following papers, which are appended in Part II to the introductory chapters in Part I according to the following numeration:

Paper 1
Zeug W, Bezama A, Moesenfechtel U, Jähkel A, Thrän D (2019) Stakeholders' Interests and Perceptions of Bioeconomy Monitoring Using a Sustainable Development Goal Framework. Sustainability 11:1511. https://doi.org/10.3390/su11061511

Paper 2
Zeug W, Bezama A, Thrän D (2020) Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements vol 07. Helmholtz-Centre for Environmental Research (UFZ), Leipzig. https://doi.org/10.13140/RG.2.2.16912.02564

Zeug W, Bezama A, Thrän D (2023) Life Cycle Sustainability Assessment for Sustainable Bioeconomy, Societal-Ecological Transformation and Beyond. In: Progress in Life Cycle Assessment. Sustainable Production, Life Cycle Engineering and Management. Springer.

Paper 3
Zeug W, Bezama A, Thran D (2021) A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. Int J Life Cycle Ass https://doi.org/10.1007/s11367-021-01983-1

Paper 4
Zeug W, Bezama A, Thran D (2022) Application of holistic and integrated LCSA: Case study on laminated veneer lumber production in Central Germany. Int J Life Cycle Ass 27:1352-1375. https://doi.org/10.1007/s11367-022-02098-x

Paper 5
Zeug W, Bezama A, Thrän D (2023) Holistic and integrated life cycle sustainability assessment of prospective biofuel production in Germany.

Related work was and will be published in the following documents:

Zeug W, Kluson F, Mittelstädt N, Bezama A, Thrän D (2021) Results from a Stakeholder Survey on Bioeconomy Monitoring and Perceptions on Bioeconomy in Germany. Helmholtz-Centre for Environmental Research, Leipzig. https://doi.org/10.13140/RG.2.2.35521.28000

Jarosch L, Zeug W, Bezama A, Finkbeiner M, Thran D (2020) A Regional Socio-Economic Life Cycle Assessment of a Bioeconomy Value Chain. Sustainability 12 https://doi.org/10.3390/su12031259

Gan Yupanqui KR, Zeug W (Forthcoming) A social life cycle assessment of a second-generation biofuel production system in east Germany.

Contribution to the Publications

The PhD candidate made the following contributions to the appended publications. The authors' names are abbreviated as follows: Walther Zeug: W.Z.; Daniela Thrän: D.T.; Alberto Bezama: A.B.; Urs Moesenfechtel U.M.; Anne Jähkel A.J.; Karla Raquel Gan Yupanqui: K.G.

Publication	Authors Contribution
Zeug W, Bezama A, Moesenfechtel U, Jähkel A, Thrän D (2019) Stakeholders' Interests and Perceptions of Bioeconomy Monitoring Using a Sustainable Development Goal Framework. Sustainability 11:1511. https://doi.org/10.3390/su11061511	D.T., U.M., A.J., and W.Z. prepared the workshops and carried out, supervised, and evaluated them. W.Z. did the data curation and general analysis as well as the conceptualization, writing, management, and submission of this research article. The manuscript has been edited by A.B. and D.T. and reviewed by all authors.
Zeug W, Bezama A, Thrän D (2020) Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements vol 07. Helmholtz-Centre for Environmental Research (UFZ), Leipzig. https://doi.org/10.13140/RG.2.2.16912.02564	W.Z. conducted the research, general analysis, conceptualization, writing, management, and submission of this research article. The manuscript has been edited by A.B. and D.T. and reviewed by all authors.
Zeug W, Bezama A, Thrän D (2023) Life Cycle Sustainability Assessment for Sustainable Bioeconomy, Societal-Ecological Transformation and Beyond. In: Progress in Life Cycle Assessment. Sustainable Production, Life Cycle Engineering and Management. Springer.	W.Z. conducted the research, general analysis, conceptualization, writing, management, and submission of this research article. The manuscript has been edited by A.B. and D.T. and reviewed by all authors
Zeug W, Bezama A, Thran D (2021) A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. Int J Life Cycle Ass https://doi.org/10.1007/s11367-021-01983-1	W.Z. conducted the research, general analysis, conceptualization, writing, management, and submission of this research article. The manuscript has been edited by A.B. and D.T. and reviewed by all authors.
Zeug W, Bezama A, Thrän D (2022) Application of Holistic and Integrated LCSA: Case Study on Laminated Veneer Lumber Production in Central Germany, forthcoming	W.Z. conducted the research, general analysis, conceptualization, writing, management, and submission of this research article. The manuscript has been edited by A.B. and D.T. and reviewed by all authors.
Zeug W, Bezama A, Thrän D, Gan Yupanqui KR (Forthcoming) Holistic and integrated life cycle sustainability assessment of prospective biofuel production in Germany.	W.Z. conducted the research, general analysis, conceptualization, writing, management, and submission of this research article. K.G. partially provided social indicator data. The data was interpreted and the manuscript edited by A.B. and D.T. and reviewed by all authors.

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Content

Part I Overarching Introduction

The present work is part and result of a cumulative dissertation prepared from 2018 to 2023, and is divided into an overarching introduction (Part I) and appended publications (Part II) (Figure 1). Part I represents a summary and synthesis of the publications in Part II. This dissertation is structured by the following steps:

i) Transdisciplinary reflection and development of understandings of sustainability and sustainability assessment in LCA (Zeug et al., 2020; Zeug et al., 2023b),
ii) Development of a systemic framework of the important aspects of such assessments by a series of stakeholder workshops (Zeug et al., 2019; Zeug et al., 2021b),
iii) Selection, identification and allocation of methods and indicators from existing LCA approaches as well as from bioeconomy monitoring systems to a sustainability concept of holistic and integrated LCSA (HILCSA) (Zeug et al., 2021a),
iv) Implementation of databases for life cycle inventory and methods for life cycle impact assessment in a software (Zeug et al., 2021a, 2022; Zeug et al., 2023a), as well as
v) Application and validation of the model and method in two case studies on laminated veneer lumber production and production of biofuels in central Germany (Zeug et al., 2022; Zeug et al., 2023a).

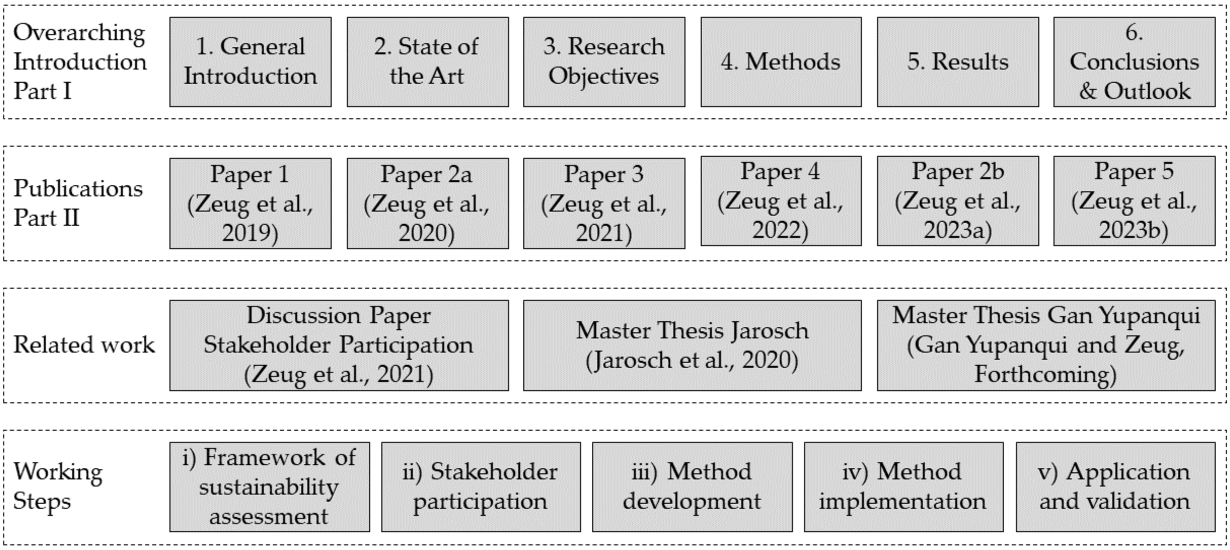


Figure 1. Structure and working steps of the dissertation “A Holistic Life Cycle Sustainability Assessment for Bioeconomy Regions”

1. Introduction

Sustainability has become a global value for science, organizations, governments, non-governmental organizations (NGOs), and other civil society actors (Future Earth, 2016). As one considerable option to achieve sustainable development, in line with the European Bioeconomy Stakeholders Manifesto, bioeconomy (BE) can be understood as "the production of renewable biological resources and the conversion of these resources, residues, by-products and side streams into value added products, such as food, feed, bio-based products, services and bioenergy" (The Bioeconomy Stakeholders Panel, 2017). However, renewable does not necessarily mean sustainable, since sustainability is not an intrinsic characteristic but rather a promising potential of BE. The vast majority of all BE and sustainability related research publications see conditional benefits but many others have a perspective of tentative criticism on BE when it comes to sustainability or even state a disadvantageous impact; only for a few and mainly on processing and technology focusing publications, sustainability was an inherent characteristic (Pfau et al., 2014).

More than 50 countries worldwide have created BE-related policy strategies, however, just a few of them, such as the EU and Germany, have established specific and integrated BE strategies and action plans (Bell et al., 2018; German Bioeconomy Council, 2018; Kleinschmit et al., 2017; Meyer, 2017) or institutions like the German BE Council. Most of these strategies mainly embrace the challenge of enabling biobased transformation, and only a few try to address potential risks and goal conflicts like environmental and social challenges politically (Dietz et al., 2018). Instead, many name vague interrelationships between economic, environmental, and social issues and mainly reflect an economic perspective (de Besi and McCormick, 2015; Ramcilovic-Suominen and Pülzl, 2018; Staffas et al., 2013). Within the EU's BE strategy, the substitution of fossil carbon by renewable materials plays a big role in key industrial sectors such as chemicals and pharmaceuticals (Bell et al., 2018), which illustrates the potential in addition to the still very important energy production (O'Keeffe et al., 2019) and primary sectors in rural regions (Bezama et al., 2017; Egea et al., 2018; Korhonen et al., 2018). In general, there is hope of a more ecological and sustainable growth that will allow both; the material prosperity of the capitalist industrial nations at the present level and future growth, as well as making this level possible for the ever-increasing world population in the periphery within ecological limits (BMBF, 2014; Kleinschmit et al., 2017).

However, apart from additional growth, the vast majority of European countries have not achieved the Paris Agreement goals yet (Climate Action Network Europe, 2018) and additional environmental risks can result from an intensified and increased use of biobased resources (Hasenheit et al., 2016; McCormick and Kautto, 2013; Spangenberg and Kuhlmann, 2020), especially the shift of risks to other countries through imports and global market effects (Backhouse et al., 2021; Budzinski et al., 2017; Giljum et al., 2016). The environmental challenges our global societies face are not only related to climate change, as it is likely that humanity is about to cross several planetary boundaries (PB) - representing the ecological limits of our planet – with feedbacks difficult to handle and partly irreversible (O'Neill et al., 2018; Rockström et al., 2009; Steffen et al., 2018). Practically no country performs well on both the biophysical and social dimensions, being the general rule that the more social needs are achieved, the more biophysical boundaries are transgressed, and vice versa (O'Neill et al., 2018). Fulfillment of societal needs is seemingly directly coupled with transgressing PB (Haberl et al., 2012; O'Neill et al., 2018). Such complex and interdependent challenges on a national and international level need holistic and systematic perspectives and solutions for structural societal change (Schütte, 2018; Thrän et al., 2020). Thus, a gradual change from biotechnology-centered visions to in general transformation-centered visions can be observed (Meyer, 2017). It should be the goal of a global BE to meet several big societal challenges (The Bioeconomy Stakeholders Panel, 2017) represented by the Sustainable Development Goals (SDGs) (El-Chichakli et al., 2016; Weidema et al., 2020). The SDGs are considered as the most appropriate goal system of holistic sustainable development available due to its virtually democratic legitimacy, wide recognition and internationally comparable indicator framework (Bosch et al., 2015; Nilsson and Costanza, 2015; Sachs et al., 2017; UN, 2017) and for these reasons increasingly becoming an overarching topic in BE strategies (EC, 2018), policies and action plans (German Bioeconomy Council, 2018; Schütte, 2018).

So, on the one hand it is crucial and urgent to define and broaden the scope of holistic sustainability of the BE (Ramcilovic-Suominen and Pülzl, 2018). In particular when it comes to the definition, integration and aggregation of social, economic and ecological criteria, firm and systematic approaches are missing (Bezama et al., 2017; Gaitán-Cremaschi et al., 2015; Ingrao et al., 2018), but many stakeholders call for a better knowledge of the environmental, social and economic impacts of the BE, especially regarding trade-offs (EC, 2018). On the other hand, methods of analysis, evaluation and assessment of the concrete risks and chances of the BE at a regional level have to be developed and discussed (Bezama et al., 2017; Ingrao et al., 2016; Wesseler and von Braun, 2017) (see section 2.1).

The potential of sustainability, which can be exploited by the substitution of fossil resources by renewable resources, is of strategic interest, and a tool for comparing the sustainability of industries and their associated products, including aggregated sustainability indices for entire life cycles within economic sectors, their sections and respective technologies, also enabling the identification of hotspots, can be the basis for further decisions (Budzinski et al., 2017). Additionally, to make real ecological improvements at a lower aggregation level visible, such a tool should include regional analyzes that are necessary in order to be able to map regional effects in the social and economic sphere and (Bezama et al., 2019), but they have to be put in a multi-regional context, i.e. taking into account all relevant sectors and the multi-regional/international interlinkages between them like global impacts such GHG-emissions and telecoupling through global supply chains (Budzinski et al., 2017).

2. State of the Art

2.1 Sustainability Concepts and Frameworks in the Context of BE and the Role of Stakeholder Participation

Broadly, sustainability can be understood as a goal about the ability of societies to co-exist on Earth over a long time by avoiding the depletion of natural resources in order to maintain an ecological balance. However, the understanding and interpretation of sustainability is still controversial, especially with regard to the extension of this term to social and economic sustainability and the associated contradictions (Elkington, 1998; UNEP, 2011b). In particular, the relations and contradictions between social, environmental and economic aspects, often referred to as so called dimensions of sustainability, remain a fundamental challenge in theoretical and practical terms (Gao and Bryan, 2017; Liu et al., 2015), since on the one hand there is a lack of integrative concepts of sustainability in sustainability assessment and on the other hand no country performs well on both the biophysical and social indicators (O'Neill et al., 2018). The hitherto unachieved resource decoupling and impact decoupling of economies show empirically the contradictions between the ideas of sustainable development and the reality so far (UNEP, 2011a).

Essential to the present holistic understandings of sustainability in sustainability assessments is the three pillar approach of the World Summit on Sustainable Development, characterized by the concepts of people, planet and prosperity/economy (Elkington, 1998; UNEP, 2011b). However, thereby suggested are kinds of several more or less differentiated entities constituting sustainability in a complementary and constructive way, but it is often also spoken of achieving a balance (Meadowcroft, 2007), already implicitly reflecting contradictions beyond a picture of misalignment between the so called three pillars. Discourses and conceptual developments on sustainability are dominated by semantics and as intuitive as popular figures (e.g. (Rockström and Sukhdev, 2016)) rather than reasonable and coherent analyzes (Liu et al., 2015; Mebratu, 1998). Most important, however, even if the term holistic is used inflationary also in the context of BE recently, it still rather represents an idea of summing up the parts or dimensions of sustainability than to understand their relations. Still, when it comes to sustainability and sustainable development, at least two key questions relevant in our context of BE arise (Ramcilovic-Suominen and Pülzl, 2018): What are the relations between humans and nature (Hopwood et al., 2005) and how these relations normatively should be structured normatively (Rametsteiner et al., 2011)?

These conceptual flaws have implications on evaluation and implementation of sustainability, resulting in methodological insufficiencies of only data-driven and/or interdisciplinary theoretically unreflected approaches which are very limited due to generally applied measurements are insufficient, not available or of low quality, and moreover they are criticized for lacking theoretical foundations (Spaiser et al., 2017). This can be traced back to a lacking reference to a comprehensive theory of sustainable development (Hopwood et al., 2005) and that political concepts like the SDGs are not guided by a founded theory as well (Nilsson and Costanza, 2015). Superficial synergies and trade-offs within the SDGs can be shown by data-driven empirical studies, but to analyze, understand and at least improve and attain them, a qualitative assessment is necessary. As well as these contradictions, trade-offs and synergies are always context-specific (Future Earth, 2016) there is a need for a general founded theory which helps to understand these specific phenomena in sustainability assessment frameworks.

Like sustainable development or the SDGs in general, the BE in specific is characterized by a number of contradictions: unclear or implicit means and ends; economic necessity of growth leading to increasing environmental impacts vs. the ecological necessity of reducing environmental impacts (El-Chichakli et al., 2016; Spaiser et al., 2017; Staffas et al., 2013); concurrency in land and resource use between nutritive, energetic and material use (Pfau et al., 2014; van Renssen, 2014); short-term achievements and long-term sustainability (Future Earth, 2016; Griggs et al., 2014); regional and global effects (de Besi and McCormick, 2015) on different scales (Gao and Bryan, 2017; Kleinschmit et al., 2017); trade-offs among economic, environmental and social effects; shifts to other countries and regions through in- and exports as forms of global injustices; re- and backfire effects of more sustainable production and consumption. Especially the majority of NGOs have a critical perspective on BE and see this concept partly as a PR campaign from industrial business to green-wash their business as usual (Gerhardt, 2018). To only foster, wait or hope for technological solutions, like in mainstream environmental economics, is considered as insufficient (Dasgupta, 2010; Dasgupta, 2013; Spaiser et al., 2017). On the background of these conflicts and contradictions, more systematic and comprehensive frameworks and understandings of BE and its social and political system were developed recently (Thrän et al., 2020).

Consequently, one approach for contextualization of sustainable BE is stakeholder integration into the framework development. Insights and results from systematic stakeholder participation from the beginning can play an important role in addressing persistent societal problems in a credible, transparent, and multi-perspective way (Bezama, 2018; Gerdes et al., 2018), as well as enable innovations (Kircher et al., 2018; Korhonen et al., 2018). Poor coherence between decision makers, scientists, and stakeholders was assessed to be at the origin of regulatory failures (BMBF, 2021; Dupont-Inglis and Borg, 2018; European Commission, 2012), and biotechnology was subject of controversial public debates, making societal acceptance an enabling factor (Małyska and Jacobi, 2018; Meyer, 2017). Previous studies on stakeholders in the context of BE projects pursued completely different goals and scopes (Bennich et al., 2018; Gerdes et al., 2018; Hansen and Bjørkhaug, 2017; Korhonen et al., 2018), were too general for our context since they do not allow conclusions on specific aspects and indicators (European Commission, 2011; The Bioeconomy Stakeholders Panel, 2017), and/or used other stakeholder categories and attributes (European Commission, 2011; Hausknost et al., 2017; Sisto et al., 2016; Stern et al., 2018; The Bioeconomy Stakeholders Panel, 2017).

What aspects of sustainability and in particular which SDGs should be addressed by holistic sustainability assessments from stakeholder's perspectives, remains an open question. In context of the project SYMOBIO, the stakeholder's perceptions and expectations on the effect of BE to SDGs in Germany were collected in a workshop series held by the UFZ in Berlin in October of 2017. This data has to be curated and analyzed to gain insights into the perceptions of stakeholders and their expectations when it comes to sustainability assessment.

2.2 *LCA and LCSA Approaches for BE Regions*

The lack of a clear definition of the BE and social, ecological and economic sustainability as well as according concrete and measurable objectives has consequences for the assessment of BE (Bracco et al., 2018). In most strategies, BE is only monitored by economic values and shares of GDP or their objectives are even non-measurable targets, but the main challenge is to link goals and measurement frameworks (ibid.). However, since 2017, socioeconomic indicators to monitor the EU's and Germany's BE are in development (Egenolf and Bringezu, 2019; Ronzon and M'Barek, 2018). A measurement and evaluation of ecological, economic or social sustainability is the motivation of the different approaches of LCAs, which are used for several applications in politics, science and business and could be applied in a multidisciplinary manner at several levels, both to global, national or regional value-chains, as well as to individual companies and specific products (Bezama et al., 2017). The framework of nearly all previous LCAs is largely based on the environmental LCA (E-LCA) according to DIN EN ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006). The specific particulate methods relevant to life cycle sustainability assessment (LCSA) are the E-LCA as an ecological, the life cycle costing (LCC, which can mean techno-economic assessments or cost/profit assessments) as an economic and the social-LCA (S-LCA) as a social sustainability assessment. Main differences are the focus on social, environmental or economic sustainability and the indicators and interactions that are to be assessed, which can be specified on the data base by physical quantitative data for E-LCAs, quantitative and qualitative data for S-LCAs and quantitative-monetarist data for LCCs (UNEP, 2009). Furthermore, however, this results in significant differences in the main methodological characteristics: functional units (FU), LCI and model, LCIA, interpretation as well as retroactive on goal and scope.

Following up the broad spectrum of LCAs and developed methods, the Life-Cycle-Sustainability Assessments (LCSAs) face the most significant methodological problems but also seem to have the most potential of empirical sustainability assessments (Balkau and Sonnemann, 2017; Onat et al., 2017). Currently, there are at least two definitions of LCSA: on the one hand the very simple and additive scheme $LCSA = ELCA + LCC + SLCA$ (Kloepffer, 2008), based on the reductionist and mechanist three pillar approach. It's argued that the three LCA methods have to be completely standardized, harmonized and synchronized. A weighting or extensive qualitative analysis are excluded. On this conception most of the sustainability assessments and in particular all the LCA and LCSA-based approaches are built. On the other hand, by the integrative approach within the framework of the LCA, further impact categories based on S-LCA and LCC are integrated, which extends the approach and covers all dimensions of sustainability on the basis of a common inventory analysis (Guinée et al., 2011).

A simple combination of particular LCA methods according to the additive scheme is only possible to a very limited extent, by comparing the final results (cf. (Ekener et al., 2018)), since there is no common methodology. The analysis of complex systems by their sub-systems means more than the sum of their parts (Halog, Anthony and Manik, Yosef, 2011), as well as the different LCA methodologies were developed for different research questions. Consistency of the goal and scope and the inventory analysis is essential for integration. Not least for the purpose of identifying trade-offs or avoiding conflicts of objectives due to their disregard, to reduce the methodological uncertainties and to estimate rebound effects (Guinée, 2016b). For instance, while strong efforts are being made to improve the environmental performance of products on the micro level, only a minimal effect on the macro level has emerged so far (ibid.). In addition, Pareto effects come to bear, i.e. effects which make a relatively small number of causes responsible for a major portion of the impacts (e.g. high energy consumption or bad working conditions in supply chains (see section 5.4), resulting in a need for hot spot analyzes (Halog, Anthony and Manik, Yosef, 2011). More recent studies aim to take social, environmental and economic aspects into account, integration, dependencies and interactions are still not sufficiently covered (ibid.). None of these studies tried to apply sustainability assessments in a manner, which would allow to assess the social, environmental and economic effects of a regional but international interlinked BE and also to refer to these effects regarding their contribution to a common global goal system like the SDGs. Recent comprehensive reviews show that most LCSA approaches more or less follow the additive and not integrated scheme, yet (Costa et al., 2019; D'Amato et al., 2020; Fauzi et al., 2019; Troullaki et al., 2021; Wulf et al., 2019; Zimek et al., 2019).

A recently developed unified appraisal framework for biomass and bioenergy conversion systems at a process-based level (Suwelack, 2016), presents a first comprehensive approach of combining several LCA-methods to an LCSA. From a technical point of view the developed and applied methods of normalization, weighting and general calculation within the LCI and impact assessment seem to be a proper way of operationalization in LCSA. However, the used sustainability framework, indicators, criteria and interpretation were not a focus, and relationships, different stakeholder perspective or the SDGs do not play a role in this study still based on a rather additive than integrative concept. Since it is process based with a high technical detail, the results and conclusions remain very specific and have a limited significance for systematic analysis of BE regions in a broader context.

As the major shortcoming of LCSA frameworks Onat et al. (2017) identified the lack of understanding the mutual dependencies and complex interactions among the sustainability indicators as well as a reductionist approach and myopic view by looking at the Environmental E-LCA, S-LCA, and LCC assessment results separately. In this regard, in sustainability concepts and LCSA in general, there are significant gaps regarding indicator sets, frameworks and software for implementation, databases, LCIAs and applications of integrated but also additive LCSAs. As well as especially S-LCA and LCC are still under development and not robustly applicable (Keller et al., 2015; Wulf et al., 2018), which is likewise true for additive and integrated LCSA. However, integrative LCSA demands for even more consistent and sophisticated

methodologies as well as software implementation than the additive scheme does, which might be the main reason why additive LCSA is mainly used. A lack of harmonization and limited comparability is the consequence, and a variety of impact categories differ across studies and methods (Costa et al., 2019). Within S-LCA the selection of indicators, LCIAs and handling of (semi-)qualitative and quantitative indicators and results propose big challenges (Wulf et al., 2019) (Guinée, 2016a). In LCC, questions arise on how to implement socio-, meso- and macroeconomic aspects beyond traditional microeconomic LCC (Zimek et al., 2019). In this regard, data availability and moreover existence of applicable databases is a major constraint (cf. (Suwelack, 2016)). Which is particularly important, when it comes to more regionalized and spatially explicit datasets in order to improve quality of results (Fauzi et al., 2019).
Against this background, it is just as important as taking planetary boundaries and global effects into account in LCSA by appropriate LCIAs (Chandrakumar, Chanjief and McLaren, Sarah J., 2018; Chandrakumar, C. and McLaren, S. J., 2018; Chandrakumar et al., 2018; Sala, 2019). In recent years, significant developments were made, especially in context of the European Commission - Joint Research Centre (EC-JRC) to integrate planetary boundaries and environmental footprints into E-LCA in order to allow meso- and macroeconomic assessments and conclusions by sector and product specific bottom-up approaches (Bjørn et al., 2020; Fazio et al., 2018; Robert et al., 2020; Sala et al., 2019; Sala and Castellani, 2019; Sala et al., 2020). Most of the shown issues go hand in hand with implementation of LCA and LCSA within a software environment, since development of LCA software, databases and LCIA methods are mutually connected and depend on each other, as well as most LCA practitioners depend on them (Fritter et al., 2020). There are further practical challenges in the operationalization of LCSA and integrated LCSA in particular, e.g. definition of coherent system boundaries, methods to conduct sensitivity and uncertainty analysis (Costa et al., 2019), rebound effects (Guinée, 2016a), trade-offs, biased decision making between social, economic and environmental aspects (Fauzi et al., 2019) among others.

In a nutshell, conventional LCAs and additive LCSAs as applied to bioeconomy in the last years do not provide sufficient information and assessment of the social, ecological and economic sustainability of bioeconomy in order to identify synergies, trade-offs and hot spots, since they have not addressed the system holistically and in regard to a necessary broad societal transformation (Talwar and Holden, 2022). Integrative LCSA is considered as the most promising approach for tackling these challenges, however, integrative LCSAs oftentimes still remain a conceptual idea or in a few cases were not implemented and conducted consistently enough.

2.3 *Inter-, Transdisciplinarity and Political Economy for Holistic Sustainability Assessment*

This broad field of sustainability concepts and frameworks, stakeholder participation as well as social, ecological and economic indicators and LCA methods, can only be addressed by a highly inter- and transdisciplinary research setting. A lot of knowledge and evidence of relationships (e.g. between social effects and climate change) are scattered across different institutions, locations and disciplines, and this fragmentation is a critical barrier to a holistic and integrated understanding of social, economic and environmental systems (Knierim et al., 2018; Nerini et al., 2017). The methods and findings of different scientific disciplines are oftentimes very rational, competent and innovative within their respective fields of expertise, but neglect or contradict insights from other disciplines and are embedded in possibly irrational frameworks or ideologies (Demirovic, 2003). Interdisciplinarity is understood as an interchange and dialogue between disciplines, whereas transdisciplinarity as a method aims for integration: an inherent contextualization and embedding findings within a greater context creating transcending insights (Klein, 2008; Knierim et al., 2018; Lubchenco et al., 2015). The resulting methodological pluralism, can lead to more consistencies and less bias (Lamont et al., 2006). Attributes like 'social' and 'economic' do not describe separate objects of scientific observation, but rather different perspectives on the same objects and the underlying relations. Transdisciplinarity means to understand a seemingly ecological project or research question as a simultaneously political-economic project and research question and vice versa. Transdisciplinarity is therefore necessary to achieve a proper integration of methods in an LCSA.

Transdisciplinarity means as well to take structural and deep rooted societal systemic problems into regard. In specific, our societal relationships to nature (SRN) are shaped by capitalism as a historically specific form of economy: a societal system that perpetuates the growth and accumulation of value (end) through societal needs using natural resources, labor and technologies (means). The fulfillment of societal needs is not the purpose of capitalist economic activities, but as well a necessary mean as all other production factors are to gain profit (Postone, 1993). Societal needs (use value) are only satisfied if they are coupled with sufficient purchasing power (exchange value). Both values use and can overuse resources, but monetary or exchange values tend to ignore the biophysical requirements of ecosystems categorically, e.g. externalities like environmental degradation are not intended to be internalized (Schleyer et al., 2017). Since the exchange value of commodities and money is the starting and the end point of every capitalist economic process, profit becomes the main driver and an end in itself. If everything depends on an abstract quantitative value, the only driver is the unlimited growth of this value, and consequentially there is no "enough". Exchange value in the long term depends on the use value and production of material commodities, leading to valorization and overexploitation of natural and human capital and likewise growing negative social impacts and transgression of planetary boundaries (PB). Solely new technologies like those used in BE in 'green' capitalism as the potential of additional growth usually expand and/or shift the exhaustion of one resource to another. Growth in GDP (exchange value) ultimately cannot plausibly be absolutely decoupled (in macroeconomic terms, although there is relative decoupling on product level) from growth in material and energy use (use value), therefore, GDP and material growth cannot be sustained infinitely in this very economic system (Common and Stagl, 2012; IPCC, 2022; Parrique T., 2019; Ward et al., 2016). In this regard, it is more appropriate to speak of the *Capitalocene* instead of the Anthropocene (Brand and Wissen, 2018), since capitalism as the currently dominant societal and economic system has led to a social-ecological crisis, and not humankind itself as the term Anthropocene suggests.

Transdisciplinarity and political economy applied to LCA methods would allow to identify social, ecological and economic synergies, trade-offs and hot spots not as arbitrary and specific to certain technologies, but as structural phenomena helping to set up sustainability frameworks and methods as well as to interpret their results.

2.4 Research Gaps to be addressed

An integrated LCSA for BE regions and beyond is still missing. To improve methodological developments in LCSA and sustainable BE research several gaps need to be closed: First, there is need for more detailed analyzes of the stakeholder's expectations regarding BE, which aspects of sustainability are important to measure and which concerns and hopes BE activities address or should address. Second, based on these insights, a sustainability framework for a holistic assessment of the BE has to structure definitions of what sustainable BE actually means, helping structuring the discourse around sustainability concepts and SDGs, as well as a better understanding of what social, ecological and economic sustainability entails to overcome reductionist approaches, epistemological traps and to improve the understanding of mutual dependencies and complex interactions. Third, the established field of LCAs has to be complemented by an integrated and holistic LCSA, providing a holistic and integrated framework and address major methodological questions regarding goal and scope, inventory analysis, impact assessment and interpretation, contributing to the whole field of life cycle and sustainability assessments. Fourth, an operationalized, validated and applied integrated and holistic LCSA by case studies on BE regions shows the holistic sustainability and sustainability potential of regional BE networks compared to other production systems. The hereby developed tool can fulfill the demands of the stakeholders to practically use it to sustainably form BE networks and regions. By identifying hotspots of unsustainable practices, socioeconomic contradictions and trade-offs when industrial metabolisms are transformed by substitution, BE strategies and action plans can be focused and the subject of governance activities specified. Beyond that, civil stakeholders like NGOs and the resulting controversial societal discourses, also profit from an evidence-based method for assessing the BE and establishing a common narrative of a sustainable BE and sustainable development.

3. Research Objectives

The general objective of this dissertation is to develop and validate an integrated LCSA model in a corresponding holistic sustainability-framework and apply it in BE networks in Germany in order to define, measure and scientifically interpret their social, economic and ecological sustainability. Furthermore, to establish LCSA in the context of BE as a needed practicable scientific tool for regional federal policymakers and practioners to establish a sustainable BE by improved governance and practice, it is necessary to analyze the expectations of all relevant stakeholders, as well as to transdisciplinary converge holistic sustainability concepts. Such a holistic approach and model of integrated LCSA of the BE should be able to identify the risks and chances, synergies, trade-offs and contradictions by qualitative and quantitative indicator-based analysis of the regional but internationally interlinked BE networks in Germany, revealing the potentials and burdens for meeting the SDGs. The model has been tested, applied and validated in concrete case studies of BE networks to demonstrate its abilities and to deliver further insights on BE product systems. A holistic sustainability assessment of specific networks of a developing BE in Germany at a national and regional scale can surface the sustainability potential of BE sectors and products compared to other fossil-based economies. Overall, the preliminary considerations and objective raise the following research questions[1].

1st *What are the expectations of the most relevant stakeholder groups of the BE in Germany and which aspects represented by SDGs are of high relevance for sustainability assessments?*

2nd *Which theoretical and conceptual considerations on BE, sustainability and its assessment are necessary for a holistic and integrated framework for LCSA (HILCSA)? How is this theoretical and conceptual framework for HILCSA formulated?*

3rd *What are criteria and aspects for implementation and operationalization of HILCSA for BE regions? What should a scope, goal, interpretation, and most importantly an LCI and LCIA look like for this?*

4th *What are the results on risks and chances of a BE transformation and the lessons learned from case studies of a validated model of holistic LCSA for BE product systems and regions?*

[1] Research question 2 and 3 changed slightly while preparing this work compared to the initial expose.

4. Methods

"All ecological projects (and arguments) are simultaneously political-economic projects (and arguments) and vice versa. Ecological arguments are never socially neutral any more than sociopolitical arguments are ecologically neutral." (Harvey and Braun, 1996)

4.1 Stakeholder Expectations of the BE in Germany and Relevance of SDGs for Sustainability Assessments

As a starting point, the stakeholder's perceptions and expectations on the effect of BE to SDGs in Germany were collected in a workshop held in Berlin in October of 2017, in order to identify societal discourses and conflicts as well as the relevancies and weightings of future indicators. As a methodological framework for the stakeholder participation process, we follow the social multicriteria evaluation (SMCE), an established general sustainability related stakeholder participation approach (Weaver and Rotmans, 2006) (Munda, 2004) (Garmendia and Gamboa, 2012). This method entails the following steps: (i) identification and classification of relevant stakeholders; (ii) definition of the problem; (iii) creation of alternatives and definition evaluation criteria; (iv) assignment of values to criteria in a multicriteria impact matrix; (v) selection of a multicriteria evaluation method; (vi) assessment of social actors' preferences, values, and weights; (vii) application of the model through a mathematical aggregation procedure; and (viii) conducting social analysis and discuss the results to check the robustness of the analysis. The workshops brought together a spectrum of relevant stakeholders according to the stakeholder-groups (UNEP, 2019) identified: 'science', 'economy' and 'society'. Selected and invited to our workshops were 200 of them in such a manner, that every organization has been represented without personnel redundancies. In total, 64 stakeholders participated. Such categorization into groups is only of limited severity, but has decisive analytical and practical advantages (polarization of societal conflicts of interest between the groups, reducing potential for conflict within the groups).

In each workshop the steps envisaged for the development of a monitoring of the German BE were introduced and we explained the objective for the participation of the stakeholders in this process, which is to provide an opinion on what is relevant from their perspective in a monitoring of the desired characteristics. Now the task for the participants was to classify the SDG sub-goals for relevance to a BE monitoring according to the given relevance categories Therefore we asked the stakeholders to arrange the different sub-goals into sections of relevance-categories, i.e. the topic of the SDG-sub-goal must / may / not be part of a BE monitoring in Germany. The stakeholder workshops discussions were also documented qualitatively.

In addition, to deepen the understanding of the BE discourse in terms of conflicts, indicators and narratives as well as to evaluate first monitoring methodologies and results, an online survey was conducted in 2021 using soscisurvey.de and structured in a way that qualitative questions and data were collected and processed (Zeug et al., 2021b), although subsequent quantification for better interpretation and presentation of the results is afterwards possible. It was not possible to aim for representativeness, as the relationships between the population and the sample is unknown. The results of the additional second stakeholder workshop of SYMOBIO in 2020 serve as the content basis for the implicit hypotheses of the questions. All other questions are derived from the project objectives and internal discussions in the project network. The online survey is divided into headings and each section is subdivided into thematic questions with a specific question type. In the analysis, only nominal and ordinal scales were used which are quantified by a rating scale. Consequentially no statistical methods can be applied to the results. Email distribution of the survey is conducted in three waves, in which over 400 BE stakeholders are contacted directly and three BE-related email newsletters are used to reach stakeholders.

4.2 Theoretical and Conceptual Considerations on BE, Sustainability and its Assessment for a Holistic and Integrated Framework for LCSA (HILCSA)

Comprehensive reviews of LCSA approaches identify the lack of transparent description and discussion about implicitly underlying concepts of sustainability, and resulting difficulties in the classification of indicators and criteria as major obstacles (Wulf et al., 2019). Consequently, the need for a transdisciplinary sustainability science aiming at understanding interactions between nature and society has often been stated in the literature for LCSA (Sala et al., 2012b) (Sala et al., 2012a), but rarely substantiated or implemented (Future Earth, 2016; Pfau et al., 2014).

By a qualitative and analytical discussion oriented on interdisciplinary materialism, critical theory, social ecology and SRN, a sustainability framework was developed and applied in context of LCSA. Therefore, it was necessary to go one step back to go two steps forward, i.e. reflecting on the social science and genesis of sustainability assessments and to identify theoretical approaches which allow for further development of LCSA.

The framework aims for embedding positivist data driven methods of science into a relativist and postmodernist philosophy of science, combining the strengths of quantitative systems modelling as well as political economy and political ecology.

4.3 Criteria and Aspects for Implementation and Operationalization of HILCSA for BE Regions

To transfer this sustainability framework and theory of SRN to LCA application, the implementation and operationalization of HILCSA follows the integrated LCSA approach, i.e. integration of these aspects and LCA methods into a common goal and scope, LCI, LCIA, results and interpretation. Existing LCA indicators and LCIA methods are used instead to develop new LCIA methods and quantify specific cause and effect chains, since the latter is beyond the scope and of this research. The selection criteria for existing LCA indicators, LCIA methods, software environments and databases are:

a. possibility of allocation to relevant SDG sub-goals and HILCSA sustainability framework,
b. capability of the given software environment to operationalize and implement them,
c. maintenance of consistency and avoid redundancies in LCIA models,
d. relevance and applicability in regional BE, and
e. transparency of methods and potential availability of data.

Thus, the methodology for developing a framework for implementation and operationalization of HILCSA is mainly guided by the relation between possibilities and capabilities of complex sustainability assessments.

To obtain a possible indicator set, indicator sets from previous research were selected as well as a review of literature on indicators for BE assessment was conducted, and the indicators were allocated to the HILCSA sustainability framework. The indicators from RESPONSA and SUMINISTRO were allocated to the SDGs on basis of preliminary work (Jarosch et al., 2020) with some adjustments, thereby criteria a and e are met. From the literature review, the FAO indicators to monitor and evaluate sustainability of BE (Bracco et al., 2019) were considered to be the most comprehensive and most recent indicator review basis available, in order to expand existing methods. All FAO indicators from product and territorial level were allocated to the HILCSA sustainability framework (criteria a).

To identify the capabilities of software environments and LCIAs for the method, a given software environment is a precondition to manage the enormous complexity behind LCA methods and data in order to make them applicable to case studies in line with the developed framework. OpenLCA was chosen as the only software environment capable of incorporating social, environmental and economic aspects in LCA as well as different FUs and activity variables (AV) (Ciroth et al., 2019; Di Noi et al., 2018). The SoCa database, which is the socio-economic extension of openLCA and Ecoinvent, handles the variety of units and characteristics of social and economic indicators by applying common ordinal risk levels and associated impact factors to different specific values of each indicator (criteria b), assessed by its specific context (Social Impacts Weighting Method) (Eisfeldt, 2017; Maister et al., 2020).

SoCa, as well as the performance reference points (PRP)-based social LCIA in RESPONSA, corresponds to an external normalization approach, which is generally recommended in the LCSA literature (Prado et al., 2012; Troullaki et al., 2021; Wulf et al., 2017) and also chosen for HILCSA (Zeug et al., 2021a). External normalization is essential to make indicators with very different properties (qualitative, quantitative, social, physical, economic) comparable. However, external normalization factors can increase the uncertainty of the whole assessment (Wulf et al., 2017) and the choice and transparency of the reference values plays a crucial role (Sala et al., 2012a, b). SoCa relies on the PSILCA data of GreenDelta and its indicator values are based on international conventions and standards, labor laws, expert opinions but also own experience and evaluation (criteria e & d) (Maister et al., 2020); RESPONSA calculates PRPs as a regional and context specific LCIA (Jarosch et al., 2020; Siebert et al., 2018; Zeug et al., 2021a). All socio-economic indicators from SoCa and RESPONSA in HILCSA are comparable on from being transferred to risk levels (normalization) and share the same impact factor of the Social Impact Weighting Method. For aggregation and balancing social indicators along the value chain, the implemented method of SoCa in openLCA based on the used AV.

Additionally, only openLCA aims explicitly at implementation of integrated LCSA. OpenLCA was considered for this work as the most promising platform, also regarding a broad set of implemented LCIA methods (criteria b). Especially for environmental impacts, there is a variety of well-established LCIA methods. To compile LCIAs for our indicator set and to define the *capabilities*, LCIA methods from literature and openLCA methods database are selected, which are able to address most SDG subgoals at their mid- or endpoint level, so they can be allocated to the framework (criteria a): open LCA – SoCa (Eisfeldt, 2017), openLCA - ReCiPe 2016 (H- Hierachrist) (Huijbregts, 2016), Impact World + (Bulle et al., 2019) and Environmental Footprint 3.0 (Fazio et al., 2018), cumulated energy demand (CED) from openLCA.

To finally gain an implemented and operationalized HILCSA framework meeting all the defined criteria, it was checked for redundancies in the indicator set and LCIAs as well as maintain as much consistency as possible from each of the individual methods (criteria c). In a last step, all indicators which are not applicable and relevant in regional BE assessments are sorted out (criteria d). For this the relevance of corresponding SDGs and sub-goals are used, which were gained by stakeholder participation (Zeug et al., 2019), and keep all indicators whose SDGs must and may be part of BE monitoring. LCAs and their indicators have to consider international effects, since first, using local or global indicators depends on the nature of environmental pressures and its causes (global – GHG, local – acidification), and second, a spatial dissociation between places of extraction, production, and consumption distributes social and economic effects globally (Parrique T., 2019). Such a practical framework for HILCSA within limited capacities is only possible if it builds on existing and appropriate methods and research that to most extent meet the methodological criteria for HILCSA. Consequently, not every assumption of these approaches goes in line with the framework, some technical detail can only be discussed and regarded to a limited extend, and compromises had to be made.

4.4 *Lessons Learned from Application and Validation of HILCSA in Case Studies and Results on Risks and Chances of a BE Transformation*

To apply and validate the HILCSA methodology, two case studies were selected according to the following criteria: production systems of regional BE in central Germany, sufficient data from databases and directly from the projects and production systems, limited complexity of production systems. In general, application means to conduct HILCSA as an LCSA methodology according to ISO 14040/14044, validation means to proof the HILCSA methodology by application to be able to address the research questions, capability of operationalization and implementation in the software environment, to be consistent in results with established LCIA methods, transparency of methodology and data, as well as to draw conclusions.

In general, the developed methodology follows the standard approach of LCA (goal and scope, LCI, LCIA, interpretation and discussion). To build the LCI LVL-model in openLCA, as a beginning, the detailed gate-to-gate techno-environmental production system of LVL in Central Germany from (Hildebrandt et al., 2019; Hildebrandt et al., 2018; Hildebrandt et al., 2017) is adapted, which were validated by participating stakeholders and producers, and made it a foreground unit process in openLCA v.1.10 embodying all activities in the organization manufacturing LVL. For supply with raw materials, transportation and background processes Ecoinvent v.3.6 APOS (Allocation at Point of Substitution) processes with social and economic data from SoCa v.1 by Green Delta are used. APOS as an attributional approach integrates the treatment of wastes and by-products in a more suitable way for assessing BE compared to other production systems, than the cut-off system models and is therefore chosen. From the RESPONSA survey and study (Jarosch et al., 2020) the real-world data of RESPONSA indicators for LVL manufacturing and forestry as well as AVs are used for the selected indicators. Following the HILCSA indicator set (Zeug et al., 2021a), 91 SDGs and SDG subgoals served as impact categories in openLCA and were quantified each by one mid or endpoint indicator as well as their given normalization factors from the chosen LCIA methods (RESPONSA, SoCa, ReCiPe 2016 End-/Midpoint H and Environmental Footprint (EF)) as well as weightings from stakeholder participation (Zeug et al., 2019). Additionally, total and renewable CED for SDG 7.3/1 respectively SDG 7.2/4 were added. Afterwards, the HILCSA-LCIA impact categories were checked for producing the same plain impact results as the used stand-alone LCIA methods, as well as for overall consistency of inventory results and impact analysis. It is not important that all flows are covered by the LCIA, but rather that all flows with a significant impact are. To finally make a relative assumption on the sustainability of LVL production in Central Germany, HILCSA-LCIA is applied to the production system of hot-rolled steel beams. The reference flow of the LVL product system is an LVL beam with a mass of $m_{LVL}^{FU} = 1469.0\ kg$. In order to make LVL and steel beams (SB) comparable regarding their functionality and the FU, a comparison factor C_{SB-LVL} on basis of their average bending capacities q (load per unit length) (Pollmeier, 2021) are calculated. As a result, a comparable steel beam with same functionality as our LVL beam has a mass and FU of $m_{SB}^{FU} = 1720.8\ kg$. For each indicator i which is assigned to a specific subgoal SDG $sSDG$, in openLCA values x for each process of the LVL product system x_{sSDG}^{LVL} are calculated, as well as cumulated (total) values for the whole product system of LVL $x_{sSDG,T}^{LVL}$ and the steel beam $x_{sSDG,T}^{SB}$.

For the second case study on Biomass-to-Liquid (BtL) biofuels, the HILCSA methodology is updated by introducing the SoCa v2 database (Green Delta, 2021), which entails updated and new indicators from the PSILCA v3 database (Maister et al., 2020) and Ecoinvent v3.7.1, resulting in a second version of HILCSA with updated and new indicators and impact categories. HILCSA v2 entails a set of 99 quantitative and qualitative indicators capable of addressing societal needs by 24 indicators, economy by 56 and the PB by 22, as well addressing 14 out of the 17 SDGs (SDG

9, 10 & 17 currently not addressed). For example, indicators on energy return on investment (EROI) are added since they are of significant importance to assess biofuels and energy systems in general (Perez-Valdes et al., 2019). Like in HILCSA v1, in HILCSA v2 most of the indicators are derived from several established life cycle impact assessment (LCIA) methods like ReCiPe, Impact World +, EF 3.0, Cumulative Energy/Exergy Demand, RESPONSA and SoCa v2. All indictor values are assessed against the progressive regulation of SRN and a societal-ecological transformation (Zeug et al., 2023b), e.g. high efficiency and effectiveness of economic processes, or less working time and a higher average renumeration lead to better assessment results in the LCIA. As in the first case study (Zeug et al., 2022), the impacts were compared in terms of substituting a fossil fuel mix (diesel, petrol, kerosene) by the same fuel mix from BtL by calculating substitution factors of impact. Both, the FU of BtL and fossil fuel system is a product basket of a total amount of 1 MJ of fuel mix, consisting out of 0.272 MJ ($6.38*10^{-3}$ kg) diesel, 0.399 MJ ($9.18*10^{-3}$ kg) petrol and 0.330 MJ ($7.66*10^{-3}$ kg) kerosene. Thus, as drop-in fuels, BtLs are qualitatively and quantitatively a full substitute of fossil fuels and no further comparison factors are needed. Since all further downstream processes in the use phase of such fuels are assumed to be the same, a cradle-to-gate approach is sufficient.

All cumulated results of all indicators of BE product system are compared to the product which can be substituted (i.e. steel beam), to assess their relative rather than absolute impact. Therefore, a factor f^{sSDG} called substitution factor of impact of an indicator (Eq. 1) is calculated, expressing the magnitude of relative sustainability. As aggregation on the SDG level, weighted mean factors are calculated for substitution of impact for each SDG f^{SDG} (Eq. 2). As weighting factors, the relevance R^{sSDG} of each of the SDG-subgoals in the context of the German BE-monitoring (Zeug et al. 2019) are used. Analogical, a total substitution-factor of impacts f is calculated on the level of all SDGs (Eq. 3).

$$f^{sSDG} = \frac{x^{LVL}_{sSDG,T}}{x^{SB}_{sSDG,T}} \qquad \text{(Eq. 1)}$$

$$f^{SDG} = \frac{\sum_{sSDG} R^{sSDG} f^{sSDG}}{\sum_{sSDG} R^{sSDG}} \qquad \text{(Eq. 2)}$$

$$f = \frac{\sum_{SDG} R^{SDG} f^{sSDG}}{\sum_{SDG} R^{SDG}} \qquad \text{(Eq. 3)}$$

Additionally, in the second case study, with regards to EROI and further comparability, an extended assessment for the use phase in personal transport car and comparison with electric drive is conducted. Of practical relevance is to have a comparison of different transport systems including not only the production but use phase of fuels, thus in the electric grid mix of 2030 in Germany the transport of one person for one kilometer by electric car, diesel car powered by fossil fuel and diesel car powered by BtL is compared with train, applying the same methodology as above and extending to cradle-to-grave (also called well-to-wheel).

5. Results

5.1 Stakeholder Participation in BE Monitoring and Assessment

5.1.1 Relevances, Interests and Perceptions

The results on stakeholder's perceptions and expectations in terms of relevance of 169 SDG-subgoals for BE in Germany, in general show that the stakeholders classified the subgoals so that

56 of them should not be part, 47 of them may be part and 66 subgoals be part of a BE monitoring (Zeug et al., 2019). For presentation of the results, the subgoals are grouped as corresponding SDGs. Most of the subgoals from SDG 3, 5, 16, and 10 were considered as relatively irrelevant, even though some of them are much more relevant. More than half of the subgoals from SDG 6, 9, and 4 may be part of future monitorings and assessments and a majority of subgoals from SDG 15, 14, and 13 were assessed as "must haves" in monitoring and stand for basic environmental aspects. At least as relevant are many subgoals of SDG 2, 12, 7, 6, and 2, representing food security, sustainable agriculture, production and consumption patterns, and sustainable infrastructure in cities and rural areas.

The reduction of waste and urban pollution (subgoals 11.6 and 12.5), the protection of ecosystems (6.6 and 15.9), food security (2.1 and 2.2), research on sustainability (12.a) and governance aspects (13.2, 17.14, and 12.2) combine a series of different SDGs with highest relevance for all stakeholder groups. In general, of 169 subgoals, the science stakeholder group gave an average score of 5.10, the business stakeholder group 4.42, and the society group 5.37. This shows a tendency of stakeholders in the science and society group to consider more subgoals as relevant for monitoring than stakeholders in the business group. Of the 10 most controversial subgoals, 5 are societal aspects: ending the discrimination of women (subgoals 5.1 and 4.1) and issues of supporting developing countries (8.a, 9.5, and 10.a). Strikingly, 4 of them were seen as very relevant by the science and society stakeholder groups, whereas business stakeholders neglected them.

Furthermore, the aggregated scores of the 17 SDGs based on the scores of their corresponding subgoals (Figure 2) show the same common strong and widespread relevance for all environmental aspects (SDGs 13–15) without significant differences between stakeholder groups. Following a preference order calculated by the mean values of the relevance of an SDG given by all stakeholder groups, ending hunger (SDG 2), responsible consumption and production (12), all environmental aspects (13–15), infrastructure (9), energy (7), and drinking water supply (5) are the most relevant SDGs for BE. These are followed by global partnerships, sustainable cities, decent work, inequalities, and education (SDGs 17, 11, 8, 4, and 10). Peace, gender equality, and health (SDGs 16, 5, 3) appear to be topics of less relevance. However, it has to be emphasized that the SDGs cannot be put into a hierarchical order, since they implicitly represent complex cause and effect relations and interlinked means and ends. Besides the expected similarities (SDGs 15, 16, 17, 11, 2, 3) and significant differences (1, 7, 8, 5, 9, 6), the strongest divergence of different stakeholder groups by far emerges in the perception of ending poverty (1). When it comes to mainly social aspects of sustainability (SDGs 1, 2, 3, 4, 5, 8, 10, 16), a clear qualitative correlation between the science and society stakeholder groups becomes visible: these stakeholder groups assign significantly more relevance to social aspects than the business stakeholder group.

From recording the discussion process at the stakeholder workshops, a series of further, partly fundamental questions and positions appeared. Stakeholders in the science group emphasized that not only national but necessarily global effects of a German, European, and transnational BE must be considered in order to identify trade-offs, leakage effects, and refire and backfire effects and avoid them in the future. Business stakeholders were particularly interested in the international regulatory framework for BE activities such as market access, commodity restrictions, trade restrictions, subsidies, and financing options, which represent general for information necessary for strategic economic management decisions in BE. For stakeholders in the society group, the main question was to what extent BE merely represents a substitution of the resource base of capitalism or is an actual socioeconomic change towards more sustainable systems. Identifying international land use changes and effects on food prices, and thus the nutritional situation of a growing population as well as the environmental effects, is also a central objective and conflict of interest.

Figure 2. Analysis of German stakeholder -group perspectives on Sustainable Development Goals regarding BE. Relevance of SDGs based on relevance of corresponding subgoals given by stakeholder groups. Order of preference is given by mean values of relevance (Ø) of an SDG given by all stakeholder groups.

Overall, the results indicate that topics of ecology from marine pollution to environmental education are as significantly relevant as food security and the associated political development and economic framework. Thus, from the perspective of all stakeholders, a series of aspects representing the social, ecological, and economic dimensions of sustainability as well as enabling factors of policy-making have to be considered in a monitoring system. Considered as relatively irrelevant are the subjective visions of discontiguous topics, such as drug abuse but also increased GDP growth. The discussions in general were highly influenced by viral societal and media discussions at the time, like urban air pollution, biofuels, waste, and urban farming.

On the one hand, our results show what may seem to be counterintuitive in terms of monitoring in one of the most industrialized nations in the world: the dimensions of sustainability are far beyond local environmental concerns, and the awareness of global environmental effects, international trade-offs, and big societal challenges such as hunger, poverty, and inequality is rising. In particular, a growing German or European BE will depend on imports (Budzinski et al., 2017), so national monitoring has to implement these aspects. On the other hand, the results show how much the relevance of different topics is a question of interests and perceptions depending on stakeholder groups, showing the need to take different BE visions and narratives into account beyond scientific discussions (cf. (Bugge et al., 2016)). Different means, ends, and values seem to be the guiding factors in what is understood as conflicting interests and perceptions, and they are context specific. Moreover, it is a question of the visions and narratives: when BE is superficially understood as a potential socioeconomic transition toward holistic sustainability, ending poverty, global partnerships, and education play more vital roles; when BE is only a substitution of primary resources, the changes in socioeconomic dimensions are abstract in contrast to environmental effects. Relationships of certain aspects of the (bio-)economy with environmental and societal effects seems to be the crucial cause, not only for the relevance of topics of monitoring but also for the interpretation of sustainability in general (Kates et al., 2005; Nilsson and Costanza, 2015). These relationships cannot be reduced to simple, one-directional causalities but rather have to be understood as a whole (Hopwood et al., 2005; Mebratu, 1998).

5.1.2 *Narratives and Visions*

In the following stakeholder survey from (Zeug et al., 2021b), the research questions are linked to the previous results. In order to grasp and map the stakeholder's perceptions of BE and corresponding narratives and visions, the widely known techno-political option space of the BE (Hausknost et al., 2017) is adopted. The respondents mapped their own vision of a desirable BE and where they see the German and European BE strategy in four quadrants (Figure 3):

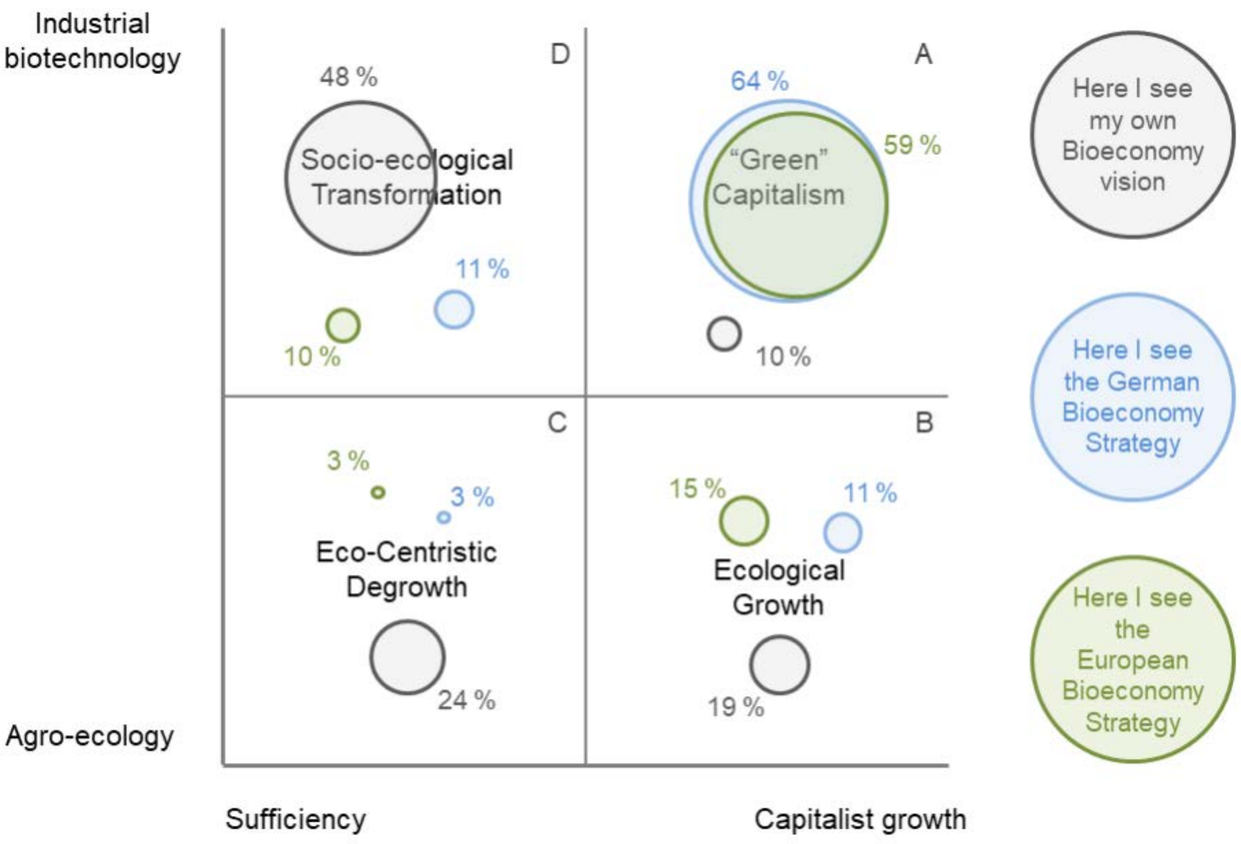


Figure 3. Shares of responses the questions "Where do you see your own BE vision?", "Where do you see the German BE Strategy?", "Where do you see the European BE Strategy?" (question label CBM01, Sci – Science, Bus– Business, NGO – Non-Governmental Organizations).

A "Green" capitalism (technology-driven transition to a (global) BE and the continuation of capitalist growth as continuous expansion and accumulation of capital, business as usual)
B Ecological growth (simultaneous agro-ecological practices and growth-based capitalist economy, visions of ecological entrepreneurship, agro-ecological innovation, smallholder practices and a regional instead of global focus)
C Ecocentric degrowth (agro-ecological practices geared towards socio-economic sufficiency, comprehensive socio-ecological transition to "near-natural" production without large-scale industrial technologies)
D Socio-ecological transformation (industrial biotechnology and sufficiency through coordinated state action, comprehensive socio-economic change towards a sufficiency perspective that satisfies human needs within planetary boundaries using advanced & large-scale industrial technologies).

As results, a majority of stakeholders see their own BE vision in a socio-ecological transformation, followed by an eco-centric vision of degrowth. In contrast, the German and European BE strategies are mostly seen as narratives of a A "green" capitalism. Having a look at the own visions of different stakeholder groups, it is noticeable that the stakeholder group business tends more towards A than all other groups, whereas NGOs preferences are balanced across all quadrants. Moreover, science, government and citizens tend mostly towards a socio-ecological transformation.

Additional results from the questionnaire show that when it comes to the societal discussion, BE is oriented mostly on previous business as usual goals, reproducing existing structures and determined by only a few actors, but most stakeholders see future discussions as quite open. This perspective gets underpinned by assessing the development of the BE as a continuation of the structural status quo: only individual sectors are changing, and corporations and industry induce mainly a technological change driven by growth and competition. However, global value chains may tend to get more regional for specific BE products. According to the openness of the discussion and in contrast to the past development of the BE, most stakeholders prefer a rather economy and society overarching societal transformation, in which environmental and social changes are main drivers and small and medium enterprises play a bigger role. In this sense, most stakeholder groups strongly encourage a sustainable future BE to entail sustainable consumption and production patterns, global responsibility and compliance with planetary boundaries, substitution of fossil fuel materials by a sufficient and efficient circular economy with the use of residual and waste materials, more sustainable agriculture that integrates ecosystem services, as well as economic and ecological justice and participation that shapes the overall economy.

Regarding future and assessments of BE, stakeholders criticized a predominant socio-economic perspective, which narrows societal well-being to growth and job creation and assumes that further positive social impacts correlate and will 'trickle down' from them. However, this can be questioned in general (Fanning and O'Neill, 2019; Postone, 1993). Furthermore stakeholders like to know explicitly of implications of the BE on social aspects like poverty, hunger, health, gender equality and economic inequalities, as well as working conditions, especially when it comes to global effects and externalization of negative impacts (cf. (Backhouse et al., 2021)).

These results from stakeholder participation strongly correspond to existing research and results, e.g. the German and European strategies like most BE strategies in general were analyzed to tend to "green capitalism" or "sustainable capital" (Hausknost et al., 2017). The preference of business stakeholders for this vision coincides with liberal growth-oriented mentalities of rather socially privileged men, which make up about 27% of the German population (Eversberg and

Fritz, 2022). In these perceptions of BE the idea of permanent unlimited growth on a bio-based basis seems plausible, and at least rhetorically by means of permanent innovation within planetary boundaries (ibid.). In contrast, there are no significant empirically cases of "socio-ecological transformations ", combining sufficiency and innovative technologies to fulfill societal needs within planetary boundaries guided by deliberative and democratic state-driven transformations (Hausknost et al., 2017). It was suspected that such a vision would be primarily encouraged from tendentially more educated groups of an eco-social-active middle class, with support for far-reaching changes and more universalistic than narrow interest-oriented viewpoints, which make up about 25 % of the German population (Eversberg and Fritz, 2022). On the basis of our results we can confirm this assumption, most respondents from the stakeholder group science encourage this vision, disagree with current developments, but as active carriers and advocates of ongoing social change hope for a more social and ecological sustainable BE and societal transformation.

From the state of the art and the results from stakeholder participation it has become clear, that narratives of BE and sustainability are determined and routed in deep perceptions and ideologies of societal relations. In the currently dominant neoclassical ideology, BE is interpreted as both: a variable production factor technology as well as additional natural resources to be used for additional growth. The notions and political BE discourses in the EU were dominated by biotechnology visions from industrial stakeholders (Hausknost et al., 2017; Staffas et al., 2013). Therefore, BE was mainly seen as the appropriate endogenous technology factor and immediate precursor in the neoclassical concept of SD by providing sufficient resources and using them to increase benefit and profit maximization, which set the stage for the win-win-win narrative of the BE (Kleinschmit et al., 2017). Bioeconomy in this sense would likely raise further huge sustainability risks when it is upscaled to an industrial level, as it is already, and will absorb large-scale biomass flows demanding significant exports and imports (Bringezu et al., 2020; Budzinski et al., 2017; Gawel et al., 2019). These aspects may be a reason for the still low public 'acceptance' or explicit criticism of the BE (Mustalahti, 2018; Stern et al., 2018) and that the majority of NGOs have a rejecting perspective on BE as a PR campaign from industrial business to green-wash their business as usual (Gerhardt, 2018; Šimunović et al., 2018). Nevertheless, a climate-neutral economy will depend on these enormous material flows of sustainable and renewable biomass. The techno-political option space of the BE (Hausknost et al., 2017) shows strong connections to the presented sustainability and economy concepts: "Sustainable Capital" corresponds to the neoclassical perspective and weak sustainability, as well as, "Eco-Growth" corresponds to the ecological economics perspective and weak sustainability as to forms of ecological modernization; "Eco-Retreat" is more an ethical vision of deep ecology, strong sustainability and ecological economics; "Planned Transition" is based on ecological economics but neither corresponds clearly to weak nor strong sustainability and will be important in the following as it by-passes the individual shortcomings of both concepts, weak and strong sustainability. (Zeug et al., 2020)

5.2 *Theoretical and Conceptual Implications from a Transdisciplinary Perspective on Sustainability Frameworks and Assessments*

5.2.1 *The Three Pillar Approach and additive LCSA*

As the previous results from stakeholder participation illustrate, BE and sustainability assessments are deeply embedded in societal discussions and underlying sustainability concepts and narratives. For the following conceptual implications on LCSA, the three-pillar approach as the most established and used sustainability framework is critically reflected. Additive LCSA takes the three parts respectively dimensions of sustainability as the point of departure and considers LCSA likewise as a linear summation and combination of the parts: E-LCA, S-LCA and LCC are carried out more or less independently from each other as separate systems (Figure 4). Broadly said, scopes, corresponding methods and indicators of the life cycle inventory (LCI), life cycle impact assessment (LCIA) as well as their individual results only have in common that they relate to the same product or FU which is intended to be assessed (cf. (Ekener et al., 2018; Suwelack, 2016; Urban et al., 2018)). When assigning the indicators to impact categories, and/or when indicators are allocated to sustainability dimensions, it becomes apparent that for some indicators no clear intuitive allocation is possible or useful. Such aspects mostly describe complex relations between two or more sustainability dimensions and are not even roughly categorizable as solely social, economic or ecological.

Dealing with such issues is difficult within the three-pillar-approach and separate assessment methods, since a simple combination of the particulate methods is only possible to a very limited extent (Costa et al., 2019; Keller et al., 2015; Wulf et al., 2019) and combining the final results with multi-criteria decision analyzes (MCDA) (Ekener et al., 2018; Sala et al., 2012a) does not represent an integration of social, environmental and economic aspects. The analysis of complex systems by their subsystems would mean more than just combining their parts (Halog, Anthony and Manik, Yosef, 2011). Such process-based approaches with a high technical detail but few general preliminary considerations result in a series of specific problems occurring in operationalization at the latest: trade-offs and conflicts of objectives (Guinée, 2016a), double-counting and problems of monetization (Kloepffer, 2008), pareto-effects of high significance within cause-effect relations, contradictions between effects on different scales (Guinée, 2016a), allocation to fuzzy impact categories (e.g. if an indicator is of primarily social, environmental or economic character or which stakeholders are effected), FUs (Costa et al., 2019), exogenous and endogenous weightings in accounting (Traverso et al., 2012), rating, normative goal systems and many more. For instance, the decoupling debate has shown that improving the environmental performance of products only has a limited effect on global environmental challenges, and pareto effects come to bear which makes a relatively small number of causes responsible for a major portion of the effects, resulting in a need for hot spot analyzes (Halog, Anthony and Manik, Yosef, 2011).

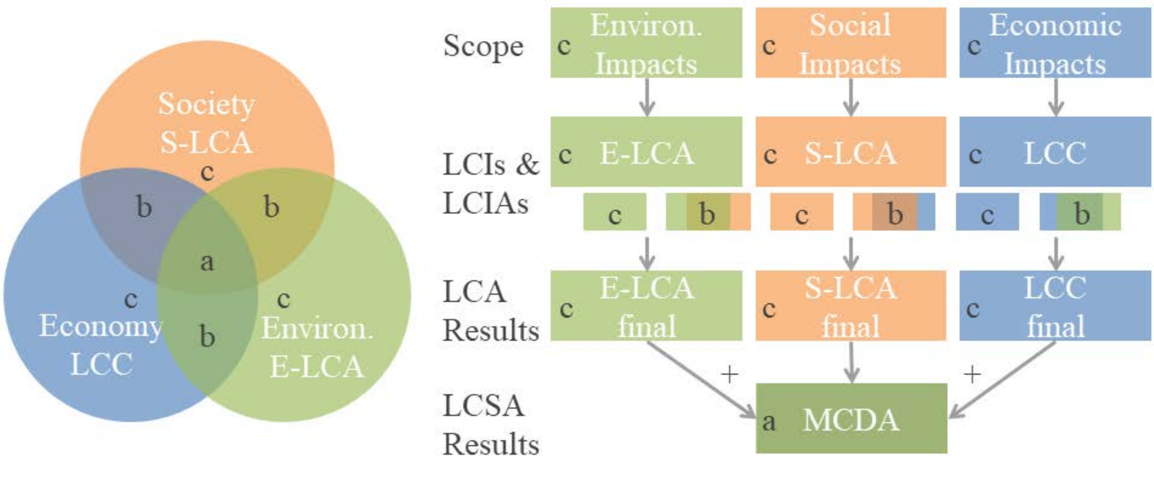


Figure 4. Three-pillar-approach of sustainability & additive scheme of LCSA=ELCA+LCC+SLCA, (c – separate systems, methods and indicators, b – intersection between two systems, indicators which cannot be clearly assigned to one system, a – all dimensions somehow combined, additive combination of methods results; LCI – Life Cycle Inventory, LCIA – Life Cycle Impact Assessment).

Generally speaking, a theoretically well-founded and holistic social, ecological or economic sustainability theory from political economy and political ecology is missing in LCSA. Integration would mean, considering social, environmental and economic aspects as one system, and holistically to transdisciplinary contextualize LCSA in social and political science.

5.2.2 Introduction of Societal Relations to Nature in Sustainability Assessment and LCA

Therefore, the concept of societal relations to nature (SRN) is implemented for a development towards a holistic and integrated LCSA (HILCSA). In SRN, nature, economy and society do not stand in an external relation to each other nor do they exist by themselves as the three-pillar approach suggests, rather, they constitute each other through their relations (Görg, 2003, 2011; Görg et al., 2017; Hummel et al., 2017; Kramm et al., 2017; Pichler et al., 2020; Pichler et al., 2017): At its core the SRN concept evolves around the idea of societal needs and SRNs normatively should be regulated to fulfill them. Social ecology and SRN conceptualize societies as simultaneously subject to biophysical and socio-cultural spheres of causation in a social metabolism. Nature and society are different things, and although distinct, not independent from one another. What nature is results from what society, culture, technology, etc. is not, and vice versa. Social metabolisms transform a society's energetic and material inputs, integrate them into societal stocks or other socio-economic systems, and discharge them to the environment as wastes and emissions. Industrial and BE metabolisms are special cases of social metabolisms (Bezama et al., 2021). However, this societal metabolism has no essential or eternal nature (Pichler et al., 2017). Instead historically, geographically and culturally specific socio-cultural mechanisms like politics and economic patterns are in place through which a society organizes its metabolism. In general, our SRN are shaped by economies, which are temporally and geographically different (e.g. transformable) social systems supposed to satisfy societal needs (ends) utilizing natural resources, labor and technologies (means) (cf. Figure 6, chapter 5.3). Especially important for LCSA are working hours as the crucial (activity) variable in production processes, since labor is not only the origin of economic value but as well relates social effects to production processes (Fröhlich, 2009; Postone, 1993).

These economic, and therefore also societal, mechanisms are understood as specific patterns of regulation, and fail when interactions with nature become dysfunctional, e.g. overexploitation of natural resources (overfishing, deforestation, soil degradation) or failure of a mechanism for effective and efficient allocation (hunger, poverty).

A good example of capitalist SRN and patterns of regulation is the apparent connection between ending poverty (SDG 1) and ending hunger (SDG 2), both considered by stakeholders as very relevant for the BE (Zeug et al., 2019). In this case, even if enough food is produced worldwide to end hunger, the pattern of regulation of our economies requires ending poverty first. Since societal needs alone (use value), sufficient resources and means do not lead to their fulfillment, as long as those needs and preconditions are not coupled with enough purchasing power and income (exchange and surplus value). The same is true for the fuel vs food debate in BE: land or crops will be used for the purpose with the highest expected surplus value (e.g. fuels), instead of the fulfillment of more basic societal needs with a higher use but lower exchange value (e.g. nutrition) (cf. (Ashukem, 2020)). (Zeug et al., 2023b)

5.2.3 Societal-Ecological Transformation and the role of LCSA

Transformations take place as changes in initial patterns of regulation to new ones when the old ones become dysfunctional (Wittmer et al., 2022), as the previously discussed patterns of regulation show and stakeholders suggest to be necessary. Such transformations will have to innovatively address normative and socio-economic barriers, like global political patterns of regulation and resulting production and consumption patterns, as well as technological and environmental challenges. For example, and with specific relevance for HILCSA, technological inventions must go hand in hand with social, economic and organizational innovations, and questions of scale arise in the field of tensions between a global socio-ecological crisis and the responsibility and scope for action at a regional and global scale.

A potential future societal-ecological transformation should incorporate the PB as the main ecological limits, e.g. a certain GHG concentration should not be exceeded as well as there is a limit for the use of land, resources, water and so on (O'Neill et al., 2018). PB are not necessarily constant over time and nor a deterministic constant, but at least most likely are scenarios in which the transgression of one PB leads to even more transgressions of other PB (Rockström et al., 2009; Steffen et al., 2018), e.g. climate change induces water scarcity and land degradation. Displayed as qualitative trends derived from quantitative charts (Roser, 2022), environmental impacts and resource use grew and grow exponentially, especially since the 1950s and temporarily are exceeding PB globally by far (Figure 5). Whereas the production of material and immaterial commodities (e.g. GDP) as the cause for transgressing PB increases even more exponentially. However, the development of social indicators like the human development index rather has a far less exponential and more linear trend. This not only illustrates the production of exchange values by commodities as a main driver of production, resource use and environmental impacts in capitalism, but as well the quality in which societal needs are disproportionally coupled to commodity production. However, these qualitative trends correspond more to industrialized countries of the global north and negative impacts are shifted especially to the global south (Bauriedl, 2016; Görg, 2015).

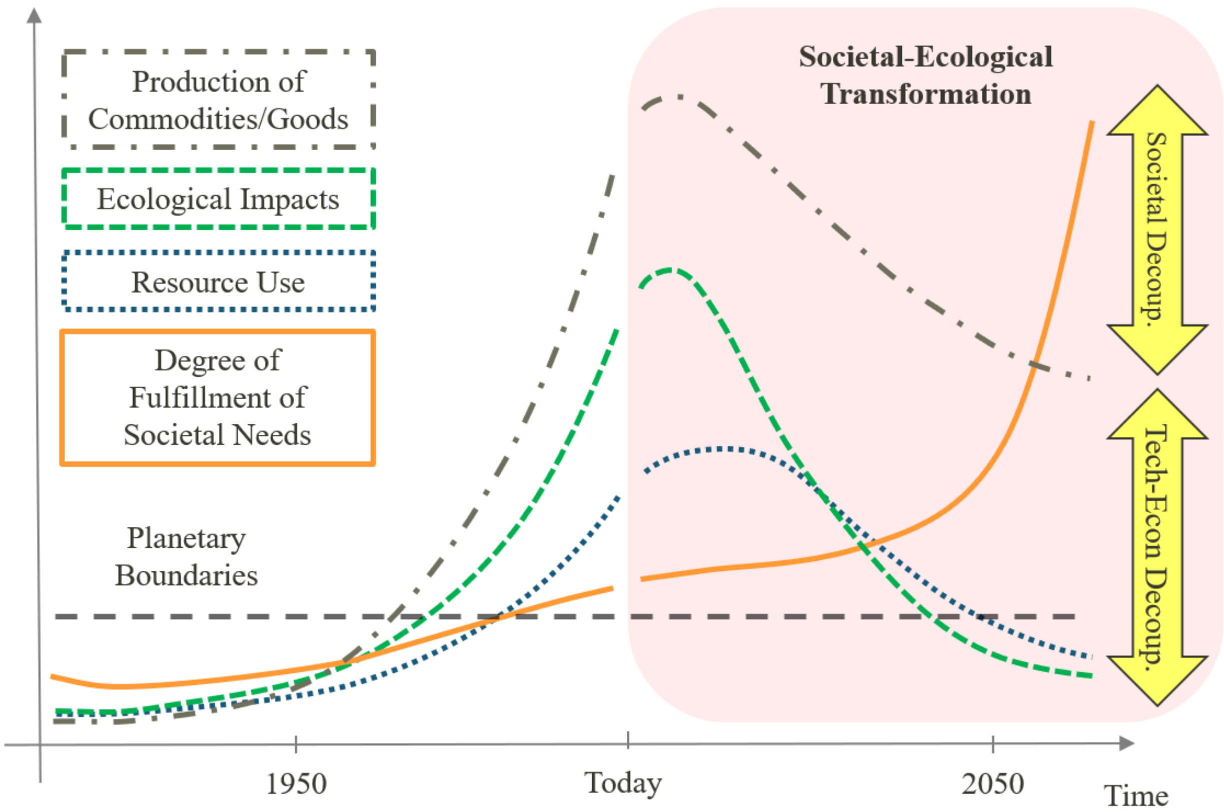


Figure 5. Societal-ecological transformation and double decoupling as qualitative trends.

A societal-ecological transformation would have to change patterns of regulation and societal relations in a way which, in technical terms, can be described as double decoupling: a societal as well as a techno-economic decoupling, which are mutually dependent and related to each other. On the one hand, the societal decoupling would have to decouple the degree of fulfillment of societal needs from an increasing production of material goods services and overcome their commodity character, e.g. sufficiency. Such a societal-ecological transformation on a societal level means mainly a reconsideration of the economy as a satisfaction of societal needs (ends) by means of natural resources, labor and technologies (means). Innovation and sustainable technologies alone will not solve this predominantly political challenge. Without a societal decoupling there is relative decoupling (fewer impacts per product, techno-economic) but no absolute decoupling (fewer impacts in total, societal), absolute decoupling is not plausible in a growing economy.

On the other hand, and as the more relevant field for the application of LCSA, the techno-economic decoupling means decoupling the remaining sufficient and necessary material production from increasing resource use and negative environmental, social and economic impacts. Sustainable BE has to be a highly effective (fulfills societal needs), efficient (achieving most with less) and just (nobody falls behind) use of renewable resources within PB. Unique about the BE provisioning system is its inherent capability of regeneration, allowing natural or biological resource stocks to replenish after extraction, and they are typically in constant interaction with their surrounding systems (Erb et al., 2022; Lindqvist et al., 2019; Zörb et al., 2018). Whereas every unit of non-renewable resources used now is a resource which will not be available in the future and thereby comprises intra- and intergenerational equity (Fedrigo-Fazio et al., 2016; Parrique T., 2019). But BE as industrial metabolism is only sustainable if: the rate of extraction does not exceed the rate of regeneration; the regenerative capacity is not diminished by extraction, processing, and utilization of resources; material and energy cycles are increasingly linked; and societal needs are fulfilled as well as they are the central objective of the economy itself. In contrast to non-renewable fossil systems, these complex interactions make the management of the BE complex and require fundamentally different strategies of planning (Erb et al., 2022; Lindqvist et al., 2019). Besides, the concept of reduce, reuse and recycle can actually be put into practice in the right order, since today a reduction or sufficiency of production and consumption is incompatible with the imperative of growth.

Hence, a societal-ecological transformation and sustainable BE corresponds strongly to the "Planned Transition" techno-political vision of BE (Hausknost et al., 2017) suggested by stakeholders. This means that both advanced technologies on a large-scale industrial level (integrated biorefineries, cascade use, eco-functional intensification of certain agricultural sectors, global trade in certain biogenic commodities, use of high-tech biotechnologies) will be needed to achieve the very ambitious demands on resource efficiency (Aguilar et al., 2018; Nitzsche et al., 2016; Olsson et al., 2016; Panoutsou et al., 2013), and further growth, capital accumulation and an invisible hand are not a necessary part of BE. Rather, not transgressing the PBs, fulfilling essential societal needs and socially conscious planning of this transformation are.

5.3 Operationalization and Implementation of Holistic and Integrated LCSA (HILCSA) for BE Regions

5.3.1 Sustainability Concept and LCA Framework for HILCSA

The sustainability concept and LCA framework of HILCSA aims to take the previously discussed complex problems into consideration, as far as possible in a broad understanding of LCSA methods. Holistic in this regard means to have the bigger picture in mind: not only a transdisciplinary and critical background theory of political economy, but as well to not fall short on the implications which some of the results may have and impose to fundamental societal transformations, instead of only technological innovation or doing some 'tweaks in the system'. Whereas integrated stands for an integrated model of sustainability and LCSA which enables redeeming the integrated approach suggested by Guinée et al. (2011): to integrate social, ecological and economic sustainability assessment into one unified method instead of additionally combining different methods.

Economic systems on a meso scale are handled as product- and process-systems in LCA, comprising both physical and social systems, mediating the relationship between natural resources and societal needs through economic infrastructures and practices. When normatively aiming at a good life for all within planetary and regional boundaries, an integrated sustainability model puts social, ecological and economic sustainability in a specific relation: SRN which fulfill societal needs (ends) by means of natural resources, labor and technologies (means). This leads to a model (Figure 6, i) in which integrated sustainability is defined as:

- Long-term and global fulfillment of societal needs and well-being as an end (social sustainability),
- Long-term stability of our environment as a basis of societal reproduction within PB (ecological sustainability),
- Technologies and economic structures as efficient, effective, sufficient and just metabolisms which enable the fulfillment of societal needs within PB (economic sustainability).

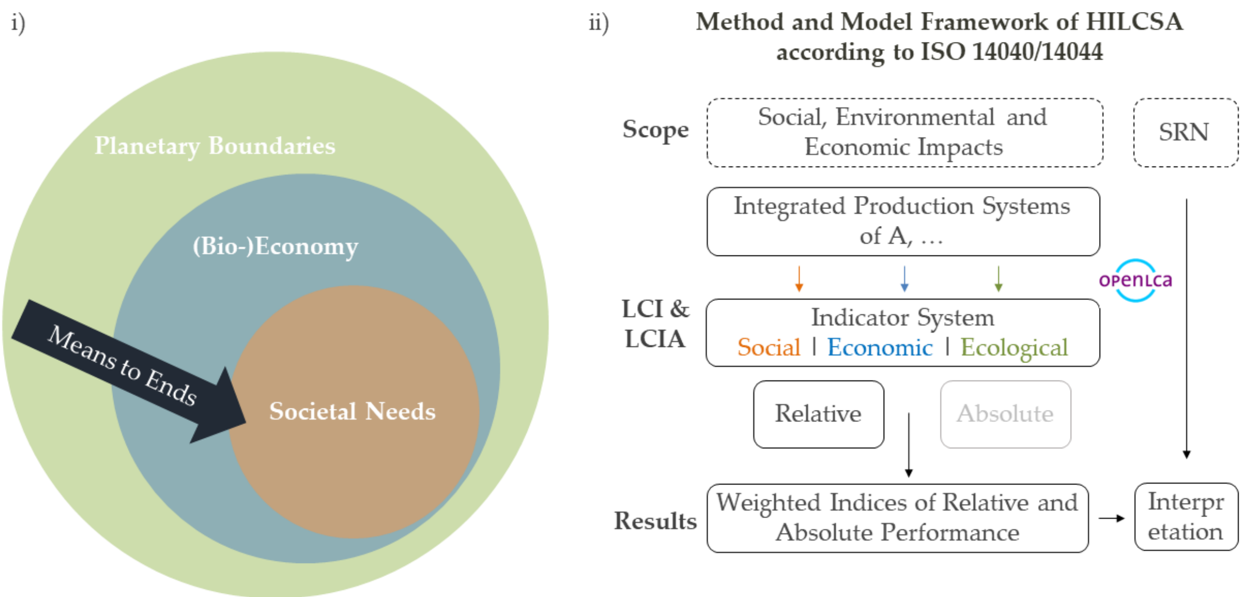


Figure 6. i) Sustainability model, ii) Framework of HILCSA = f (S-LCA, E-LCA, LCC) (integrated product and production systems in openLCA entail environmental, social and economic data).

Second, in contrast to the additive LCSA (LCSA = S-LCA + E-LCA + LCC), the HILCSA (HILCSA = f (S-LCA, E-LCA, Economic-LCA)) framework builds on this integrated sustainability framework for operationalization and integrates social, economic and environmental aspects in a common goal and scope, LCI, LCIA, results and interpretation (Figure 6, ii). Thus, it is based on ISO 14040 and 14044. Economic sustainability in this sense is the enabling criteria for actually reaching social sustainability and ecological sustainability at once, profit or growth is neither a criterion nor an end itself: economic sustainability means to fulfill necessary societal needs at a sufficient level with the highest possible resource efficiency without transgressing PB. Between indicators or sustainability aspects there is no compensation or credit (e.g. positive assessment results of indicators are offset with negative results of other indicators in indices) applied, as it is sometimes suggested in LCSA. Simply because there is no meaningful mechanism of compensating GHG emissions by improvements in health at working conditions within a production system. For allocation and weighting of indicators in HILCSA, certain SDGs and their previously determined relevances are assigned indicators of societal needs, economy and PB, however, due to the complex interactions one indicators can have impacts on several SDGs: societal needs (SDG 1, 2, 3, 4, 5, 11, 16, 17); economy (SDG 6, 7, 8, 9, 10, 12); PB (SDG 13, 14, 15). The initial indicator set of HILCSA is presented in Part II (Zeug et al., 2021a).

Although HILCSA is applicable for production systems in general, the focus on BE is given by specific indicators on i.e. land-use-change, biomass extraction or CEDs without the net calorific value of biomass for material use. For the LCI, the operational core of HILCSA are integrated production systems and processes entailing social, environmental and economic data which are modeled in the software environment of openLCA, mainly using the SoCa database (Di Noi et al., 2018; Eisfeldt, 2017) completed by additional data gathering (e.g. questionnaires (Jarosch et al., 2020)). The SoCa add-on as a combination of Ecoinvent and PSILCA (Product Social Impact LCA) database as well as a basic LCSA functionality in openLCA is fundamental to this.

5.3.2 *Initial LCI and LCIA for HILCSA*

From the studies and methods considered, in total 708 possible indicators are identified for bioeconomy assessment on territorial and product level. The FAO indicator report (Bracco et al., 2019) provides the most comprehensive overview of possible BE related indicators, 248 on product level and 252 on territorial level, and is a helpful reference for setting up possibilities of an indicator system. While it does not provide directly applicable indicators or methods for HILCSA, taking it as a reference template and allocating LCIAs to it already produces a bioeconomy-specific indicator system. Thereof 566 nonredundant (criteria c) indicators can possibly be applied to regional bioeconomy assessments by allocating them to SDGs and HILCSA sustainability framework (criteria a). These indicators describe 118 social, 130 environmental and 318 economic aspects assigned to 74 SDGs and sub-goals. For 95 SDG sub-goals there are no indicators yet, mainly SDG 16, 17, 10 and 3. Especially for SDG 16 there no direct indicator links in current literature and it is more a cross-cutting issue for bioeconomy (Calicioglu and Bogdanski, 2021).

In the following, all indicators whose relevance of corresponding SDGs is significant for bioeconomy monitoring are kept (criteria d, “must & may be part of monitoring” (Zeug et al., 2019), and which are available within LCIA methods and databases of openLCA (criteria b & e). Some of the SDG sub-goals and indicators which are not applicable in a LCSA of bioeconomy are excluded from the LCI (criteria b), e.g. policy coherence in sustainable development (SDG 17.14). As a result, HILCSA is capable of 109 indicators. To cover organizational social aspects of region companies, 12 indicators from RESPONSA were selected and considered as practically applicable for the provisioning system and 4 indicators for societal needs (mostly addressing working conditions). Some RESPONSA indicators are left out since there is a redundancy and too high level of detail (Jarosch et al., 2020) or SoCa covers them. When indicators are already available within an established LCIA method, we prefer them because of their better practicability and robustness. Likewise, to cover technological aspects 7 indicators mainly including technological process characteristics (e.g. efficiencies, cascading factor) were selected from SUMINISTRO, delivering valuable data for later case studies (Hildebrandt et al., 2020; Siebert et al., 2018). All other (mid-/endpoint) indicators come with the LCIA methods available in openLCA (Acero et al., 2016) and chosen for HILCSA: SoCa, ReCiPe 2016 (H), Impact World + and EF 3.0.

As a typical consequence in LCSA, this framework is not as detailed as in stand-alone methods (Taylor et al., 2017). Rather the goal is to avoid a piecemeal approach to sustainable transformation and the capability of delivering a holistic picture on trade-offs, synergies, hotspots, significant risks and chances as well as a fundamental understanding as discussed before. In addition, more indicators do not necessarily lead to a better quality necessarily, but an adequate impact category coverage is particularly important (Lindqvist et al., 2019). The 109 possible indicators are currently the maximum indicators available regarding their coverage in LCIA methods, data availability and robustness, as well as they already cover most of the relevant aspects.

In Table 1 all indicators are allocated to the sustainability framework from above. Indicators have a qualitative (categorical, limited number of values) or quantitative (continuous, unlimited number of values) type of data, and are categorized by having a physical FU (material flow) or an AV (working hours), and their unit of measurement which is the same as from the source of the indicator.

In general, a unit, volume or mass of products (material flow) is used as reference flows providing FUs (Sahoo et al., 2019). For the purposes of HILCSA, openLCA with SoCa as software environment for implementation of HILCSA sufficiently supports a variety of FUs (mass, volume, product units, WFE) as well as working hours as AV. Only one FU or reference material flow is not sufficient for accounting impacts on social, economic and environmental systems. Rather, additional AVs need to be used (Costa et al., 2019; Zamagni et al., 2013). The AV for balancing social and some economic impacts has similarities with elementary flows, and is used to represent the impact share of a process step or unit process. The crucial difference is that most social and economic effects of the production of a commodity are not directly related to the amount of physical output of a process, but are mediated through complex socio-economic relations balanced by the number of working hours required to produce the FU (Dreyer et al., 2006; Grießhammer et al., 2006; UNEP, 2020; Zeug et al., 2020). Nevertheless, working hours are indirectly related to some social indicators, e.g. drinking water coverage or displacements of local communities, for which new approaches are under development (Ciroth et al., 2019; UNEP, 2020).

As mentioned, the indicators of HILCSA have an absolute (impact pathway) or relative (reference scale) character important for their LCIA. The relevance of the indicator is derived from the respective relevance of its SDG and subgoals according to our stakeholder participation process, and shown as a decimal score ranging from 4.43 to 9.33. Since all indicators in the LCI are not modified and are integrated in HILCSA as they were presented in their original studies, we will not discuss any indicators individually here, but refer to the relevant literature. Within the LCIA, indicators are liked by classification, normalization, weighting and aggregation to the sustainability framework and the SDGs as well as subgoals as end point impact categories. From 109 indicators, 20 are assigned to societal needs, 60 to the provisioning system and 29 to planetary boundaries - thereby covering 30 SDGs and sub-goals. As part of the LCIA, in RESPONSA and partly SUMINISTRO the performance of organizations of the life cycle was compared with a statistical reference and resulting dimensionless PRP (Siebert et al., 2018) give an indication on the social performance of a product life cycle (e.g. LVL) (Hildebrandt et al., 2020; Jarosch et al., 2020). For most of the planetary boundaries-indicators and some indicators of societal needs, whose impact have their cause in physical emissions (e.g. emissions and health), we follow impact pathway LCIA approaches to assess consequential social impacts through characterizing the cause-effect chain (cf. (UNEP, 2020)).

There are a series of heterogeneous and mostly incompatible environmental LCIA methods for the environmental assessment of bioeconomy value-added chains (Cristobal et al., 2016), but we follow the recommendation of the EC-JRC by using the LCA-based Product Environmental Footprint (PEF) methods (EC and JRC, 2010; Fazio et al., 2018). Environmental Footprint and PEF are most suitable in HILCSA because of two main reasons: they provide a best practice to include global effects into a meso-level assessment such as LCSA, and thereby bridge the gap to global and national goal systems like the SDGs (Wulf et al., 2018) as well as planetary boundaries. The growing importance of planetary boundaries and the finite nature of the environment led to developing absolute sustainability assessment methods in LCA recently (Bjørn et al., 2020; Sala et al., 2020). Absolute sustainability assessment methods evaluate if an industrial metabolism on different scales (ranging from products, regions to whole economies) is (un-)sustainable in an absolute sense of regional and global boundaries for a comprehensive set of impact categories. However, there are planetary boundaries SDGs and subgoals not covered by Environmental Footprint (e.g. Ozone Formation/Depletion, loss of biodiversity, terrestrial acidification/toxicity) (Chandrakumar et al., 2018) for which we chose mid- and endpoint indicators from ReCiPe 2016 (H- Hierachrist) (Huijbregts, 2016; Huijbregts et al., 2017) and Impact World+ (Bulle et al., 2019). However, Impact World + is still to be implemented in openLCA in near future.

Combining several LCIA methods within one framework is necessary to cover all impact categories and not problematic in principle (Di Noi et al., 2018; Wulf et al., 2018). Though, a consistent implementation of several LCIA requires a careful analysis of their units, impact factors and normalization methodologies as well as to avoid double counting one impact in several LCIAs and impact categories. Even more important and controversial in LCSA than in LCA, are the optional steps of normalization, weighting, and aggregation of impact categories, due to increased complexity of results and how to communicate them to different stakeholders (Andreas et al., 2020; Wulf et al., 2017). These steps are comprehensively discussed in the papers and case studies (see Part II).

Table 1. Indicators, LCIA methods and properties in HILCSA (SF- sustainability Framework, FU – Functional Unit, AV – Activity Variable, R – Relevance of SDG and sub-goals, wh – Working hours, mf – material flow, qual – qualitative, quan - quantitative).

SF	SDG Code	Source	ID	Indicator Name	Data type	FU/ AV	Unit of Measurement	R
Societal needs	1	SoCa	1/1	Social security expenditures	quan	wh	% of GDP	6.61
	1.2	SoCa/Responsa	1.2/1	Payment according to basic wage	qual	wh	y/n	6.94
	1.4	Responsa	1.4/1	Capital participation	qual	wh	y/n	6.94
	1.4	Responsa	1.4/2	Profit-sharing and bonuses	qual	wh	y/n	
	2	Recipe/Impact World (Endpoint)	2/1	Water consumption - human health	quan	mf	Daly/m3 consumed	9.33
	2.3	SoCa	2.3/1	Human rights issues faced by indigenous people	quan	wh	Score	6.39
	2.3	SoCa	2.3/2	Presence of indigenous population	qual	wh	y/n	
	3.9	SoCa	3.9/1	DALYs due to indoor and outdoor air and water pollution	quan	wh	DALY rate	8.61
	3.9	SoCa	3.9/2	Pollution level of the country	quan	wh	Index	

	3.9	Recipe/Impact World (Endpoint)	3.9/3	Global Warming - Human health	quan	mf	DALY/kg CO_2 eq.	
	3.9	Recipe/Impact World (Endpoint)	3.9/4	Stratospheric ozone depletion - Human health	quan	mf	DALY/kg CFC11 eq.	
	3.9	Recipe (Endpoint)	3.9/5	Photochemical ozone formation - Human health	quan	mf	DALY/kg NOx eq.	
	3.9	Recipe/Impact World (Endpoint)	3.9/6	Ionizing Radiation - Human health	quan	mf	DALY/kBq Co-60 emitted to air eq.	
	3.9	Recipe/Impact World (Endpoint)	3.9/7	Fine particulate matter formation - Human health	quan	mf	DALY/kg PM2.5 eq.	
	3.9	Recipe/Impact World (Endpoint)	3.9/8	Toxicity - Human health (cancer)	quan	mf	DALY/kg 1,4-DCB emitted to urban air eq.	
	3.9	Recipe/Impact World (Endpoint)	3.9/9	Toxicity - Human health (non-cancer)	quan	mf	DALY/kg 1,4-DCB emitted to urban air eq.	
	4	SoCa	4/1	Public expenditure on education	quan	wh	% of GDP	4.43
	5.1	SoCa	5.1/1	Gender wage gap	quan	wh	%	5.83
	5.1	Responsa	5.1/3	Rate of female employees	quan	wh	%	
	5.1	Responsa	5.1/6	Measures to improve gender equality	qual	wh	y/n	
	11.6	Recipe/Impact World (Endpoint)	11.6/1	If production site is in urban region (Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted), see 3.9/7				9.17
Provisioning System	6.1	SoCa	6.1/1	Drinking water coverage	quan	wh	%	8.61
	6.2	SoCa	6.2/1	Sanitation coverage	quan	wh	%	4.44
	6.4	FAO Product	6.4/1	Amount of water used in the whole forestry wood chain (m3) [8] /water consumption	quan	mf	m^3/t	7.22
	7.2	FAO Product	7.2/1	Change in consumption level of fossil fuel resources / product unit [2]	quan	mf	%	5.56
	7.2	CED	7.2/2	Share of fossil energies, CED	quan	mf	%	
	7.3	EF 3.0	7.3/1	Resource use, energy carriers	quan	mf	MJ	5.83
	7.3	CED	7.3/2	Cumulated Energy Demand	quan	mf	MJ	
	8.4	Suministro	8.4/1	Increasing the resource efficiency of biomass conversion	quan	mf	w/w	5.83
	8.4	Suministro	8.4/2	Cascading factor	quan	mf	w/w	
	8.4	Suministro	8.4/3	Maximizing land use efficiency (forest biomass, agroforestry and agrarian biomass)	quan	mf	t saw logs/ ha, t fiber/ ha, t sugar / ha , t pulp/ha , t/ ha*t/t Sucrose	
	8.4	Suministro	8.4/4	Increase in material efficiency	quan	mf	e.g. U-Value, Tensile modulus	
	8.5	SoCa/Responsa	8.5/1	Weekly hours of work per employee	quan	wh	h	5.00
	8.5	Responsa	8.5/2	Compensation for overtime	qual	wh	y/n	

	8.5	Responsa	8.5/3	Access to flexible working time agreements	qual	wh	y/n	
	8.5	Responsa	8.5/4	Rate of part-time employees	quan	wh	%	
	8.5	Responsa	8.5/5	Rate of marginally employees (max. 450€)	quan	wh	%	
	8.5	Responsa	8.5/6	Rate of fixed-term employees	quan	wh	%	
	8.5	Responsa	8.5/7	Rate of employees provided by temporary work agencies	quan	wh	%	
	8.5	Responsa	8.5/8	Rate of disabled employees	quan	wh	%	
	8.5	Responsa	8.5/9	Rate of foreign employees	quan	wh	%	
	8.5	SoCa	8.5/10	Net migration rate	quan	wh	‰	
	8.5	SoCa	8.5/11	International Migrant Stock	quan	wh	%	
	8.5	SoCa/Responsa	8.5/12	Average remuneration level	quan	wh	€	
	8.5	SoCa	8.5/13	Sector average wage, per month	quan	wh	USD	
	8.5	SoCa	8.5/14	Unemployment rate in the country	quan	wh	%	
	8.6	Responsa	8.6/1	Rate of vocational trainees	quan		%	4.72
	8.7/8.8	SoCa	8.7/2	Children in employment, total	quan	wh	% of children	5.00
	8.7/8.8	SoCa	8.7/5	Trafficking in persons	quan	wh	Tier	
	8.7/8.8	SoCa	8.7/6	Frequency of forced labor	quan	wh	‰	
	8.7/8.8	SoCa	8.7/7	Goods produced by forced labor	quan	wh	#	
	8.7/8.8	SoCa	8.7/8	Right of Collective bargaining	quan	wh	Score	
	8.7/8.8	SoCa	8.7/9	Right of Association	quan	wh	Score	
	8.7/8.8	SoCa	8.7/10	Trade union density	quan	wh	%	
	8.7/8.8	SoCa	8.7/11	Right to Strike	quan	wh	Score	
	8.7/8.8	SoCa/Responsa	8.7/12	Rate of non-fatal accidents at workplace	quan	wh	#/yr and 100k empl.	
	8.7/8.8	SoCa/Responsa	8.7/13	Rate of fatal accidents at workplace	quan	wh	#/yr and 100k empl.	
	8.7/8.8	Responsa	8.7/14	Sick-leave days	quan	wh		
	8.7/8.8	SoCa/Responsa	8.7/15	Presence of sufficient safety measures	quan	wh	# per 100k empl.	
	8.7/8.8	Responsa	8.7/16	Measures to support older employees	qual	wh	y/n	
	8.7/8.8	SoCa	8.7/19	Evidence of violations of laws and employment regulations	quan	wh	# per 1k empl.	
	8.7/8.8	SoCa	8.7/20	Workers affected by natural disasters	quan	wh	%	
	9.5	Responsa	9.5/1	Rate of employees in research and development	quan	wh	%	5.83
	12.2	SoCa	12.2/4	Level of industrial water use (related to total withdrawal)	quan	mf	% of total	8.89
	12.2	SoCa	12.2/5	Level of industrial water use (related to renewable water resources)	quan	mf	% of renewable	
	12.2	Recipe/Impact World (Endpoint)	12.2/6	Fossil resource scarcity	quan	mf	USD2013/kg Cu	
	12.2	SoCa	12.2/7	Extraction of fossil fuels	quan	mf	t/cap	
	12.2	SoCa	12.2/8	Extraction of biomass (related to population)	quan	mf	t/cap	

	12.2	SoCa	12.2/9	Extraction of biomass (related to area)	quan	mf	t/km²	
	12.2	SoCa	12.2/10	Extraction of industrial and construction minerals	quan	mf	t/cap	
	12.2	SoCa	12.2/11	Extraction of ores	quan	mf	t/cap	
	12.2	EF 3.0	12.2/12	Resource use, mineral and metals	quan	mf	kg Sb eq.	
	12.2	Recipe (Midpoint)	12.2/13	Ionizing Radiation	quan	mf	Bq C-60 eq. to air	
	12.5	Suministro	12.5/1	Reduction of waste from fossil-based auxiliaries	quan	mf	%	9.17
	12.5	Suministro/FAO Product	12.5/2	Maximizing the recycled content at the end of its life/% of product is actively being recovered and recycled [5]	quan	mf	%	
	12.6	Suministro	12.6/1	Maximizing or Guaranteeing high standards of raw material provision	quan	mf		8.61
	12.6	SoCa	12.6/2	Certified environmental management systems	quan	mf	# per 10k empl.	
	12.6	SoCa	12.6/3	Presence of anti-competitive behavior or violation of anti-trust and monopoly legislation	quan	mf	# per 10k empl.	
	16.5	SoCa	16.5/1	Public sector corruption	quan	mf	Score	7.22
	16.5	SoCa	16.5/1	Active involvement of enterprises in corruption and bribery	quan	mf	%	
Planetary Boundaries	13	EF 3.0	13/1	Climate Change	quan	mf	kg CO_2 eq.	7.53
	13	EF 3.0	13/2	Climate Change (fossil)	quan	mf	kg CO_2 eq.	
	13	EF 3.0	13/3	Climate Change (biogenic)	quan	mf	kg CO_2 eq.	
	13	Recipe (Midpoint)	13/9	Photochemical Ozone Formation, Ecosystems/Photochemical Ozone Formation, Human Health	quan	mf	kg NOx eq.	
	13	Recipe/Impact World (Midpoint)	13/10	Stratospheric Ozone Depletion	quan	mf	kg CFC-11 eq.	
	13	EF 3.0	13/20	Climate Change (land use change)	quan	mf	kg CO_2 eq.	
	14	Recipe (Endpoint)	14/1	Global Warming - Freshwater ecosystems	quan	mf	Species.year/kg CO_2 eq.	8.37
	14	EF 3.0	14/2	Eutrophication freshwater	quan	mf	kg P eq.	
	14	EF 3.0	14/3	Ecotoxicity freshwater	quan	mf	CTUe	
	14	EF 3.0	14/4	Water scarcity	quan	mf	m³ world equiv.	
	14	EF 3.0	14/5	Acidification terrestrial and freshwater	quan	mf	Mole of H+ eq.	
	14	Impact World (Endpoint)	14/6	Thermally polluted water	quan	mf	PDF.m2.yr	
	14	Impact World (Endpoint)	14/7	Water availability, freshwater ecosystem	quan	mf	PDF.m2.yr	

	14.1	Recipe (Endpoint)	14.1/1	Toxicity - Marine ecosystems	quan	mf	species·yr/kg 1,4-DBC emitted to sea water eq.	8.33
	14.1	EF 3.0	14.1/2	Eutrophication marine	quan	mf	kg N eq.	
	14.3	Impact World (Endpoint)	14.3/1	Marine acidification, long term	quan	mf	PDF.m2.yr	6.94
	14.3	Impact World (Endpoint)	14.3/2	Marine acidification, short term	quan	mf	PDF.m2.yr	
	15.1	EF 3.0	15.1/1	Land Use	quan	mf	Pt	7.50
	15.1	Recipe (Midpoint)	15.1/2	Terrestrial Acidification	quan	mf	kg SO_2 eq.	
	15.1	Recipe (Midpoint)	15.1/3	Terrestrial ecotoxicity	quan	mf	kg 1,4-DB eq.	
	15.1	Impact World (Endpoint)	15.1/4	Water availability, terrestrial ecosystem	quan	mf	PDF.m2.yr	
	15.1	EF 3.0	15.1/5	Eutrophication terrestrial	quan	mf	Mole of N eq.	
	15.5	Recipe (Endpoint)	15.5/1	Global Warming - Terrestrial ecosystems	quan	mf	Species.year/kg CO_2 eq.	8.33
	15.5	Impact World (Endpoint)	15.5/2	Ionizing radiation, ecosystem quality	quan	mf	PDF.m2.yr	
	15.5	EF 3.0	15.5/3	Land occupation, biodiversity/Land transformation, biodiversity	quan	mf	m2 arable land eq .yr	
	15.5	Recipe (Endpoint)	15.5/4	Photochemical ozone formation - Terrestrial ecosystems	quan	mf	Species.year/kg NOx eq.	
	15.5	Recipe (Endpoint)	15.5/5	Acidification - Terrestrial ecosystems	quan	mf	Species.year/kg SO2 eq.	
	15.5	Recipe (Endpoint)	15.5/6	Toxicity - Terrestrial ecosystems	quan	mf	species*yr/kg 1,4-DBC emitted to industrial soil eq.	
	15.5	Recipe (Endpoint)	15.5/7	Water consumption - terrestrial ecosystems	quan	mf	species.yr/m3 consumed	

5.4 Application and Validation of HILCSA in Case Studies and Results on Risks and Chances of a BE Transformation

In context of this dissertation the HILCSA method is applied in two case studies, first the production of laminated veneer lumber (LVL) and second the production of biofuels (BtLs). Regarding the methodology, the goals are to apply and validate HILCSA, to show its capabilities and application as well as to achieve further development and improvement.

5.4.1 Application of Holistic and Integrated LCSA: First Case Study on LVL Production in Central Germany

5.4.1.1 Goal and Scope

Goal of the first HILCSA application is to assess the relative social, environmental and economic impacts of LVL production as risks and chances of regional BE product systems, their contributions to the SDGs and a socio-ecological transformation. As HILCSA at the current state is a relative assessment method, in this case LVL based on renewable raw materials is compared with steel beams made of fossil raw materials, both having the same functionality per FU. Beech wood is the main resource for the product system of LVL production in Central Germany and LVL serves as supporting structures in timber construction and also can be processed further to components for other applications (Jarosch et al. 2020; Pollmeier 2018). We speak about regional BE, as it is the case here, when a predominant share of resource extraction, semi-finished products and manufacturing take place within a spatial area of no more than 100km radius. This radius is the average transport distance for roundwood in Germany (Schusser et al. 2019; Obkircher et al. 2013).

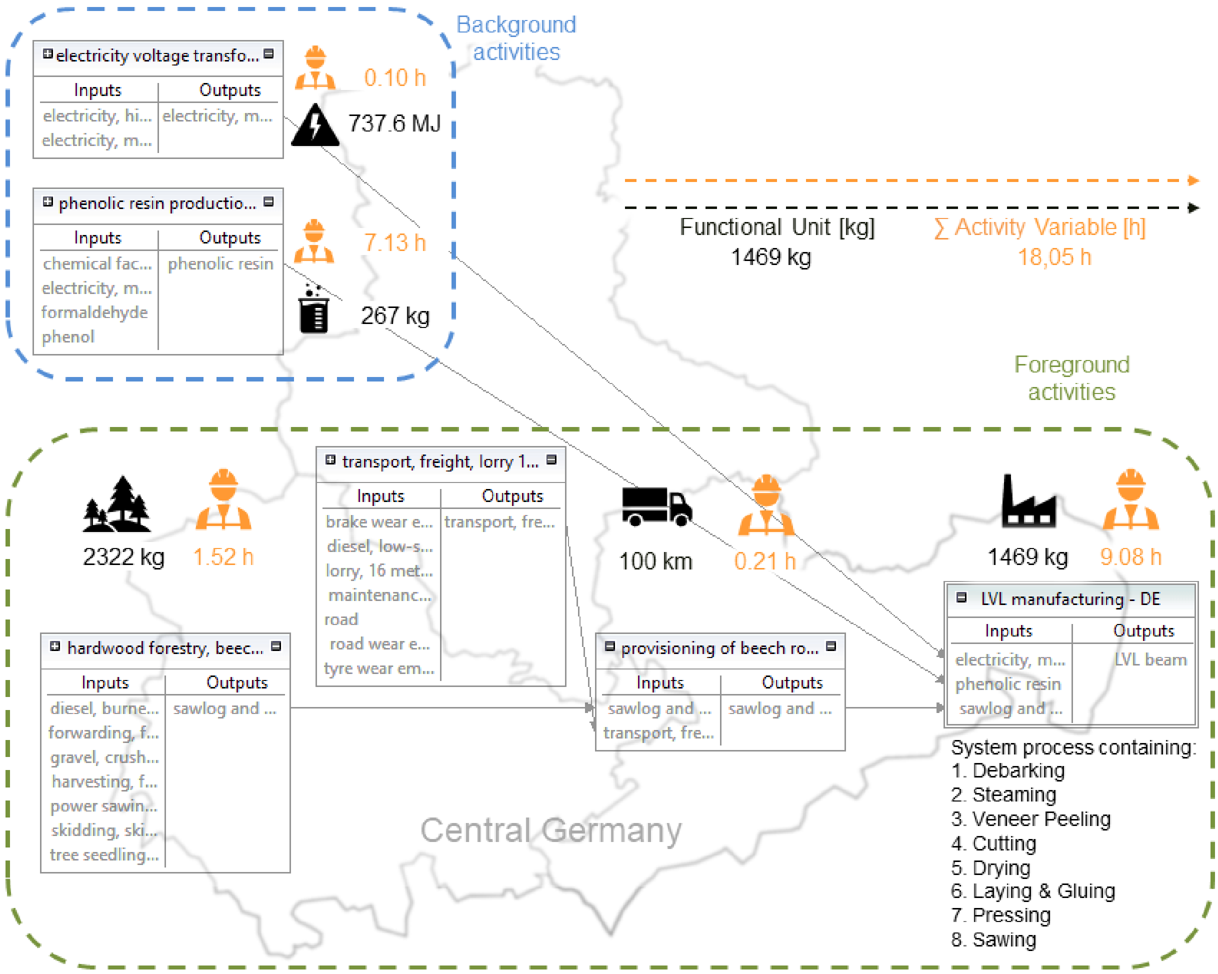


Figure 7. Product system of LVL production in Central Germany with foreground and background activities, based on openLCA model graph ("+" indicates hidden upstream flows and processes for inputs; position of processes is schematic; all mass given as wet mass).

Economic system boundaries are defined by the involved organizations performing foreground activities in LVL production, resulting in a cradle-to-gate product system (Figure 7). All other processes are background activities and provide foreground processes with energy and ancillary by-educts material flows, which do not necessarily take place in Central Germany and are fully covered by Ecoinvent upstream processes. The LVL manufacturing process is an aggregated system and was assessed in technical detail and validated in previous studies (Hildebrandt et al., 2020; Hildebrandt et al., 2019; Jarosch et al., 2020).

5.4.1.2 *Life Cycle Inventory*

The LCI in this case is founded on the holistic and integrated sustainability and indicator system of HILCSA. In the first version of HILCSA, it entails 91 social, environmental and economic indicators which are assigned to 25 SDGs (Part II, (Zeug et al., 2022)). For each process of the foreground system the indicator data is adopted and added from previous studies, however, data for RESPONSA indicators is only available for the forestry process and manufacturing process but not for the transport process or background processes (Table 2), thereby reducing the number of indicators in final assessment to 74. All other indicator inventory data comes with the processes from Ecoinvent 3.3 with SoCa v.1, especially in case of the background processes as well as the forestry process and transport process. Due to data protection of process details we cannot provide quantitative LCI data but an aggregated system process for LVL manufacturing entailing all inputs, outputs and emissions.

Table 2. Inventory for production of one LVL beam (1469 kg, FU), main material and energy input and output flows for FU with according working time (AV).

Processes	Main material & energy I/O flows		AV	Data source
	Input	Output		
Hardwood forestry, beech wood (unit process)		2.11 m³ roundwood (solid m³ with bark, wet mass = 2322 kg)	1.52 h	Ecoinvent+SoCa (hardwood forestry, beech, sustainable forest management ǀ saw log and veneer log, hardwood, measured as solid wood under bark ǀ APOS, U)
Transportation (unit process)	232 tkm transport service (100 km distance); 2.11 m³ roundwood (pile at forest)	2.11 m³ roundwood (pile at factory)	0.21 h	Ecoinvent+SoCa (transport, freight, lorry 16-32 metric ton, EURO5 ǀ transport, freight, lorry 16-32 metric ton, EURO5 ǀ APOS, U), distance (Schusser et al. 2019; Obkircher et al. 2013)
Phenolic resin production (unit process)		267 kg phenolic resin	7.13 h	Ecoinvent+SoCa (phenolic resin production ǀ phenolic resin ǀ APOS, U)
Electricity (unit process)		737 MJ electricity	0.10 h	Ecoinvent+SoCa (electricity voltage transformation from high to medium voltage ǀ electricity, medium voltage ǀ APOS, U)
LVL manufacturing (system p.)	2.11 m³ roundwood; 267 kg phenolic resin; 737 MJ electricity	1469 kg LVL beam (total mass of one module)	9.08 h	Manufacturer, unit processes and detail I/O flows under data protection

For each process we have material flow (mf) inputs as well as outputs, with one output flow being the reference flow and FU of this process (e.g. for the forestry process the FU is 1 m³ saw log and veneer log, measured as solid wood under bark). From S-LCA results (Jarosch et al., 2020) and the SoCa database it is known that producing the FU, an LVL beam with m_{LVL}^{FU}, requires specific amounts of working time in each upstream process (e.g. 0.72 h for 1 m³ saw log and veneer log, 9.08 h for m_{LVL}^{FU}). This working time per FU of a specific process is the AV for all social and economic indicators of SoCa and RESPONSA.

Such indicators are balanced and handled as output flows of specific risk levels (very low risk; low risk; medium risk; high risk; very high risk; no data) with an AV within a process in openLCA. Processes containing social, economic and environmental data ready for being further calculated in openLCA with HILCSA are integrated processes. In case of RESPONSA-indicators, we assign risk levels to PRPs according to the evaluation scheme in (Table 3). PRPs are determined before by using the RESPONSA model (Jarosch et al., 2020; Siebert et al., 2018; Zeug et al., 2021a). All indicators have a unit of measurement at primary data level, in case of social and economic indicators of SoCa and RESPONSA indicator values get dimensionless in the inventory when being transformed to risk levels.

Table 3. Evaluation scheme for HILCSA indicators according to their source, performance and risk assessment, impact factors, substitution factor of impact and colors of risk indication. (PRP – performance reference points, SDG – sustainable development goal))

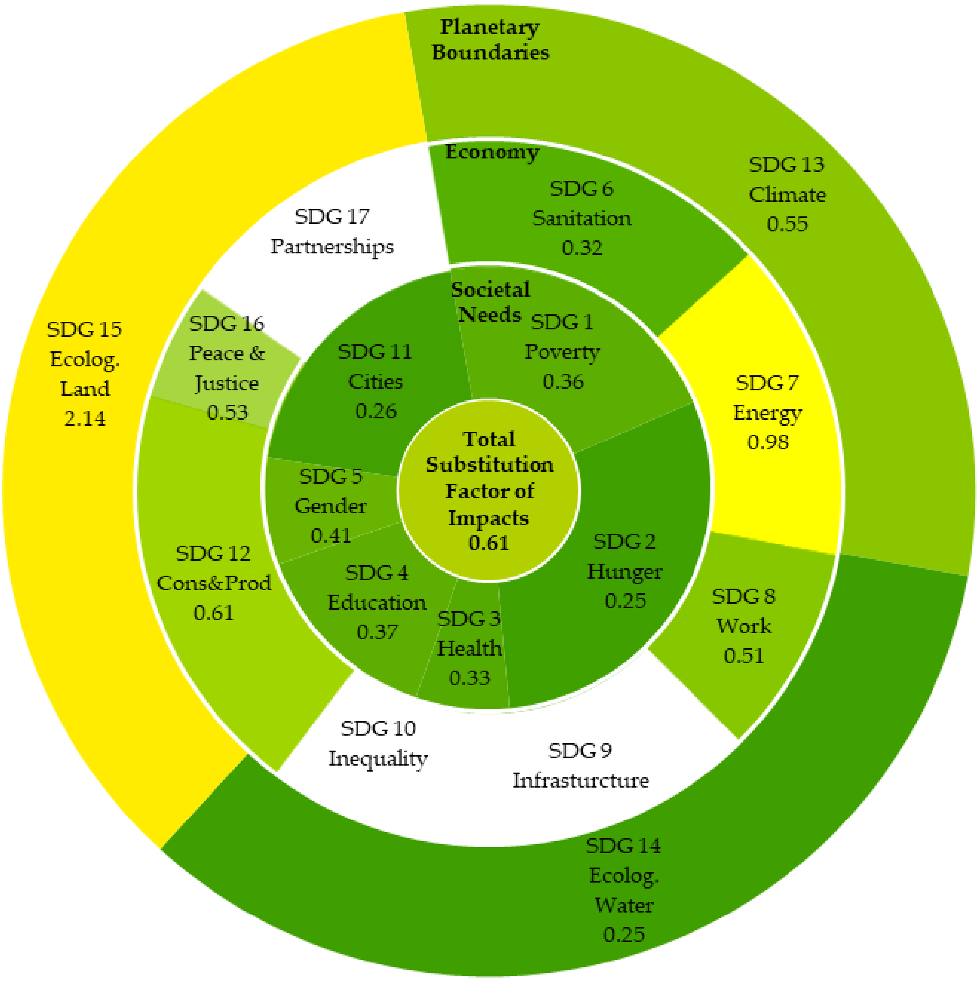
RESPONSA Rating in PRP r^{PRP}	SOCA / RESPONSA Risk levels	Impact factors SoCa / RESPONSA	Substitution-factors of impact / color f^{sSDG} f^{SDG} f
$8.0 < r^{PRP} \leq 10$	Very Low	0.01	$f = 0.01$
$6.0 < r^{PRP} \leq 8.0$	Low	0.1	$f = 0.1$
$4.0 < r^{PRP} \leq 6.0$	Medium	1	$f = 1.0$
$2.0 < r^{PRP} \leq 4.0$	High	10	$f = 10$
$0 < r^{PRP} \leq 2.0$	Very High	100	$f = 100$

5.4.1.3 *Life Cycle Impact Assessment*

In the LCIA, each indicator is assigned to SDGs of the sustainability framework as end point impact categories (Table A 1). To some SDGs a number of indicators are assigned, i.e. SDG 3.9 (Reduce pollution of air/water/ soil, health protection), SDG 8.7 & 8.8 (Worker rights, labor protection rights, promoting safe work environment, abolition of forced labor / trafficking / child labor), SDG 13 (Take urgent action to combat climate change and its impacts). However, there is no indicator which is assigned to several impact categories (SDGs) in exactly the same way, only if production sites are in urban regions (SDG 11.6), then indicator ID14 is used there instead. In context of this and the second case study, none of the standard LCIA methods or characterization factors are changed when integrated into LCSA, in order to keep consistency and only present rather plain results. Only in the CED LCIA we excluded the energetic gross calorific value of biomass flows, otherwise this energy content of wood would be handled as if this energy is already consumed, although it is still contained by the LVL beam. The in-detail results for all indicators are presented in comprehensive tables in Part II (Zeug et al., 2022).

Finally, for all indicators (except of RESPONSA, since RESPONSA inventory data is not available for steel) the values of LVL are compared to steel beam to assess their relative impact. For this normalization substitution factors of impact f^{sSDG} are calculated for each indictor. In a following aggregation of these normalized factors weighted mean factor f^{SDG} are applied for each SDG the f^{sSDG} is assigned to (Figure 8). The weightings are based on the relevance of SDG-subgoals determined for the German BE-monitoring by stakeholder participation.

As a highest level of aggregation by aggregating all SDGs, analogically, a total substitution-factor of impacts f of all SDGs is calculated according to the impact factors from the Social Impact Weighting Method from above, we assign them the according risk level and color as described in Table 3.



Risk	Impact Factor / Color
Very Low	0.01
Low	0.1
Medium	1
High	10
Very High	100

Figure 8. Relative holistic sustainability of LVL compared to steel beam production, presented in form of the holistic sustainability framework for HILCSA of the BE (Zeug et al. 2020) (SDGs are viewed in size according to their relevance for German BE assessments from (Zeug et al. 2019); colors and values represent the substitution factors of impacts (Table 2); white = no data).

5.4.1.4 Interpretation

At the highest aggregation level over all SDGs, the total substitution factor of impact of this case study of LVL relative to steal beams is $f = 0.61$, which indicates that the risks and impacts of LVL production in Central Germany are considered to be lower compared to the production of steel beams. Beneficial effects of this substitution ($f < 0$) can be a better social sustainability (societal needs; SDG 1, 2, 3, 4, 5, 11) as well as economic sustainability (economy; SDG 6, 8, 12 16) and mostly ecological sustainability (PB; SDG 13, 14). However, LVL production has some risks ($f < 0$) compared to steal production when it comes to SDG 7 (energy) and SDG 15 (life on land).

Taking a look at the substitution-factors of impact on SDG-subgoal level, out of 74 indicators (excluding RESPONSA), for 70 indicators $f^{sSDG} < 1.0$ from which 56 indicators $f^{sSDG} < 0.5$, which means that the LVL production can be considered as relatively more sustainable and mostly has less than half of the weighted impacts than steel beam production. Besides overall good relative social sustainability, in other words low risks and low f, there are relatively very low impacts on human health toxicity ($f^{ID15} = 0.02$; $f^{ID16} = 0.09$) which is traced back to the high impacts of mining, treating slag and sulfidic tailings in steel production. On the other side, SDG 7 (energy) as part of economic sustainability in the provisioning system, only has a medium risk level and $f^{SDG7} = 0.98$, which means there is no advantage of LVL in this regard. The two relevant indicators are CED (ID25) and Share of fossil energies in CED (sfCED) (ID24) with $f^{ID25} = 0.91$ and $f^{ID24} = 1.05$, respectively $CED^{LVL} = 36375\ MJ$ and $CED^{SB} = 39982\ MJ$ as well as $sfCED^{LVL} = 0.98$ and $sfCED^{SB} = 0.93$. These results show us that the CED of LVL and steel beam production is comparable, although in case of LVL phenolic resin production is accountable for 91 % of LVLs CED.

Interestingly, the share of fossil energies in LVL production is slightly higher than of steel, since on the one hand they share more or less the same comparable power grids for electricity, but wood is mainly harvested and transported by diesel fuel driven machines with a $sfCED = 0.99$. As it can be expected, most significant negetive impacts of LVL production come from forestry and its effects on land use (ID83) represented in SDG 15 (life on land) with $f^{ID83} = 18.15$ respectivley $f^{SDG15} = 2.14$. However, the climate change due to land use change (ID73) in total is better than of steel $f^{ID73} = 0.96$ as well as the overall negative effects on climate change (ID70) are far less $f^{ID70} = 0.39$. In general, it is striking that phenolic resin production for 70 out of 74 indicators is the main contributor of negative impacts in LVL production (except level of industrial renewable water use (ID57), extraction of biomass related to area (ID61), climate change due to land use change (ID73), land use (ID83)), even though its mass fraction of the final product is only 18.2 %. Our results suggest that substituting steel beams by LVL beams can make a significant contribution towards holistic sustainability and contributing to the SDGs. However, LVL would be even much more sustainable and favorable when fossil components like phenolic resin are substituted by renewable alternatives, which is not only true for ecological (cf. (Hildebrandt et al. 2020)) but also for social and economic sustainability. Nonetheless, it remains of high importance to reduce land use and negative land use change impacts of forestry and to at least only use FSC certified wood is highly recommended.

A LCIA check in openLCA suggests that all relevant flows are covered by HILCSA LCIA, only a number of flows with very small fractions are not covered which would also be the case in stand -alone methods like ReCiPe or EF3.0. The results suggest that the social, economic and environmental impacts and sustainability of LVL production are very sensitive to the quantity and quality of binder which is applicated, in this case fossil based phenolic resin, as well as the sustainability of forestry.

5.4.2 *Application of Holistic and Integrated LCSA: Second Case Study on prospective biomass to liquid production in Germany*

5.4.2.1 *Goal and Scope*

This case study and application of HILCSA on BtL from FT aims on the one hand to indicate the sustainability as well as which substitution effects, hotspots, trade-offs, and synergies a BtL production in Germany would have compared to conventional fossil fuels. On the other hand, the study aims to distinguish under which technical, economic, and social conditions would such technologies would be environmentally, socially, and economically desirable. The case study relies on the technical, economic and logistical flow model from the BECOOL project (Dögnitz et al., 2022), and the given material and energy flow data of this prospective BtL production, which is assumed to take place in Brandenburg/Germany with its foreground processes, as a cradle (biomass sourcing) to gate (fuel mix at refinery) life cycle providing 1 MJ fuel mix as FU (Figure 9). Again, the production system is a regional BE system with a 100-km radius in the foreground system, and all other upstream and downstream flows and processes are modelled by Ecoinvent.

Straw is sufficiently available in the region for this BtL production system. Sorghum however, is not produced yet but considered as a future single crop or in a double cropping system in Central Germany (Dögnitz et al., 2022). Residual wood is available as residual forest wood or residual wood from industry, and in this case, we choose residual soft- and hardwood from industry since this resource base is available in real world and for modelling in Ecoinvent v3. Biomasses for gasification needs to have a moisture content (mc) of maximum 20% (Dögnitz et al., 2022), and in this case sorghum is dried from 68 % mc to 28 % mc at field, residual soft- and hardwood has 41 % mc and straw 18 % mc after drying at field. The mc of biomass feedstock is a vital parameter, since every kg of moisture from wet mass (wm) needs to be removed by around 2.3 MJ of unrecoverable energy (Sikarwar et al., 2017).

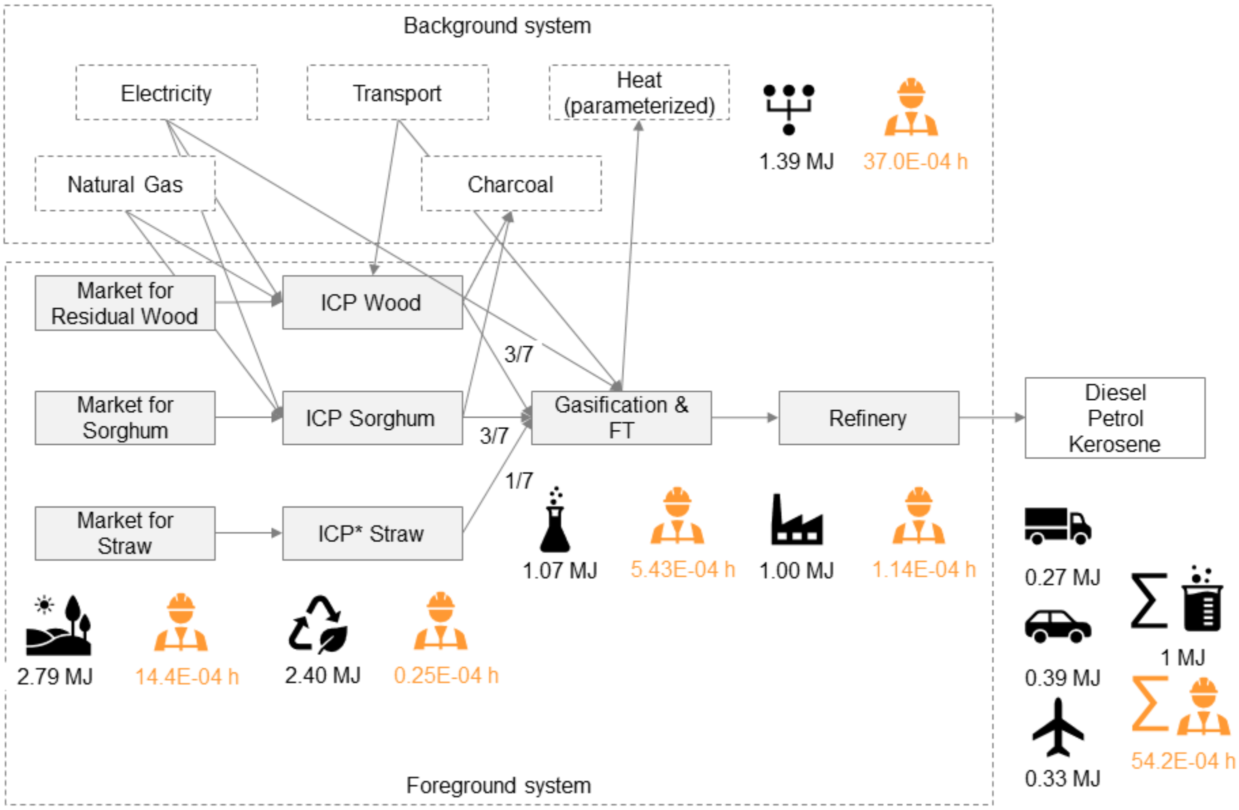


Figure 9. Product system and flow sheet model for BtL production (Quantities are gross calorific energy of product output in MJ and required working time in h for production of 1 MJ BtL fuel mix (FU); FT – Fischer Tropsch synthesis, ICP – intermediate collection point (collection and drying of biomass by slow pyrolysis and support firing), ICP* - intermediate collection point without drying of biomass)

All biomasses are collected, as well as residual wood and sorghum additionally dried, at intermediate collection points (ICPs, small-scale decentralized units containing storage & slow pyrolysis units providing heat for drying). From the ICPs the biomass is transported 50 km by road to gasification and FT synthesis. The mix of biomass is a share of 3/7 sorghum, 3/7 residual wood and 1/7 straw of biomass measured as dry mass (dm) for gasification. Subsequently, a gas cleaning and FT synthesis (around 100 MWth) is taking place, which is a highly exothermic reaction converting syngas to a synthetic crude oil (syncrude). For transport of syncrude to the refinery 50km by road are assumed and activities end with a mix of refined petroleum products (1 MJ of diesel, petrol and kerosene as FU).

All social and economic relations and data involved in the described product system, including working hours, are gained in the LCI from the SoCa database, literature review and results from RESPONSA (Gan Yupanqui and Zeug, Forthcoming).

5.4.2.2 *Life Cycle Inventory*

For this second case study the SoCa v2 database based on Ecoinvent v3.7 is implemented as far as possible and complements non-existing data by creating additional processes and flows. The resulting material and energy flows, as well as required working hours for producing 1 MJ of BtL fuel mix as FU in the 2030 energy system are shown in (Table 4). Information on biomass is provided by the SoCa market processes for straw, residual soft- and hardwood, as well as a custom-made sorghum market and production process. Transport distances of biomass supply to the decentral ICPs are included in the Ecoinvent market processes and on this basis assumed as 20 km for the market of sorghum.

Table 4. Material & energy flows and working hours for BtL production system of 1 MJ fuel mix (kg as dry mass, MJ as energy gross calorific value, Biom – Biomass, Refi – Refinery, ICP – Intermediate Collection Point, Gasifi – Gasification, Elec – Electricity.

Category			**Material and Energy**					**Working Hours in E-04 h**			
			Unit	**Sorg**	**Straw**	**RW**	**Total**	**Sorg**	**Straw**	**RW**	**Total**
Biom	Biom O / ICP I	Biom wet	kg	0.0695	0.0199	0.0697	0.1591	0.71	0.08	8.73	9.53
			mc	28%	18%	41%					
			MJ	1.1746	0.3335	1.2793	2.7873				
ICPs	Biom O / Gasifi I	Biom dried	kg	0.0589	0.0195	0.0589	0.1373	0.13		0.13	0.25
			mc	20%	18%	20%					
			MJ	0.9954	0.3258	1.0814	2.4026				
	Energy	Elec I	MJ	0.0018		0.0019	0.0038				
		NG I	MJ	0.0075		0.0079	0.0154				
	By-Product	Char O	kg	0.0030		0.0031	0.0077				
			MJ	0.0982		0.1023	0.2006				
Gasifi	Gasifi O / FT I	Syn-gas	m^3	0.3118				1.18			
			MJ	1.6838							
	Energy	Elec I	MJ	0.0299							
FT Synthesis	FT O / Refi I	Syn-crude	kg	0.0257				5.08			
			MJ	1.0739							
	Energy	Elec I	MJ	0.2095							
		Heat O	MJ	1.0912							
Refi	Fuel Mix O	Petrol	kg	0.0092				0.65			1.14
			MJ	0.3984							
		Kero-sine	kg	0.0077				0.23			
			MJ	0.3298							
		Diesel	kg	0.0064				0.26			
			MJ	0.2718							
FU	Total		MJ	1.0000				Foreground			17.18
								Background			37.00
								Total			54.18

However, ICPs are not implemented in any database nor are specific technological, economic or social details for this process available. But in principle ICPs correspond to an industrial biomass furnace for heat production which is adopted from SoCa as an approximation (energetic conversion efficiency 85 %, loss of 1.5 % dm due to storage and transportation). Biomass gasification is modeled directly by a fluidized bed gasifier for wood from Ecoinvent/SoCa. The subsequent gas cleaning and FT synthesis of the syngas is associated with the greatest uncertainties in the modeling, since in the data from BECOOL syngas production, gas cleaning and FT synthesis are accounted as one process and therefore had to be separated for the following model in two processes: the previous Ecoinvent syngas gas production process and a simplified gas cleaning and FT synthesis process. Unfortunately, there are neither FT models in Ecoinvent nor general stand-alone LCAs of this rather long known technology available. For this reason, the modeling of this process was carried out by subtracting the inputs and outputs of the gasification process from the input and output data for the combined process from BECOOL, in order to obtain an approximation for the gas cleaning and FT synthesis process. The input data, assumptions and results are consistent with the literature (Albers, 2021; Iribarren et al., 2015; Iribarren et al., 2013; Sikarwar et al., 2017; Tock et al., 2010) and were discussed with experts from the field, in particular the high demand for electric energy for gas cleaning and the significant amount of waste heat from the FT reaction (energetic conversion efficiency relatively poor with 56 %).

Above all, the released waste heat of 1.016 MJ per MJ syncrude has to be partially used in order to keep the entire process chain economically and ecologically responsible. However, to determine which share of waste heat can be used is a complex problem, due to numerous dependencies such as temperature level, facility size, facility location (stand-alone, chemical park, near to residential infrastructures, etc.) determining a realistic assumption. Consequentially, the share of waste heat use is introduced as a parameter in the model ranging from 0 to 100% of waste heat as an avoided product in openLCA for the market for heat. Within the openLCA modelling, avoided products lead to a credit for impacts for the BtL system in the amount of the impacts that would arise if this amount of heat were generated by the usual heat market. A waste heat use of at least 30% one the one hand was considered feasible even under comparatively poor conditions by experts, and on the other hand in the LCIA this share results in very low GHG-emissions in BtL production. For this reason, the main results of this research are presented for a 30% share of waste heat use from FT synthesis (a sensitivity analyzes for the used share of waste heat is conducted in (Zeug et al., 2023a)).

As the last process step, syncrude oil is refined to 1 MJ fuel mix consisting of specific shares for diesel, petrol and kerosene using a refinery inventory and model from Ecoinvent v3.7. The fossil fuel product system as refence to compare BtLs is as well using the same refinery processes, product split and product basket, but is based on the entire Ecoinvent upstream flow for fossil crude oil instead of syncrude. All data on social indicators for RESPONSA indicators for BtL was determined and adopted from (Gan Yupanqui and Zeug, Forthcoming).

5.4.2.3 *Life Cycle Impact Assessment*

The LCIA is based on the holistic and integrated sustainability framework and indicator system of HILCSA, but the indicator system in this updated HILCSAv2 entails 99 social, environmental and economic indicators which are assigned to 14 SDGs. As in HILCSAv1, all indicators are derived from ReCiPe, Impact World +, EF 3.0, Cumulative Energy/Exergy Demand, RESPONSA and SoCa v2. Each indicator is assigned to societal needs and social sustainability, economy and economic sustainability, planetary boundaries and ecologic sustainability, as well as an SDG and it's weighting; has a qualitative or quantitative data type; is allocated by material flows (FU) or working time (AV); has a unit of measurement which is mostly not quantitatively comparable to other indicators; an evaluation scheme and impact factors for quantification. All indicator results are presented in Part II (Zeug et al., 2023a).

In general, only normatively negative impacts are accounted and higher impact values represent a higher risk and less sustainability. For FT synthesis indicator values can be negative, which is a result of giving credits by providing an avoided product in openLCA modelling (feature of openLCA to operationalize a system expansion, int his case assuming that the heat produced elsewhere will be substituted via the heat produced of the FT process). As in HILCSAv1, all socio-economic indicators are comparable on from being transferred to risk levels (normalization) (Table 3). Finally, indicator values of BtL are compared to fossil fuels (except RESPONSA since inventory data is not available for fossil fuels) to assess their relative rather than absolute impact. For this, the substitution factors of impact are calculated and weighted in the same way as before. Since all impact results are calculated for the FU of 1 MJ fuel mix, the indicator values for cumulative energy and exergy demand represent the EROI and EXROI directly.

As aggregated impact assessment results the indicator results are aggregated to substitution factors factor f^{SDG} for each SDG and presented in the sustainability framework in Figure 10. White SDGs (9, 10, 17) are not addressed yet and hatched SDGs are based on an insufficient indicator basis and have limited significance, i.e. SDG 2 (nutrition) only entails indicators on water consumption and indigenous rights or SDG 11 (cities) only entails fine particulate matter emissions.

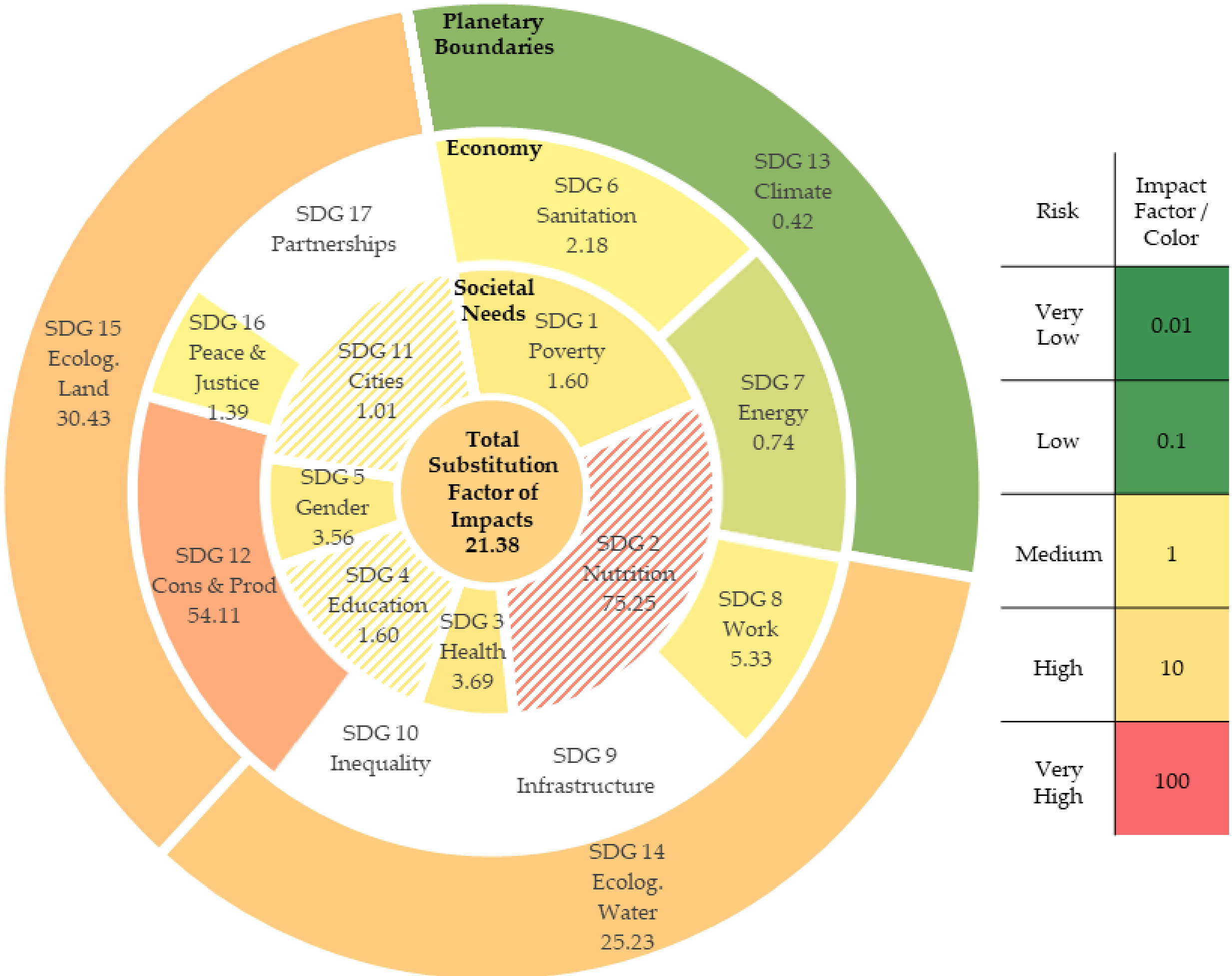


Figure 10. Relative sustainability of BtL compared to fossil fuels, presented in form of the holistic sustainability framework for HILCSA of the BE (Substitution factor of impact and color aggregated for each SDG according to the table; SDGs are viewed in size according to their relevance for German stakeholders; white SDGs are not addressed yet, hatched SDGs have insufficient indicators).

For the practical relevance of comparing different transport systems, the results as f^{SDG} of transport of one person for one kilometer by electric car, diesel car powered by fossil fuel, and diesel car powered by BtL compared with train (Figure 11) are respectively total factors of substitution of 6.50 for the diesel car powered by fossil fuel, 9.16 for the car powered by BtL, and 6.46 for the electric car.

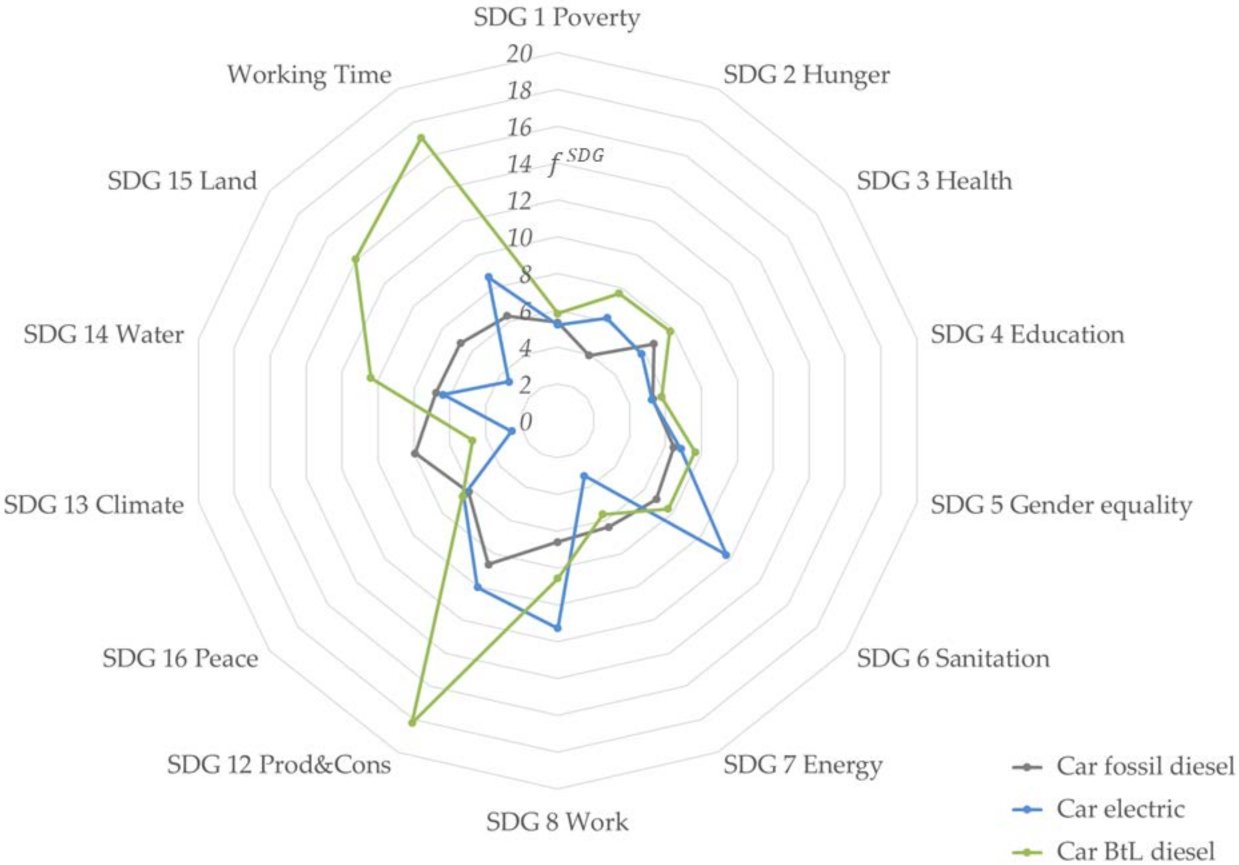


Figure 11. Relative sustainability of transport of one person for one kilometer by electric car, diesel car powered by fossil fuel and diesel car powered by BtL with train (train as reference $f = 0$, electric grid mix of 2030 in Germany).

5.4.2.4 Interpretation

Under the main assumptions of this study (30% heat use in FT-synthesis and electricity grid mix for 2030 in Germany), the total substitution factor of impacts of BtL compared to fossil fuels $f = 21.38$ indicates significant higher impacts of BtL production (social sustainability $f^{SN} = 29.48$, economic sustainability $f^{ECO} = 17.56$, ecological sustainability $f^{PB} = 19.50$). There are sustainability potentials for climate change (SDG 13, $f^{SDG13} = 0.42$) and energy (SDG 13, $f^{SDG13} = 0.72$). However, there is a trade-off by all other SDGs and significant risks for hunger (SDG 2, $f^{SDG2} = 75.25$), sustainable consumption and production (SDG 12, $f^{SDG12} = 54.11$), ecology in water (SDG 14, $f^{SDG14} = 25.23$) and on land (SDG 15, $f^{SDG15} = 30.43$). In detail, very high risks result for hunger and food security (SDG 2, $f^{ID5} = 125.57$) and sustainable use of water resources (SDG 14, $f^{ID87} = 142.35$) in terms of water consumption for sorghum and straw production; for sustainable consumption and production (SDG 12) due to the embodied forest area footprint of residual wood ($f^{ID63} = 674.19$); as well as for terrestrial ecosystems (SDG 15) due to land use ($f^{ID91} = 139.29$) of wood and high water consumption of sorghum and electricity production ($f^{ID99} = 125.57$). We note that high impacts for SDG 2 hunger and food security do not result from direct use or land use of resources for potential food production, but indirectly by water use and indirect land use changes putting additional pressure on environmental and agricultural systems. There are additional significant high risks ($f^{ID} > 10$) for pollution of air, water and soil and human health (SDG 3.9) as a result of wood ash treatment from gasification ($f^{ID17} = 19.75$); a high number of migrant workers and migration flows under tendentially bad conditions in sectors with low qualification (SDG 8.5, $f^{ID41} = 11.23$, $f^{ID43} = 16.20$); non-fatal accidents and safety measures (SDG 8.7, $f^{ID54} = 15.66$, $f^{ID57} = 20.22$), increased use of minerals and metals (SDG 12.2, $f^{ID71} = 19.23$) and marine toxicity (SDG 14.1, $f^{ID89} = 10.39$) accounted to gasification coming from the high electricity demand and its background system; and a high embodied agricultural area footprint from biomass cultivation (SDG 12, $f^{ID61} = 24.38$). In total, for 76 out of 99 indicators in HILCSA, the BtLs have a worse sustainability performance than fossil fuels ($f^{ID} > 0$). Main contributors are the high demand for electricity for 39 indicators, followed by residual wood with 22 and sorghum production with 8 indicators.

In regard to socio-economic risks accounted by working time, the risk levels are comparable, but overall socio-economic impacts are higher in BtL production since more working time is required in total. In other words, qualitative working conditions in both production systems are similar due to a widely common background system incorporating most working time, but they quantitatively occur more often in BtL production resulting in higher impacts.

For 16 out of 99 indicators BtL production has less impacts than fossil fuel production; in terms of less ionizing radiation effecting human health (SDG 3.9, $f^{ID14} = 0.22$) and climate (SDG 12.2, $f^{ID72} = 0.22$); less cumulative energy and exergy demand (SDG 7.3, $f^{ID28} = 0.59$, SDG 7.3, $f^{ID29} = 0.89$); less trafficking of persons (SDG 8.7, $f^{ID49} = 0.59$); better association and bargaining rights (SDG 8.7, $f^{ID52} = 0.31$); and less acidification of water SDG 14, $f^{ID88} = 0.75$ and terrestrial ecosystems (SDG 15.5, $f^{ID95} = f^{ID97} = 0.64$). For 6 out of 99 indicators the impacts of BtL production are negative ($0 > f > -0.27$), due to negative GHG emissions in BtL production of -3.0 g CO_2 eq. / MJ (fuel mix) compared to 12.4 g CO_2 eq. / MJ (fuel mix) for fossil fuel production, effecting human health (SDG 3.9, $f^{ID11} = -0.25$), fossil resource scarcity (SDG 12.2, $f^{ID67} = -0.12$) climate change (SDG 13, $f^{ID78} = -0.24$), freshwater ecosystems (SDG 14, $f^{ID84} = -0.25$) and terristral ecosystems (SDG 15.5, $f^{ID95} = -0.25$). However, in case of all indicators with less impact ($1 > f$) the positive effects are coming mainly from credits given by heat use in FT-synthesis and avoiding conventional heat production. Independent of the heat use parameter, there is no scenario in which increased heat use would lead to outperforming fossil fuels in terms of total factor of substitution.

These results relate only to production phase and not to use phase of fuels. The production of each MJ FT-BtL fuels, without credits from heat use, would emit 30.95 g CO_2 eq (REDII background data for FT diesel from wood: 13.5 – 20.9 g CO_2 eq per MJ). Even with credits from heat use, the use of BtL fuels is not carbon neutral, on the contrary, since the combustion of 1 MJ of fuel releases around 72 g CO_2 (calculation of internal diesel combustion from Ecoinvent), the use of every MJ BtL fuel results in the emission of around 69 g CO_2 which is 19 % less than fossil fuels (cf. Figure 11, SDG 13 Climate change). The production of such BtLs cannot be carbon neutral, since in this case already the provision of biomass (before ICPs) is related to 7.6 g CO_2 eq. emissions for 0.16 kg(dm) biomass needed to produce 1 MJ BtL, due to transportation, energy for harvesting, machines and cultivation contributing 7.5 g CO_2 eq. from fossil origin.

Finally, when comparing the transportation systems and use phases of fuels, Figure 11 shows that all types of car-based individual transportation have significant higher impacts than transportation by train. In case of BtL powered diesel cars the significant risks are rooted in the same processes, work, material and energy flows as described before for BtL. Not surprisingly, electric cars have a comparable good performance in terms of energy efficiency and GHG emissions, however, the battery production entails major risks for workers, communities and environment in global supply chains. Whereas fossil diesel powered cars entail most GHG emissions and air pollution.

6. Conclusion and Outlook

The following conclusions and outlook of this dissertation provide an overall synthesis of the results, how the initial research questions are addressed with which limitations, the value added to methods and BE assessment as well as potential development.

6.1 Stakeholder Expectations and Participation

As a point of departure, the stakeholder participation process made evident that sustainability has to be approached as a holistic and complex subject, because “social,” “environmental,” and “economic” aspects are equally important to consider and interconnected, entailing institutional, political and societal factors in a regional and global context. Eventually, this is the reason why HILCSA is not only a plain LCA method, but refers to broader societal discussions and underlying interest, perceptions, and values of different stakeholder groups. As most stakeholders and previous research suggests, BE should not just be considered as a substitution of the resource basis but rather as a societal and economic transformation towards more sustainable development. Thus, the results cover a variety of aspects, especially issues of vital societal discussion, in order to avoid shortened analyzes and possibly false scientific, political and media conclusions. And although BE product systems can be set up as regional systems with regional biomass sources, our results from the two case studies, especially the second one, show what stakeholders suggest and are interested in, that global effects and supply chains and associated with its externalizations of negative impacts continue to play a vital role especially for social sustainability. However, to a lower degree than in fossil production systems. For this, sustainability assessments such as HILCSA and monitoring activities (Egenolf and Bringezu, 2019) can support democratic processes by providing an evidence base to argue for a narrative and vision of this transformation (Hopwood et al., 2005; Meadowcroft, 2009). The successive changes of the European and German BE strategies toward transformation-centered visions are first steps in this direction. Although, the stakeholder’s perceptions on the German and European BE strategies indicate that transformation is still not addressed sufficiently, and the fundamental and in-depth change of structural societal principles required by the concept of a societal-ecological transformation is unlikely to be taken up by such strategies in the future. Nevertheless, addressing this complexity and interlinkages, future policy strategies and legislation in Germany should be strongly interministerial, coordinated by a common strategy, appropriate measures at a federal and regional level (Schütte, 2018), as well as to implement stakeholder participation from the beginning.

It is concluded that according to most of the respondents, for a BE to be socially assertive and successful transformation towards sustainability, it needs to go beyond business-as-usual and claim a global responsibility to provide a good life for all within planetary boundaries (O'Neill et al., 2018; Zeug et al., 2020). Even though this will lead to inevitable conflicts with a regressive-authoritarian social camp making up 17 % of the German population (Eversberg and Fritz, 2022), which will probably resist any progressive transformation and doubt about climate change in order to be able to maintain certain identities and lifestyles. However, it is important to note that for the actual environmental impacts of people’s consumption and lifestyles, not primarily their mentalities, but their income is most significant (ibid) (Eversberg and Holz, 2020). And even consumption and lifestyles have a limited impact, since capitalism can be understood primarily as a societal relation of production and subsequently of consumption (Postone, 1993).

In context of this dissertation and the determined relevance of aspects and SDGs, only German stakeholders were included and the focus is the German BE. However, not only international stakeholders play a role in highly interlinked national economies but the results are context-specific and only applicable in a limited and abstract manner to other regional contexts. Since the continued pursuit of ambitious stakeholder participation can make a significant contribution to policy coherence, to avoid regulatory failures and developing a sustainability assessment framework, it is necessary to continue stakeholder participation, especially when HILCSA is applied in other regions. Addressing all stakeholders and their expectations is beneficial for the acceptance and usage of HILCSA as well as BE practices and concepts. Although the formats of stakeholder participation conducted in this research are not fundamentally new, their application and implementation of results to LCSA in a quantitative and qualitative manner is.

Regarding the first research gap, this research successfully took up stakeholder participation to identify the central societal debates on BE to structure a practical framework for LCSA in general, as well as to specifically determine weighting factors for the operationalization of HILCSA and a comprehensive set of indicators. Thereby HILCSA is able to better support decision making on multiple levels and enriches the social debate. However, stakeholder participation should be regularly continued to on the one hand to track societal debates on BE and sustainability in general and to adjust HILCSA likewise, on the other hand to conduct participation formats in different regions when HILCSA is applied there in order to adapt indictor selection and weightings.

Unfortunately, this dissertation and especially the stakeholder integration part was largely prepared within the Covid-19 crisis from 2020 to 2022. Thus, the stakeholder participation activities had to be limited to online surveys and desk research.

6.2 *Theoretical Concepts for Sustainability and Methodological Frameworks*

This research illustrated that the fundamental problems in sustainability concepts as well as perceptions and interests of stakeholders make the inclusion of transdisciplinary research on underlying societal relationships with nature necessary, in order to improve the understanding of these complex relationships, and to ultimately develop a better basis for sustainability assessments such as HILCSA. The three-pillar approach oftentimes is still used, although criticized as insufficient for a long time in social sciences. By taking up the SRN, HILCSA is not only able to address some of the methodological short comings of existing methods, e.g. insufficient sustainability definitions and additive LCSA, but as well embedding them into a future perspective by taking up the decoupling problem as a starting point for societal-ecological transformation. Following the shown implications on BE and its assessment demonstrate the need and potential of a sustainable BE for societally and techno-economically decoupling human well-being from environmental impacts to avoid a social and environmental crisis. However, considered all together, the absolute decoupling hypothesis appears highly compromised, if not clearly unrealistic in a business as usual scenario (Haberl et al., 2017; Parrique T., 2019). To strive for gains in technological efficiency is absolutely necessary, but alone not sufficient like BE in general has to be embedded in a societal-ecological transformation. Consequentially, research on BE is part of a societal discussion and competing and contradicting narratives and visions of a sustainable future development. Such aspects have so far received little attention in LCA and LCSA.

This transdisciplinary research on the one hand introduced the SDGs as a progressive measurable and normative targets and objectives for LCSAs in context of BE, as well as understanding societal needs, provisioning systems and ecological boundaries not as separate entities, but rather as facets of one and the same object in LCA. A better understanding of what 'social', 'ecological' and 'economic' means can overcome reductionist approaches and epistemological traps and improve the understanding of mutual dependencies and complex interactions. This sets the basis and locks up potential for a holistic and integrative framework of LCSA with a common scope, goal, LCI, FUs and variables, impact assessment and interpretation. Especially in the last step of interpretation, these improved understandings of SRN help to analyze risks, chances, synergies and trade-offs better as well as to draw far-reaching conclusions from them.

Addressing the second research question (s. section 3), the HILCSA framework entails a first of its kind understanding and definition of social, ecological and economic sustainability, to establish relations of means and ends within them, as well as to relate concrete indicator results of BE production systems to their contribution to specific SDGs. Thereby this transdisciplinary research embedded positivist methods of engineering and natural sciences into a relativist and postmodernist philosophy of social sciences, which enables to combine the strengths of quantitative systems modelling, socio-technical analysis and stakeholder-based learning. With special regard to a regional BE this can help to bridge the gap between science, society, politics and economic actors in public interest.

But reflecting these implications makes as well clear that societal conflicts will remain a challenge which cannot be solved by research alone. Since the developed frameworks address universal interests, this research primarily addresses stakeholders with rather universal then particular interests, such as governments and NGOs, e.g. entities able to provide and critically accompanying the organizational and planning capacity of political coordination necessary for this transition. Focusing on underlying political economy illustrated that the overall possibilities of achieving sustainability by BE are limited as long as sustainability is not a central objective of the general economy and its patterns of regulation itself. If the concept of a sustainable BE as a solution for global challenges is put at risk, a lot is at stake, because there will be no alternatives other than BE to produce the needed material goods from renewable instead of fossil resources. For future development of HILCSA it is necessary to stay on close scientific exchange with other disciplines and to adopt and constantly improve with them, e.g. when better understandings of societal discourses and conflicts evolve in social sciences and when better models in sustainability research can potentially address them.

6.3 Operationalization and implementation of Holistic and Integrated LCSA

Putting the theoretical considerations into practice, first resulted in a holistic and integrated sustainability framework and LCSA framework. Integrating mainly quantitative S-LCA, E-LCA and economic assessments as well as qualitative research methods is compensating some shortcomings of LCSA. The initially proposed set of 109 indicators for HILCSA within the openLCA software environment is capable of addressing societal needs, the provisioning system and the planetary boundaries. Thereby HILCSA is capable of addressing 14 out of 17 SDGs (with the exception of SDG 9, 10 & 17), including all relevant and problematic developing SDGs. Addressing the third research question, by integrating a variety of indicators from different LCIA methods and a common normalization, the HILCSA framework provides to some extend answers to most of the open questions and significant problems of LCSAs in general, in terms of goal and scope, LCI, LCIA and interpretation. As well as this framework substantiates the idea of an integrated LCSA proposed by (Guinée et al., 2011), and shows main advantages compared to additive LCSA, in specific: identifying trade-offs and conflicts of objectives, avoiding double-counting and problems of monetization, including cause-effect relations, combining different scales, allocation to clear impact categories, clear FUs and AVs in one method, transparent and participatory weightings, rating by PRPs and risk levels as well as a normative goal systems by including SDGs.

Another major value added in terms of LCI and LCIA, is the first of its kind LCSA method actually applicable in an existing software environment (openLCA), is its linkage to databases, the integration of innovative S-LCA methods as well as overcoming the problem of economic sustainability assessment. The HILCSA framework is able to quantify and qualify the (dis-)ability of BE product systems to address and assess the problem the second dimension of double decoupling. By identifying hotspots of unsustainable practices, socioeconomic contradictions and trade-offs when industrial metabolisms are transformed by substitution, specific BE strategies and action plans can be focused and the subject of governance activities specified. Such sustainability assessments are potentially able to structure the discourse around sustainability concepts, the implementation of SDGs and regional transitions to holistic sustainable bioeconomies. The deployment of local bioeconomies, improving the knowledge base and linking of local measurements to global goals can support policy makers and underpin policy coherence from a local to international level (European Commission 2018), for which HILCSA is considered as an appropriate tool. When advantages of bioeconomies compared to fossil-based economies become clearer, a substitution and transition can be fostered better by all stakeholders, potential risks can be minimized alongside benefits becoming maximized. Such projections thus result in several areas of application, namely the analysis of possible consequences of actions, anticipating problems before they arise, discussing effects of a possible future on the present and developing an idea of future conditions (Halog, A. and Manik, Y., 2011). Additionally, regional BE practitioners benefit from a holistic assessment of their activities and the local and global context they are acting within, when their contribution to global goals gets clear for policymakers and consumers, e.g. when it comes to the promotion and subsidization of timber construction products. Beyond that, also civil stakeholders like NGOs and associated controversial societal discourses profit from an evidence-based method for assessing BE and establishing a common narrative of a sustainable BE and sustainable development, e.g. when it gets clear that not regional BE in general but specific dependencies of global supply chains and political economy are responsible for most negative impacts.

However, absolute sustainability assessment methods in forms of distance to target (DTT) are not robustly available in LCA and although planned, they were not implemented in HILCSA yet (Zeug et al., 2021a). But as soon as they are, absolute sustainability assessment methods and DTT will allow to calculate a product system and regional specific environmental threshold in regard to PB, e.g. how much kg CO2 eq. per product or regional BE network can be considered as (un-)sustainable. We are confident that the specific indicator values of mostly environmental indicators can be assigned to the same risk levels, in regard to the risk of transgressing PB when producing a specific product or operating a regional economy. Meanwhile, the stress on PB has been adopted as normalization factors in the EF 3.0 method (Bjørn et al., 2020; Bjørn and Hauschild, 2015; Sala et al., 2020) and as well as the Recipe Endpoint indicators which are assigned to PB SDGs of our sustainability framework (Zeug et al., 2021a). A significant progress will be made, when planetary boundaries are downscaled in a methodically robust manner in the

EU to specific regions, provisioning and product systems (Ryberg et al., 2020). The development of a holistic and fully integrated LCIA for absolute LCSA, is a promising long-term research objective for meeting possibilities and capabilities of LCSA. But requires extensive cooperation with software developers and LCIA experts, to which as well as to critical discussion, we explicitly invite all interested researchers. Not to be neglected as well is the improvement of participation of stakeholders via SDG relevance and further ongoing reflections, in order to ensure their wide recognition and acceptance of their results.

6.4 Lessons Learned from Case Studies: Identifying Risks and Chances of Regional BE by Applying & Validating HILCSA

6.4.1 Risks and Chances of Regional BE in Case of LVL and BtL and Validation of HILCSA

In regard to the fourth research question, HILCSA applied to the two case studies was well able to identify the holistic sustainability and potential of regional BE networks. In case of LVL compared to steel beams the calculated substitution factors of impact for social $f_{social} = 0.31$, ecological $f_{ecological} = 1.01$ and economic $f_{economic} = 0.60$ sustainability showed that LVL seems to have a significant better social and economic sustainability. When these aggregated sustainability indicators are performing this well, a further expansion and political support of such product systems can be recommended, and when significant amount of steel beams are substituted then sustainability potentials may be realized. A political support or regulation should encourage that fossil phenolic resin is avoided and replaced by renewable binders.

However, having a detailed look at the social indicator data and inventory, this is mainly due to the less toxicity of materials, immissions on humans and their working environments, but also higher expenditures for social security and education as well as a lower gender wage gap. Regional analyzes show that different technical production processes are not the main cause of social impacts, but the far more global distribution of primary production chains of the steel industry and thereby externalization of social deprivations (cf. (Backhouse et al., 2021)). Such effects get visible by integrated and holistic methodologies including political economy, and would probably be neglected or falsely allocated to technologies in conventional LCA. Additionally, from a quantitative analysis, we see that the most significant negative impacts of LVL production come from forestry and its effects on land use with a substitution factor $f = 18.15$, e.g. LVL production takes up more than 18 times the land use of steel since steel as a fossil resource was accumulated inside the earth whereas wood has to steadily grow on its surface. However, the potential impact on climate change due to land use change in total is better than that of steel $f = 0.96$ as well as the overall potential negative effects on climate change are far less $f = 0.39$.

In case of the more complex BtL case study, from a technological perspective, the sensitivity and significance of biomass is relatively low (except of residual wood and sorghum) due to the high efforts and impacts of biomass conversion. Biomass gasification contributes comparably high environmental impacts and consumes 30% of input biomass energy. FT-synthesis is the most volatile, sensitive and high-risk process step, but further significant technological improve of this technology is not in sight. Mainly because of the very high electric energy demand of 0.195 MJ / MJ (syncrude), the FT-synthesis comes with high impacts, as well as an energetic conversion efficiency of only 56%, which is responsible for increased impacts in all upstream processes. The resulting significant amount of 1,02 MJ / MJ (syncrude) waste heat and its potential use is decisive for the ecological, economic, and social sustainability as well as overall feasibility of the BtL production.

For ecological sustainability, all non-GHG related indicators suggest that FT-BtLs entail significantly more environmental risks than fossil fuels ($f^{SDG14} = 25.23$, $f^{SDG15} = 30.43$), independently of the degree of heat use. This is mainly due to the higher use of water, land, materials, and toxic emissions at land ecosystems and of course the need for energy and related impacts. Seemingly low or negative substitution factors of impact are due to the credits given by heat use but no carbon molecule would be taken out of the atmosphere. BtL production is not carbon neutral or even negative, as a misinterpretation of the results from could wrongly suggest. The production of each MJ FT-BtL fuel results in 30.95 g CO_2 eq, which is 2.51 times more than in the case of the production of 1 MJ of fossil fuels. In regard to social sustainability, the required working time and its allocation to regions suggests that, besides Germany, significant social and economic impacts are located and related to India, South Africa, Russia, China, and Chile. These impacts are due to resources and production of the entire background systems, from metals and rare earths to hard coal, chemicals, and food to produce wind turbines, factories, by-educts, electronics, harvesters and so on. Only about 15E-04 h working time per MJ (28 %) takes place in Germany and the remaining 39E-04 h (72 %) around the globe. With around 19E-04 h (35 %) India is the biggest contributor, with nearly this entire workflow relating to hard coal mining, which is not surprising since India is the world's second largest coal producer.

As the results show, the production of BtL by FT technology from such feedstock entail social, environmental, and economic risks to such an extent that a large-scale substitution of fossil fuels as a drop-in solution should not be followed from a sustainability perspective. The parameterized results show that for the entire range from 0 to 100 % heat use there are high risks and few benefits for sustainable fuel production with this technology, which makes the site decision important for waste heat use but not decisive for the perspective of such technologies. If this BtL production would be fostered and suggested as a drop-in solution, the risk is high for a continued lock-in effect in car dependency (Mattioli et al., 2020), non-sustainable biomass use paths over a long period of time (Aktionsforum Bioökonomie, 2022), as well as delays to structural transformations (Eversberg and Fritz, 2022), especially since there are better alternatives in the form of electricity driven public and individual transport, as well as liquid fuels that can be produced without biomass directly from CO_2 and energy (Treyer et al., 2021) that do not have additional impacts on land use and water.

As discussed, the developed HILCA methodology is able to address all research questions to a certain extent. By two case studies the capability of operationalization and implementation in the software environment is proven. All indicator results are consistent with established LCIA methods and the transparency of methodology and data is of comparable quality. The complex results of HILCSA allow in detail hot spot analyzes of technologies, as well as to draw and communicate general conclusions through aggregated results.

6.4.2 *Lessons Learned and Future HILCSA Methodology Development*

First, as part of the mandatory sensitivity analysis of the method in both case studies most sensitiveness of aggregated results comes from the weighting factors for SDGs from stakeholder participation. In other regional contexts the weightings should be newly determined and the indicator set should be adapted as well, e.g., when child labor, hunger, land grabbing, repressive working conditions, or modern forms of slavery play a more significant role. However, the overall aggregated results do not change fundamentally, e.g., when in the BtL case study all weightings R^{sSDG} and resulting R^{SDG} are set as equal ($R = 1$), then $f = 14.83$, $f^{SN}_{R=1} = 14.77$, $f^{PB}_{R=1} = 18.77$, and $f^{ECO}_{R=1} = 12.52$. Especially for such prospective technology assessments further participation formats in Brandenburg with involved stakeholders would be necessary to ensure collaborative creation, collaboration, and cooperation. The limitations of these first two case studies do not allow an in-depth analysis of structural societal elements, such as ownership, control, agency, power relations, and political legislation (Plank et al., 2021), which would be very relevant for social, environmental, and economic impacts when this BtL production would be put into actual practice. Furthermore, in the HILCSA case studies it is not possible yet to determine the overall potential of any biofuel or LVL production to address the double decoupling problem within planetary boundaries, i.e., how much biofuels or LVL could be produced sustainably. A missing cost analyzes in HILCSA makes a classic economic classification of the results more difficult, but can be supplemented in joint projects.

In terms of overall data quality, the input data from other projects as well as database quality of Ecoinvent and SoCa are the determining and hardly to address factors, since they can only be addressed to a limited extend by HILCSA itself, e.g. by improving and cross-checking third party data and implementing a data quality assessment matrix from openLCA. Primary data from producers is handled with care due to data-protection but as well checked for plausibility. The data quality indications of Ecoinvent/SoCa can be gained from the source and will be addressed in detail in further case studies, i.e. by build in data quality checks. However, as the two case studies showed, when applicated with very limited time and resources, as usual in LCA, HILCSA does not entail a detailed modelling of the technical aspects of production processes. This means that it is highly probable that specific technological parameters can vary, have progressed in the meanwhile, turn out to be different in other locations, or fail to include potential unknown, additional impacts.

As discussed above, absolute sustainability assessments and DTT methods are not applicable in general and in HILCSA case studies yet, but downscaling PB to regions, production systems and products, and thereby not only providing information on absolute sustainability, but also on relative sustainability if a substitution in a specific context is feasible and in fact relatively sustainable. Thus, the presented case studies are not able to determine the overall potential of any biofuel production to address the double decoupling problem within planetary boundaries, i.e., how much biofuels could be produced sustainably.

Currently, environmental footprint methods as the basis for absolute sustainability assessments and their implementation in LCIAs are in a final transition phase (JRC, 2019) and will be applicable in context of SDG frameworks like HILCSA (Sala, 2019). Instead of only presenting plain results for environmental indicators, context specific risk levels like for the other indicators could be applied in future case studies entailing absolute sustainability assessments, resulting in a higher consistency and comparability of results as well. Important in this regard is that such LCIA methods are implemented timely in openLCA and that openLCA is constantly developed further to integrate social and economic aspects. For future developments of HILCSA the implementation of circular economy indicators which are still under development is aimed at, such as the circularity index, longevity, recycling rate and reuse potential (Bezama, 2023; Calisto Friant et al., 2020; D'Amato, 2021; Helander et al., 2019; Jerome et al., 2022; Leipold, 2021; Moraga et al., 2019; Padilla-Rivera et al., 2020).

In terms of social sustainability assessment, S-LCA specific functionalities of openLCA as part of HILCSA must be improved regarding a better documentation, more straight forward implementation in the LCI and especially more flexible option in creating complex and multi-level LCIA methods. Partly quite inconvenient work flows by lack of automatization, linkage of data and working interfaces (e.g. with Excel) result in using the ILCD format and editing in XML language. Whereas the quality of environmental indicators in LCA is good and their application largely mature, there is significant potential for improvement of indicator and data quality of social and economic indicators in Ecoinvent, SoCa and how to apply and allocate them in HILCSA.

The existing indicators of HILCSA need to be further streamlined with the sustainability framework, e.g. to implement more specific indicators for contribution of product systems to fulfill societal needs and their contribution to human well-being or to describe economic effectiveness and justice of allocation of the produced goods. In further development of HILCSA methodology, the missing SDGs and SDGs with a weak and insufficient indicators basis should be improved by more and refined indicators, as well as the indicator set and methodology should be updated and improved constantly. For example, SDG 2 nutrition would require product system specific indicators and LCIA methods which would allow statements on an end-point indicator such as food availability within a specific region, or SDG 10 inequalities indicators on how specific production systems foster or improve societal inequalities. However, there are limitations, such as for SDG 17 indicators describing a cause-effect relationship between specific BE products and strong international partnerships are hard to imagine. Furthermore, BE-related and innovative cultivation methods, secondary renewable resources and conversion technologies should be better considered in Ecoinvent to improve variability, accuracy and system boundaries of such production systems. In such cases, Ecoinvent datasets can be complemented by desk-research on cross-referencing data form the literature and none-LCA models. As well the substitution factors of impacts work well for the purpose of relative sustainability assessment of two products, but in the current form not applicable to more complex products systems on a meso and macro-economic scale.

To address the discussed inability of HILCSA to address the societal dimensions of the decoupling problem, for future developments of HILCSA the extension to hybrid LCSA entailing multi regional input output analyzes (MRIO) (Asada et al. 2020; Budzinski et al. 2017; Crawford et al. 2018; Teh et al. 2017) can be a promising approaches to address the shown challenges. As a combination of process analysis (bottom-up) and input-output-analysis (top-down) in compiling the LCI (Wood and Hertwich, 2012), meeting the previously raised requirement of combining mono-regional bottom-up detail with the necessity of global top-down requirements. Actual hybrid LCAs are established tools (e.g. (Treloar, 1997; Treloar, 1998) (Deng et al., 2011) (Pairotti et al., 2015) (Jang et al., 2015)) and access to broad methodological literature exists (e.g. (Suh and Huppes, 2005) (Miller and Blair, 2009)). Recently there has been a debate on if hybrid LCAs really deliver more accurate and meaningful results than process-based LCAs (contra (Yang et al., 2017), pro (Pomponi and Lenzen, 2018)). Drawn conclusions are that the error from using aggregated I/O-models has to be smaller than from the truncations and aggregations of individual processes, which depends on the method and comprehensibility of putting up aggregated I/O-tables of sectors and how they can later be disaggregated when applying them to more specific sectoral or regional contexts (Pomponi and Lenzen, 2018). In particular, the error of hybrid LCAs is smaller, when more feedbacks and coupling between sectors exists (ibid.) which is true for the BE. However, until recently there has been no systematic framework for classifying and defining hybrid LCI methods and even until today there are no standardized software for conducting hybrid LCAs (Crawford et al., 2018). The present classification of hybrid LCIs defines for types of methods (Tiered, Path Exchange, Matrix Augmentation and Integrated) "found within a spectrum that is between process and I/O analysis" (ibid., p. 1281) and the most appropriate to our purposes seems to be the integrated LCI (Suh and Huppes, 2000) defined as following: *„Integrates process and input-output data within a single matrix framework, using a set of vectors referred to as upstream and downstream cut-off matrix to link the two matrices. These vectors are used to represent inputs from the input-output matrix into a process (upstream cut-off matrix), and sales of goods and* *services to input-output sectors (downstream cut-off matrix"*(ibid., p. 1277). As a main characteristic it integrates process-based and I/O-LCAs into a common framework, has been used fairly consistently as applicable framework and applied in case studies (Wiedmann et al., 2011) (Dadhich et al., 2015), for (regional) BE by using MRIO (Acquaye et al., 2012) (Thyssen and Zeller, 2016) (Smetana et al., 2017) and full regional production and consumption systems (Zeller et al., 2018).

However, at this point, the mutual dependency and relation of macroeconomic societal decoupling and microeconomic techno-economic decoupling (PB) leads unavoidably to fundamental questions of political economy and political ecology: How to socially organize and normatively analyze the fulfillment of societal needs by economies within PBs? For various previously mentioned reasons, but especially due to the twisted relations of means and ends, this question is unlikely to be solved within capitalist societal relations and their intrinsic compulsion to grow. On the other hand, in political economy and political ecology, a new discourse is rising in the direction of which the approaches of an absolute sustainability assessment and HILCSA point implicitly: new forms of distributed planned economies. Planning economy means to mentally, organizationally and institutionally shape processes of determining, through assessment and decisions, on which paths, with which steps, in which temporal and organizational sequence, under which framework conditions and finally with which 'costs' and consequences a certain goal seems to be achievable (Nuss and Daum, 2021). Of course, planning in this regard, as a mental anticipation of actions, is already immanent for the current economic system, especially in times of large digital platforms but under very different preconditions (Bastani, 2019; Morozov, 2019; Phillips and Rozworski, 2019). Climate change as a relatively new global problem can only be countered by means of collective planning, however, the debate on capitalist market economies versus socialist planned economies has a long tradition and comes down to the question of which societal and technical basis, how and supported by which tools an economy is organized and coordinated (Groos, 2021). Against the background of societal decoupling, it would be of particular interest to implement whether and to what extent the product manufactured and evaluated actually meets social needs in terms of effectiveness, sufficiency and justice. However, this is beyond current LCSA frameworks and would require more interdisciplinary research on political economics.

For such future theoretical perspectives as well as current assessment, HILCSA allows an integrative (environmental, economic, social in one method) and holistic (transdisciplinary and critical) sustainability analysis and assessment based on aggregated indicators qualitative discussion, retrospective and prospective. At this early stage, the indicator and impact assessment sets are not as detailed as in the stand-alone methods, rather the goal is to avoid a piecemeal approach to SD (Taylor et al., 2017) and to deliver a comprehensive picture of trade-offs, synergies, hotspots, significant risks and chances and a fundamental understanding. By assessing and analyzing social, environmental, and economic impacts, both case studies show that only focusing on GHG, for example, could lead to severely abbreviated or incorrect results on sustainability with the risks of misguided conclusions and policy mismanagement. Currently, the techno-economic dimension of decoupling can be described relatively well, the societal dimension of decoupling only partially with the need for transdisciplinary cooperation and integration. But HILCSA can partly bridge scales already, since assessment of regional BE (meso) is able to connect product systems (micro) with SDGs and planetary boundaries (macro). Beyond BE, in principle HILCSA framework is applicable to many areas since the general method can access many databases due to full software implementation. Additionally, stakeholder participation is integral part of HILCSA which not only in regard to weighting but as well for its societal reflection and acceptance a major improvement in LCA. At this point, however, LCSAs can no longer be sharply and meaningfully separated from political and macroeconomic topics, which was proposed in additive LCSA.

6.5 Concluding Remarks on Political (Bio-)Economy and Transformation

In a nutshell, as our two case studies showed for different technologies and resources uses and with different quantitative and qualitative dimensions, although BE can substitute fossil materials and partly has lower negative impacts (relative decoupling), forestry and agriculture use relatively much more land for primary resource production than fossil resources (Bringezu et al., 2020; Liobikiene et al., 2020; O'Brien et al., 2017). If BE is only seen as a substitution of resources in a capitalist and growing economy, then PB like land use will be transgressed way faster than in a fossil economy. A sustainable BE with necessary reasonable carbon-negative processes which can lead to arithmetic carbon neutrality needs to regrow more biomass than is harvested in the long term (Norton et al., 2019), as well as to actively take out carbon from the atmosphere and store or use carbon in bio-products with carbon capture and storage (BECCS) applications (Borchers et al., 2022). However, a large scale of social, environmental, and economic problems and problem shifts, such as land use and global inequalities is limiting the possibility of such technologies to effectively address climate change (Hornborg, 2017). Carbon neutrality of production is becoming a dangerous and popular ideological modern myth: a myth since production processes using materials and energy cannot be carbon neutral. Dangerous purposeful or unintended misinterpretations of carbon neutrality lead to the invisibility of emissions and may even trigger more emissions and a loss of precious time and action to implement measures of actual radical GHG reductions. Furthermore, as it widely fulfills the societal function of not fostering societal-ecological transformations and instead remain tied to the currently dominant patterns of political economy. Most people, scientists and politicians know very well that carbon negative technologies alone are not able to overcome the demand for transformations, but this belief remains an ideological fantasy since "even if we do not take things seriously, even if we keep an ironic distance, we are still doing them" (Žižek, 1989). At many points our results are pointing at well-known fundamental political problems of sustainability, which illustrates that the socio-ecological crisis is not primarily a crisis of knowledge, but a crisis of practice. HILCSA is able to identify these dilemmas and conflicts, to identify production systems of BE and how to improve them in order to mitigate negative impacts. However, identified fundamental contradictions of political economy cannot be solved by this.

In other words, substituting fossil resources with renewable resources under the same quantitative and qualitative production and consumption patterns will be unsustainable and makes an absolute decoupling seem implausible. Achieving ultimately sustainability seems to be very unlikely by BE in business-as-usual societal conditions, but when BE is embedded in a societal-ecological transformation. Processes based on renewable resources in specific regions do not only have a better ecological, but also better social and economic sustainability as synergies. However, the dependency on sustainability from regions does not only apply to fossil industries, but BE can be very unsustainable when renewable material flows reproduce global social and economic inequalities and externalization of effects of sourcing and production (Asada et al., 2020; Backhouse et al., 2021; Eversberg and Holz, 2020). The main negative social and economic impacts result from worse working conditions in the agricultural and forestry sector in Germany as well as significant externalized risks in working conditions in global supply chains.

Such a need of change in patterns of regulation in political economy is demonstrated by the so-called fuel versus food debate of bioenergy, i.e., hunger and malnutrition as a consequence of increased use of biomass and land use for bioenergy is not primarily a problem of the applied (first generation bioenergy) technologies, but of political economy in terms of use and exchange value, and consequentially cannot be overcome by only technological means. Even if enough food is produced worldwide to end hunger, the pattern of regulation of our economies requires ending poverty first. Societal needs alone (use value), sufficient resources and means do not lead to their fulfillment as long as those basic needs are not coupled with enough purchasing power (exchange and surplus value). Land or crops will be used for the purpose with the relatively higher expected surplus value (e.g. fuels), instead of the fulfillment of more basic societal needs with a higher use but lower exchange value (e.g. nutrition) (cf. (Ashukem, 2020)). However, land use conflicts are increasingly perceived as central conflicts of the future and regulations like RED III tend to take them more into account.

In particular, the results illustrate a specific problematic configuration of the BE, i.e., resources are comparably cheap and the technologies are expensive, which is in contrast to fossil energy where technology is cheap but feedstock expensive (Birch, 2021; Calvert et al., 2017). Especially in the case of BtL, using cheap resources like biological wastes and residues does not automatically have fewer and less negative impacts, not in processing nor in biomass resourcing. While first generation biofuel production competes with food production, second generation biofuels compete with an environmentally and economically favorable material use of biomass and biodiversity needs(Albers, 2021). In this case, straw, sorghum and residual wood as feedstock result in a combination of first- and second-generation biofuel production entailing both downsides, i.e., a high land and water use as well as competition to material use due to non-existing cascades. Second generation or advanced biofuels may be an option for biomass at the end of a material cascade use. However, in a circular economy, biofuels will play a minor but important role (Bioökonomierat, 2022a, b) since their use and production in principle is not circular but needed for specific applications.

Even when most biomass is regionally produced in Germany, global fossil-based supply chains externalize most of the negative social, economic, and partly ecologic effects to countries in the periphery, which we know well from other economic sectors. Less human labor is required in Germany, where technology and added value is concentrated , and downsides and trade-offs are exported, especially when the German BE relies on increasing biomass imports (Backhouse et al., 2021; Brand and Wissen, 2018). Both case studies illustrate and witness that even when progressive impulses of BE would mostly be expected in technology and resource substitution, a general transformation of working conditions and global political economy in line with the conclusions reported by Fritz (2022) is nowhere in sight. Thus, the biggest challenges are not expected to be technological ones, but rather the societal overcoming of deep structural entrenchment in mindsets of political economy, 'fossilism', and growth oriented capitalism (Eversberg and Fritz, 2022).

BE and circular economy as well as sustainability assessments are for both societal-ecological transformations and "green" capitalism necessary and meaningful. Less unsustainable practices even under SRN of capitalism are viable to retain the environmental basis for anything beyond. However, the overall possibilities of achieving sustainability by BE and sustainability assessments are limited as long as social, ecological and economic sustainability are not a central objective of the general economy and its patterns of regulation itself.

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List of Acronyms

AV	Activity variable
BE	Bioeconomy
BtL	Biomass to liquid
CED	Cumulated energy demand
DTT	Distance to target
E-LCA	Environmental LCA
FT	Fischer Tropsch
FU	Functional unit
HILCSA	Holistic and integrated life cycle sustainability assessment
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact analyzes
LCSA	Life cycle sustainability assessment
LVL	aminated veneer lumber
MCDA	Multi criteria decision analysis
NGOs	Non-governmental organizations
PB	Planetary boundaries
PRP	Performance reference points
SB	Steel Beams
SDGs	Sustainable Development Goals
SRN	Societal relations to nature
S-LCA	Social LCA

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Part II Publications

Publication	Comment	Pages
Zeug W, Bezama A, Moesenfechtel U, Jähkel A, Thrän D (2019) Stakeholders' Interests and Perceptions of Bioeconomy Monitoring Using a Sustainable Development Goal Framework. Sustainability 11:1511. https://doi.org/10.3390/su11061511	Reproduced with permission from MDPI	73 - 97
Zeug W, Bezama A, Thrän D (2020) Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements vol 07. Helmholtz-Centre for Environmental Research (UFZ), Leipzig. https://doi.org/10.13140/RG.2.2.16912.02564		98 - 137
Zeug W, Bezama A, Thrän D (2023) Life Cycle Sustainability Assessment for Sustainable Bioeconomy, Societal-Ecological Transformation and Beyond. In: Progress in Life Cycle Assessment. Sustainable Production, Life Cycle Engineering and Management. Springer.	Reproduced with permission from Springer Nature In Print	137 - 168
Zeug W, Bezama A, Thran D (2021) A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy. Int J Life Cycle Ass https://doi.org/10.1007/s11367-021-01983-1	Reproduced with permission from Springer Nature	169 - 195
Zeug W, Bezama A, Thran D (2022) Application of holistic and integrated LCSA: Case study on laminated veneer lumber production in Central Germany. Int J Life Cycle Ass 27:1352-1375. https://doi.org/10.1007/s11367-022-02098-x	Reproduced with permission from Springer Nature	196 - 219
Zeug W, Bezama A, Thrän D, Gan Yupanqui KR (2023) Holistic and integrated life cycle sustainability assessment of prospective biofuel production in Germany.	Reproduced with permission from Elsevier In Print	220 - 272

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Stakeholders' Interests and Perceptions of Bioeconomy Monitoring Using a Sustainable Development Goal Framework

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Abstract: The bioeconomy as an industrial metabolism based on renewable resources is characterized by, not intrinsic, but rather potential benefits for global sustainability, depending on many factors and actors. Hence, an appropriate systematic monitoring of its development is vital and complexly linked to Sustainable Development Goals (SDGs) as well as diverse stakeholder expectations. To structure a framework of the important aspects of such a monitoring system, we conducted a series of stakeholder workshops to assess the relevance of SDGs for the bioeconomy. Our results show how the complexities of these issues are perceived by 64 stakeholders, indicating significant commonalities and differences among six SDGs, including specific interests, perceptions, and, in some cases, counterintuitive and contradictory issues. Eventually, the idea of a bioeconomy is a question of the perception of ends and means of a societal transformation toward holistic sustainability. Global implications like trade-offs, hunger, poverty, and inequalities are aspects of high relevance for monitoring of bioeconomy regions in which they actually do not seem to be substantial.

Keywords: bioeconomy; sustainability; sustainability assessment; monitoring; stakeholders; stakeholder participation; SDGs; holistic sustainability

1. Introduction

Sustainable development has been and remains a challenge for policymakers and the scientific community, as the definition of sustainability and the strategies for how to actually foster it still remain ambiguous [1], even though it has mostly become a collective global value of governments, science, nongovernmental organizations (NGOs), and civil society actors [2]. Needless to say, it is not yet possible to ensure a sustainable future since there are no certain global pathways for guaranteed sustainable development. As one considerable option to achieve sustainable development, in line with the Communiqué of the Global Bioeconomy Summit 2015 [3] bioeconomy (BE) can be understood as "the knowledge-based production and utilization of biological resources, innovative biological processes and principles to sustainably provide goods and services across all economic sectors" [4]. We follow this existing definition, even though sustainability is not an intrinsic characteristic but rather a promising potential of BE. However, there is still no unified definition of bioeconomy [5], because there is a whole range of stakeholders with diverse interests and perceptions. The vast majority of BE and sustainability related publications see conditional benefits but many others have a perspective of tentative criticism of BE, when it comes to ecological and social sustainability or even state a disadvantageous impact [6, 7]. For only a few publications mainly focusing on policies, sustainability is an inherent characteristic [6, 7]. Three ideal types of BE visions have been identified in the broad scientific field but are mainly influenced by a technical perspective: (a) a biotechnology vision, (b) a bioresource vision, and (c) a bioecology vision [8]. These visions can be differentiated by dominant aims and objectives (economic growth for a and b, job creation for a, sustainability for b and c); values created by BE (commercialization of research and technology for a, valorisation of bioresources for b, integrated production and high-quality products for c); drivers and mediators of innovation (research and development for a and b, optimization of resources and land use for b and c, agroecological practices and ethics for c); and spatial focus (global clusters/central regions for a, rural/peripheral regions for b and c) [8]. Furthermore, the diversity of BE concepts is represented in media discussions by several policy narratives partly similar to the named visions: biotechnology-centred BE, resource-centred BE, agroecological BE, BE as skilfulness, and climate change–centred BE [9].

1.1. Bioeconomy Strategies and Policy

Meanwhile, more than 50 countries worldwide have created BE-related policy strategies. However, just a few of them, such as the EU and Germany, have established specific and integrated BE strategies and action plans [4, 10, 11] or institutions like the German BE Council. Nonetheless, the number of these endeavours has increased about 30% since 2015 [12, 13]. Most of these strategies mainly embrace the challenge of enabling biobased transformation, and only a few try to address potential risks and goal conflicts politically [14]. As a consequence, they address environmental and social challenges only to a lesser extent. Instead, many name vague interrelationships between economic, ecological, and social issues and mainly reflect an economic perspective on topics such as biotechnology, eco-efficiency, competitiveness, innovation, reaching or retaining a leading world position, growth in economic output, and (re-)establishing a next-generation industry at large [1, 5, 10, 11, 15, 16]. Within the EU's BE strategy, the substitution of fossil carbon by renewable materials plays a big role in key industrial sectors such as chemicals and pharmaceuticals [11], which illustrates the potential in addition to the still very important energy production [17] and primary sectors in rural regions [18, 19]. Many strategies highlight the contribution of BE to the circular economy and lately also to the improvement of food quality, alternative food resources, and high-tech sectors [4]. Moreover, the global dimensions and interconnections of a present and future BE are rarely addressed, and international collaborations play a minor role in these national rather than international strategies [4]. These are major shortcomings, since the vast majority of European countries also have not yet achieved Paris Agreement goals [20] and ecological as well as social risks and chances [7, 21-23] result from an intensified and increased use of biobased resources, especially the shift of risks to other countries through imports and global market effects [24, 25]. However, it should be the goal of a global BE to meet several big societal challenges [26] and to address a series of SDGs [27].

The updated BE strategy of the European Commission in 2018 is a step forward by aligning the strategy to maximize its contribution to the SDGs (in particular SDGs 2, 7, 8, 9, 11, 12, 13, 14, 15) as well as the Paris Agreement [28]. Similar intentions could be implicitly found in 2010 in the first German Bioeconomy Strategy, in which five thematic fields of action were defined: "(i) global food security, (ii) sustainable agricultural production, (iii) healthy and safe foods, (iv) the industrial application of renewable resources, and (v) the increasing use of biomass-based energy" [29]. Complex and interdependent challenges on a national and international level need holistic and systematic perspectives and solutions for structural societal change [29]. Thus, a gradual change from biotechnology-centred visions to transformation-centred visions can be observed [30]. However, while BE can be seen as an emerging area of policy in Europe and Germany, specific and coherent legislation is still missing, as well as an effective, globally coordinated governance framework. Comprehensive monitoring and assessment approaches are seen as prerequisites to implementing legislation and governance frameworks on a national and international level [14, 31].

1.2. SDGs as a Normative Framework for the Bioeconomy

The SDGs are considered to be the most appropriate global framework of goals for holistic sustainable development available, due to their rudimentary democratic character, wide recognition, and internationally comparable indicator framework [32-34]. For these reasons, they are increasingly becoming an overarching topic in BE strategies, policies, and action plans [4, 35]. Putting forward such a goal system is a normative political challenge, beyond descriptive and empirical science, and is determining the controversial understanding and interpretation of sustainability [2, 36], leading to some characteristics of the SDGs as (i) mainly containing elements of holistic sustainable development but presented as separate and not fully integrated [34]; (ii) implicitly interdependent, with complex synergies, trade-offs, and contradictions also depending on regions [37]; and (iii) goals and targets combining policy ends with means without proposing a hierarchy [38].

Previous research [2, 27] has outlined 11 out of 17 SDGs that are potentially highly relevant to a developing global BE (see Figure 1).

Figure 1. Sustainable development goals (SDGs) potentially highly relevant to a developing global bioeconomy (adapted from [2, 27, 37, 39-42]).

The diverse and rapidly developing field of new biotechnologies has the potential to address a series of SDGs in the energy and chemical sectors by substituting fossil materials; in the health care sector with new drugs, vaccines, and diagnostics; and in the primary sector by increasing food supplies and conserving natural resources [43]. When it comes to their implementation by measures, which should be in a simultaneous and not sequential manner [44], policymakers still lack tools and evidence to identify interdependencies and balance or to prioritize the most important issues [29, 37, 45]. Besides, there is a risk of reversing achievements by poor governance, escalating conflicts, and insecurity [46].

1.3. What Gets Measured Can Get Managed

Because of all these complex risks and chances, we should consciously evaluate and discuss potential options such as bioeconomy based on evidence, to achieve more sustainability before and during integration into policy, economy, and society. Hence, monitoring BE development and sustainability is vital and reasonable but no internationally agreed methodology exists and the framework conditions of such are not trivial due to diverse notions of what to actually monitor, especially when it comes to nontechnical aspects such as socioeconomics connected with visions and narratives.

The first contributions from science toward implementation can be to develop scientifically robust tools with defined indicators in order to help operationalize the SDGs on a global, national, and regional scale: to identify urgent challenges, to measure and manage progress, to assess and evaluate BE-supporting policies [31], and to fill data gaps in order to begin a process of data-driven and evidence-based implementation as well as follow-up [38, 47, 48]. Ideally, the analysis and interpretation of such measurements should be done by independent government-backed organizations within a global collaboration and according to international standards [49]. An increasing number of national strategies acknowledge the necessity of establishing complex BE monitoring systems [15]. Although defined and applied measurements of progress and sustainability are fundamental [16], they remain a major challenge [15] due to insufficient concepts, methods, and data. Thus far, for urgent use in political governance, there are no holistic, indicator-based, intersectoral or holistic monitoring systems available and quantitative assessments of how bioeconomy addresses the SDGs do not exist [29]. The purpose of BE monitoring is not just to show whether it is big or small but above all to understand its development and driving forces, and it should ultimately be about well-being–related outcomes [31]. Furthermore, it is also about understanding the relationships between different BE sectors (e.g., between material and energy streams) and at least the effects and potential impacts on society, economy, and nature as well as on their relationships. Short-term results can be adaptations of national and international policies and strategies, like the lacking environmental policy by the EU [10], setting global standards for meaningful certification [27], and delivering valid information to stakeholders such as NGOs and economic actors. Recently launched projects on an EU-wide scale, such as BioMonitor [50], BioSAM [51], and Sat-BEE [52], are moving on a EU-wide scale move in this promising direction.

Regarding this context, necessities and requirements of a smart monitoring system for assessing the sustainability of German BE must derive key criteria, indicators, and models from an integrated and holistic modelling approach. Several national statistical authorities and the Inter-Agency and Expert Group (IAEG) on SDGs [32] have drawn up comprehensive indicators or indicator sets for each subgoal so that suitable indicators for all SDG subgoals can be specified. However, the SDGs and their individual subgoals represent a general global political agenda and cannot be applied directly to BE; they serve more to identify the normative aspects of BE monitoring than already constituting the monitoring framework itself. So far, such a comprehensive monitoring system fulfilling all the named criteria does not exist on any national scale, and Systematic Monitoring and Modelling of the BE (SYMOBIO), of which our study is a part [53], will be the first of its kind. Developing an appropriate monitoring framework is a challenge, because it has to be general in order to cover all relevant topics but also detailed in order to identify specific hotspots of general interest [54]. Due to the limited extent of the monitoring and its framework, the topics, drivers, and hotspots need to be selected and weighted, especially when it comes to the global dimensions of BE.

1.4. Stakeholder Participation: A Necessity Rather Than a Burden

In that regard, the insights and results from systematic stakeholder participation from the beginning can play an important role in addressing persistent societal problems in a credible, transparent, and multi-perspective way [35, 47], as well as enable innovations [55]. Public decision making on sustainability is characterized by uncertainty, different values and interests, communities in dispute, as well as urgency [56-58], so that holistic approaches have included multiple fields of knowledge and perspectives of different stakeholders [59, 60]. Most of the policy strategy developments in BE have already adopted a more or less participatory approach by stakeholder conferences, workshops and surveys [4], and private–public partnerships to encourage successful market integration [15]. Poor coherence between decision makers, scientists, and stakeholders was assessed to be at the origin of regulatory failures [61, 62], and biotechnology was the subject of controversial public debates, making societal acceptance an enabling factor [63]. Basing BE policy on a broad societal debate should be a democratic imperative, and NGOs, as important public-opinion formers, have to participate [64]. Thus, the new European Bioeconomy Strategy explicitly calls for strategic and systematic approaches to bringing all stakeholders together in an attempt at policy coherence [28]. Therefore, researchers, initiatives, NGOs, and market actors have to be linked more closely with multilateral policy processes and intergovernmental discussions [12, 27, 34, 44], far beyond the traditional "triple helix" concepts (public sector, academia, business) or "fig leaf" participation, and should be mobilized by a common vision of a sustainable BE system. Otherwise, stakeholders with specific interests may dominate these developments and not necessarily contribute to the public good [6].

Previous studies on stakeholders in the context of the bioeconomy pursued completely different goals and scopes [35], were too general for our context [26, 65], and/or used other stakeholder categories and attributes [26, 65] and/or used other stakeholder-categories and attributes [66, 67]. From an organizational point of view, Future Earth's Knowledge-Action Networks [68] set a good and ambitious example by initiating a growing number of locally implemented and globally networked collaborative frameworks of researchers and practitioners in both public and private sectors and civil society. Such an approach has the potential not only to provide a knowledge base for short-term democratic agendas of incentives and measures toward a potentially sustainable BE but also to actually put them into practice. So, shortcomings and insufficiencies of policy strategies can be overcome, risks and conflicts can be minimized, and difficult choices can be made to, at least practically, implement the SDGs simultaneously [69, 70]. Science should contribute to these smart policies by providing a fundamental and integrated knowledge base of synergies, trade-offs, obstacles, and ways to combine these goals, identifying high-priority objectives and investigating questions that society defines as important [2, 12].

1.5. Present Knowledge Gaps and Objectives of This Research

In a nutshell, as the main causes of several far-reaching effects impeding the potential sustainable development of BE, we see the different interests and perceptions of sustainable development in general and of BE specifically among stakeholders. This manifests as a missing common definition, diverse and partly opposing visions and narratives, and insufficient governance frameworks. Holistic and extensive monitoring systems of the social, ecological, and economic effects of BE at an intersectoral level are in demand as the first step to address these issues. But the complexity of sustainability and economic systems like BE already generates too much information and normative conflicts for limited working groups to identify the most relevant aspects. This leads us back to the main causes. Stakeholder participation is therefore the most appropriate means to identify the key objectives in the first place. As a framework to grasp potential objectives, the SDGs offer a globally recognized general holistic goal system with some indicators and related comprehensive debates and are already implemented in most sustainability strategies and policies.

Accordingly, the general objective of this study is to capture, map, and analyse the societal interests and perceptions of the most relevant stakeholder groups of BE in Germany empirically by means of the SDGs. In reflecting upon their sometimes contradictory interests by the relevance of the SDGs, we want to provide indications for identification of key objectives and potential indicators and a basis for necessary weightings for the monitoring of BE. Additionally, insights into underlying perceptions can clarify the constellation of visions and narratives. The developed scientific tools could support evidence-based decision making in short-term governance, long-term political strategies, public and media discussions, and business processes to successfully implement a coherent vision of a BE pathway as a transformation addressing several big societal challenges.

2. Methods

Stakeholder perceptions and expectations regarding the effect of BE in SDGs in Germany were collected in a workshop series held in Berlin in October 2017. Research on practices or methods of stakeholder participation concerning BE or comparable issues or objectives is nascent (see [26, 35, 65-67]) but is led by different objectives and specific methodologies. Stakeholder analysis should explore configurations of sustainability issues like the bioeconomy from multiple or at least different, perspectives [71] and deliver critical reflections on social preferences without forcing consensus [59]. The chosen method of stakeholder participation should therefore provide an introduction to the topic; be able to identify potential and relevant stakeholders, their interests, perceptions, and priorities in relation to sustainability issues; and identify shared problem perceptions, and at least create a basis for a monitoring-framework for the German bioeconomy [59]. For our methodical framework we used established general approaches of stakeholder participation in terms of sustainability, in this case social multicriteria evaluation (SMCE) [59, 71-74]. This method entails the following steps [59, 72, 73]: (i) identify and classify relevant stakeholders; (ii) define the problem; (iii) create alternatives and define evaluation criteria; (iv) assign values to criteria in a multicriteria impact matrix; (v) select a multicriteria evaluation method; (vi) assess social actors' preferences, values, and weights; (vii) apply the model through a mathematical aggregation procedure; and (viii) conduct social analysis and discuss the results to check the robustness of the analysis. We oriented our methodology in line with these steps and established methods but we did not follow a set of formal axioms; and rather, we composed the right methods for the right problem [73].

2.1. Identifying and Bringing Together a Spectrum of Relevant Stakeholders

We divided the workshops into three parts, held on different days, according to the stakeholder groups identified [75]: science, business, and society. To include a total set of stakeholders with the aspiration of representing all relevant stakeholders of German BE, we looked up the participants of important BE events in Germany from 2011 to 2017. Out of this, we identified 400 persons and the organizations they were assigned to. We selected and invited 200 of them to our workshops in such a manner that every organization was represented without personnel redundancies. The actual participants of our workshops were those persons or their stand-ins who responded our invitation, a total of 64. According to the role, objective or interest of their organizations, we classified them into one of our stakeholder groups. Relevant nongovernmental organizations were represented by 6 major environmental organizations; 6 important developmental aid, food, and agriculture associations; 1 journalist; and 2 foundations. Those 15 stakeholders were classified as the society stakeholder group and represented the main relevant actors of NGOs when it comes to discussions on BE in Germany. The business stakeholder group comprised 9 associations from the biochemical, bioenergy, agricultural, and manufacturing industry sector; 5 working BE companies; 4 BE consulting agencies; and 3 other associations, such as certifiers, for a total of 21. Thereby, the most important BE branches, clusters, and representatives of different commercial interests and fields of action could participate. The science stakeholder group consisted of 28 national and non-profit research institutes with explicit engagement in BE research topics, among them 13 universities. This wide and well-networked research community on BE, which covers technological, ecological, economic, and societal issues of an established and developing BE with global interdependencies, was able to represent interdisciplinary expertise on all potentially relevant BE-related issues.

To ensure the quality of our method and the results, it was very important that all perspectives of the different stakeholders were presented at the workshops and that not only professionally organized groups but also social actors, participated [73], which we achieved. As a shortcoming, such classification into groups is only of limited accuracy, since the groups and the stakeholders could only be roughly defined. But it has decisive analytical and practical advantages. On the one hand, the perceptions of reality and the expectations of monitoring can be polarized but without forcing consensus, and fundamental societal conflicts of interest can be modelled. For those debates, monitoring can provide a scientific basis for decision making and formation of opinions. On the other hand, the potential for conflict in the stakeholder workshop process was reduced, resulting in greater productivity and consistency in the groups as well as more precise evaluation.

2.2. Identification of Interests and Perceptions in Relation to the Problem Being Addressed and Indication of Relative Priorities

In each workshop, we introduced the participants to the problem via a short presentation on the current situation and challenges of the bioeconomy, the problems, and envisaged steps for the development of a monitoring methodology of the German BE (see introduction). Basically, we explained the objective of their participation in this process, which was to provide opinions, from their perspective, on what is relevant in a monitoring system with the desired characteristics. We explicitly stated that this question should be thought of independently from how to measure it via indicators, since the creation of a monitoring framework at this stage should not be compromised by detailed challenges of the indicator-based measuring itself. The quality of monitoring, modelling, and other concepts that reflect reality or the system was also essentially dependent on how far all relevant aspects of perceptions of this reality were at least taken into account. To reduce the complexity in multicriteria evaluation (MCE), the virtually infinite information space has to be reduced to a limited set of narratives, expectations, and goals [59].

Now the task for the participants was to classify the SDG subgoals according to their relevance to BE monitoring in the given relevance categories (must be, may be or should not be part of national BE monitoring). In order to initiate the discussion process within a stakeholder group, to gain an even more differentiated picture of expectations and perceptions, and to reduce the complexity of the SDGs, the stakeholder groups were again divided into several smaller working groups (consisting of 4 persons on average), each of which had to categorize a specific part of the overall SDG subgoals. Thereby we lowered the risk that powerful stakeholders would influence the whole stakeholder group [72] and force consensus. Which part of the SDG subgoals a working group categorized was random and not determined by seeming expertise. We explained to the participants that specific political goal formulation of the SDG subgoal should not be of importance per se but only represents the abstract subject that was connoted by the goals and may be important to BE and its monitoring. Therefore, we asked the stakeholders to arrange the different subgoals into sections of relevance classes: the topic of the SDG subgoal must be, may be or should not be part of BE monitoring in Germany. We explicitly chose an ordinal variable here, since the character of variables is crucial for the fundamental issue of compensability [73]. The classification of each topic was discussed within the small working group under the supervision and assistance by one of our team members. Subsequently, all working groups were able to assess and comment on the categorization of the other groups via sticky notes in a feedback matrix according to attribute more relevance, less relevance, questions, and new ideas.

This option of deliberation is particularly important, because preferences and priorities can change and be formed through the discussion process. We followed ideas of deliberative and discursive democracy rather than simply aggregating individual preferences and assuming that they were fixed [59, 76, 77]. We were thus able to document the stakeholder workshops in this process and in the collection of all working groups by noting key points of discussion. We explicitly encouraged the participants to leave the SDG setting and name their own subject areas, which also outlined very concrete, stakeholder-specific questions. This method is only applicable if the stakeholders can come together in person with a sufficient amount of time, which is a potential shortcoming when these resources are scarcer. Moderators have to follow the discussions within these smaller working groups carefully to avoid dominant individuals forcing consensus.

2.3. Scoring, Aggregation, and Robustness

After each workshop, we transferred the categorized SDG subgoals and related feedback to a spreadsheet matrix for quantification (see Supplementary Material). The use of a relevance classification with ordinal variables originates "non-compensatory aggregation procedures and gives the weights the meaning of importance-coefficients [78-80]." As a consequence, the respective relevant weights cannot be understood as trade-offs or as compensatory between different issues [59, 73] in a national monitoring system of BE. This is especially important in this case, since the SDGs should be seen and handled as a whole, and to avoid misunderstanding of a potential compensatory character related to sustainability issues. Otherwise we would implicitly assume that, for example, environmental impacts could compensate hunger, which is obviously not true even if there is a complex relationship between them.

The ordinal variable values of relevance (must/may/not) were rescaled to dimensionless ordinal variable scores of 3.0 to 1.0 for further processing, aggregation, and visualization (must: 3.0; may: 2.0; not: 1.0). Some of the SDG subgoals (subgoals 1.b, 6.5, 17.8, 10.2, 12.c, 8.10) were considered by some stakeholder groups as not at all applicable to monitoring or their meaning could not be deduced, and they got a value of 0.0. To incorporate the important role of discussions between working groups into the results, we operationalized them by adjusting their values if there were one or more items of feedback of more or less relevance attributed. For each given item of feedback, the related score of the SDG subgoal was increased (more relevance) or decreased (less relevance) by an adjustment value of 0.2. Since the ordinal scale reached from 3.0 to 1.0 and every stakeholder group was made up, on average, of 5 working groups (which means the given ordinal score can be theoretically increased or decreased up to a maximum of 0.8), a sensitivity analysis on this adjustment value was conducted to ensure robustness. In the chosen configuration, we got adjusted scores from 0.0 to 3.4. If the adjustment values would have been higher than 0.2, in some cases the group feedback would have distorted the results too much and scores would have become negative. If they would have been lower than 0.2, the results would have been too insensitive to feedback. We qualitatively appraised this configuration as an adequate compromise between methodical robustness efficiency and overall comprehensibility to conduct it as a feasible workshop with so many participants and within a limited time.

The adjusted scores that emerged from each stakeholder group for each subgoal were then collated. By a consistent equal weighting of all stakeholder groups, the scores of one group for the SDG main goal were calculated by simple linear aggregation of the average scores of the corresponding subgoals (see Figure 2). Likewise, for every SDG subgoal, an average score of all scores given by the 3 stakeholder groups was calculated. Since there is no meaning behind a differentiation of relevance below an ordinal score of 1.0 ("not" category) but values between 0.0 and 1.0 existed, we treated them in the subsequent rescaling as an ordinal score of 1.0. By using trivial transformation and normalization (cf. [73], Equation (23.7)), we scaled the ordinal scores from 1.0 to 3.4 to a scale of 0.0 (1.0) to 10.0 (3.4). The only purpose of this rescaling was to have a more intuitive and better reading and presentation of the results, and only these scores were subsequently used.

This aggregation procedure met the main requirements: all SDGs were treated in general as equally important and specifically were weighted by importance coefficients; all stakeholders were treated as equally important; and the aggregation and allocation of subgoals to main goals followed the legitimized system of the SDGs. The chosen approach is a purely qualitative method and assessment even if ordinal variables were rescaled as numerical scores for better processing and presentation. In this case, basic mathematical operations were conducted or average values were calculated. However, they did not necessarily meet all mathematical assumptions and requirements or produce precise results but were used for the purpose of presentation and visualization.

Consequently, the data and results have no sufficient quantitative characteristics for statistical analysis. However, for future research and the application of such methods, more relevance classes and scales could be chosen, such as Likert scales, if this is feasible. This would avoid several scores of different subjects having the same value, which was the case in our study. Improving this would lead to a better resolution of aggregated scores, clearer rankings, and more options for further statistical analysis. Furthermore, the participants would be able to assign significantly more importance to aspects that are relevant from their point of view, for example, food security.

2.4. Using Input from Stakeholders to Evaluate the Understanding of a Problem and Discuss the Results

Based on social choice theory [81], this method of deliberative and discussed preferences of members of society and their decisions is supposed to reflect the convergence of collective preference [66]. Assuming this, the results from the stakeholder groups and the general aggregation are able to reflect the appropriate relevance of a group. The top third of the SDG subgoals, up to a score of 6.66, which respectively rank 48th, we consider as highly relevant for monitoring (i.e., "must" category). In the middle third, at scores of 3.33 to 6.66, ranking 67th to 113th, we see all SDG subgoals and topics as optional and nice to have (i.e., "may" category). From rank 113 to 169, with normalized scores of 3.33 to 0.00, the aspects of sustainability with little to no relevance (i.e., "not" category) for BE in Germany are distributed. These scores are the aggregate scores of all stakeholder groups for each subgoal.

Nevertheless, it is necessary to provide the complete ranking of all aspects and not exclude or just select some alternatives a priori [72]. It was discussed that these results of scaled societal preferences could be used in a later stage of monitoring development to set up the weightings of the utilized parameters. However, the elicitation of weights should not be used in the further context of political evaluation but rather ethical and political principles [72], and thus those weights are limited for the presented application in quantitative monitoring. Our scaled results offer the first important insights into constellations of such preferences. However, just as important are the documented discussions, which enable us to interpret and give a first understanding of these constellations and which interests and perceptions are behind them. Since we assess no common method of multivariate statistics applicable to our data in a scientifically robust manner, our analyses have a qualitative character.

3. Results: Reflecting Interests and Perceptions

In order to avoid lengthy tables, we have included the scores of all stakeholder groups for each subgoal in Tables A1–A3 for detailed consideration. In summary, the stakeholders classified the subgoals so that 56 of them should not be part (score < 3.33, "not" category), and 47 of them may be part (score 3.33 to 6.66, "may" category) of this monitoring. Another 66 subgoals were classified as so relevant that the issues they represent must be part of monitoring German BE (score ≥ 6.66, "must" category).

For presentation of the results, the subgoals are grouped as corresponding SDGs. First, from the "not" category (see Table A1 and Table 1), 36 subgoals had little relevance (score 0.00 to 3.33), which means that at least one working group of a stakeholder group assigned them any relevance by their own classification or gave feedback on them. The remaining 20 subgoals (score = 0.00) had no relevance at all for any stakeholder group or working group. Most of the subgoals from SDG 3, 5, 16, and 10 are part of this class, even though some of them are much more relevant (e.g., "reduce pollution of air/water/soil, health protection" (score(3.9) = 8.61); "reduction of bribery/corruption" (score(16.6) = 7.22); "improvement of representation/participation of developing countries" (score(10.6) = 7.50)).

Secondly, the same amount or more than half of the subgoals from SDG 6, 9, and 4 may be part of future monitoring. This class of 47 SDG subgoals (27% of all subgoals, see Table A2 and Table 1) may be part of a monitoring system and includes subgoals with scores between 3.33 and 6.66. Of these, 59.6% scored higher than 5.00, therefore tend to be in the "must" category and should be carefully evaluated before being neglected.

Finally, the widest class represents 39% of all subgoals that must be part of a monitoring system from a stakeholder perspective (see Table A3 and Table 1). A majority of subgoals from SDG 15, 14, and 13 were assessed as "must haves" in monitoring and stand for basic environmental aspects. At least as relevant are many subgoals of SDG 2, 12, 7, 6, and 2, representing food security, sustainable agriculture, production and consumption patterns, and sustainable infrastructure in cities and rural areas.

Table 1. From the stakeholder perspective, relative frequencies of SDG subgoals in a class of relevance in % (ordered according to the SDGs, whose subgoals occur mainly in the most relevant classes).

SDG Code	SDG	% of Sub-Goals in Class of Relevance		
		Must	**May**	**Not**
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	83.3	16.7	0.0
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	75.0	25.0	0.0
12	Ensure sustainable consumption and production patterns	72.7	27.3	0.0
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	70.0	30.0	0.0
7	Ensure access to affordable, reliable, sustainable and modern energy for all	60.0	40.0	0.0
13	Take urgent action to combat climate change and its impacts*	60.0	40.0	0.0
6	Ensure availability and sustainable management of water and sanitation for all	50.0	50.0	0.0
11	Make cities and human settlements inclusive, safe, resilient and sustainable	50.0	20.0	30.0
1	End poverty in all its forms everywhere	42.9	28.6	28.6
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	25.0	62.5	12.5
17	Strengthen the means of implementation and revitalize the global partnership for sustainable development	42.1	21.1	36.8
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	16.7	41.7	41.7
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	10.0	50.0	40.0
10	Reduce inequality within and among countries	20.0	30.0	50.0
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	8.3	8.3	83.3
5	Achieve gender equality and empower all women and girls	0.0	22.2	77.8
3	Ensure healthy lives and promote well-being for all at all ages	7.7	0.0	92.3

Taking a closer look at the 10 most relevant SDG subgoals according to their average scores by overall stakeholder groups shows a set of very different aspects with relatively close scores of relevance (see Table 2). The reduction of waste and urban pollution (subgoals 11.6 and 12.5), the protection of ecosystems (6.6 and 15.9), food security (2.1 and 2.2), research on sustainability (12.a) and governance aspects (13.2, 17.14, and 12.2) combine a series of different SDGs as well as high relevance by all stakeholder groups. A high average score results from high relevance by all stakeholders and indicates consensus regarding their importance.

Table 2. From stakeholder perspective: top 10 most relevant SDG subgoals for monitoring of bioeconomy. shgSci, stakeholder group science; shgBus, stakeholder group business; shgSoc, stakeholder group society; aggr., aggregated results of all stakeholder groups, mean values.

SDG Code	SDG Sub-Goal	Score 0.0–10.0				Rank aggr.
		shgSci	**shgBus**	**shgSoc**	**aggr.**	
11.6	Reduce urban environmental impacts, air quality, waste treatment	9.17	9.17	9.17	9.17	1
12.5	Reduction of waste generation (prevention, reduction, recycling and reuse)	9.17	9.17	9.17	9.17	1
2.1	Food access, food security	9.17	9.17	8.33	8.89	3
13.2	Climate protection measures, politics, strategies,	10.00	8.33	8.33	8.89	3

	planning					
6.6	Protection of all water-related ecosystems	9.17	8.33	9.17	8.89	5
12.2	Sustainable management of natural resources	8.33	9.17	9.17	8.89	5
12.a	Strengthen research on sustainable production/consumption	9.17	8.33	9.17	8.89	5
15.9	Aichi biodiversity targets, ecosystem and biodiversity values	9.17	8.33	9.17	8.89	5
17.14	Policy coherence in sustainable development	9.17	8.33	9.17	8.89	5
2.2	End malnutrition, food security	8.33	9.17	8.33	8.61	10

Next, regarding stakeholder-specific scores of individual subgoals and the differences between them, on average they are most significant in the "may" category, followed by the "not" category, and subgoals in the "must" category are the least controversial (see Table 3). Of 169 subgoals, the science stakeholder group gave an average score of 5.10, the business stakeholder group 4.42, and the society group 5.37. This shows a tendency of stakeholders in the science and society group to consider more subgoals as relevant for monitoring than stakeholders in the business group. Related to all subgoals, there is no clear evidence of a general higher convergence of the scores of science and business, science and society or business and society compared to the others. However, a detailed view of the 10 most controversial subgoals shows that 5 of them are societal aspects: ending the discrimination of women (subgoals 5.1 and 4.1) and issues of supporting developing countries (8.a, 9.5, and 10.a). Strikingly, 4 of them were seen as very relevant by the science and society stakeholder groups, whereas business stakeholders neglected them.

Concerning feedbacks to attribute more or less relevance given by the different working groups within a stakeholder-group: 6 working groups of the stakeholder group science attributed 52 times more and 3 times less relevance to sub-goals as their colleagues; 5 working groups of business attributed 22 times more and 4 times less relevance; and in the case of 4 working groups of the stakeholder group society 28 feedbacks that gave more relevance were recorded.

Table 3. From stakeholder perspective: top 10 most controversial SDG subgoals for monitoring of bioeconomy between stakeholder groups. shgSci, stakeholder group science; shgBus, stakeholder group business; shgSoc, stakeholder group society; aggr., aggregated results of all stakeholder groups, mean values; Ø Diff., average difference between scores.

SDG Code	SDG Sub-Goal	Score 0.0–10.0				Ø Diff.
		shgSci	shgBus	shgSoc	aggr.	
5.1	Eliminate discrimination against women	9.17	0.00	8.33	5.83	6.11
7.3	Double rate of increase of energy efficiency	9.17	8.33	0.00	5.83	6.11
8.4	Resource efficiency in consumption/production	9.17	0.00	8.33	5.83	6.11
8.a	Support developing countries/technical assistance	8.33	0.00	9.17	5.83	6.11
9.5	Strengthen/promote scientific research in developing countries	8.33	0.00	9.17	5.83	6.11
12.c	Abolish fossil fuel subsidies	9.17	8.33	0.00	5.83	6.11
12.7	Sustainable public procurement	5.00	10.00	0.83	5.28	6.11
8.6	Increase share of youth employment, education and vocational training	9.17	5.00	0.00	4.72	6.11
10.a	Justice, treatment of developing countries	5.00	0.00	9.17	4.72	6.11
4.1	Equal access/free education from elementary schools on (girls/boys)	0.83	0.00	9.17	3.33	6.11

Furthermore, a first glance at the aggregated scores of the 17 SDGs based on the scores of their corresponding subgoals (see Figure 2) shows the same common strong and widespread relevance for all environmental aspects (SDGs 13–15) without significant differences between stakeholder groups. Following a preference order calculated by the mean values of the relevance of an SDG given by all stakeholder groups, ending hunger (SDG 2), responsible consumption and production (12), all environmental aspects (13–15), infrastructure (9), energy (7), and drinking water supply (5) are the most relevant SDGs for monitoring of the German BE. These are followed by global partnerships, sustainable cities, decent work, inequalities, and education (SDGs 17, 11, 8, 4, and 10).

Peace, gender equality, and health (SDGs 16, 5, 3) appear to be topics of less relevance. However, against the background of these orders of preference and relevance, we have to emphasize that the SDGs cannot be put into a hierarchical order, since they represent a complex and interlinked means–end continuum of socioeconomic relationships. The loss of information in this representation lies in subgoals whose relevance has been assessed significantly differently from the other subgoals of the same key goal. For example, subgoal 11.6 (urban pollution, air quality, waste treatment) is assigned much higher relevance (score(11.6) = 9.17) than SDG 11 in general (score(11) = 6.17).

An interesting aspect from the results shown in Figure 2 regarding the different stakeholder groups, besides the expected similarities (SDGs 15, 16, 17, 11, 2, 3) and significant differences (1, 7, 8, 5, 9, 6), is that the strongest divergence by far emerges in the perception of ending poverty (1). No clear evidence can be found for a general convergence of relevance between specific stakeholder groups over all 17 SDGs, as well as for all 169 subgoals. But again, when it comes to mainly social aspects of sustainability (SDGs 1, 2, 3, 4, 5, 8, 10, 16), a clear qualitative correlation between the science and society stakeholder groups becomes visible: these stakeholder groups assign significantly more relevance to social aspects than the business stakeholder group. For all other SDGs, the differences in relevance between stakeholder groups do not have a significant qualitative correlation.

Figure 2. Analysis of German stakeholder -group perspectives on Sustainable Development Goals regarding bioeconomy. Relevance of SDGs based on relevance of corresponding subgoals given by

stakeholder groups. Order of preference is given by mean values of relevance (Ø) of an SDG given by all stakeholder groups. However, SDGs cannot be put into hierarchical order because they represent a complex and interlinked means–end continuum of socioeconomic relationships.

From recording the discussion process at our stakeholder workshops, a series of further, partly fundamental questions and positions appeared, some in line with the additionally proposed aspects above. Stakeholders in the science group emphasized that not only national but necessarily global effects of a German, European, and transnational BE must be taken into account in order to identify trade-offs, leakage effects, and refire and backfire effects and avoid them in the future. Business stakeholders were particularly interested in the international regulatory framework for BE activities such as market access, commodity restrictions, trade restrictions, subsidies, and financing options. In addition, price indicators of products and raw materials as well as political-economic instruments, for example, internalization of external costs or physical material flows, were relevant for them. These issues stand in general for information necessary for strategic economic management decisions in BE. For stakeholders in the society group, the main question was to what extent BE merely represents a substitution of the resource base of capitalism or is an actual socioeconomic change toward a more sustainable world. Identifying international land use changes and effects on food prices, and thus the nutritional situation of a growing population as well as the ecological effects, is also a central objective and conflict of interest.

Overall, the results indicate that topics of ecology from marine pollution to environmental education are as significantly relevant as food security and the associated political development and economic framework. Thus, from the perspective of all stakeholders, a series of aspects representing the social, ecological, and economic dimensions of sustainability as well as enabling factors of policy-making have to be considered in a monitoring system. Relatively irrelevant are the subjective visions of discontiguous topics, such as drug abuse but also increased GDP growth.

4. Discussion: Means, Ends, Perceptions, and Contradictions

Our empiric results, aggregated into main goals, mainly corroborate the findings of previous research and discussions on BE-related SDGs. Many of the SDGs that experts have defined as important (see Figure 1) are also highly relevant for most our stakeholders, such as ending hunger (SDG 2), water and sanitation (6), energy (7), sustainable growth and infrastructure (8 and 9), sustainable cities (11), sustainable consumption (12), climate change (13), and terrestrial and oceanic ecology (14 and 15). However, stakeholders in general see less relevance of health issues (SDG 3) but consider ending poverty (1), global partnerships (17), and education (4) as far more important. We assume that the reasons for this are the popular, general scientific, political, and societal discourse dimensions of BE (fuel vs. food, green cities and green growth) in case of similarities. Two convergent issues, ensuring food security and ending malnutrition (subgoals 2.1 and 2.2), are among the most relevant subgoals from all stakeholder perspectives, emphasizing that biomass should be primarily used for nutritional purposes. On the other hand, the potential of biopharmaceutical technologies and products in the health sector still seems to be an unpopular topic of discourse of specialists in this field, since research and development of medication and access to them (subgoals 3.b and 3.8) are classified as irrelevant. Better communication of BE high-tech potentials (e.g., biopharmaceuticals) and their transparent development would also help in this regard and contribute to faster implementation.

Taking a closer look at the SDG subgoals, it is quite surprising that reduction of urban environmental impact and waste (subgoals 11.6 and 12.5), ranking at number 1, may not seem to be the most popular BE-associated topic (see Table 2). Even though waste is a feedstock with significant potential for the bioeconomy, not only in highly industrialized economies [82]. Of course, there are strong connections between urban development and climate change [83], and green cities and sustainable urbanization play a certain role in the BE discourse [4]. But we assume this significance could also be strengthened by viral societal and media discussions, as urban air pollution was in Germany at the time of our workshops, where some stakeholders made remarks on such topics as biofuels, waste, and urban farming. These are well-known lessons learned from the fuel versus food debate [84, 85] and show the strong influence of sometimes volatile topics of medial narratives affecting policy process and public opinion [9]. This does not mean that these topics are therefore less relevant. The high relevance of most ecological aspects and sustainable consumption and production is in line with the results of general surveys on the perceptions of BE. In addition, it also became clear how important the governance frameworks and policy coherence (subgoal 17.14) appear among all stakeholders, showing the relevance of enabling factors and interdisciplinary aspects that are quite uncommon in monitoring systems.

On the one hand, our results show what may seem to be counterintuitive in terms of monitoring in one of the most industrialized nations in the world: the dimensions of sustainability are far beyond local ecological concerns, and the awareness of global environmental effects, international trade-offs, and big societal challenges such as hunger, poverty, and inequality is rising. In particular, a growing German or European BE will depend on imports [25], so national monitoring has to implement these aspects. Nevertheless, when a monitoring framework of regionally quite diverse BEs is developed on a global scale or with another regional focus [14], in our case subordinate aspects like health (SDG 3), education (4), gender equality (5), economic growth and jobs (8), and peace and justice (17) can be much more relevant aspirations. Even within the EU, the socioeconomic effects of biobased activities are found to be highly heterogeneous [51].

On the other hand, our results show how much the relevance of different topics is a question of interests and perceptions depending on stakeholder groups, showing the need to take different BE visions and narratives into account beyond scientific discussions (cf. [8]). Our results show rather strong particular interests by business stakeholders in contrast to more universal interests by society and science stakeholders. This became particularly clear in most of the social aspects, and a closer look at the most and least contentious SDG subgoals (see Table A2) supports this assessment, as well as the most significant difference in relevance between stakeholder groups: the assessment of ending poverty (SDG 1), to which business stakeholders assign far less relevance than the others. However, a bias that those stakeholders are not at all interested in societal challenges is contrasted by their interest in ending hunger. Even though there are similarities in the relevance of some SDGs as assessed by different stakeholders, all stakeholder perspectives are motivated by specific means of achieving specific ends based on values that can, of course, overlap and change in an ongoing progress or regress. These different means, ends, and values seem to be the guiding factors in what we have understood as conflicting interests and perceptions, and they are context-specific. Furthermore, they seem to be the main reason for a lacking common definition of BE. It has been assumed that all stakeholders should have an incentive to internalize external effects [31, 86], which remains to be fundamentally questioned [87, 88]. Moreover, it is a question of the visions and narratives: when BE is superficially understood as a potential socioeconomic transition toward holistic sustainability, ending poverty, global partnerships, and education play more vital roles; when BE is only a substitution of primary resources, the changes in socioeconomic dimensions are abstract in contrast to environmental effects. The successive changes of the European and German BE strategies toward transformation-centred visions underline the first case. Addressing this complexity and interlinkages, future policy strategies and legislation in Germany should be strongly interministerial, coordinated by a common strategy and appropriate measures at a federal and regional level [29].

One intrinsic quality of the SDGs is to implicitly combine ends and means. In the emphasized case, purchasing power (ending poverty, SDG 1) is a necessary condition for the purpose of satisfying needs (ending hunger, SDG 2), at least within the current widespread economic system. Regarding this, the characteristic for the discussion process was the relevance of individual subgoals determined by how and to what extent stakeholders rate these as more or less related to BE. Such subjective perception of the mediating relationships of certain aspects of the (bio-)economy with ecological and societal effects seems to be the crucial cause, not only for the relevance of topics of monitoring but also for the interpretation of sustainability in general [34, 89]. These relationships cannot be reduced to simple, one-directional causalities but rather have to be understood as a whole

[90, 91]. Inherent contradictions between socioeconomic development and ecological sustainability, which manifest as conflicts and trade-offs between partly incompatible SDGs [92, 93], exemplify this and remain a global governance challenge [14].

Comparing our results with the mentioned BE visions [8] and narratives [9] is possible only to a very limited extent, since the objectives, methodologies, and criteria are too different and aspects overlap. However, no vision or narrative can be clearly allocated to a specific stakeholder group, and vice versa. In our case, we cannot define clear images of "heroes," "villains," or "victims" [9]. While the qualitative and quantified interests and perceptions show an affinity of the business stakeholder group to biotechnology-centred visions and narratives of the society stakeholder group, mainly ecological and social ones, the science stakeholder group shares interests with all visions and narratives.

We have shown that it is crucial for a monitoring system to be able to inform and measure the aspects of and provide information about current and future risks and chances resulting from a developing bioeconomy. Regarding our main objective, to identify the most important aspects of monitoring BE from a stakeholder perspective, the subgoals of the "must" and "may" categories should be a substantial basis for the development of a national monitoring framework for BE in Germany (see Table A3 and Table A2). Consequently, besides the more common ecological and economic aspects, food security, sustainable production, infrastructure, and final consumption (SDGs 2, 8, 11, 12) have been integrated explicitly as key objectives in "Conceptualization of an Indicator System for Assessing the Sustainability of the Bioeconomy" [54] in the context of SYMOBIO. Furthermore, the science stakeholder group in particular followed our hint to leave the SDG setting and proposed a series of issues specific to the discussions around BE that were not part of the SDGs but should nevertheless be implemented (e.g., new primary biomass resources, national and global potentials; advanced indicators to measure leakage, rebound, reduction, and substitution effects; awareness, acceptance, and significance regarding BE; BE-specific energy consumption, emissions, footprints, and animal welfare; political evaluation of BE and indicators for policy strategies). When it comes to indices formed through aggregation, the relevance order and scores can be particularly important for necessary weightings.

5. Conclusions

We propose a comprehensive set of 66 aspects that must be part and 47 that may be part of a monitoring system. It is evident that sustainability has to be approached as a holistic and complex subject, because "social," "ecological," and "economic" aspects are at least equally important. In addition, institutional, political, and societal enabling factors are part of this. We emphasize that ambitious assessment and monitoring cover a variety of aspects, especially issues of vital societal discussion. Taking into account only certain issues, as too often in the past, can cause shortened analyses and possibly false scientific, political and media conclusions. Being sensitive to this can lead to a scientific knowledge base for these debates and their outcomes, as well as may avoid existential crises and discursive dead ends like the fuel versus food nexus and debate. Therefore, we have proposed indicators that all stakeholders consider important but also those that are valued differently in terms of their relevance.

The primary and obvious limitation of this research is the inclusion of only German stakeholders and the focus on monitoring the German bioeconomy. Not only international stakeholders play a role in highly interlinked national economies but the results are context-specific and only applicable in a limited and abstract manner to other regional contexts. Besides, in methodological terms, the way of collecting the relevance of aspects and aggregating can be improved by using more appropriate qualitative scales, such as Likert scales, and ultimately our setup of stakeholder groups has limited accuracy. Our results have a qualitative character and thus we did not conduct statistically sound quantitative analysis.

Future studies on stakeholder participation, interests, and perceptions should include international stakeholders and multiregional BEs. This is fundamental when implementing global governance frameworks, not only for BE. By increasing the number of stakeholders and methods of data collection, quantitative statistical analysis should be conducted as well as in-depth interviews to gain more solid insight into underlying interest, perceptions, and values. Those studies have to be aware of universal and particular interests of specific stakeholder groups. When it comes to developing further strategies to realize the SDGs by BE and implementing measures in legislation, governance frameworks, and practices based on evidence from monitoring [54], we also propose closer interactions with global institutions and structures like the Sustainable Development Solutions Network [46]. The continued pursuit of ambitious stakeholder participation can make a significant contribution to policy coherence and to avoiding regulatory failures in the future. By developing a monitoring framework oriented to addressing all stakeholders and their expectations as much as possible, benefits from the acceptance and usage of the monitoring, as well as bioeconomy concepts, are likely to be achieved.

Further basic research on societal relationships with nature can improve our understanding of these complex relationships [94, 95]; however, global negotiation processes including all stakeholders will have to organize these relationships [68]. Following previous research and most stakeholders, BE should not just be considered as a substitution of the resource basis but rather as a societal and economic transformation toward more sustainable development [1, 30]. Both a transition necessary to achieve sustainability and the already inevitable effects of being late at doing this will lead to significant political disruptions in the short and long term, so the need for democratic practices is urgent [91, 96]. Monitoring can support such processes by providing an evidence base, necessary because holistic sustainability is not an intrinsic character of either BE or other economies. Beyond that and most importantly, we all need to argue for a narrative, means–end continuum, and vision of this transformation that is given by neither the SDGs nor the BE themselves. It would also be a significant step toward a common BE definition.

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Appendix A

Table A1. From stakeholder perspective: 56 SDG subgoals with little or no relevance to monitoring of German bioeconomy. shgSci, stakeholder group science; shgBus, stakeholder- group business; shgSoc, stakeholder group society; aggr.,. aggregated results of all stakeholder groups, mean values.

SDG Code	SDG Sub-Goal	Score 0.0–10.0				Rank
		shgSci	shgBus	shgSoc	aggr.	aggr.
4.4	Increase number of adolescents/adults with apprenticeship	0.83	4.17	4.17	3.06	114
5.c	Gender equality/self-determination of women	8.33	0.83	0.00	3.06	114
8.5	Productive full employment, decent work, pay equity	0.83	4.17	4.17	3.06	114
10.3	Equal opportunities, abolition of discriminatory laws/policies/practices	5.00	4.17	0.00	3.06	114
16.9	Legal identity	8.33	0.83	0.00	3.06	114
16.b	Non-discriminatory legislation	4.17	5.00	0.00	3.06	114
17.10	Fair and multilateral trading systems	5.00	4.17	0.00	3.06	114
17.16	Financial aid, development assistance	0.83	4.17	4.17	3.06	114
3.1	Lower maternal mortality	0.00	4.17	4.17	2.78	122
3.2	Reduction of deaths newborns/children <5 years	0.83	3.33	4.17	2.78	122

3.3	Fighting AIDS, tuberculosis, malaria, etc.	8.33	0.00	0.00	2.78	122
3.8	Access to health care/insurance, medicines, vaccines	8.33	0.00	0.00	2.78	122
3.d	Health risks, early detection	8.33	0.00	0.00	2.78	122
4.6	Greatly reduce illiteracy worldwide	0.00	0.00	8.33	2.78	122
5.5	Leadership positions/equal opportunities for women	8.33	0.00	0.00	2.78	122
8.1	Per capita economic growth, GDP increase	8.33	0.00	0.00	2.78	122
9.a	Development aid for technology in developing countries	0.00	0.00	8.33	2.78	122
10.7	Secure, responsible migration policy/mobility	0.00	0.00	8.33	2.78	122
16.6	Transparent institutions	0.00	0.00	8.33	2.78	122
17.12	Customs and quota-free market access	4.17	0.00	4.17	2.78	122
17.17	Building partnerships/exchange of experience (public, private, civil society)	4.17	0.00	4.17	2.78	122
17.5	Investment promotion	8.33	0.00	0.00	2.78	122
17.99	Capacity building international cooperation	0.00	0.00	8.33	2.78	122
5.b	Use of basic technologies, self-determination of women	0.00	3.33	4.17	2.50	137
16.a	Capacity building in combating violence/terrorism/crime	4.17	0.00	0.83	1.67	138
3.5	Strengthen prevention/treatment of drug abuse	0.00	0.00	4.17	1.39	139
8.b	Global strategy on youth employment	4.17	0.00	0.00	1.39	139
10.c	Lower transaction costs of international home transfers	4.17	0.00	0.00	1.39	139
11.1	Affordable housing	0.00	0.00	4.17	1.39	139
11.7	Secure access to green areas/public space	0.00	0.00	4.17	1.39	139
16.4	Reduction of financial and arms flows/organized crime	0.83	3.33	0.00	1.39	139
16.10	Protect access to information/fundamental freedoms	0.00	3.33	0.00	1.11	145
10.4	Political measures fiscal/wage policy/social protection	0.83	0.00	1.67	0.83	146
1.3	Social protection systems and measures	0.83	0.00	0.83	0.56	147
16.2	End abuse/exploitation of children	0.00	0.00	0.83	0.28	148
1.b	Policy Frameworks for pro-poor and gender-sensitive development strategies	0.00	0.00	0.00	0.00	149
3.4	Reduce premature mortality (e.g., cardiovascular disease)	0.00	0.00	0.00	0.00	149
3.6	Reduce traffic accidents	0.00	0.00	0.00	0.00	149
3.7	Strengthen sexual and reproductive health and education	0.00	0.00	0.00	0.00	149
3.a	Health care, education, tobacco control (according to WHO agreement)	0.00	0.00	0.00	0.00	149
3.b	Research and development of vaccines	0.00	0.00	0.00	0.00	149
3.c	Health financing, education and number of healthcare professionals	0.00	0.00	0.00	0.00	149
4.a	Construction Educational Facilities/Safe Learning Environment	0.00	0.00	0.00	0.00	149
4.c	Increase number of teacher training teachers	0.00	0.00	0.00	0.00	149
5.2	Eliminate violence against women	0.00	0.00	0.00	0.00	149
5.3	End harmful practices for women (e.g., forced marriage, genital mutilation)	0.00	0.00	0.00	0.00	149
5.4	Structural integration of unpaid caring and housework as a service	0.00	0.00	0.00	0.00	149
5.6	Access strengthen sexual and reproductive health	0.00	0.00	0.00	0.00	149
8.8	Worker rights, labour protection rights, promoting safe work environment	0.00	0.00	0.00	0.00	149
8.9	Promoting policies of sustainable tourism	0.00	0.00	0.00	0.00	149
10.2	Self-determination, political/social/economic inclusion	0.00	0.00	0.00	0.00	149
11.5	Reduce deaths/Economic losses due to environmental disasters	0.00	0.00	0.00	0.00	149
16.1	Reduce violence-related mortality	0.00	0.00	0.00	0.00	149
16.3	Promoting the rule of law/access to justice	0.00	0.00	0.00	0.00	149
16.8	Participation of developing countries in steering institutions	0.00	0.00	0.00	0.00	149
17.8	Capacity building technologies/innovation/research in communications sector	0.00	0.00	0.00	0.00	149

Table A2. From stakeholder perspective: 47 SDG subgoals that may be part of monitoring German bioeconomy. shgSci, stakeholder group science; shgBus, stakeholder group business; shgSoc, stakeholder group society; aggr., aggregated results of all stakeholder groups, mean values.

SDG Code	SDG Sub-Goal	Score 0.0–10.0				Rank
		shgSci	shgBus	shgSoc	aggr.	aggr.
2.3	Increase agricultural productivity, income (small producers)	5.83	5.00	8.33	6.39	67
1.5	Increase resistance of population against extreme climate events	8.33	1.67	8.33	6.11	68
4.3	Promote gender equality	8.33	5.00	5.00	6.11	68
5.1	Eliminate discrimination against women	9.17	0.00	8.33	5.83	70
7.3	Double rate of increase of energy efficiency	9.17	8.33	0.00	5.83	70
8.5	Resource efficiency in consumption/production	9.17	0.00	8.33	5.83	70
8.a	Support developing countries/technical assistance	8.33	0.00	9.17	5.83	70
9.2	Sustainable industrialization	0.83	8.33	8.33	5.83	70
9.5	Strengthen/promote scientific research in developing countries	8.33	0.00	9.17	5.83	70
9.c	Access to information and communication technology	8.33	8.33	0.83	5.83	70
10.1	Income growth	8.33	0.83	8.33	5.83	70
12.c	Abolish fossil fuel subsidies	9.17	8.33	0.00	5.83	70
14.2	Sustainable management of coastal ecosystems	5.00	4.17	8.33	5.83	70
1.a	Financial support/development aid, eradication of poverty	8.33	0.00	8.33	5.56	80
4.5	Gender disparities (parity indices)	8.33	4.17	4.17	5.56	80
6.5	Integrated management of water resources	0.00	8.33	8.33	5.56	80
6.b	Improvement of water management, sanitation	4.17	8.33	4.17	5.56	80
7.2	Increase share of renewable energies, energy mix	8.33	8.33	0.00	5.56	80
9.1	Resilient infrastructure	8.33	0.00	8.33	5.56	80
9.b	Support local technology development in developing countries	0.00	8.33	8.33	5.56	80
11.4	Protection of world cultural and natural heritage	0.83	7.50	8.33	5.56	80
12.b	Monitoring sustainable tourism	0.00	8.33	8.33	5.56	80
14.6	Prohibit fishing subsidies	0.00	8.33	8.33	5.56	80
16.7	Democratic decision-making	4.17	4.17	8.33	5.56	80
17.11	Increase exports of developing countries	4.17	8.33	4.17	5.56	80
17.14	Policy coherence in sustainable development	4.17	8.33	4.17	5.56	80
12.7	Sustainable public procurement	5.00	10.00	0.83	5.28	93
8.7	Worker rights, abolition of forced labour/trafficking/child labour	5.83	0.83	8.33	5.00	94
8.6	Increase share of youth employment, education and vocational training	9.17	5.00	0.00	4.72	95
10.a	Justice, treatment of developing countries	5.00	0.00	9.17	4.72	95
2.b	Trade restrictions, - prevent distortions, stop agricultural export subsidies	5.00	0.00	8.33	4.44	97
6.2	Sanitation/hygiene	5.00	0.00	8.33	4.44	97
11.2	Infrastructure/traffic system	5.00	4.17	4.17	4.44	97
17.15	Political scope regarding poverty elimination	5.00	4.17	4.17	4.44	97
13.3	Education and awareness about climate protection	4.17	8.33	0.83	4.44	101
4.b	Increase number of scholarships	8.33	4.17	0.00	4.17	102
6.a	Capacity building for wastewater treatment/reprocessing	0.00	4.17	8.33	4.17	102
13.1	Emergency plans	4.17	0.00	8.33	4.17	102
14.b	Conservation/sustainable use of oceans, convention on the law of the sea	4.17	0.00	8.33	4.17	102
15.7	Combat poaching/trade of protected plants	4.17	0.00	8.33	4.17	102
17.19	Measurement of sustainable development	0.00	4.17	8.33	4.17	102
5.a	Financial equality, legal framework for women (e.g., pension, real estate)	8.33	3.33	0.00	3.89	108
15.c	Combating poaching/wildlife trade	3.33	0.00	8.33	3.89	108
4.1	Equal access/free education from elementary schools on (girls/boys)	0.83	0.00	9.17	3.33	110
4.2	Equal access/free education from preschool/kindergarten on (girls/boys)	0.83	0.00	9.17	3.33	110
10.5	Regulation/supervision of global financial markets	5.00	4.17	0.83	3.33	110
8.2	Econ. productivity increase through diversification	1.67	0.00	8.33	3.33	113

Table A3. From stakeholder perspective: 66 SDG subgoals that must be part of monitoring German bioeconomy. shgSci, stakeholder group science; shgBus, stakeholder group business; shgSoc, stakeholder group society; aggr., aggregated results of all stakeholder groups, mean values.

SDG Code	SDG Sub-Goal	Score 0.0–10.0				Rank
		shgSci	shgBus	shgSoc	aggr.	aggr.
11.6	Reduce urban environmental impacts, air quality, waste treatment	9.17	9.17	9.17	9.17	1
12.5	Reduction of waste generation (prevention, reduction, recycling and reuse)	9.17	9.17	9.17	9.17	1
2.1	Food access, food security	9.17	9.17	8.33	8.89	3
13.2	Climate protection measures, politics, strategies, planning	10.00	8.33	8.33	8.89	3
6.6	Protection of all water-related ecosystems	9.17	8.33	9.17	8.89	5
12.2	Sustainable management of natural resources	8.33	9.17	9.17	8.89	5
12.a	Strengthen research on sustainable production/consumption	9.17	8.33	9.17	8.89	5
15.9	Aichi biodiversity targets, ecosystem and biodiversity values	9.17	8.33	9.17	8.89	5
17.4	Reduction of over-indebtedness/external debt	9.17	8.33	9.17	8.89	5
2.2	End malnutrition, food security	8.33	9.17	8.33	8.61	10
2.4	Sustainable systems in food production (resilience)	9.17	8.33	8.33	8.61	10
2.a	Investment in rural infrastructure, agricultural research and consulting	9.17	8.33	8.33	8.61	10
3.9	Reduce pollution of air/water/ soil, health protection	8.33	8.33	9.17	8.61	10
4.7	Education for sustainable development	9.17	8.33	8.33	8.61	10
6.1	Access to affordable drinking water, food security	8.33	9.17	8.33	8.61	10
8.3	Promoting decent work, innovation, creativity, SMEs	9.17	8.33	8.33	8.61	10
12.3	Food waste/losses, post-harvest losses, resource efficiency	9.17	8.33	8.33	8.61	10
12.4	Environmentally friendly handling of chemicals and waste	9.17	8.33	8.33	8.61	10
12.6	Reporting on sustainability information	8.33	9.17	8.33	8.61	10
15.2	Sustainable forest management/reforestation	9.17	8.33	8.33	8.61	10
15.a	Conservation, sustainable use, biodiversity, ecosystems	8.33	8.33	9.17	8.61	10
15.b	Forest conservation/reforestation	9.17	8.33	8.33	8.61	10
2.5	Preserve genetic diversity of seeds/plants/animals	8.33	8.33	8.33	8.33	23
2.c	Stability food market, fluctuations of food prices, reserves	8.33	8.33	8.33	8.33	23
6.3	Increase water quality, pollution/chemicals, sewage/reprocessing	8.33	8.33	8.33	8.33	23
9.4	Sustainable renewal of industrial infrastructures	8.33	8.33	8.33	8.33	23
12.8	Information for consciousness about sustainable development	8.33	8.33	8.33	8.33	23
14.1	Reduce marine pollution, marine litter/nutrient pollution	8.33	8.33	8.33	8.33	23
14.4	Overfishing/management plans	8.33	8.33	8.33	8.33	23
14.5	Preserve coastal and marine areas	8.33	8.33	8.33	8.33	23
14.7	Sustainable management of fisheries, aquaculture, tourism	8.33	8.33	8.33	8.33	23
15.5	Protecting natural habitats, threatened species, biodiversity	8.33	8.33	8.33	8.33	23
17.1	Mobilizing local resources, taxes and duties	8.33	8.33	8.33	8.33	23
17.18	Capacity expansion in data collection	8.33	8.33	8.33	8.33	23
17.6	North-south/south-south/triangular cooperation	8.33	8.33	8.33	8.33	23
11.a	Regional development planning, linkage of urban and rural areas	10.00	4.17	9.17	7.78	36
15.1	Preservation/sustainable use of terrestrial and inland freshwater ecosystems	5.00	8.33	9.17	7.50	37
10.6	Improvement of representation/participation of developing countries	5.83	8.33	8.33	7.50	38
11.3	Sustainable urbanization	8.33	9.17	5.00	7.50	38
12.1	Sustainable consumption and production patterns	9.17	5.00	8.33	7.50	38
15.4	Conserving mountain ecosystems/biodiversity	9.17	8.33	5.00	7.50	38
10.b	Efficient and effective development assistance/financial	4.17	9.17	8.33	7.22	42

	flows/direct investment					
16.5	Reduction of bribery/corruption	9.17	4.17	8.33	7.22	42
17.13	Global macroeconomic stability	4.17	9.17	8.33	7.22	42
6.4	Efficient water use of all sectors	8.33	8.33	5.00	7.22	45
11.c	Support sustainable construction, local materials)	8.33	9.17	4.17	7.22	45
15.8	Prevent invasive species	8.33	8.33	5.00	7.22	45
1.1	Eliminate extreme poverty, pay equity	8.33	4.17	8.33	6.94	48
1.2	Poverty reduction, pay equity	8.33	4.17	8.33	6.94	48
1.4	Enable economic participation for all people	8.33	4.17	8.33	6.94	48
7.1	Access affordable, modern energy services	8.33	4.17	8.33	6.94	48
7.a	Access to research and technology, renewable energy	4.17	8.33	8.33	6.94	48
7.b	Infrastructure development, modern energy services	8.33	4.17	8.33	6.94	48
8.10	Promote national financial institutions for financial infrastructure	8.33	4.17	8.33	6.94	48
9.3	Access financial services SMEs	4.17	8.33	8.33	6.94	48
11.b	Urban planning of resource efficiency/mitigation of climate change	4.17	8.33	8.33	6.94	48
13.a	Financing of climate protection measures in developing countries	4.17	8.33	8.33	6.94	48
13.b	Development of management capacities, climate protection measures	4.17	8.33	8.33	6.94	48
14.3	Reduce acidification of the oceans	4.17	8.33	8.33	6.94	48
14.a	Scientific cooperation, transfer of marine technologies/research capacities	4.17	8.33	8.33	6.94	48
14.c	Access small-scale marine resources/markets	8.33	8.33	4.17	6.94	48
15.3	Combat desertification, area remediation	8.33	8.33	4.17	6.94	48
15.6	Just use/access to benefits of genetic resources	8.33	8.33	4.17	6.94	48
17.3	Financial and technical cooperation	4.17	8.33	8.33	6.94	48
17.2	Compliance pledges financial assistance	4.17	8.33	8.33	6.94	48
17.7	Diffusion of environmentally sound technologies	8.33	4.17	8.33	6.94	48

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Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements

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Discussion Paper

Towards a Holistic and Integrated Life Cycle Sustainability Assessment of the Bioeconomy – Background on Concepts, Visions and Measurements

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Abstract:

Current economic and social systems transgress several ecological planetary boundaries by far but without sufficiently fulfilling human needs and this in a globally unequal way, posing enormous challenges to political strategies and economic structures. To tackle these challenges, under a bioeconomy, a variety of industrial metabolisms, strategies and visions on substituting fossil resources by renewables and hereto associated societal transformations is formulated. Social, ecological and economic (holistic) sustainability, however, is not an intrinsic character of bioeconomy but rather a possible potential which has to be assessed. Life Cycle Assessments and Life Cycle Sustainability Assessments provide promising frameworks and methods for such holistic sustainability assessments, but face major challenges in regard to underlying sustainability concepts and implementation. First, we discuss and analyze the status quo of Life Cycle Sustainability Assessment especially in regard to underlying sustainability and economic concept and identify their strengths, weaknesses and research gaps. Secondly, we characterize the current bioeconomy discourse and propose a transdisciplinary, holistic and integrated framework for Life Cycle Sustainability Assessment. Based on this discussion and the proposed framework, holistic and integrated Life Cycle Sustainability Assessment can provide a transdisciplinary understanding and specific information on the absolute and relative holistic sustainability of provisioning systems to allow efficient and effective governance.

Keywords: bioeconomy; holistic sustainability; sustainability assessment; SDGs; transdisciplinarity; LCA; LCSA; ILCSA; HILCSA

Content

Figures

Tables

List of Abbreviations

BE	Bioeconomy
CE	Circular Economy
DTT	Distance To Target
EW-MFA	Economy-Wide Material and Energy Flow Accounts
ES	Ecosystem Services
E-LCA	Environmental Life Cycle Assessment
HILCSA	Holistic and Integrated Life Cycle Sustainability Assessment
IAMs	Integrated Assessment Models
ILCSA	Integrated Life Cycle Sustainability Assessment
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
PRP	Performance Reference Points
PB	Planetary Boundaries
SES	Social Ecological Systems
S-LCA	Social Life Cycle Assessment
SRN	Societal Relations to Nature
SDGs	Sustainable Development Goals

1. Introduction

The ecological challenges our global societies face are not only climate change, but it is likely that humanity is about to cross several planetary boundaries (PB) - representing the ecological limits of our planet – with increasing strong, intrinsic, bio- and geophysical feedbacks that are difficult to influence by human actions and partly irreversible (Steffen et al., 2018, Rockström et al., 2009, O'Neill et al., 2018). The political and economic impacts on human societies will be massive, sometimes abrupt and undoubtedly disruptive [ibid.]. To curb this developments and to achieve a sustainable stabilized development pathway within PB in the long-term, a coordinated, deliberate and conscious effort by societies is needed to reconsider our relationship with the ecological system (Steffen et al., 2018), for which a radical change - a transformation - in the way we organize our lives is urgently needed (Editorial Nature Sustainability, 2018).

As one way to address these challenges of decoupling and more sustainable resource use more than 50 countries worldwide have now developed bioeconomy (BE) related policy strategies (German Bioeconomy Council, 2018b, Kleinschmit et al., 2017, Meyer, 2017, Bell et al., 2018) to achieve what is in each strategy is understood as sustainable development. Following the definitions of the European BE Stakeholders Manifesto, the German BE Council and the German BE strategy, in this work we understand BE broadly as "the production of renewable biological resources and the conversion of these resources, residues, by-products and side streams into value added products, such as food, feed, bio-based products, services and bioenergy" "within the framework of a sustainable economy" (German Bioeconomy Council, 2018a). However, there is still no unified definition of BE (OECD, 2018, Meyer, 2017). Broadly, (bio-)economies can be understood as provisioning systems mediating the relationship between resource use and social outcomes. The novelty of the concept of a 'new' BE is the objective to achieve higher efficiency by innovative technologies in biomass usage, maximizing the added value of the produced goods (Ingrao et al., 2018) as well as being a main source of sustainable materials for nearly all economic sectors (Future Earth, 2016). Additionally, it can also be about a cross-sectoral networking of provisioning systems in a circular economy (CE) (European Commission, 2018, Bezama et al., 2019). Meanwhile the Sustainable Development Goals (SDGs) are becoming the standard normative sustainability framework also in BE strategies, policies, and action plans (German Bioeconomy Council, 2018b, Gerdes et al., 2018). Taking the chance of linking BE strategies with the SDGs has already broadened the scope of the BE and its sustainability, and stakeholder participation has shown that social, environmental and economic aspects of sustainability are equally important and related (Zeug et al., 2019).

Renewable or bio, however, does not necessarily mean sustainable. Sustainability is not an intrinsic characteristic but rather a promising potential of BE and only if sustainability is a central objective of the economy itself (Chisti, 2010, Pfau et al., 2014, Gawel et al., 2019). Evaluating the ecological, social and economic risks and chances of a developing BE requires scientific and comparable methods of holistic sustainability assessments. In the past, research studies on BE mainly focused upon the technical valorization of biomass and environmental impacts, due to the need for developing an actual technological basis and the material potential for a BE and a possible transformation. However, there is a lack of holistic and systematic approaches to the BE at national and regional levels, and consequently to understand the social, psychological, political and economic barriers to a societal transformation towards sustainable bioeconomies in a transdisciplinary manner (Ingrao et al., 2018, Pfau et al., 2014, Gawel et al., 2019). A measurement and evaluation of so called ecological, economic or social sustainability at different scales is the central motivation of different methodological frameworks of life cycle assessments (LCA) and their combination or integration in life cycle sustainability assessments (LCSA) (Bezama et al., 2017). Especially the latter methods of holistic assessment are still at an early stage and a number of research questions concerning methods, harmonization, data and indicators are open (Zimek et al., 2019, Guinée, 2016a, Ingrao et al., 2018). The most comprehensive review of LCSA approaches available identifies the lack of transparent description and discussion about implicitly underlying concepts of sustainability, and resulting difficulties in the classification of indicators and criteria as major obstacles (Wulf et al., 2019).

Considering this, the goal of this work is twofold: first we discuss and analyze the status quo of LCA and LCSA, especially in regard to their underlying sustainability and economic concepts. Secondly, we characterize the current BE discourse and propose a transdisciplinary, holistic and integrated framework for LCSA in the context of BE. For this research we do not apply specific methods, rather we are building on existing comprehensive reviews, reflect on backgrounds and underlying concepts, discuss approaches going beyond the status quo and argue for a methodological framework addressing some of the identified issues.

2. Life Cycle Assessments in the Context of Bioeconomy

Since it is uncertain if BE has a positive impact on global sustainability, there is a need for comprehensive approaches for measuring and assessing sustainability of the BE as prerequisites for creating effective governance (Dietz et al., 2018). When it comes to policy mixes to address the named decoupling challenges and to implement the SDGs via transformations, the interdependencies of social, economic and ecological systems and possible alternatives are vital (Fedrigo-Fazio et al., 2016). This chapter provides a closer discussion of LCA and LCSA approaches to identify their methodological potentials, but also their partly deep-rooted problematic issues which are obstacles for a further development and application of LCSA.

2.1. Social, Environmental and Economic LCA

Especially LCA became increasingly part of policy documents and legislation as tools for supporting effective and efficient policy and decision making, e.g. the Joint Research Centre (JRC) of the European Union built up a European Platform on LCA for harmonization and more consistent use (JRC, 2019). LCAs as well as LCSAs can be broadly characterized by their scales (global, national or regional value-chains, companies and specific products) and scopes (social, economic and ecological aspects) (Bezama et al., 2017).

In this chapter, we take a look at the different scales: LCAs of specific products, production processes and concrete economic facilities and organizations on the micro-level of assessment methods are particularly important for the assessment of relative decoupling, because thresholds are determined indirectly by processes and resource extraction, rather than by resources themselves (Fedrigo-Fazio et al., 2016). However, the sole evaluation of process chains is not sufficient, as e.g. the reduction of GHG in a specific industry does not mean that national or global emissions would also be reduced significantly, what makes assessments on a macro-level necessary (Budzinski et al., 2017, O'Keeffe et al., 2016). In between, as a relatively new field, LCAs and LCSAs are used for regional assessments of material flows and their effects (Balkau and Bezama, 2019). Regions differ in their social, economic and environmental conditions with corresponding differences in strategy, research and implementation. At a sectoral and regional level analyzes are necessary in order to map regional effects in the social and economic sphere and to make visible real ecological improvements at a meso aggregation level of clusters and networks. Region-specific LCA approaches can support local stakeholders by identifying specific sustainability potential, which can be tapped on site by specific measures in contrast to more general, strategic and nation-wide approaches. Thus, in future, research especially meta- and sector-wide studies of regional effects and interventions are needed (Ingrao et al., 2018). Thereby, also effective policy can be increased by providing specific and generally applicable information and there is a higher chance of stakeholder engagement and acceptance on this meso-level (Fedrigo-Fazio et al., 2016) (Figure 1).

Secondly, and more importantly for this research, let us consider the different scopes. Means to monitor progress in reaching the targets set in BE policies and strategies is lacking in many countries. Not only due to a lack of appropriate methods, but also due to a lack of a clear definition of the BE concept and of concrete and measurable targets and objectives, e.g. different interpretations of sustainability and economy as well as missing clear connection to target systems like the SDGs (Bracco et al., 2018). From our point of view, assessing the BE regarding ecological, social as well as economic sustainability is difficult, since it is not always evident what is actually meant by that. When BE is superficially understood as a potential socioeconomic transition toward holistic sustainability, ending poverty, global partnerships, and education play more vital roles. If, on the other hand, BE is understood only as a substitution of primary resources, the changes in socioeconomic dimensions are insignificant in contrast to environmental effects (Zeug et al., 2019). In most strategies, BE is only monitored by economic values and shares of GDP or their objectives are even non-measurable targets, but the main challenge is how to link complex goals and measurement frameworks (Bracco et al., 2018). Since recently, socioeconomic indicators to monitor the EU's and Germany's BE are in development (Ronzon and M'Barek, 2018, Egenolf and Bringezu, 2019).

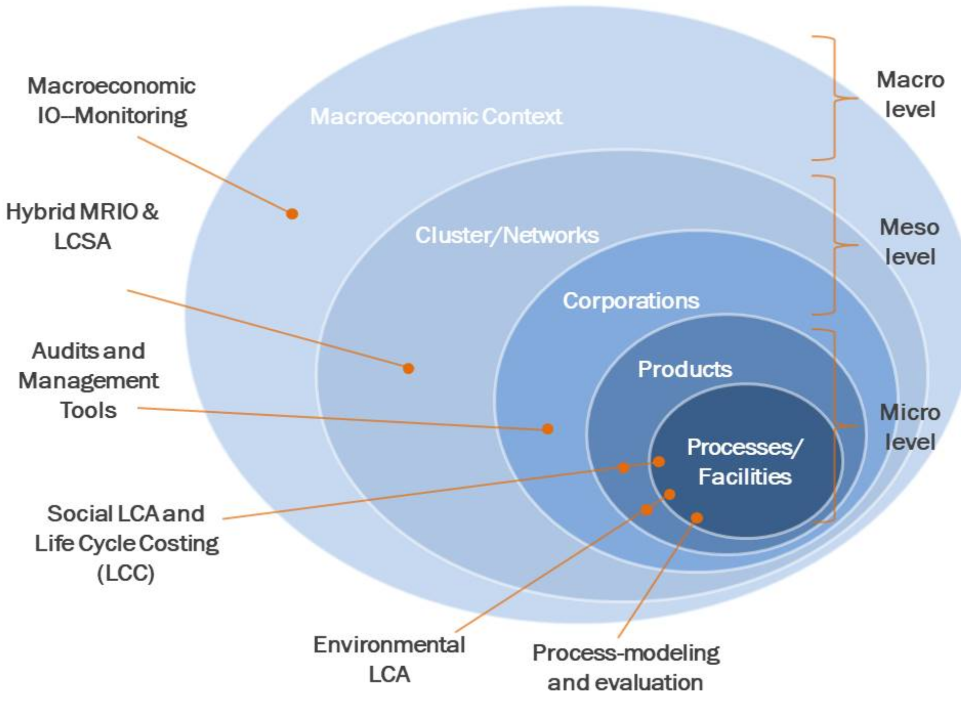

Figure 1, Scales and scopes of BE and appropriate methods of assessment, adapted from (Thrän et al., 2014)

The framework of nearly all LCAs is largely based on environmental LCA (E-LCA) according to DIN EN ISO 14040 and 14044 (Grießhammer et al., 2006, ISO 14040, 2006, ISO 14044, 2006). Main differences are the scopes being assessed: respectively social, environmental or economic sustainability and corresponding indicators (see Table 1). These can be specified by physical quantitative data for E-LCAs, quantitative and qualitative data for Social-LCAs (S-LCA) and quantitative-monetarist data for life-cycle-costing (LCCs) (UNEP, 2009). Recent reviews of LCA methodologies applied to BE showed that 86% of them, the vast majority of all studies, are E-LCA approaches (D'Amato et al., 2020). Apparently, this division of LCA methods is very much based on the three-pillar approach and its characteristics (see section 3.1).

In summary, the existing approaches show significant differences in the main methodological characteristics: goal and scope, functional units, life cycle inventory and model, impact assessment and interpretation. Most important, clear cause and effect chains in S-LCA but also relations between the different assessment methods are missing, especially when it comes to several stakeholders and scales like workers, local communities and national societies (cf. (Jarosch et al., 2020)). Still, LCAs and their indicators should necessarily consider international effects, since first, using local or global indicators depends on the nature of environmental pressures and its causes (global – GHG, local – acidification), and second, a spatial dissociation between places of extraction, production, and consumption distributes the social and economic effects globally (Parrique T., 2019). Mostly, the used indicators in social, environmental and economic assessments tend to be indicators of a weak sustainability approach, when the dimensions of sustainability are seen as interlinked systems and not as embedded and interdependent spheres (Liobikiene et al.).

Table 1, Examples of typical dimensions of sustainability, goals, sub-goals and indicators for the assessment of a BE (cf. (Liobikiene et al.))

Dimensions (Impact categories)	Social sustainability	Ecological sustainability	Economic sustainability
Goals (indices)	Prosperity, health, knowledge	Protection of water, soil and atmosphere	Growth of human-, nature- and real capital
Sub-goals (Indices)	Income and distribution, work safety and stress, qualification, R&D	Climate change, toxicity, resources	Education, demography, resources, investment, profitability
Indicators	Share of employees in the BE sector; labor productivity; public acceptance	The contribution of BE to the reduction of environmental impact; consumption and potential of biomass; Land footprint	Value added and revenue; factor productivity; R&D subsidies and investments; Patents of biotechnologies

2.2. Status Quo of LCSA

LCSAs as the combination or integration of S-LCA, E-LCA and LCC aims to provide a broader and more holistic perspective in sustainability assessments and has been considered by many researchers as essential for a movement towards global sustainable development (OECD, 2018, Zimek et al., 2019, Wagner and Lewandowski, 2018, Balkau and Sonnemann, 2017, Onat et al., 2017, Gao and Bryan, 2017, de Besi and McCormick, 2015). However, LCSA faces the most significant methodological problems. At least there are currently two definitions of LCSA. On the one hand the widely used and highly operationalizing and additive scheme (LCSA=ELCA+LCC+SLCA) first proposed by Klöpffer in 2008 (Klöpffer, 2008). It argues that on the basis of the three-pillar approach, the three methods have to be standardized, harmonized, synchronized (mostly this means an analog brief structure as in DIN EN ISO 14040 and 14044) and then combined whereas extensive qualitative analyses are excluded. On the other hand, there is at least the idea of an integrative approach first proposed by Guinée in 2011, where within a common sustainability concept and methodical framework impact categories from E-LCA, S-LCA and LCC are integrated into a holistic assessment. In this case, LCSA can be understood less as a firm model, but rather more as a flexible framework. Since the sustainability of the BE is a multi-disciplinary and multidimensional field, a series of research papers emphasize and argue that especially integrated approaches are specifically required in this case (Pfau et al., 2014).

At least to date, the authors of this study are not aware of any framework or application of a real integrative and holistic approach of LCSA. Rather, as recent comprehensive reviews (Zimek et al., 2019, D'Amato et al., 2020, Wulf et al., 2019, Fauzi et al., 2019, Costa et al., 2019) and a recent search for LCSAs at Web of Sciences (Suwelack, 2016, Wagner and Lewandowski, 2018, Ekener et al., 2018, Mahbub et al., 2019, Vogt Gwerder et al., 2019, Nieder-Heitmann et al., 2019, Opher et al., 2019) show: most LCSA approaches more or less follow the additive scheme and, like LCAs, are explicitly or implicitly based on the three-pillar-approach (Zimek et al., 2019). An explicit theoretically founded framework of holistic sustainability is often missing, which in practical terms leads to different social, economic and ecological dimensions and indicators which are not integrated. But still rather juxtaposed parts and at the end additionally combined by MCDA (Figure 2).

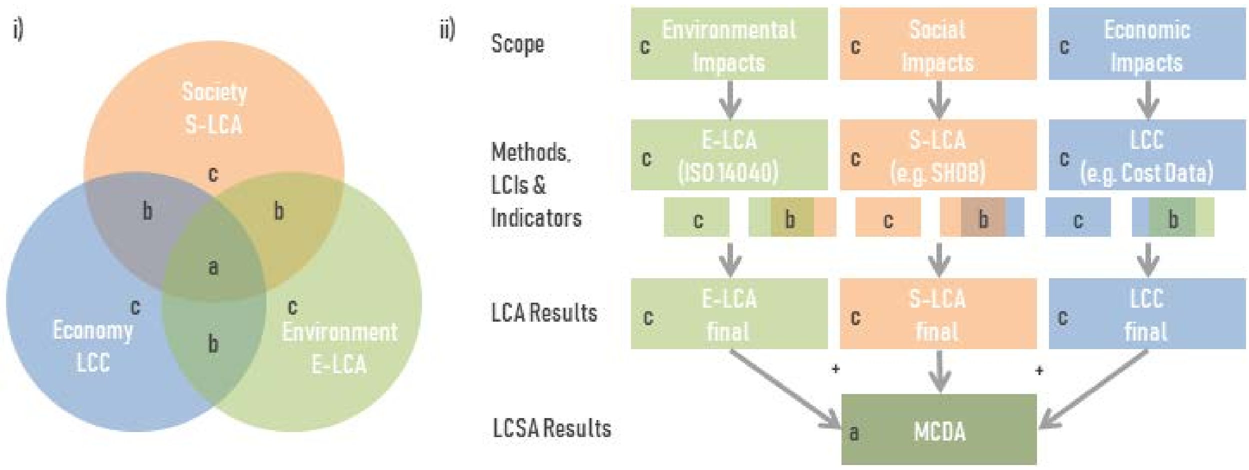

Figure 2, i) Three-pillar-approach of holistic sustainability in LCSA, ii) Widely used additive scheme of LCSA (LCSA=ELCA+LCC+SLCA) by Klöpffer based on i) (c – separate systems (sustainability concepts), methods and indicators (LCSA), b – Intersection between two systems (sustainability concepts), indicators which cannot be clearly assigned to one system (LCSA), a – all dimensions somehow combined (sustainability concepts), additive combination of methods results (LCSA)) (cf. (Suwelack, 2016) Fig. 2.1, (Wagner and Lewandowski, 2018) Fig. 8.22, (Egenolf and Bringezu, 2019) Fig. 1, (Ekener et al., 2018) Fig. 1, (Mahbub et al., 2019) Fig. 1, (Vogt Gwerder et al., 2019) Fig.1))

As an example for this, we consider in a generalized form three LCSA methods (Suwelack, 2016, Wagner and Lewandowski, 2018, Ekener et al., 2018)() and one systematic monitoring approach (Egenolf and Bringezu, 2019) with application in the BE: In all cases the conceptual starting point is the three pillar approach of holistic sustainability which is mostly not discussed explicitly, controversially or extensively (Figure 2, i)). Since this domain takes the three parts respectively dimensions of sustainability as the point of departure and considers LCSA as a linear summation and combination of the parts, E-LCA, S-LCA and LCC are carried out more or less independently from each other as separate systems (Figure 2, ii)) (c). Broadly said, scopes, corresponding methods, indicators and LCIs as well as their individual results only have in common that they relate to the same product or functional unit which is to be assessed (cf. (Suwelack, 2016, Wagner and Lewandowski, 2018, Ekener et al., 2018)). When assigning the indicators to impact categories, and/or already when indicators are allocated to sustainability dimensions, it becomes apparent that for some indicators or aspects no clear intuitive allocation is possible or useful (e.g. aspects like sustainable final consumption/production, infrastructures, development of rural areas, employment (Egenolf and Bringezu, 2019)). Such aspects mostly describe complex relations between two or more sustainability dimensions and are not even roughly categorizable as solely social, economic or ecological (b). How to deal with such issues is difficult within the three-pillar-approach and separate assessment methods. It not only runs the risk of generating double counting, but also generates unclear cause and effect chains, fuzzy impact categories (e.g. if an indicator is of primarily social, environmental or economic character or which stakeholders are effected) and allocation as well as misleading interpretations. The separate results of S-LCA, E-LCA and LCC are at the end additively combined by MCDA. Relationships between interlinked systems and the SDGs do not play an immanent role.

However, a simple combination of the particulate methods is only possible to a very limited extent (Keller et al., 2015, Wulf et al., 2019, Costa et al., 2019) and also combining the final results with MCDA (Ekener et al., 2018) does not represent a real integration. This is because there is no common methodology and the analysis of complex systems by their subsystems would mean more than just combining their parts (Halog and Manik, 2011). In this regard a series of specific problems results in the operationalization: trade-offs and conflicts of objectives (Guinée, 2016b), double-counting and problems of monetization (Klöpffer, 2008), pareto-effects of high significance within cause-effect relations, contradictions between effects on different scales (Guinée, 2016a), allocation from effects to impact categories (UNEP, 2011), functional units (Costa et al., 2019), exogenous and endogenous weightings in accounting (Traverso et al., 2012), rating, normative goal systems and many more. For instance, the decoupling debate has shown that improving the ecological performance of products only has a limited effect on global environmental challenges, and pareto effects come to bear which makes a relatively small number of causes responsible for a major portion of the effects, resulting in a need for hot spot analyzes (Halog and Manik, 2011). Furthermore, such process-based approaches with a high technical detail, but few general preliminary considerations and conclusions, remain very specific and have a limited significance for systematic analysis of BE regions in a broader context.

Beyond this, there is another approach pursued by ifeu (Institut für Energie- und Umweltforschung Heidelberg), which represents a first but little-noticed development towards integrated LCSA (ILCSA) (Onat et al., 2017, Zimek et al., 2019). Besides integrating other topics, e.g. local environmental effects, a barrier analysis and feedstock availability, there is an integration of S-LCA, E-LCA and LCC by a common LCI with qualitative and quantitative indicators (cf. Figure 4, ii)) as well as an integrated unit process ((Keller et al., 2015) Fig. 2), which we will build on later. But in this method no result integration by aggregation and weighting is conducted, rather benchmark procedures for every indicator. Furthermore, there is no integrated or holistic concept of sustainability and its relations or a connection to SDGs (which did not exist at the time) and stakeholders (Wulf et al., 2019, Keller et al., 2015).

In a nutshell, most of the problems and limitations of the previous presented additive and partly integrated LCSAs can be traced back to deficits in the underlying sustainability concepts, resulting in conceptual, methodological and analytical flaws (Wulf et al., 2019). Thus, the lack of understanding the mutual dependencies and complex interactions among the sustainability indicators, a reductionist approach and myopic view by looking at results of E-LCA, S-LCA, and LCC separately were identified as the major shortcoming of existing LCSA frameworks (Onat et al., 2017, Zimek et al., 2019, Wulf et al., 2019). Generally speaking, a well-founded social, ecological or economic sustainability theory in LCSA is missing. A framework of a holistic sustainability concept based on the SDGs can be regarded as the major hurdle of an integration of the LCA methods and their operationalization in LCSA. In the following chapter we therefore take a look at established concepts of sustainability to gain a better understanding of the implicit backgrounds of LCSA, its deficits and possible alternatives.

3. Background on Sustainability and Economic Concepts and Frameworks

Sustainability and SD have mostly become a collective global value, but remain a challenge for all stakeholders like policymakers, the scientific community, NGOs, business and civil society as the definition of sustainability as a societal transformation and the regional strategies that actually foster it are still ambiguous and continuously debated (Jordan, 2008, Dresner, 2002, Ramcilovic-Suominen and Pülzl, 2018, Editorial Nature Sustainability, 2018, Future Earth, 2016). Terms and concepts of a transformations towards sustainability remain fuzzy and there is much ambiguity and disagreement about the meaning and function of these concepts (Görg et al., 2017). Nonetheless, such transformation will most likely have to innovatively address normative and socioeconomic barriers, like global political patterns of regulation and production and consumption patterns, as well as the technological and ecological challenges (Ingrao et al., 2018). The understanding of sustainability gets even more controversial when it comes to the holistic extension by social and economic dimensions (UNEP, 2011, Elkington, 1998) as well as their relations and contradictions, which remain a fundamental challenge in theoretical and practical terms as we have shown for LCSA (Liu et al., 2015, Gao and Bryan, 2017). Because on the one hand there are neither theoretically in the academic discourse established nor successfully applied integrative concepts of holistic sustainability, and on the other hand practically no country performs well on both the biophysical and social indicators: the more social thresholds countries achieve, the more biophysical boundaries they transgress, and vice versa (O’Neill et al., 2018). Previous research and models building on the “safe and just space”-framework and Doughnut Economics (O’Neill et al., 2019) show that in fact many wealthy nations achieve most of the social thresholds, but at a level of resource use that two to six times beyond the per capita biophysical boundaries (e.g. Germany achieves 11 out of 11 social thresholds but still transgresses 5 out of 7 PBs) (O’Neill et al., 2018). For example, Germanys’ environmental footprint is 3.3 times higher than its biocapacity (variable regional and global ecosystems capacity to produce biological resources and to absorb emissions and waste) (GFN, 2019, Network, 2019, Schaefer et al., 2006, Bringezu et al., 2020). At the moment well-being and prosperity seem to be immanently coupled to CO_2 emissions and a high material footprint, but least tightly coupled to the intensity of human use of terrestrial ecosystems due to increases of livestock productivity (O'Neill et al., 2018, Haberl et al., 2012). Nonetheless, especially some social indicators as secondary education, sanitation, access to energy, income and nutrition, which are most important for developing countries, are still most tightly coupled to economic growth and (fossil) resource use (O'Neill et al., 2018).

3.1. Sustainability and Economic Concepts

Although, the terms SD and sustainability are mostly used synonymously today, they actually do not mean the same thing. SD is as a process-oriented approach by means of which sustainability is intended to be achieved. It is based on a dualist anthropocentric view that humankind has a special and almost detached relationship with nature and is only interested in the instrumental or utilitarian value attached to an ecosystem (shallow ecology). Resources should be conserved to be available for future generations and nature should be cared about only to the extent that it is in human interests (Hector et al., 2014). SD is a discursive frame interlinking environmental concerns with human needs by introducing a way to reconcile economic growth with environmental and social concerns on a global scale (Ramcilovic-Suominen and Pülzl, 2018, Meadowcroft, 2007). On the other hand, (strong) sustainability strives for some form of dynamic equilibrium in which the needs of humankind and the needs of nature are both satisfied. In a broader notion of environmental-preservationist this means that the natural world ought to be preserved and must not be allowed to deteriorate, disappear or be dominated by humans (deep ecology) (see Table 2). Here humanity is an integral part of nature, not separate from it and nature has an intrinsic value independent from human or economic interest (Mebratu, 1998, Hector et al., 2014). This polarized constellation of anthropocentric (weak sustainability, shallow ecology, SD) and ecocentric (strong sustainability, deep ecology) views is an epistemological trap: a discussion gets stuck as positions are permanently irreconcilable and based on different self-evident axioms (Hector et al., 2014). This shapes (bio-)economy discourses, practices and assessments:

On the one hand neoclassical environmental economics correspond to weak sustainability because they possess a clearly anthropocentric concept of SD, characterized by benefit and profit maximization. It is assumed that natural capital can be substituted with artificial capital, environment is frequently undervalued, tends to be overused and if the environment only were given its 'proper value' in economic decision-making terms, it would also be protected much more highly (Hector et al., 2014, Mebratu, 1998, Redclift and Benton, 1994). But even within neoclassical models only this constant substitutability of capital stocks and the timely availability of backstop technologies as the BE allow the assumption of non-existent growth limits, without depleting non-renewable and overuse renewable resources (Smulders, 1995). Thus, unlimited economic growth is only possible if enough human capital is allocated in R&D to sufficiently increase the efficiency of resource consumption (Barbier, 1999, Victor et al., 1994, Verdier, 1995, Michel and Rotillon, 1995). When SD is intermeshed with neoclassical economics and in this sense transferred to sustainability assessments like LCSA, we have to be aware of these aspects and of its shortcomings: besides it tends to overlook or deliberately rejects the interests of non-human species, it tends to be mechanistic and reductionist, and based on a positivist view of the ecological system where humankind is regarded as being almost detached from it (Hector et al., 2014). Resulting in a dualism of humankind and nature with a clear hierarchical order that humankind rules over nature (Görg, 2004). Then SD and also LCAs not only tend to treat environmental problems without tackling the underlying causes and assumptions that underlie our current political and economic thinking (Mebratu, 1998), but also see social, environmental as economic aspects and sustainability as rather detached from each other resulting in non-integrative and additive LCSA approaches. Additionally, most LCA based approaches clearly represent an explicit or implicit positivism: reality is seen as independent, objective, empirical and measurable; there are general laws between variables representable by mathematics; methods are model simulations, manipulation of variables and quantitative data; and governance or policymakers 'outside' the system have to pull 'levers' to steer developments.

Table 2, Contents of popular sustainability concepts (Hector et al., 2014, Ramcilovic-Suominen and Pülzl, 2018, Hopwood et al., 2005, Mebratu, 1998)

	Shallow Ecology	Deep Ecology
	Weak sustainability	Strong sustainability
Keywords	Prudentially-conservationist	Environmental-preservationist
	Anthropocentric	Ecocentric
	Sustainable development	Sustainability
Content	Humanity with specific relation towards nature, instrumental value of ecosystems, positivist view, mechanistic systematization, substitutability of capitals, objective: economic sustainable development	Humanity as integral part of nature, intrinsic value of ecosystems, monist and morally egalitarian view, preservation of nature and non-substitutability, objective: sustainable equilibrium

On the other hand, as a result of this criticism and shortcomings, in the 1980s ecological economy developed as an interdisciplinary and more qualitative concept tending towards strong sustainability (Georgescu-Roegen, 1971). In this time and context of ecological economics the term ‘bioeconomics’ occurred for the first time, but had a completely other meaning than the current term of BE (Birner, 2018) and key messages of both are: the earth is seen as a closed system in which the economy is a subsystem and, therefore, there are limits to resource extraction; a sustainable society system with a high quality of life of all inhabitants within the natural limits is sought; complex systems are of great uncertainties and require a preventative approach; a fair distribution and an efficient allocation are necessary (Costanza et al., 1997, Hauff and Jörg, 2013). In terms of sustainability assessment and LCSA of BE, a consequence is to consider PB as absolute limits of resource extraction. In contrast to pursuing individual gain, benefit and profit maximization, the ecological economy is strengthening the importance of ecological systems for the safeguarding or improvement of human living conditions. In other words, it is about the welfare of the whole society (Hauff and Jörg, 2013). Again in LCSA, this means to switch from GDP and revenues as a form of economic sustainability to a more diverse and direct set of economic indicators like the SDGs. In particular, the assumption of a substitutability of natural and artificial capital is called into question, since human capital is needed to make efficient use of natural capital, and natural capital is needed to generate anthropogenic capital (Hector et al., 2014, Hauff and Jörg, 2013). Capitals are indeed substitutable, but any number of workers and machines or an increase in productivity cannot completely replace the starting materials necessary for production. A necessary increase in productivity can be achieved through three approaches relevant for the BE and their restrictions: increasing flow of natural resources per unit of natural capital, limited by biological growth rates; increasing product output per unit of resource input, limited by mass conservation; increasing efficiency of use of conversion of raw materials into products, limited by technology (Costanza et al., 1997). Models based on the I = P A T function (I – Impacts, P – Population, A – Affluence/ per capita consumption, T – Technologies/economic intensity of resources or pollution) show that growth in GDP ultimately cannot plausibly be decoupled from growth in material and energy use, therefore, GDP and material growth cannot be sustained infinitely in this very economic system (Ward et al., 2016, Common and Stagl, 2005).

The techno-political option space of the BE (Hausknost et al., 2017) shows strong connections to the presented sustainability and economy concepts: “Sustainable Capital” corresponds to the neoclassical perspective and weak sustainability; “Eco-Growth” corresponds to the ecological economics perspective and weak sustainability; “Eco-Retreat” is more a ethical vision of deep ecology, strong sustainability and ecological economics; “Planned Transition” is based on ecological economics but neither corresponds clearly to weak nor strong sustainability.

3.2. Sustainability Frameworks Behind Sustainability Assessments

Since the Brundtland Commission Report in 1987 SD is defined as meeting the needs of the present without compromising the ability of meeting needs in the future (Brundtland et al., 1987). Economic growth to reduce poverty was the specific sense of a solution conferred to, and, in doing so, to create the wealth, technology and commitment necessary to reduce ecological damage. Meanwhile, the so-called three pillar approach (people, planet and prosperity) of the World Summit on SD in 2002 has prevailed and is essential to the present understandings of sustainability (Elkington, 1998, UNEP, 2011, Hector et al., 2014). However, thereby suggested are kinds of several more or less differentiated entities constituting sustainability in a complementary and constructive way (Meadowcroft, 2007). The most established resulting model (see Figure 3) from the three pillar approach is the reductionist model of interlinked systems (Holmberg et al., 1992) as the dominant model which is still mainly used (cf. (Rockström and Sukhdev, 2016)), especially in LCSA (Zimek et al., 2019). And there is a rather less-established model of integrated systems more according to ecological economics (Mebratu, 1996). Presumably rather less-established, since its theoretical conception is less intuitive and requires a well-founded theory as well as its practical implications are far stronger (see section 5).

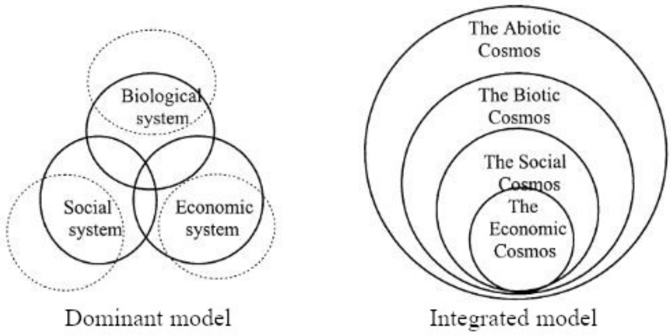

Figure 3, Schemes of sustainability concepts (Mebratu, 1998, Fig. 1)

The established dominant model lead into inflexible and polarized oppositions due to its reductionist epistemological foundations in terms of normatively weak vs. strong and hierarchically of ecological vs. social vs. economic (Redclift and Benton, 1994, Trzyna et al., 1995). Thus, in the ongoing discussion of the last years, a broad spectrum of blended approaches emerged, mainly on the background of complex interactions, spillover effects and increasing importance of transdisciplinarity (Liu et al., 2015). Lately, the lack of a holistic and systematic understanding of social and ecological systems (SES) of the simplified three-pillar-approach was increasingly discussed, even if the term holistic is used inflationary (de Schutter et al., 2019, Purvis et al., 2019). Most important, however, in BE and particularly in LCSA the dominant idea is still to sum up the parts or dimensions of sustainability than to understand their relations: a strong holistic domain has the tendency to take the whole as the conceptual point of departure and take the parts as an add-on, whereas a strong reductionist domain takes the parts as the point of departure and considers the whole as a linear summation. Both approaches proclaim that they apply holistic thinking; however, they are missing the most important element of holistic thinking, i.e. the interactions and relations between the parts in the whole. (Mebratu, 1998)

In a nutshell, a closer look at different economic concepts and sustainability concepts makes clearer why there has been such a mainly technological focus on BE and in most sustainability assessments: in all economic concepts innovations and backstop technologies like the ones strived for by the BE play a decisive role, in neoclassical economics for maintaining growth and the further accumulation of more natural capital. Following ecological economics for our LCSA we assume that a further increase in GDP levels is not considered societal appropriate, since quantitative growth no longer directly improves quality of life and the output of the present level of production in these societies should rather be different and more just distributed (O'Neill et al., 2018, Jackson, 2017, Williams, 2010). If the purpose of the economy is societal wellbeing and to satisfy social needs, GDP is a poor proxy for this, a misleading long-term goal, and should be replaced by more comprehensive goals and indicators like the SDGs (Costanza et al., 2014, Kubiszewski et al., 2013, Ward et al., 2016).

For our work in general, sustainability means finding ways to organize a system where society and nature are mutually connected in a reasonable manner, and therefore a better understanding of the inherent complexity of such a system has to be gained so that we can reconsider our actions and ensure that a system will last (Editorial Nature Sustainability, 2018). In terms of considering the underlying societal and economic principles as well as accepting PB and a limited substitutability of capital, this tends towards strong sustainability. Still, when it comes to sustainability, SD and BE, related key questions arise (Ramcilovic-Suominen and Pülzl, 2018): What are the relations between humans and nature (Hopwood et al., 2005)? In the debate on sustainability and SD the relations of nature, economy and society, especially when it comes to the implications on evaluation, assessment (LCSA) and implementation, receive little attention. And too often the economic, social, political, and cultural crisis is not seen as the cause of our environmental crisis (Mebratu, 1998). And how these relations should be structured normatively (Rametsteiner et al., 2011)? Only data-driven approaches are very limited due to frequently appropriate measures are insufficient, not available or of low quality and moreover they are criticized for lacking theoretical foundations (Spaiser et al., 2017). New concepts of a sustainability science cross-system and transdisciplinary analysis answering these questions should aim at understanding interactions between nature and society, multiple facets of sustainability problems on scales from local to global, which calls for the knowledge input of different disciplinary fields (Zamagni, 2012, Zamagni et al., 2013, Anand, 2016) (cf. (Kates et al., 2001)). Positivism is only one science perspective and IAMs, and LCSAs as IAMs, should be based on a plurality of approaches (Geels et al., 2016).There is a growing consensus about the need for a new way of scientific and sustainability thinking beyond traditional dualisms (subject/object, mind/matter, nature/society, and so on) and mechanistic model, which includes natural sciences, political economy, systems theory, critical theory and cultural theory to understand system complexity like in the societal relations to nature (see section 5) (Mebratu, 1998, Görg et al., 2017).

We have shown in this chapter how basic concepts of weak sustainability, neoclassical and environmental economics as well as the three-pillar-approach implicitly define most of the perceptions of LCSA and respective shortcomings. However, there are alternatives like the integrated model of sustainability setting the basis for our LCSA framework. Before developing our framework further we want to introduce a brief discussion on BE itself, since our LCSA is tailor-made for an application in BE assessment and monitoring.

4. Bioeconomy Under Changing Paradigms

4.1. A Changing Bioeconomy Discurse

Regarding our previous considerations about neoclassical and environmental economics, BE as a knowledge-based use and valuation of biological resources for commercial and industrial purposes (Birner, 2018) can be interpreted as both: a variable production factor technology as well as (additional) natural resources to be used. Therefore, BE was mainly seen as the appropriate endogenous technology factor and immediate precursor in the neoclassical concept of SD by providing sufficient resources and using them efficiently to increase benefit and profit maximization. The notions and political BE discourses in the EU were dominated by biotechnology visions from industrial stakeholders (Bugge et al., 2016, Staffas et al., 2013), i.e., striving to increase economic growth by using bio-resources (Liobikiene et al., Hausknost et al., 2017). Our preceding discussion of economic concepts and sustainability makes clearer why there is such a technological focus on BE: in all economic concepts but especially in the still dominating neoclassical ones, innovations and backstop technologies as well as substitution play a decisive role for maintaining growth and the further accumulation of natural capital.

This led to a major environmental frame of a BE: firstly boosting the economy and secondly benefiting the environment (Kleinschmit et al., 2017). This supposed win-win idea of the BE (Kleinschmit et al., 2017), strongly corresponding to the named concepts of weak sustainability, GE and GG (Liobikiene et al.), also results in weak-sustainability environmental policy integration in BE policy goals and strategies (Kleinschmit et al., 2017). Most of the many papers discussing the role of sustainability in BE criticize the technological focus and the disregard of environmental as well as excluding society and socioeconomic effects (Gawel et al., 2019, Pfau et al., 2014, Kleinschmit et al., 2017, Dietz et al., 2018). Especially the majority of NGOs have a critical perspective on BE and see this concept mainly as a PR campaign from industrial business to green-wash their business as usual (Gerhardt, 2018). In fact, a particularly conspicuous aspect is that sustainability has been addressed regularly, but seldom defined or specified as we will approach it in this work (Pfau et al., 2014, Gawel et al., 2019). In addition to ecological risks, there are also economic and social risks result from an intensified and increasing use of biobased resources (Siebert et al., 2016) as well as their shift to other countries through imports and a competition with the production of food in terms of product and land use (Suwelack, 2016, Ashukem, 2020). A biotechnology as a high-tech sector may raise huge sustainability risks when it is upscaled to an industrial level, and will absorb large-scale biomass streams demanding significant exports and imports (Bringezu et al., 2020, Gawel et al., 2019). These aspects may be a reason for the still low public awareness or critzism of the BE (Stern et al., 2018, Mustalahti, 2018). But it is the very acceptance, sustainability and societal desirability as well as the mutual understanding, level of knowledge and engagement of stakeholders which are decisive for its success (Pyka and Prettner, 2018, Zeug et al., 2019).

Nevertheless, a climate-neutral economy will depend on these enormous material flows of sustainable and renewable biomass and their material-energetic use integrated into the system. Unique about the BE provisioning system is its inherent capacity of regeneration, allowing natural or biological resource stocks to replenish after extraction, and they are typically in constant interaction with their surrounding systems (Lindqvist et al., 2019, Zörb et al., 2018). Whereas every unit of non-renewable resources used now, is a resource which will not be available in the future and thereby comprising intra- and intergenerational equity (Parrique T., 2019, Fedrigo-Fazio et al., 2016). But the BE socio-ecological system is only renewable and sustainable if: the rate of extraction does not exceed the rate of regeneration; the regenerative capacity is not diminished by extraction, processing, and utilization of the resource; and human needs are fulfilled as well as well-being is achieved by its economy practices. In contrast to non-renewable fossil systems, these complex interactions make the management of the BE complex and require fundamentally different strategies (Lindqvist et al., 2019). The main limiting long-term factors of the BE will be the conversion efficiency of 1–2% of plants turning sunlight into carbon; and the limited areas where sun shines, sufficient water is available and plants can grow without causing negative feedbacks like accelerating forestry erosion or soil erosion. A growing BE in Europe has already led to an abrupt increase in harvested forest area since 2015 and may hamper forest-based climate mitigation if it keeps up like this (Ceccherini et al., 2020).

Thus, a transition towards a sustainable BE implies a profound re-coupling of complex social and natural systems, which requires fundamental changes not only in technologies, but also in societal, economic, cultural and political conditions (Birner, 2018). Consequently, in recent years, BE is no longer seen only as a technological vision, but increasingly as a diverse set of political and economic concepts (Peltomaa, 2018, Hausknost et al., 2017). The focus of BE has switched from substitution to additional turnover and production due to declining fossil resource prices and back again (Birner, 2018). Beyond ecological benefits, our previous research showed that addressing societal challenges and not just to substitute a resource base is a major concern of relevant stakeholders (Zeug et al., 2019). So an urgently needed innovation is not only an extension of the fossil resource base by additional products, additionally valorizing and tending towards overexploitation of the biosphere (Lewandowski et al., 2018). But to aim for innovative products, technologies and provisioning system based on renewable resources, which at least can substitute the most disadvantageous fossil production systems in the medium term (e.g. by biofuels in aviation, bioplastics, wood in construction sector), reduce environmental impacts and simultaneously fulfill human needs as an end. This does not mean that there is a contradiction between substitution and innovation. On the contrary, innovation is one of the prerequisites for substitution. Beyond economic substitution, for most of the biophysical–social indicator linkages diminishing marginal utilities were identified: from a certain degree of affluence and fulfillment of human needs every additional unit of resource use contributes less to social performance, making sufficiency an essential factor for economic sustainability (O'Neill et al., 2018). Thereby the concept of reduce, reuse and recycle can actually be put into practice in the right order, since today a reduction or sufficiency of production and consumption is often not part of political BE strategies.

Therefore and because of the global challenges to be addressed, BE is inter- and transdisciplinary researched as a societal change aiming for social, political and economic sciences to deal with the necessary transformation processes (Center for Development Research (ZEF), 2018, Schütte, 2018). The perspectives on BE have been expended to all pillars of sustainability and economic, environmental and social aspects have at least been taken into account in concepts, narratives, political strategies and assessments (Liobikiene et al., Gawel et al., 2019). A sustainable BE not only can address several global challenges (Lewandowski et al., 2018, Schütte, 2018), rather it has to, to gain long-term social and political acceptance and to become established. Such meta-discourses are significantly effecting the BE and the recent trend within the European BE policy, strategies and narratives implies that the sustainability meta-discourse should be placed in the very core of BE (Takala et al., 2019). Transitioning to a sustainable BE entails more than tapping new growth or only substituting fossil inputs by renewable resources, which means the BE concepts have to be shifted from a solely technological to a more socio-technological focus (Gawel et al., 2019). Whether the resource base of the bio-economy is sustainable is doubted and credibility and acceptance of the BE can only be achieved when the absolute environmental and social benefits of bio-based products are proven (Gawel et al., 2019). Thus, not only economic institutions, organizations, and production techniques, but rather societal structures are currently seen as a major challenge of a dynamic BE (Dietz et al., 2018, Knierim et al., 2018).

In summary the BE discourse remains highly dynamic, ranging from an early technological focus win-win BE to newer concepts of BE as a complex societal change entailing a number of contradictions (Ronzon and M’Barek, 2018, Lindqvist et al., 2019, Balkau and Bezama, 2019): unclear or implicit means and ends; economic growth leading to increasing environmental impacts vs. the ecological necessity of reducing environmental impacts (Staffas et al., 2013, Spaiser et al., 2017, El-Chichakli et al., 2016); concurrency in land and resource use between nutritive, energetic and material use (Pfau et al., 2014, van Renssen, 2014, Ashukem, 2020); short-term achievements and long-term sustainability (Griggs et al., 2013, Future Earth, 2016); regional and global effects on different scales (Kleinschmit et al., 2017, Gao and Bryan, 2017, O'Keeffe et al., 2019); trade-offs among economic, ecological and social effects; shifts to other countries and regions through in- and exports as well as re- and backfire effects.

4.2. Bioeconomy Strategies and Policies

The updated BE strategies of the EU in 2018 (European Commission, 2018) and of Germany in 2020 (BMBF and BMEL, 2020) are steps forward in the direction of a holistically sustainable BE by aligning the strategies to maximize their contribution to several of the SDGs (SDGs 2, 7, 8, 9, 11, 12, 13, 14, 15) as well as the Paris Agreement. However, still neither the German nor the European BE strategy is well defined and deep-seated, they do not entail specific actions for a real transition towards sustainability and economic issues seem to be far more important than ecological or social issues (Gawel et al., 2019). Nevertheless, there are increasingly clear ambitions by officials and ministries fostering even more holistic and systemic perspectives and solutions using the SDGs as a framework for implementation (Schütte, 2018). The question remains how politics can foster the development of a sustainable BE in first place by means of bio-based research, product subsidies, changes in regulatory frameworks or increasing societal participation an awareness for a more sustainable production and consumption (Dietz et al., 2018, Gawel et al., 2019). Conflicting goals of the BE, far beyond the original ‘food versus fuel’ debate, represent the second major challenge of a sustainable BE framework (Dietz et al., 2018). Finally, the EU’s Green New Deal strives to put decoupling, a social and economic transformation, SDGs, (regional) bio- and circular-economy, stakeholder participation, transdisciplinary research as well as social, environmental and economic sustainability at the heart of the EU’s policy making and actions from 2020 on (Commission, 2020). Applying all these aspects to economic activities in specific sectors on a local level is difficult and will always be complex and political (Fedrigo-Fazio et al., 2016, de Schutter et al., 2019), and thus leads to the need for a scientific discussion and assessment of these risks and opportunities.

In recent years a specific political focus has been set on regional BE strategies, regional development and regional assessments like LCAs and LCSAs (European Commission, 2019, de Besi and McCormick, 2015, Bezama et al., 2017, Smetana et al., 2017). Main drivers for this, especially in industrialized and urbanized countries, are fostering rural development and revitalization, the advantages of local and decentralized production in saving transportation, increasing options for reuse and recycling, flexible and local development stimulating small-scale production, as well as social benefits through local employment and a fairer distribution of incomes (Pfau et al., 2014, Siebert et al., 2018). Focusing on specific regions allows better adaptation to regional characteristics, such as feedstocks or the knowledge of local stakeholders and their networks (de Besi and McCormick, 2015, Pfau et al., 2014). A better or even starting collaboration with a variety of stakeholders can bridge the gap between science and society, and can link up with societal infrastructure and public interest (Pfau et al., 2014). Thus, new research programs on BE foster communication and participation of all stakeholders (Schütte, 2018).

Considering that critical environmental impacts are related to food and energy BE activities, the import potential for additional non-food purposes in industrialized countries is limited under previous conditions, because in low income countries those capacities fulfil fundamental human needs with substantive products and services (de Schutter et al., 2019). On the other side, as BE-related deprivations in high income countries have been identified overconsumption, degradation of globally coupled ecosystems, and growing inequalities in the rural-urban context [ibid.]. From a progressive governance perspective the BE and its development can be characterized as a typical low-carbon transition which entails not only technical changes, but also changes in consumer behavior, markets, institutions, infrastructure, business models and cultural discourses (Geels et al., 2016). Consequently, BE is a case for integrated assessment models (IAMs) like LCSAs and studies regarding the BE have to make the social and political contextual factors with respect to the choice and implementation of a technology path more explicit (Schubert et al., 2015, Geels et al., 2016).

In a nutshell, chapter 4.1 and 4.2 show that the technological options and innovations of BE are more and more seen within a vision of a societal transformation towards sustainability. This is due to the several environmental, social and economic challenges adressed by the SDGs which have to be addressed. In this regard, LCSAs are not only necessary for assessing the BE, but the BE as a research object proposes diverse methodological challenges for LCSAs.

5. A Transdisciplinary Framework of Holistic and Integrated LCSA for the BE

Not surprisingly, setting up a new LCSA framework and model of ecological, social and economic sustainability assessment for regional BE is a very complex task in view of the problems outlined above. The high expectations that are placed on a BE as a technological and social innovation that can assert itself socially and politically are: maintaining and rebuilding natural capital as well as maintain and improve the quality of life for a growing world population at the same time (El-Chichakli et al., 2016). As an overarching goal, we are arguing for an BE-framework that aims for providing “a good life for all within PB” (O’Neill et al., 2018). In the following, we address the identified problems by introducing the SDGs as a normative goal system of holistic sustainability, make principles of transdisciplinary research applicable for LCSA, introduce the Societal Relations to Nature (SRN) as a well-founded theory of holistic sustainability and present a framework of holistic and integrated LCSA (HILCSA) based on these.

5.1. Integrating SDGs as a Normative Goals System

There is a growing consensus that the SDGs are an appropriate global framework of goals and a guiding system for SD available and are increasingly becoming an overarching topic in BE strategies, policies, and assessments (e.g. (BioMonitor, 2018, Calicioglu, forthcoming)) (Zeug et al., 2019). In this context the SDG subgoals and indicators are aspired to become an international, harmonized and comprehensive set of 230 global indicators, and although many obstacles have to be overcome, good data and clear metrics are critical (Schmidt-Traub et al., 2017). Nevertheless, sustainability research should not only be about good data, but about evidence that allows practical decision making towards more sustainability (Shepherd et al., 2015, Bezama, 2018).

However, the SDGs represent a general global political agenda and cannot be applied directly to BE. They mainly contain elements of holistic SD, but are presented as separate and not fully integrated (Nilsson and Costanza, 2015), implicitly interdependent, with complex synergies, trade-offs, and contradictions also depending on regions (Nerini et al., 2019, Nilsson et al., 2016). On the one hand there are dependencies, like climate change (SDG 13) on agricultural production and thus on reduce poverty and hunger (SDG 1, 2). Climate change, in turn, has a number of further social effects on e.g. increasing gender inequality (Nerini et al., 2019). On the other hand, narrowed policies on tackling climate change can lead to adversely effects on communities and SD (Nerini et al., 2019). Accordingly, a BE transformation implies possible risks and chances regarding the SDGs, e.g. food security (SDG 2) can increase via higher yields and new production methods, but decreased by higher food prices; poverty and inequality (SDG 1, 10) can be reduced by technology transfer and leapfrogging but also increased by economic exclusion (Ashukem, 2020); natural resources (SDG 7, 14, 15) can be conserved by improved production methods and degraded through inefficient production and overuse; climate change (SDG 13) can be mitigated by emission reduction or exacerbated through direct and indirect land use changes (Dietz et al., 2018). In general, the SDGs combine policy ends with means without proposing a hierarchy (Schmidt-Traub et al., 2017) and should be implemented as a set in a simultaneous and not sequential manner (Lubchenco et al., 2015).

In this regard the SDGs serve more to identify the most important normative aspects, drivers, and hotspots and therefore need to be selected and weighted for LCSA. This is important, since most strategy papers somehow consider ecological and socioeconomic sustainability aspects of the BE, but they hardly define concrete objectives and how these will be measured (Wesseler and von Braun, 2017). On the other hand, recently it was shown that goal systems and indicator frameworks of S-LCA approaches like RESPONSA are developed in a particular context and tend to cover only a few social SDGs, but then very intensively (Jarosch et al., 2020). Nonetheless, not every SDG indicator of global relevance necessarily plays a role in regional BE assessments, even when external or international effects are considered. Most suitable an identification of relevant SDGs and aspects is a systematic stakeholder participation from the beginning, which in general can play an important role in addressing persistent societal problems in a credible, transparent, and multi-perspective way (Bezama, 2018, Gerdes et al., 2018). In specific, a poor coherence between decision makers, scientists, and stakeholders was assessed to be at the origin of regulatory failures (European Commission, 2012, Dupont-Inglis and Borg, 2018), and biotechnology was and is the subject of controversial public debates, making societal acceptance an enabling factor (Meyer, 2017, Małyska and Jacobi, 2018). In our previous study (Zeug et al., 2019) the most important SDGs for the stakeholders involved were identified and quantified by dimensionless scores of relevance in the following descending order: ending hunger (SDG 2); sustainable consumption and production (SDG 12); terrestrial ecology (SDG 15); oceanic ecology (SDG 14); water and sanitation (SDG 6); climate change (SDG 13); affordable and clean energy (SDG 7); industrialization, innovation and infrastructure (SDG 9); no poverty (SDG 1). Sometimes volatile topics of medial narratives have a strong influence, and more important aspects also came up in the discussion of the stakeholders: (a) that the concerns of stakeholders about BE-sustainability are far beyond local ecological concerns; (b) the awareness of global environmental effects, international trade-offs, and big societal challenges such as hunger, poverty, and inequality is rising, (c) but also that there are strong particular interests by business stakeholders in contrast to more universal interests by society and science stakeholder.

Nearly all of the SDGs identified as important for the BE and vice versa are SDGs developing difficultly: (SDG 1) poverty declines but the goals will not be reached; (SDG 2) hunger is rising again due to various reasons; (SDG 12) consumption and productions patterns remain unchanged at a global level, the global material footprint is rapidly growing and economic growth and natural resource use are far from being decoupled; (SDG 13, 14, 15) only marginal ecological achievements were made and in many areas like biodiversity loss, deforestation and climate change the development is alarming; (SDG 6, 7, 9) infrastructures, sanitation, water and energy are developing comparatively good (UN, 2019b). As well nearly all of the SDGs have in common that their development is highly unequally distributed around the world and thereby also defining regional risks for a developing BE to address. But also chances of SDG-aligned BE outcomes are most likely to emerge at the sub-national level of society, since a multi-sector and multi-actor perspective can support social and technical innovations of urban and rural communities (de Schutter et al., 2019, Kuhmonen and Kuhmonen, 2015).

However the SDGs themselves aren't guided by a founded theory and neither provide a understanding of societal and natural systems, nor they incorporate a narrative of transformation, nor a means-ends-continuum or an ultimate-end the goals and targets are proposed for (Nilsson and Costanza, 2015, Costanza et al., 2014). Therefore the SDGs only represent a transformative development pathway to a limited extent. More scientific approaches to the refinement of the framework are needed as well as a systematic means-ends separation between ultimate goals, to attain human wellbeing in the long term depending, and an enabling development like global public goods, resources and capital (Nilsson and Costanza, 2015). This complexity of achieving sustainability across multiple social, economic and environmental dimensions entails a series of trade-offs and synergies between targets, interventions and policies, differing between countries, spatial scales, and timeframes. Some of these trade-offs will remain independently from smart policy measures and a socio-economic system, e.g. through finite resource constraints (Gao and Bryan, 2017). Other progressive developments, like socio-economic development by health programs and government spending or the decoupling of violence and inequality, are possible without these constraints (Spaiser et al., 2017). Empirically, by means of the SDGs it was shown that there are contradictions between human well-being and nature as PB, which can only be solved by global transformations (UN, 2019a). For our development and application of an HILCSA framework, the SDGs mainly set a comparable and legitimated normative holistic goal system and impact categories with additional possibilities in future data acquisition.

5.2. Transdisciplinary as a Consequence of Research on Sustainability

The need for a transdisciplinary sustainability science aiming at understanding interactions between nature and society has often been stated in the literature, but rarely substantiated or implemented (Pfau et al., 2014, Future Earth, 2016). One reason for this is that transdisciplinarity is a necessary consequence rather than a founding principle of such approaches like in sustainability sciences (Rhyner, 2016, Bettencourt and Kaur, 2011). A lot of knowledge and evidence of relationships (e.g. between SD and climate action) are scattered across different institutions, locations and disciplines, and this fragmentation is a critical barrier to a holistic and integrated understanding of the social–environmental systems embodied in the SDGs (Nerini et al., 2019, Knierim et al., 2018). The methods and findings of different scientific disciplines are oftentimes very rational, competent and innovative within their respective fields of expertise, but neglect or contradict insights from other disciplines (Demirovic, 2003). We understand interdisciplinarity as an interchange and dialogue between disciplines, whereas transdisciplinarity aims for integration: an inherent contextualization and embedding findings within a greater context creating transcending insights (Klein, 2008, Knierim et al., 2018, Lubchenco et al., 2015). Real-world problems are the starting point of transdisciplinary research, to gain a better understanding of social-ecological problems and contribute to their solution is the research objective (Kramm et al., 2017, Jahn et al., 2012). Of course modern science is much too complex to be covered by one person and so transdisciplinary practice means at least to work together, recognize each other and involve stakeholders to develop novel conceptual and methodological frameworks with the potential to produce transcendent theoretical and practical approaches (Hummel et al., 2017, Klein, 2008, Rosenfield, 1992). The resulting methodological pluralism, can lead to more consistencies and less bias (Lamont et al., 2006). In recent years often used is the term of “socio-economic” systems or problems, which is a good example for transdisciplinarity: the attributes ‘social' and ‘economic' do not describe separate objects of scientific observation, but rather different perspectives on the same objects, whereas a socio-economic approach describes the integration of both perspectives when looking at this object. And it is of specific importance for LCAs and LCSA, since companies are not just producers of commodities and services, they are also the fundamental social place, where employment is organized, employees are being integrated into a social structure, and where individuals are connected with the labor market and systems of social security (soeb.de, 2020).

In the case of presenting a framework for holistic sustainability assessments with a systematic view on a developing regional BE, transdisciplinarity means to understand a seemingly ecological project or research question as a simultaneously political-economic project and research question and vice versa. Consequentially, ecological arguments can never be neutral any more than sociopolitical arguments are ecologically neutral (Harvey and Braun, 1996). This means for achieving a sustainable transition to a BE, there is not only a need to transform so called societal and industrial mind-sets, and not only a question of a few ‘tweaks’ to the system, but rather it is a question of transformations of our very fundamental societal relations to nature (SRN) (de Besi and McCormick, 2015, Kramm et al., 2017). Different means, ends, and values seem to be the guiding factors in what we have understood as conflicting interests and perceptions in BE assessments (Zeug et al., 2019). Simply setting ambitious goals, but ignoring ideologies, religious beliefs and institutions, including formal and informal rules and customs will not be sufficient (Norström, 2013). Since only technological fixes, a solely focus on industrial efficiency or simply replace fossil resources with biomass are in danger of maintaining the same production and consumption system as the fossil-based economy (de Besi and McCormick, 2015). Such insights go back to the early interdisciplinary materialism, later critical theory and social ecology and are applied in the concept of SRN. They reveal that there is no non-normative science; if there is no explicit scientific value judgement there is an implicit social value judgment confirming the status quo (Kramm et al., 2017, Hummel et al., 2017, Amidon, 2008). Regarding the IAMs of low-carbon transition, the following framework approach is still using post-positivist methods of modelling, but embeds them into a relativism and postmodernism philosophy of science, and thereby combines the strengths of quantitative systems modelling, socio-technical analysis and initiative-based learning by stakeholder participation. A combination of all three approaches is not trivial, but is most promising for IAMS of transitions (Geels et al., 2016). Transdisciplinarity is therefore necessary to achieve a proper integration of methods in an LCSA.

5.3. Societal Relations to Nature as a Founded Theory

As shown in section 3.1, none of the dualistic approaches alone is sufficient, neither anthropocentric nor ecocentric, neither weak nor strong sustainability, and especially not the dominant and reductionist model of sustainability. But rather the integrated model and a corresponding holistic thinking based on the interactions and relations between the parts and the whole. Therefore, we take up the concept of SRN towards a holistic LCSA of the BE. In SRN nature, economy and society do not stand in an external relation to each other nor do they exist by themselves as the three-pillar approach suggests, rather, they constitute each other through their relations (Kramm et al., 2017, Hummel et al., 2017, Görg et al., 2017, Görg, 2003): The SRN concept at its core evolves around the idea of basic human needs and SRN should be regulated to satisfy them. Thus, SRN is not only complementary and a well-founded theory for the SDGs, but also incorporates the concept of provisioning systems, justice (Menton et al., 2020), equity, and SD. Social ecology and SRN conceptualizes human societies as simultaneously subject to biophysical and socio-cultural spheres of causation in a social metabolism. Nature and society are different things, and although distinct, not independent from one another. Social metabolisms transform a society’s energetic and material inputs, integrate them into societal stocks or to other socio-economic systems, and discharge them to the environment as wastes and emissions. Industrial and BE metabolisms are special cases of social metabolisms. In well-established methods like economy-wide material and energy flow accounts (EW-MFA) societal metabolisms at the European level have been quantified and measured. However, this societal metabolism has no essential or eternal nature, especially not in the Anthropocene (Pichler et al., 2017). Instead historically, geographically and culturally specific socio-cultural mechanisms like politics and economic patterns are in place through which a society organizes its metabolism. This is decisive for SRN, not the sum of individual needs.

These mechanisms are understood as patterns of regulation, and of course can fail when interactions with nature become dysfunctional, e.g. overexploitation of natural resources (overfishing, deforestation, soil degradation) or failure of a mechanism for cost-efficient provision (hunger, poverty). Although there is the idea of being able to dominate nature, and nature is in fact increasingly shaped by human activities, it is becoming increasingly clear that global societies are significantly affected by environmental impacts and crisis trends. Albeit, in unequal measure in the Global South and the Global North. It doesn't apply to all SRN, but the dominant mode is the imperative of capital accumulation, growth and the predominance of the production of surplus values over the production of use values, whereby the production of surplus values goes hand in hand with the valorization and overexploitation of its capital (nature and humans). Transformations take place as changes of initial patterns of regulation to new ones when the old ones become dysfunctional. The SDGs can be interpreted as the attempt to initiate such social-ecological transformations. The role of power relations in enabling and maintaining unsustainable resource use patterns, the role of social-ecological innovations within transformation processes and transregional interdependencies have been identified as emerging clusters of challenges in societal metabolism. For example, technological inventions must go hand in hand with social, economic and organizational innovations, and questions of scale arise in the field of tensions between a global socio-ecological crisis and the responsibility and scope for action at local and regional level. Therefore, the view of a separation of LCSA and global macroeconomic-political problems as in the additional LCSA approach is criticized.

In terms of scales SRN have three different spatial and temporal levels which correspond to the scales and scope of BE assessments (Figure 1): the micro level of individual actions; the meso level of organizations and institutions (provisioning systems); and the macro level of societal powerful patterns of regulation. In our case of BE we focus on the meso level of provisioning systems, which link natural objects (e.g. forests) to the societal realms of action and decision-making via the utilization of resources. Putting SRN into research practice means to identify a case consisting of an issue and a problem. Here the issue is a developing regional BE having social and ecological effects. The problem is that there are risks and chances of such a BE for implementing the SDGs. Finally, the scientific goal is to decontextualize or generalize the case knowledge produced to make conclusions for solving a problem of an issue. Progress has been made in recent years to empirically and quantitatively describe socioeconomic metabolisms by EW-MEFA on the macro scale, also for addressing decoupling problems (Haberl et al., 2017). Although, on the meso scale (e.g. through LCAs) the concept of SRN and socioeconomic metabolisms has not been applied so far. Besides absolute global PB, there are also regionally specific local boundaries (e.g. biodiversity, land-use changes). For such a relation of local boundaries with holistic regional sustainability framework and LCSAs, the concept of ecosystem services (ES) in context of SRN and social ecology is promising.

ES concepts are neither about ecosystems nor about societal goods and human wellbeing solely, but about the interdependencies between human wellbeing (benefits) and nature when ‘natural ecosystems’ are transformed into human-modified cultural landscapes by human interventions (labor, technology). Additionally, ES are also open for stakeholder participation and finding these regional boundaries through non-monetary evaluations. On a regional scale transdisciplinary approaches offer new possibilities of deliberative methods to find normative constellations of human needs by stakeholder participation (e.g. interviews and discussions). On the contrary, solely monetary approaches or the search for a big number have failed (e.g. TEEB (Tisdell, 2015)). This is because goods or services have a use value when they fit human needs and create a benefit depending on specific cultural value systems. Monetary exchange values in capitalist societies, however, are governed by exchange relations on global markets. And thus, tend to ignore the relevance of regional ecosystems and nature for the actual benefits they provide. Both values use and can overuse resources, but monetary or exchange values tend to ignore the biophysical requirements of ecosystems categorically (Schleyer et al., 2017). Common to both values, and especially important for HILCSA, is that working hours are the critical functional variable in the production processes of provisioning systems, which not only produces values but also relates social effects to productions processes (Fröhlich, 2009).

In this regard a good example of SRN and patterns of regulation which are behind the SDGs is the apparent connection between ending poverty (SDG 1) and ending hunger (SDG 2), both considered by stakeholders as very relevant for the BE (Zeug et al., 2019). In this case, even if enough food is produced worldwide to end hunger, the pattern of regulation of our provisioning system requires ending poverty first. Since in the current economic system human needs alone (use value), sufficient resources and means do not lead to their fulfillment, as long as those needs and preconditions are not coupled with enough purchasing power and income (exchange and surplus value). The same is true for the fuel vs food debate in BE: land or crops will be used for the purpose with the highest expected surplus value like fuels, instead of the fulfillment of more basic human needs with a higher use value like nutrition (cf. (Ashukem, 2020)). Beyond that, SRN include socioeconomic relations like the decoupling between a significantly increasing labor productivity and economic material output through automatization and digitalization, but a stagnation and even falling of GDP per capita, private employment and even more so in income and inequality, especially in affluent and industrialized countries (Brynjolfsson and Andrew, 2015). But also globally the labor’s share of GDP had declined since there is a tendency towards higher capital productivity in capital than in labor and so shifting the investments from labor to capital (Karabarbounis and Neiman, 2013). When a growing economic production and material output is not decoupled from its ecological impacts, but income and affluence is decoupled from this very production, then a good life for all within PB will be hard to achieve when income is a prerequisite for achieving nearly all social thresholds.

For our purposes the SDGs represent a limited number of universal and satiable human needs as well as their means (Figure 5). The fulfilment of such needs provides conditions for wellbeing in the broader context of society, and if unsatisfied should be understood as deprivations (de Schutter et al., 2019). Consequently, as for every economy, the end of the BE should be the fulfillment of human needs. Earlier, it was argued for putting human needs and well-being in the center of LCSA, but from an anthropocentric viewpoint with rather conceptual ideas (Schaubroeck and Rugani, 2017, Schaubroeck, 2018). However, in our framework of LCSA based on SRN, social sustainability means the fulfillment of human needs as the end and ultimate goal of an ecological sustainable BE within planetary boundaries, which also implies the transformation of patterns of regulation and SRN.

5.4. A Background Framework for Holistic Life Cycle Sustainability Assessments

We identified the three pillar approach (section 2.2) and the underlying dominant reductionist model of interlinked systems (section 3.2) as inappropriate for an integrated and holistic LCSA as well as a cause of major methodological problems. Instead, first, we propose an integrated sustainability framework filling the identified research gap of a missing framework for HILCSA (Figure 4, i)). Second, in contrast to the additive LCSA (LCSA = S-LCA + E-LCA + LCC), our HILCSA (HLCSA = f (S-LCA, E-LCA, LCC)) framework for operationalization will build on this integrated sustainability framework and integrates social, economic and ecological aspects in a common goal and scope, life cycle inventory, impact assessment, results and interpretation (Figure 4, ii)).

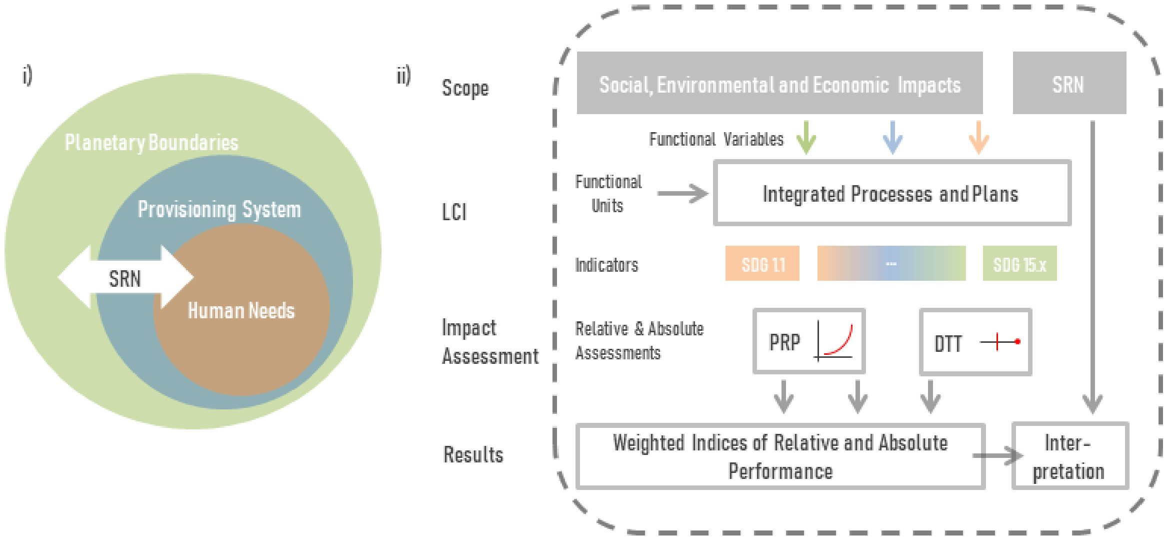

Figure 4, i) The integrated model of holistic sustainability in LCSA based on the SRN, ii) Holistic and integrative scheme of HILCSA (HILCSA=f(S-LCA,E-LCA,LCC)) based on i) (SRN - Societal Relations to Nature, PRP – Relative method of impact assessment by Performance Reference Points, DTT – Absolute method of impact assessment by Distance To Target, LCI – Life Cycle Inventory)

In the following, we mainly discuss the integrated sustainability framework based on our reflection on sustainability concepts, the SDGs and transdisciplinary application of the SRN (Figure 5).

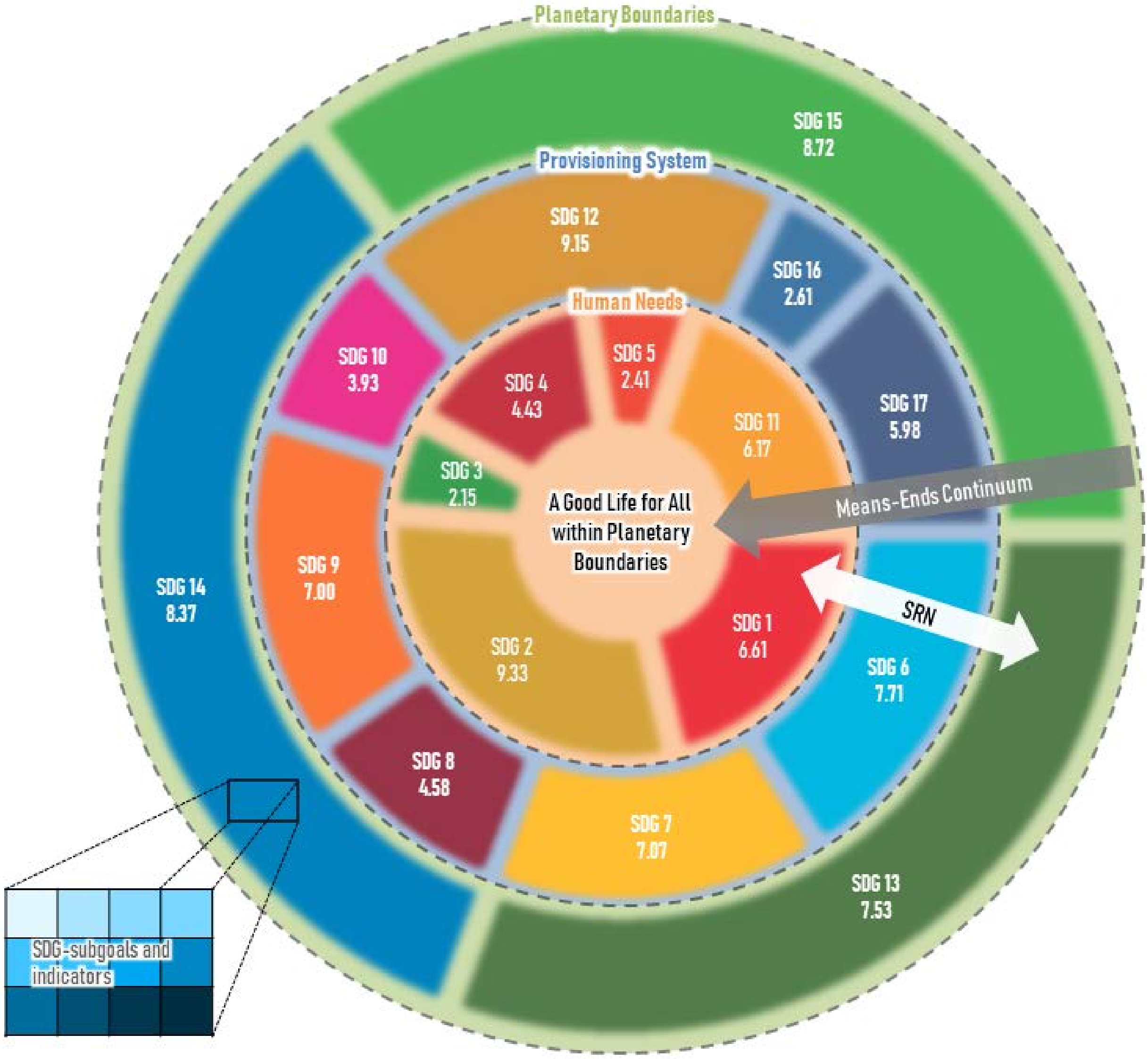

Figure 5, Holistic sustainability framework for HILCSA of the BE (SDGs are viewed with their relevance for German BE assessments from (Zeug et al., 2019) and according size, for each SDGs the SDG-subgoals and indicators as well as their relevance is taken from (Zeug et al., 2019))

We understand the BE as an open or semi-open provisioning system of a social metabolism on the meso-level of SRN. Its function is to link social outcomes and renewable resource use by innovative technologies. BE comprises both physical and social systems, mediating the relationship between biophysical and social thresholds by economic networks of physical infrastructure. Besides political governance and the influence of stakeholders (science, organizations and corporations, NGOs, producers, consumers, local and global communities) on different levels, these relations are structured by markets as exchange platforms and as dominating pattern of regulation (in the current economy system of surplus and exchange values). Economic quality in this regard is understood as the relative and absolute efficiency, sufficiency and effectiveness of linking social and biophysical systems, which overall means to meet most of the social goals and thresholds with the lowest resource use possible (O'Neill et al., 2018) A sustainable regional bioeconomy should aim at the provisioning of a good life for all within global PB and regional boundaries. Hence, it corresponds strongly to the "Planned Transition" techno-political vision of BE (Hausknost et al., 2017). This means that on the one hand advanced technologies on a large-scale industrial level (integrated biorefineries, cascade use, eco-functional intensification of certain agricultural sectors, global trade in certain biogenic commodities, use of high-tech biotechnologies) will be needed to achieve the very ambitious demands on resource efficiency (Olsson et al., 2016, Nitzsche et al., 2016, Aguilar et al., 2018, Panoutsou et al., 2013). On the other hand, further growth and capital accumulation is not a necessary sustainable goal of the BE. Rather, not transgressing the PBs and fulfilling essential human needs and the SDGs (especially SDGs 1, 2, 7, 11 &12) are.

In specific, the characteristics of and relations between concrete aspects represented by SDG sub-goals and indicators will be analyzed and described for the application in our upcoming research on a regional HILCSA model. Due to the complex interactions, there can be no truly clean analytical distinction (de Schutter et al., 2019), but certain SDGs can be assigned to the following relations: the more efficient fulfillment of human needs as the end of a sustainable BE and all efforts are placed in the center (SDG 1, 2, 3, 4, 5, 11); BE and economy as a social activity and provisioning systems represents the societal means (technologies, infrastructures) which fulfill human needs by natural resources within PB, it relates social and natural systems (SDG 6, 7, 8, 9, 10, 12); the natural system as stock of renewable resources and their regeneration are placed as the limiting PB (SDG 13, 14, 15); institutions of the patterns of regulation are part of the provisioning system (SDG 16, 17). These relations represent the missing means-ends-continuum. The relevance which each of the SDGs has for the measurement and assessment of regional BE in Germany, in this case for HILCSAs, was evaluated by our previous stakeholder participation (Zeug et al., 2019) and is presented in section 5.1. In Figure 5 different relevances are represented by the different size of the SDGs relative to the other SDGs within the according social, economic or natural system (Appendix A).

This framework also makes clearer what can actually be understood by holistic and social environmental and economic sustainability:

- Social sustainability is the long-term and global fulfillment of human needs and social well-being as an end
- Ecological sustainability is the long-term stability of our environment as a basis of reproduction within planetary boundaries
- Economic sustainability stands for technologies and economic structures which are efficient, effective and just provisioning systems relating human needs and environment

Goal and scope of our HILCSA is to assess the social, environmental and economic risks and chances of a regional BE, its contributions to the SDGs and a sustainability transformation. Therefore a holistic scope and understanding is given by the SRN. Our focus is also on the comparison of bio-economy products made from renewable raw materials such as wood with other products. Regarding the LCI, the operational core of our model are integrated processes and plans of regional BE value chains and provisioning systems implemented in openLCA software environment. We will lay out the actual implementation and operationalization of our HILCSA in detail future publications. In this LCI, the relevancies of the SDG sub-goals determine the weightings of a future set of impact categories and indicators. At the first stage in a holistic assessment the indicator set will not be as detailed as in the stand alone methods, rather the goal is to avoid a piecemeal approach to SD (Taylor et al., 2017) and to deliver a holistic picture on trade-offs, synergies, hotspots, significant risks and chances and a fundamental understanding. The impact assessments will incoporate two types: relative performance of a particular BE system in relation to a fossil reference system (PRP); and the absolute benchmarking of a particular BE system against the SDGs and PBs (DTT). In contrast to the previous LCSA methods, where the separate and different results are at the end additively combined by MCDA, our SDG oriented HILCSA uses the relevancies of SDG sub-goals given by stakeholders as exogenous weightings of indices on different levels of aggregation according to the SDG framework. Decisive for the generation of indices in a systematic-interactionist approach like ours, but above all for the interpretation of those quantitative results is a comprehensive and well-founded theory of sustainability and a sustainable BE, which we provided in this work.

6. Conclusions and Outlook

Taking up the decoupling problem as a starting point of our consideration of BE and its assessment shows the need and potential of a sustainable BE for decoupling human well-being from environmental impacts to avoid a social and ecological crisis. Some nations show the ability of achieving the social thresholds at a much lower level of resource use, and give a sense of the possibility space for achieving the social thresholds within PB (O'Neill et al., 2018). However, considered all together, the decoupling hypothesis appears highly compromised, if not clearly unrealistic in a business as usual scenario (Parrique T., 2019). To strive for gains in technological efficiency is absolutely necessary, but alone not sufficient anymore and as well a societal change entailing the BE is necessary. Traditional additive LCSA approaches are valuable, but face major methodological and practical problems for assessing the BE. On the other hand, the SDGs can provide progressive measurable and normative targets and objectives for BE assessments, as well as transdisciplinary and well-founded theories like SRN consider human needs, provisioning systems and ecological boundaries not as separate entities, but rather as facets of one and the same object; the social industrial metabolism. This sets the basis and locks up potential for a holistic and integrative framework of HILCSA with a common scope, goal, LCI, functional units and variables, impact assessment and interpretation, which we will implement in forthcoming research. In the last step of interpretation, those results can be put in context to an ideal or desirable BE and the contribution of a regional BE for implementing the SDGs, risks, chances, synergies and trade-offs can be described. With special regard to a regional BE this can help to bridge the gap between science, society, politics and economic actors in public interest. Thereby we embed positivist methods of science into a relativist and postmodernist philosophy of science, which enables us to combine the strengths of quantitative systems modelling, socio-technical analysis and stakeholder-based learning. Applying the SDGs or absolute goals as PB in LCA, however, goes beyond established approaches and brings up methodical transdisciplinary challenges we will address in our upcoming research. Relative (PRP) as well as absolute (DTT) methods of impact assessment are proposed to allow results for comparing provisioning systems as well as to assess if a provisioning system is efficient enough for PB. As an indicator set the SDG indicators and Dashboards provide not only a harmonized basis for also consider trans-regional aspects but an ever improving data basis. A challenge will be that private industrial actors in a capitalist market have an intrinsic interest in capital accumulation and increasing output, and by themselves will not embark to the SDGs or PB. States are therefore the only entities able to provide the organizational and planning capacity by political coordination necessary for this transition (Hausknost et al., 2017). Corporations are still key actors, but guided by societal rules and strategies. For this, however, a necessary change of patterns of regulation is necessary in a way that states themselves are not depending on abstract economic growth, which has been identified by stakeholders as a relatively minor objective (Zeug et al., 2019).

However, the overall possibilities of achieving sustainability by BE are limited as long as sustainability is not a central objective of the general economy and its patterns of regulation itself. If the concept of a sustainable BE as a solution for global challenges is put at risk, a lot is at stake, because there will be no alternatives other than BE to produce the needed material goods from renewable instead of fossil resources.

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Appendix A

Table A1, SDG Sub-Goals and their relevances allocated to the human needs, provisioning system and planetary boundaries. Since the SDG subgoals are only to be understood in the SRN, this assignment is not distinct. The relevance factor (R) is used in a HILCSA as a weighting factor for the corresponding indicators.

Human Needs			Provisioning System			Planetary Boundaries		
SDG Code	SDG Sub-Goal	R	SDG Code	SDG Sub-Goal	R	SDG Code	SDG Sub-Goal	R
1.1	Eliminate extreme poverty, pay equity	6.94	6.1	Access to affordable drinking water, food security	8.61	13.1	Emergency plans	4.17
1.2	Poverty reduction, pay equity	6.94	6.2	Sanitation / hygiene	4.44	13.2	Climate protection measures, politics, strategies, planning	8.89
1.4	Enable economic participation for all people	6.94	6.3	Increase water quality, pollution / chemicals, sewage / reprocessing	8.33	13.3	Education and awareness about climate protection	4.44
1.5	Increase resistance of population against extreme climate events	6.11	6.4	Efficient water use of all sectors	7.22	13.a	Financing of climate protection measures in developing countries	6.94
1.a	Financial support / development aid, eradication of poverty	5.56	6.5	Integrated management of water resources	5.56	13.b	Development of management capacities, climate protection measures	6.94
2.1	Food access, food security	8.89	6.6	Protection of all water-related ecosystems	8.89	14.1	Reduce marine pollution, marine litter / nutrient pollution	8.33
2.2	End malnutrition, food security	8.61	6.a	Capacity building for wastewater treatment / reprocessing	4.17	14.2	Sustainable management of coastal ecosystems	5.83
2.3	Increase agricultural productivity, income (small producers)	6.39	6.b	Improvement of water management, sanitation	5.56	14.3	Reduce acidification of the oceans	6.94
2.4	Sustainable systems in food production (resilience)	8.61	7.1	Access affordable, modern energy services	6.94	14.4	Overfishing / management plans	8.33

2.5	Preserve genetic diversity of seeds / plants / animals	8.33	7.2	Increase share of renewable energies, energy mix	5.56	14.5	Preserve coastal and marine areas	8.33
2.a	Investment in rural infrastructure, agricultural research and consulting	8.61	7.3	Double rate of increase of energy efficiency	5.83	14.6	Prohibit fishing subsidies	5.56
2.b	Trade restrictions, - prevent distortions, stop agricultural export subsidies	4.44	7.a	Access to research and technology, renewable energy	6.94	14.7	Sustainable management of fisheries, aquaculture, tourism	8.33
2.c	Stability food market, fluctuations of food prices, reserves	8.33	7.b	Infrastructure development, modern energy services	6.94	14.a	Scientific cooperation, transfer of marine technologies / research capacities	6.94
3.9	Reduce pollution of air/water/ soil, health protection	8.61	8.2	Econ. productivity increase through diversification	3.33	14.c	Access small-scale marine resources / markets	6.94
4.1	Equal access / free education from elementary schools on (girls / boys)	3.33	8.3	Promoting decent work, innovation, creativity, SMEs	8.61	14.b	Conservation / sustainable use of oceans, convention on the law of the sea	4.17
4.2	Equal access / free education from preschool / kindergarten on (girls / boys)	3.33	8.4	Resource efficiency in consumption / production	5.83	15.1	Preservation / sustainable use of terrestrial and inland freshwater ecosystems	7.50
4.3	Promote gender equality	6.11	8.5	Productive full employment, decent work, pay equity	3.06	15.2	Sustainable forest management / reforestation	8.61
4.5	Gender disparities (parity indices)	5.56	8.6	Increase share of youth employment, education and vocational training	4.72	15.3	Combat desertification, area remediation	6.94
4.7	Education for sustainable development	8.61	8.8	Worker rights, labor protection rights, promoting safe work environment	0.00	15.4	Conserving mountain ecosystems / biodiversity	7.50
4.b	Increase number of scholarships	4.17	8.7	Worker rights, abolition of forced	5.00	15.5	Protecting natural habitats, threatened	8.33

				labor / trafficking / child labor			species, biodiversity	
5.1	Eliminate discrimination against women	5.83	8.10	Promote national financial institutions for financial infrastructure	6.94	15.6	Just use / access to benefits of genetic resources	6.94
5.a	Financial equality, legal framework for women (e.g. pension, real estate)	3.89	8.a	Support developing countries / technical assistance	5.83	15.7	Combat poaching / trade of protected plants	4.17
11.2	Infrastructure / traffic system	4.44	9.1	Resilient infrastructure	5.56	15.8	Prevent invasive species	7.22
11.3	Sustainable urbanization	7.50	9.2	Sustainable industrialization	5.83	15.9	Aichi biodiversity targets, ecosystem and biodiversity values	8.89
11.4	Protection of world cultural and natural heritage	5.56	9.3	Access financial services SMEs	6.94	15.a	Conservation, sustainable use, biodiversity, ecosystems	8.61
11.6	Reduce urban environmental impacts, air quality, waste treatment	9.17	9.4	Sustainable renewal of industrial infrastructures	8.33	15.b	Forest conservation / reforestation	8.61
11.a	Regional development planning, linkage of urban and rural areas	7.78	9.5	Strengthen / promote scientific research in developing countries	5.83	15.c	Combating poaching / wildlife trade	3.89
11.b	Urban planning of resource efficiency / mitigation of climate change	6.94	9.b	Support local technology development in developing countries	5.56			
11.c	Support sustainable construction, local materials)	7.22	9.c	Access to information and communication technology	5.83			
			10.1	Income growth	5.83			
			10.5	Regulation / supervision of global financial markets	3.33			
			10.6	Improvement of representation / participation of	7.50			

	developing countries	
10.a	Justice, treatment of developing countries	4.72
10.b	Efficient and effective development assistance / financial flows / direct investment	7.22
12.1	Sustainable consumption and production patterns	7.50
12.2	Sustainable management of natural resources	8.89
12.3	Food waste / losses, post-harvest losses, resource efficiency	8.61
12.4	Environmentally friendly handling of chemicals and waste	8.61
12.5	Reduction of waste generation (prevention, reduction, recycling and reuse)	9.17
12.6	Reporting on sustainability information	8.61
12.7	Sustainable public procurement	5.28
12.8	Information for consciousness about sustainable development	8.33
12.a	Strengthen research on sustainable production / consumption	8.89

12.b	Monitoring sustainable tourism	5.56
12.c	Abolish fossil fuel subsidies	5.83
16.5	Reduction of bribery / corruption	7.22
16.7	Democratic decision-making	5.56
17.1	Mobilizing local resources, taxes and duties	8.33
17.2	Compliance pledges financial assistance	6.94
17.3	Financial and technical cooperation	6.94
17.4	Reduction of over-indebtedness / external debt	8.89
17.6	North-south / south-south / triangular cooperation	8.33
17.7	Diffusion of environmentally sound technologies	6.94
17.11	Increase exports of developing countries	5.56
17.13	Global macroeconomic stability	7.22
17.14	Policy coherence in sustainable development	5.56
17.15	Political scope regarding poverty elimination	4.44
17.18	Capacity expansion in data collection	8.33
17.19	Measurement of sustainable development	4.17

Chapter 8

Life Cycle Sustainability Assessment for Sustainable Bioeconomy, Societal-Ecological Transformation and Beyond

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Abstract.
Decoupling the fulfillment of societal needs from an ever-increasing production of goods together with decoupling this sufficient production from negative environmental, social and economic impacts, is and will be the major challenge of our economic systems to avoid an even deeper socio-ecological crisis. The ascending bioeconomy practices have to be assessed with regard to their potential to provide a good life for all within planetary boundaries Addressing this, life cycle sustainability assessment (LCSA) is necessary to integrate social, environmental and economic sustainability assessments. However, LCSAs are still in their infancy and a series of practical problems can be traced back to a lack of sound sustainability concepts and applied political economy/ecology. We reflect on social, ecological and economic sustainability, our societal relations to nature and a necessary societal-ecological transformation in order to structure a systemic framework for holistic and integrated LCSA(HILCSA). This framework allows an implementation in openLCA, conducting the inventory and impact assessment with harmonized databases and more coherent results compared to previous approaches. For further development we identify questions of political economy/ecology as significant. The idea of a bioeconomy as well as systemic assessments is a question of the perception of ends and means of a societal transformation.

Keywords: life cycle sustainability assessment, bioeconomy, political economy, decoupling

8.1 Preliminary Considerations on Implicitly Underlying Concepts

8.1.1 Sustainability Concepts and (Bio)Economy Under Different Paradigms of Capital

The ecological challenges our global societies face are not only related to climate change, as it is likely that humanity is about to cross several planetary boundaries (PB) - representing the ecological limits of our planet – with feedbacks difficult to handle and partly irreversible (O'Neill et al. 2018; Rockström et al. 2009; Steffen et al. 2018). Practically no country performs well on both the biophysical and social dimensions, being the general rule that when the more social needs are achieved, the more biophysical boundaries are transgressed, and vice versa (O'Neill et al. 2018). For example, Germany's environmental footprint is 3.3 times higher than its biocapacity (Bringezu et al. 2020; GFN 2019; Network 2019; Schaefer et al. 2006). Fulfillment of societal needs is seemingly directly coupled with transgressing PB (Haberl et al. 2012; O'Neill et al. 2018).

As one way to address these challenges more than 50 countries worldwide have now developed bioeconomy (BE) related policy strategies (Bell et al. 2018; German Bioeconomy Council 2018b; Kleinschmit et al. 2017; Meyer 2017) to achieve sustainable development, depending on how this is understood in the respective strategies. BE is broadly understood as "the production of renewable biological resources and the conversion of these resources, residues, by-products and side streams into value added products, such as food, feed, bio-based products, services and bioenergy" "within the framework of a sustainable economy" (German Bioeconomy Council 2018a). However, there is and most probably will be no unified definition of BE (Birner 2018), since different and partly contradicting interest groups (Bioökonomierat 2022; Meyer 2017; OECD 2018) and diverse social mentalities result in conflicts (Eversberg and Fritz 2022; Zeug et al. 2019), e.g. bioeconomy as a technological solution to enable further growth in 'green capitalism' vs. bioeconomy as a socio-ecological transformation. Nevertheless, a common approach can be to see BE as part of a social-ecological transformation to address global challenges of the 21st century (Bioökonomierat 2022).

Sustainability as a state, or more precisely sustainable development (SD) as a process, is often attributed to meeting the needs of the present without compromising the ability of meeting needs in the future (Brundtland et al. 1987). Economic growth to reduce poverty was the specific sense of a solution conferred to, and, in doing so, to create the wealth, technology and commitment necessary to reduce ecological damage. The terms SD and sustainability are often used synonymously, although SD is based on a dualist anthropocentric view that humankind has a special and almost detached relationship with nature and is only interested in the instrumental or utilitarian value attached to an ecosystem (shallow ecology). Resources should be managed to be available for future generations, natural and human capital are interchangeable and nature should be cared about only to the extent considered as human interests (Hector et al. 2014). This results in a dualism of humankind and nature with a clear hierarchical order that humankind rules over nature (Görg 2004). On the other hand, (strong) sustainability strives for some form of dynamic equilibrium in which the needs of humankind and the needs of nature are both satisfied. In a broader notion of environmental-preservationist this means that the natural world ought to be preserved and must not be allowed to deteriorate, disappear or be dominated by humans (deep ecology). Here humanity is an integral part of nature, not separated from it, and nature has an intrinsic value (Hector et al. 2014; Mebratu 1998). This polarized constellation of anthropocentric (weak sustainability, shallow ecology, SD) and ecocentric (strong sustainability, deep ecology) views is an epistemological trap: the two positions are permanently irreconcilable and based on different self-evident axioms (Hector et al. 2014) (Zeug et al. 2020) (Table 8.1).

Tab. 8.1. Contents of popular sustainability concepts (Hector et al. 2014; Hopwood et al. 2005; Mebratu 1998; Ramcilovic-Suominen and Pülzl 2018)

Keywords	Shallow Ecology Weak sustainability Prudentially-conservationist Anthropocentric Sustainable development	Deep Ecology Strong sustainability Environmental-preservationist Ecocentric Sustainability
Content	Humanity with specific relation towards nature, instrumental value of ecosystems, positivist view, mechanistic systematization, substitutability of capitals, objective: economic sustainable development	Humanity as integral part of nature, intrinsic value of ecosystems, monist and morally egalitarian view, preservation of nature and non-substitutability, objective: sustainable equilibrium

These discourses, mostly implicitly, shape understandings of (bio-)economy and sustainability assessment methods today: On the one hand, neoclassical environmental economics are associated with weak sustainability because they clearly possess an anthropocentric concept of SD, characterized by ‘benefit and welfare’, which in capitalism is synonymous with profit maximization. It is assumed that natural capital can be substituted with artificial capital, the environment is frequently undervalued, tends to be overused and if the environment only were given its ‘proper value’ in economic decision-making terms, it would also be protected much more highly (Hector et al. 2014; Mebratu 1998; Redclift and Benton 1994). But even within neoclassical models, this constant substitutability of capital stocks, the timely availability of innovations and backstop technologies (enable the use of resources for an indefinitely long time) like BE allow the assumption of non-existent growth limits, without depleting non-renewable and overuse renewable resources (Bennich and Belyazid 2017; Smulders 1995). Thus, unlimited economic growth is only possible if enough human capital is allocated to R&D to sufficiently increase the necessary efficiency of resource use without necessitating fundamental changes (Barbier 1999; Michel and Rotillon 1995; Perdomo Echenique et al. 2022; Verdier 1995; Victor et al. 1994). This points to why there is such a mainly technological focus on BE and in most sustainability assessments. With that come conceptual and methodological shortcomings: tending to overlook or deliberately reject the relevance of non-human species, tending to be mechanistic and reductionist about society, ecology and economics (Hector et al. 2014). Consequentially, sustainability assessments not only tend to treat environmental problems without tackling the underlying causes and assumptions that underlie our current political and economic thinking (Mebratu 1998), but also to see social, environmental as economic aspects and sustainability as rather detached from each other. As a result, approaches develop which are non-integrative and additive that entail explicit or implicit positivism. From a positivistic perspective, reality is seen as independent, objective, empirical and measurable; there are general laws between variables representable by mathematics; methods are model simulations, manipulation of variables and quantitative data; and governance or policymakers 'outside' the system have to pull 'levers' to steer developments.

On the other hand, there is an interdisciplinary and more qualitative concept of ecological economics tending towards strong sustainability (Georgescu-Roegen 1971). In this time and context of ecological economics the term 'bioeconomics' occurred for the first time, but had a completely other meaning than the current term of BE (Birner 2018): the earth is seen as a closed system in which the economy is a subsystem and, therefore, there are limits to resource extraction; a sustainable society-wide system with a high quality of life of all inhabitants within the natural limits is sought; complex systems are of great uncertainties and require a preventative approach; a fair distribution and an efficient allocation are necessary (Costanza et al. 1997; Hauff and Jörg 2013). In terms of sustainability assessment, a consequence is to consider PB as absolute limits of resource extraction. In contrast to pursuing individual gain, benefit and profit maximization, the ecological economy is strengthening the importance of ecological systems for the safeguarding or improvement of societal conditions. In other words, it is about the welfare of the whole society (Hauff and Jörg 2013). In particular, the assumption of substitutability of natural and artificial capital is called into question, since human capital is needed to make efficient use of natural capital, and natural capital is needed to generate anthropogenic capital (Hauff and Jörg 2013; Hector et al. 2014). Capitals are indeed substitutable, but any number of workers and machines or an increase in productivity cannot completely replace the starting materials necessary for production. A necessary increase in productivity can be achieved through three approaches relevant for the BE and their restrictions: increasing the flow of natural resources per unit of natural capital, limited by biological growth rates; increasing product output per unit of resource input, limited by mass conservation; increasing efficiency of use of conversion of raw materials into products, limited by technology (Costanza et al. 1997).

In the currently dominant neoclassical ideology, BE is interpreted as both: a variable production factor technology as well as additional natural resources to be used for additional growth. The notions and political BE discourses in the EU were dominated by biotechnology visions from industrial stakeholders (Hausknost et al. 2017; Staffas et al. 2013). Therefore, BE was mainly seen as the appropriate endogenous technology factor and immediate precursor in the neoclassical concept of SD by providing sufficient resources and using them to increase benefit and profit maximization, which set the stage for the win-win-win narrative of the BE (Kleinschmit et al. 2017). Biotechnology in this sense would likely raise further huge sustainability risks when it is upscaled to an industrial level, as it is already, and will absorb large-scale biomass flows demanding significant exports and imports (Bringezu et al. 2020; Budzinski et al. 2017; Gawel et al. 2019). A growing BE in Europe has already led to an increase in harvested forest area and imported biomass and may hamper forest-based climate mitigation (Erb et al. 2022; Palahí 2021). These aspects may be a reason for the still low public 'acceptance' or explicit criticism of the BE (Mustalahti 2018; Stern et al. 2018) and that the majority of NGOs have a rejecting perspective on BE as a PR campaign from industrial business to green-wash their business as usual (Gerhardt 2018; Šimunović et al. 2018). Nevertheless, a climate-neutral economy will depend on these enormous material flows of sustainable and renewable biomass. The techno-political option space of the BE (Hausknost et al. 2017) shows strong connections to the presented sustainability and economy concepts: "Sustainable Capital" corresponds to the neoclassical perspective and weak sustainability, as well as, "Eco-Growth" corresponds to the ecological economics perspective and weak sustainability as to forms of ecological modernization; "Eco-Retreat" is more an ethical vision of deep ecology, strong sustainability and ecological economics; "Planned Transition" is based on ecological economics but neither corresponds clearly to weak nor strong sustainability and will be important in the following. (Zeug et al. 2020).

8.1.2 Sustainability and LCSA

Measurement and evaluation of so called ecological, economic or social sustainability at different scales is the central motivation of different methodological frameworks of life cycle assessments (LCA) and their combination or integration in life cycle sustainability assessments (LCSA). Especially the latter methods of LCSA are still at an early stage and face significant methodological problems (Guinée 2016; Ingrao et al. 2018; Zimek et al. 2019). Comprehensive reviews of LCSA approaches identify the lack of transparent description and discussion about implicitly underlying concepts of sustainability, and resulting difficulties in the classification of indicators and criteria as major obstacles (Wulf et al. 2019). At least there are currently two definitions of LCSA (Sala et al. 2012a; Sala et al. 2012b). On the one hand, the widely used and highly operationalizing and *additive* scheme (LCSA=ELCA+LCC+SLCA), first proposed by Klöpffer in 2008 (Kloepffer 2008). It argues that on the basis of the three-pillar approach, the three methods of environmental-LCA (ELCA), social-LCA (SLCA) and life cycle costing (LCC) have to be standardized, harmonized, synchronized (mostly this means an analog brief structure as in DIN EN ISO 14040 and 14044) (Valdivia et al. 2021) and then combined, whereas extensive qualitative analyses are excluded. On the other hand, there is at least the idea of an *integrative* approach first proposed by Guinée in 2011 (Guinée et al. 2011), where within a common sustainability concept and methodical framework impact categories from E-LCA, S-LCA and LCC should be integrated into a holistic assessment. However, as recent comprehensive reviews (Costa et al. 2019; D'Amato et al. 2020; Fauzi et al. 2019; Troullaki et al. 2021; Wulf et al. 2019; Zimek et al. 2019) show: nearly all LCSA approaches more or less follow the additive scheme and are explicitly or implicitly based on the three-pillar-approach (Zimek et al. 2019) with respective consequences.

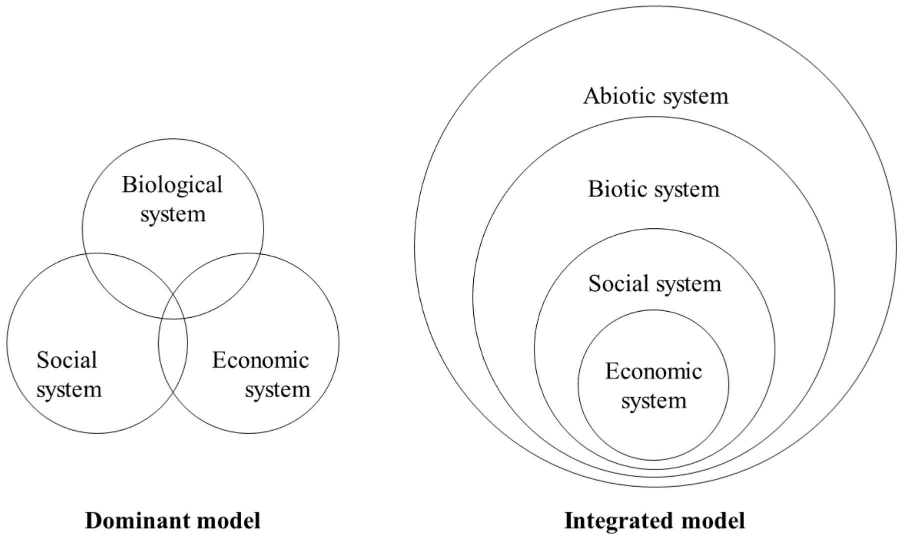

Fig. 8.1. Schemes of sustainability concepts, adopted from (Mebratu 1998, Fig. 1)

The so-called three pillar approach (people, planet and prosperity) of the World Summit on SD in 2002 has prevailed and is essential to the present understandings of sustainability (Elkington 1998; Hector et al. 2014; UNEP 2011). In the updated guidelines for S-LCA, prosperity is even directly identified with profit (UNEP 2020). Thereby suggested are kinds of several more or less differentiated entities constituting sustainability in a complementary and constructive way (Meadowcroft 2007). The most established and used resulting model (see Fig. 8.1, left) from the three pillar approach is the reductionist model of interlinked systems (Holmberg et al. 1992) as the dominant model (cf. (Rockström and Sukhdev 2016)). However, it leads to inflexible and polarized oppositions due to its reductionist epistemological foundations of ecological vs. social vs. economic, and oftentimes some kind of equilibrium or viable and equitable state is considered as sustainability in the center or when dimensions are overlapping (Elkington 1998; Redclift and Benton 1994; Trzyna et al. 1995).

Additive LCSA takes the three parts respectively dimensions of sustainability as the point of departure (Fig. 8.2) and considers LCSA likewise as a linear summation and combination of the parts: E-LCA, S-LCA and LCC are carried out more or less independently from each other as separate systems (Fig. 8.2, c). Broadly said, scopes, corresponding methods and indicators of the life cycle inventory (LCI), life cycle impact assessment (LCIA) as well as their individual results only have in common that they relate to the same product or functional unit which is to be assessed (cf. (Ekener et al. 2018; Suwelack 2016; Urban et al. 2018)). When assigning the indicators to impact categories, and/or when indicators are allocated to sustainability dimensions, it becomes apparent that for some indicators no clear intuitive allocation is possible or useful (e.g. aspects like sustainable final consumption/production, infrastructures, development of rural areas, employment (Egenolf and Bringezu 2019)). Such aspects mostly describe complex relations between two or more sustainability dimensions and are not even roughly categorizable as solely social, economic or ecological (b).

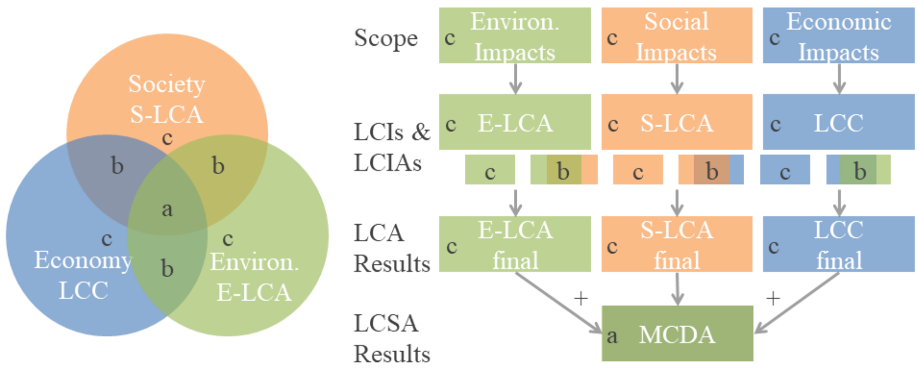

Fig. 8.2. Three-pillar-approach of sustainability & additive scheme of LCSA=ELCA+LCC+SLCA, (c – separate systems, methods and indicators, b – intersection between two systems, indicators which cannot be clearly assigned to one system, a – all dimensions somehow combined, additive combination of methods results; LCI – Life Cycle Inventory, LCIA – Life Cycle Impact Assessment)

Dealing with such issues is difficult within the three-pillar-approach and separate assessment methods, since a simple combination of the particulate methods is only possible to a very limited extent (Costa et al. 2019; Keller et al. 2015; Wulf et al. 2019) and combining the final results with MCDA (Ekener et al. 2018; Sala et al. 2012a) does not represent an integration of social, ecological and economic aspects. The analysis of complex systems by their subsystems would mean more than just combining their parts (Halog and Manik 2011). Such process-based approaches with a high technical detail but few general preliminary considerations result in a series of specific problems occurring in operationalization at the latest: trade-offs and conflicts of objectives (Guinée 2016), double-counting and problems of monetization (Kloepffer 2008), pareto-effects of high significance within cause-effect relations, contradictions between effects on different scales (Guinée 2016), allocation to fuzzy impact categories (e.g. if an indicator is of primarily social, environmental or economic character or which stakeholders are effected), functional units (Costa et al. 2019), exogenous and endogenous weightings in accounting (Traverso et al. 2012), rating, normative goal systems and many more. For instance, the decoupling debate has shown that improving the ecological performance of products only has a limited effect on global environmental challenges, and pareto effects come to bear which makes a relatively small number of causes responsible for a major portion of the effects, resulting in a need for hot spot analyzes (Halog and Manik 2011). Generally speaking, a theoretically well-founded and holistic social, ecological or economic sustainability theory from political economy and political ecology is missing in LCSA. Integration would mean, considering social, ecological and economic aspects as one system, and holistically thinking about the transdisciplinary contextualization of LCSA in social and political science (see section 2). In the ongoing discussion of the last years, a broad spectrum of blended approaches emerged (de Schutter et al. 2019; Liu et al. 2015; Purvis et al. 2019; Sala et al. 2012b). However, there is another rather less-established model of integrated systems in accordance with ecological economics (see Fig. 8.1, right) (Mebratu 1996). Presumably rather less-established, since its theoretical conception is less intuitive and requires a well-founded theory, as well as its practical implications are far stronger. In the following, we will introduce a founded theory to employ this concept in models of sustainability assessment, in particular LCSA.

8.2. Introduction of Critical Concepts for Progress in LCSA

8.2.1 Transdisciplinarity

Our previous considerations already show the importance of implicitly underlying social science and economics and how they influence LCA and LCSA approaches. Consequently, the need for a transdisciplinary sustainability science aiming at understanding interactions between nature and society has often been stated in the literature for LCSA (Sala et al. 2012a; Sala et al. 2012b), but rarely substantiated or implemented (Future Earth 2016; Pfau et al. 2014). A lot of knowledge and evidence of relationships (e.g. between SD and climate action) are scattered across different institutions, locations and disciplines; this fragmentation is a critical barrier to a holistic and integrated understanding of social, economic and environmental systems (Knierim et al. 2018; Nerini et al. 2019). The methods and findings of different scientific disciplines are oftentimes very rational, competent and innovative within their respective fields of expertise, but neglect or contradict insights from other disciplines and are embedded in possibly irrational frameworks or ideologies (Demirovic 2003). We understand interdisciplinarity as an exchange and dialogue between disciplines, whereas transdisciplinarity as a research paradigm of sustainability sciences aims for holistic thinking: an inherent contextualization and embedding of findings within a greater context creating transcending insights (Klein 2008; Knierim et al. 2018; Lubchenco et al. 2015). Real-world problems are the starting point of transdisciplinary research, to gain a better understanding of social-ecological problems and contributing to their solution is the research objective (Jahn et al. 2012; Kramm et al. 2017). Of course, modern science is much too complex to be covered by one person and so transdisciplinary practice means at least working together, recognizing each other and involving stakeholders to develop novel conceptual and methodological frameworks with the potential to produce transcendent theoretical and practical approaches (Hummel et al. 2017; Klein 2008; Rosenfield 1992). The resulting methodological pluralism can lead to more consistency and less bias (Lamont et al. 2006). Attributes like 'social' and 'economic' do not describe separate objects of scientific observation, but rather different perspectives on the same objects and the underlying relations. Transdisciplinary means to understand and reflect a seemingly ecological research question as a simultaneously political-economic research question and vice versa. Consequentially, ecological arguments can never be neutral any more than sociopolitical or economic arguments are ecologically neutral (Harvey and Braun 1996). This means that for achieving a sustainable transition to a BE, there is not only a need to transform so called societal and industrial mindsets, and not only a question of a few 'tweaks' to the system. Instead, it is actually a question of transformations of our very fundamental societal relations to nature (SRN) (de Besi and McCormick 2015; Kramm et al. 2017; Pichler et al. 2020). Different means, ends, and values seem to be the guiding factors in what we have understood as conflicting interests and perceptions in BE assessments (Zeug et al. 2019). Simply setting ambitious goals, but ignoring ideologies, social norms and values, religious beliefs and institutions, including formal and informal rules and customs will not be sufficient (Norström 2013; Stegemann and Ossewaarde 2018). Only technological changes and innovations, a sole focus on industrial efficiency or simply replacing fossil resources with biomass are in danger of maintaining the same production and consumption system as the fossil-based economy (de Besi and McCormick 2015). Such insights go back to early interdisciplinary materialism, later critical theory, and social ecology are applied to the concept of SRN. They reveal that there is no non-normative science; if there is no explicit scientific value judgment there is an implicit one confirming the status quo (Amidon 2008; Hummel et al. 2017; Kramm et al. 2017). Regarding progress in LCSA, the following framework aims for embedding positivist data-driven methods of science into a relativist and postmodernist philosophy of science, combining the strengths of quantitative systems modeling as well as political economy and ecology. Even though this is and will remain a field of tension (Bauriedl 2016), due to the complexity and different perspectives of methods. Transdisciplinarity is, therefore, necessary to achieve a proper integration of methods in an LCSA. As well on a regional scale, transdisciplinary approaches offer new possibilities of deliberative methods to find normative constellations of societal needs through stakeholder participation (e.g. interviews and discussions).

8.2.2 *Societal Relations to Nature*

As shown, none of the dualistic approaches alone is sufficient, neither anthropocentric nor ecocentric, neither weak nor strong sustainability, and especially not the dominant and reductionist model of sustainability. But rather the integrated model and a corresponding holistic thinking based on the interactions and relations between the parts and the whole. Therefore, we take up the concept of SRN towards a holistic and integrated LCSA (HILCSA). In SRN nature, economy and society do not stand in an external relation to each other nor do they exist by themselves as the three-pillar approach suggests, rather, they constitute each other through their relations (Görg 2003; Görg 2011; Görg et al. 2017; Hummel et al. 2017; Kramm et al. 2017; Pichler et al. 2020; Pichler et al. 2017):

The SRN concept at its core evolves around the idea of societal needs and SRNs should be regulated to fulfill them. Thus, SRN is not only complementary and a well-founded theory for the SDGs, but also incorporates the concept of provisioning systems, justice (Menton et al. 2020), equity, and critically reflected SD. Social ecology and SRN conceptualize societies as simultaneously subject to biophysical and socio-cultural spheres of causation in a social metabolism. Nature and society are different things, and although distinct, not independent from one another. What nature is results from what society, culture, technology, etc. is not, and vice versa. Social metabolisms transform a society's energetic and material inputs, integrate them into societal stocks or other socio-economic systems, and discharge them to the environment as wastes and emissions. Industrial and BE metabolisms are special cases of social metabolisms (Bezama et al. 2021). However, this societal metabolism has no essential or eternal nature (Pichler et al. 2017). Instead historically, geographically and culturally specific socio-cultural mechanisms like politics and economic patterns are in place through which a society organizes its metabolism. In general, our SRN are shaped by economies, which are temporally and geographically different (e.g. transformable) social systems supposed to satisfy societal needs (ends) utilizing natural resources, labor and technologies (means). Especially important for LCSA are working hours as the crucial (activity) variable in production processes, since labor is not only the origin of economic value but as well relates social effects to production processes (Fröhlich 2009; Postone 1993).

These economic, and therefore also societal, mechanisms are understood as specific patterns of regulation, and fail when interactions with nature become dysfunctional, e.g. overexploitation of natural resources (overfishing, deforestation, soil degradation) or failure of a mechanism for effective and efficient allocation (hunger, poverty). Although there is the idea of being able to dominate nature, and nature is increasingly shaped by societal activities, it is becoming increasingly clear that global societies are significantly affected by environmental impacts and crisis trends. In this regard, we speak of the *Capitalocene* instead of the Anthropocene (Brand and Wissen 2018), since capitalism as the currently dominant societal and economic system has led to a social-ecological crisis, and not humankind itself as the term Anthropocene suggests. In specific our SRN are shaped by capitalism as a historically specific form of economy: a societal system that perpetuates the growth and accumulation of value (end) through societal needs using natural resources, labor and technologies (means). The fulfillment of societal needs is not the purpose of capitalist economic activities, but as well a necessary mean as all other production factors are to gain profit (Postone 1993). But why is the production of raw materials, resource consumption and negative impacts growing and need to grow too? In 'capital-ism' the imperative of capital accumulation, growth and the predominance of the production of surplus values over the production of use values is dominant (Postone 1993). Societal needs (use value) are only satisfied if they are coupled with sufficient purchasing power (exchange value). Both values use and can overuse resources, but monetary or exchange values tend to ignore the biophysical requirements of ecosystems categorically, e.g. externalities like environmental degradation are not intended to be internalized (Schleyer et al. 2017). Since the exchange value of commodities and money is the starting and the end point of every capitalist economic process, profit becomes the main driver and end in itself. If everything depends on an abstract quantitative value, the only driver is the endless growth of this value, and consequentially there is no "enough". Exchange value in the long term depends on the use value and production of material commodities, leading to valorization and overexploitation of natural and human capital and likewise growing negative social impacts and transgression of PB. Solely new technologies like BE in green capitalism as the potential of additional growth usually expand and/or shift the exhaustion of one resource to another. Growth in GDP (exchange value) ultimately cannot plausibly be decoupled from growth in material and energy use (use value), therefore, GDP and material growth cannot be sustained infinitely in this very economic system (Common and Stagl 2012; IPCC 2022; Parrique T. 2019; Ward et al. 2016). Economic growth was also identified by stakeholders as a relatively irrelevant objective (Zeug et al. 2019; Zeug et al. 2021b). Beyond that, a significant increase in labor productivity through automatization and digitalization leads to exponentially growing economic material output but stagnation and even a decrease in GDP per capita, profit rates, real loans and equality, especially in affluent and industrialized countries (Brynjolfsson and Andrew 2015; Piketty 2014). But also globally the labor's share of GDP had declined since there is a tendency toward higher capital productivity in capital than in labor and so shifting the investments from labor to capital (Karabarbounis and Neiman 2013). When growing economic production is not decoupled from its ecological impacts, but income and affluence are decoupled from this very production, then a good life for all within PB will be hard to achieve when income is a prerequisite for achieving nearly all societal needs.

A good example of capitalist SRN and patterns of regulation is the apparent connection between ending poverty (SDG 1) and ending hunger (SDG 2), both considered by stakeholders as very relevant for the BE (Zeug et al. 2019). In this case, even if enough food is produced worldwide to end hunger, the pattern of regulation of our economies requires ending poverty first. Since societal needs alone (use value), sufficient resources and means do not lead to their fulfillment, as long as those needs and preconditions are not coupled with enough purchasing power and income (exchange and surplus value). The same is true for the fuel vs food debate in BE: land or crops will be used for the purpose with the highest expected surplus value (e.g. fuels), instead of the fulfillment of more basic societal needs with a higher use but lower exchange value (e.g. nutrition) (cf. (Ashukem 2020)).

8.2.3 Societal-Ecological Transformation

Transformations take place as changes in initial patterns of regulation to new ones when the old ones become dysfunctional (Wittmer et al. 2022). The role of power relations in enabling and maintaining unsustainable resource use patterns, the role of social-ecological innovations within transformation processes and transregional interdependencies have been identified as emerging clusters of challenges in societal metabolism (Pichler et al. 2020). Terms and concepts of transformations toward sustainability remain fuzzy and there is much ambiguity and disagreement about the meaning and function of these concepts (Görg et al. 2017). Such transformation will have to innovatively address normative and socio-economic barriers, like global political patterns of regulation and resulting production and consumption patterns, as well as technological and ecological challenges. For example, technological inventions must go hand in hand with social, economic and organizational innovations, and questions of scale arise in the field of tensions between a global socio-ecological crisis and the responsibility and scope for action at the local and regional levels.

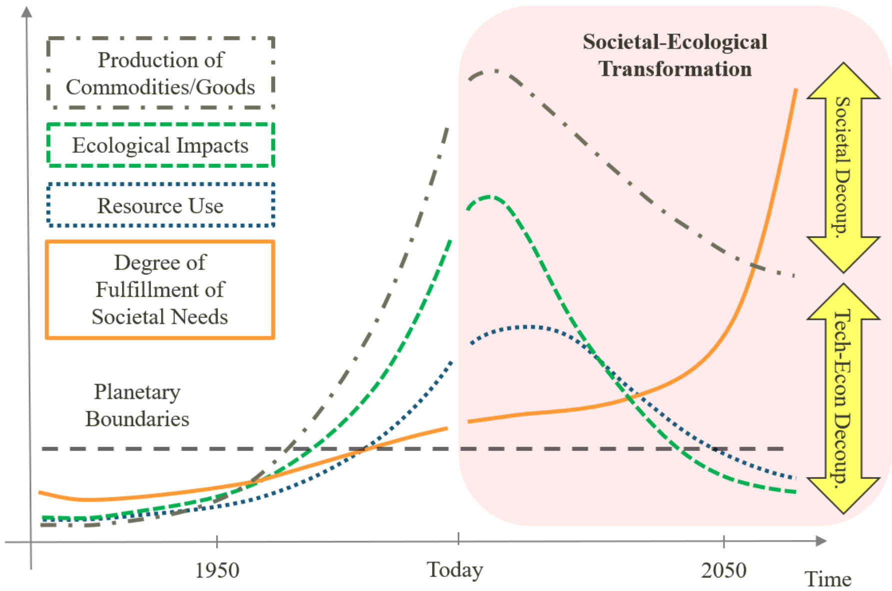

Fig. 8.3. Societal-ecological transformation and double decoupling as qualitative trends

A potential future societal-ecological transformation should incorporate the PB as the main ecological limits, e.g. a certain GHG concentration should not be exceeded as well as there is a limit for the use of land, resources, water and so on (O'Neill et al. 2018). PB are not necessarily constant over time and nor a deterministic constant, but at least most likely are scenarios in which the transgression of one PB leads to even more transgressions of other PB (Rockström et al. 2009; Steffen et al. 2018), e.g. climate change induces water scarcity and land degradation. In difference to common concepts of PB, from a perspective of political ecology, PB should be understood as socially constructed and politically contested (Bauriedl 2016; Görg 2015). As a qualitative simplification, we assume the PB as constant (Fig. 8.3) and their transgression as to be avoided.

Displayed as qualitative trends derived from quantitative charts (Roser 2022), ecological impacts and resource use grew and grow exponentially, especially since the 1950s and temporarily are exceeding PB globally by far. Whereas the production of material and immaterial commodities (e.g. GDP) as the cause for transgressing PB increases even more exponentially (ibid.)(cf. section 8.2.2). However, the development of social indicators like the human development index rather has a far less exponential and more linear trend. This not only illustrates the production of exchange values by commodities as a main driver of production, resource use and environmental impacts in capitalism, but as well the quality in which societal needs are disproportionally coupled to commodity production. However, these qualitative trends correspond more to industrialized countries of the global north and negative impacts are shifted especially to the global south (Bauriedl 2016; Görg 2015).

A societal-ecological transformation would have to change patterns of regulation and societal relations in a way which, in technical terms, can be described as double decoupling: a societal as well as a techno-economic decoupling, which are mutually dependent and related to each other. On the one hand, the societal decoupling would have to decouple the degree of fulfillment of societal needs from an increasing production of material goods and overcome their commodity character, e.g. sufficiency. Such a societal-ecological transformation on a societal level means mainly a reconsideration of the economy as a satisfaction of societal needs (ends) by means of natural resources, labor and technologies (means). Innovation and sustainable technologies alone will not solve this predominantly political challenge. This does not mean that there is a contradiction between substitution and innovation. On the contrary, innovation is one of the prerequisites for substitution. Beyond economic substitution, for most of the biophysical–social indicator linkages diminishing marginal utilities were identified: from a certain degree of affluence and fulfillment of societal needs every additional unit of resource use contributes less to social performance, making sufficiency an essential factor for economic sustainability (O'Neill et al. 2018). Without a societal decoupling there is relative decoupling (fewer impacts per product, techno-economic) but no absolute decoupling (fewer impacts in total, societal), absolute decoupling is not plausible in a growing economy. LCSA in this regard can provide some information by the following dimension.

On the other hand, the techno-economic decoupling means decoupling the remaining sufficient and necessary material production from increasing resource use and negative ecological, social and economic impacts. A BE and circular economy (D'Amato 2021) will be decisive but are not sustainable per se and therefore LCSA can make significant contributions for sustainability assessments. Sustainable BE has to be a highly effective (fulfills societal needs), efficient (achieving most with less) and just (nobody falls behind) use of renewable resources within PB. Unique about the BE provisioning system is its inherent capacity for regeneration, allowing natural or biological resource stocks to replenish after extraction, and they are typically in constant interaction with their surrounding systems (Erb et al. 2022; Lindqvist et al. 2019; Zörb et al. 2018). Whereas every unit of non-renewable resources used now is a resource which will not be available in the future and thereby comprises intra- and intergenerational equity (Fedrigo-Fazio et al. 2016; Parrique T. 2019). But BE as industrial metabolism is only sustainable if: the rate of extraction does not exceed the rate of regeneration; the regenerative capacity is not diminished by extraction, processing, and utilization of resources; material and energy cycles are increasingly linked; and societal needs are fulfilled as well as they are the central objective of the economy itself. In contrast to non-renewable fossil systems, these complex interactions make the management of the BE complex and require fundamentally different strategies of planning (Erb et al. 2022; Lindqvist et al. 2019). The main limiting long-term factors of BE is the conversion efficiency of 1–2% of plants turning sunlight into carbon; and the limited areas where the sun shines, sufficient water is available and plants can grow without causing negative feedbacks like accelerating forestry erosion, soil erosion or biodiversity loss. Besides, the concept of reduce, reuse and recycle can actually be put into practice in the right order, since today a reduction or sufficiency of production and consumption is incompatible with the imperative of growth.

Hence, a societal-ecological transformation and sustainable BE corresponds strongly to the “Planned Transition” techno-political vision of BE (Hausknost et al. 2017). This means that on the one hand advanced technologies on a large-scale industrial level (integrated biorefineries, cascade use, eco-functional intensification of certain agricultural sectors, global trade in certain biogenic commodities, use of high-tech biotechnologies) will be needed to achieve the very ambitious demands on resource efficiency (Aguilar et al. 2018; Nitzsche et al. 2016; Olsson et al. 2016; Panoutsou et al. 2013). On the other hand, further growth, capital accumulation and an invisible hand are not a necessary part of BE. Rather, not transgressing the PBs, fulfilling essential societal needs and socially conscious planning of this transformation are.

8.3 Holistic and Integrated Life Cycle Sustainability Assessment

The framework of HILCSA aims to take the previously discussed complex problems into consideration, as far as it is possible in a broad understanding of LCSA methods. Holistic in this regard means to have the bigger picture in mind: not only to have a transdisciplinary and critical background theory of political economy, but as well to not fall short on the implications which some of the results may have and impose fundamental societal transformations, instead of only technological innovation or doing some ‘tweaks in the system’. Whereas integrated stands for an integrated model of sustainability (cf. Fig. 8.1) which enables redeeming the integrated approach suggested by Guinee (Guinee et al. 2011): to integrate social, ecological and economic sustainability assessment into one unified method instead of additionally combining different methods (see section 1.2).

First, the spatial and temporal level of LCSA in general and HILCSA in particular, which deals with social-ecological transformations and SRN, is the mesolevel of economic organizations and institutions as actors of industrial metabolism. Besides, there are micro levels of individual actions and macro levels of societal powerful patterns of regulation. On this meso scale, HILCSA is in particular useful to assess techno-economic and relative decoupling, and needs to at least be aware of implications and relations of the micro and macro scale, or embedded in a transdisciplinary framework. We deem the three-pillar approach as not suitable for an integrated and holistic LCSA as well as a cause of major methodological problems (section 8.1.2). Instead, we propose an integrated sustainability framework filling the identified research gap of a missing framework for HILCSA (Fig. 8.4, i)). Second, in contrast to the additive LCSA (LCSA = S-LCA + E-LCA + LCC), the HILCSA (HLCSA = f (S-LCA, E-LCA, LCC)) framework builds on this integrated sustainability framework for operationalization and integrates social, economic and ecological aspects in a common goal and scope, LCI, LCIA, results and interpretation (Fig. 8.4, ii)).

Economic systems on a meso scale are handled as product- and process-systems in LCA, comprising both physical and social systems, mediating the relationship between natural resources and societal needs through economic infrastructures and practices. When normatively aiming at a good life for all within planetary and regional boundaries, an integrated sustainability model puts social, ecological and economic sustainability in a specific relation: SRN which fulfill societal needs (ends) by means of natural resources, labor and technologies (means). This leads to a model (Fig. 8.4 i)) in which integrated sustainability is defined as:

- Long-term and global fulfillment of societal needs and well-being as an end (social sustainability)
- Long-term stability of our environment as a basis of societal reproduction within PB (ecological sustainability)
- Technologies and economic structures as efficient, effective, sufficient and just metabolisms which enable the fulfillment of societal needs within PB (economic sustainability)

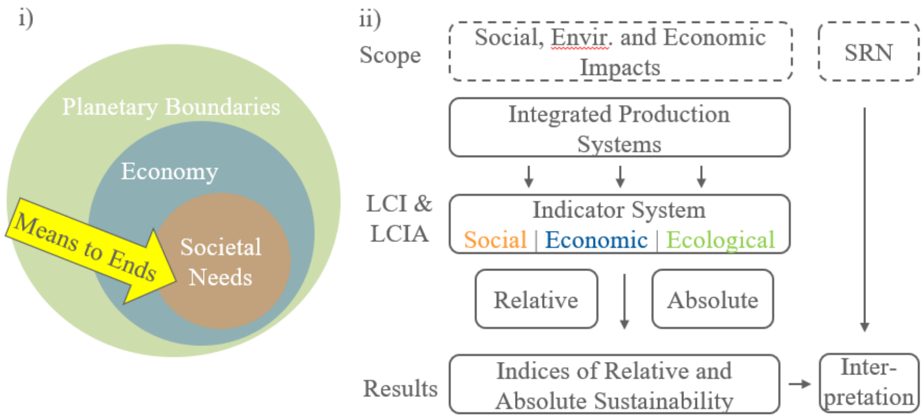

Fig. 8.4. i) Sustainability model, ii) Framework of HILCSA = f (S-LCA, E-LCA, LCC) (integrated product and production systems in openLCA entail ecological, social and economic data)

Economic sustainability in this sense is the enabling criteria for actually reaching social sustainability and ecological sustainability at once, profit or growth is neither a criterion nor an end itself. In a phase before or at the beginning of a societal-ecological transformation, economic sustainability means at least to fulfill most societal needs with the lowest resource use possible.

Between indicators or sustainability aspects there is no compensation or credit (e.g. positive assessment results of indicators are offset with negative results of other indicators in indices) applied, as it is sometimes suggested in LCSA. Simply because there is no meaningful mechanism of compensating GHG emissions by improvements in health at working conditions within a production system. As well as, not transgressing one PB revokes the transgression of another PB; if only one PB is transgressed a long-term reproduction of societies is at stake.

For allocation and weighting of indicators in HILCSA, certain SDGs can be assigned to societal needs, economy and PB, however, a clean analytical distinction is not possible due to the complex interactions (de Schutter et al. 2019): societal needs (SDG 1, 2, 3, 4, 5, 11, (16, 17)); economy (SDG 6, 7, 8, 9, 10, 12); PB (SDG 13, 14, 15) (Zeug et al. 2019; Zeug et al. 2021a; Zeug et al. 2020; Zeug et al. 2022a). We built a SDG framework in previous studies (Zeug et al. 2019) as well as developed (Zeug et al. 2021a; Zeug et al. 2020) and applied (Zeug et al. 2022a; Zeug et al. 2022b) HILCSA. The SDGs are applicable as a commonly agreed on goal and indicator framework. In the following, we are deepening the discourse for further development and applications of (HI)LCSA approaches.

8.3.1 Operationalization and First Results of HILCSA Case Study on Laminated Veneer Lumber

The common goal and scope of HILCSA is the assessment of social, environmental and economic risks, chances, synergies, trade-offs and contradictions of production systems with a focus on BE (Fig. 8.4, ii)). Although HILCSA is applicable for production systems in general, the focus on BE is given by specific indicators on i.e. land-use-change, biomass extraction or cumulated energy demands without the net calorific value of biomass for material use. For the LCI, the operational core of HILCSA are integrated production systems and processes entailing social, ecological and economic data which are modeled in the software environment of openLCA, mainly using the SoCa database (Eisfeldt 2017) (Di Noi et al. 2018) completed by additional data gathering (e.g. questionnaires (Jarosch et al. 2020)). The SoCa add-on as a combination of Ecoinvent and PSILCA (Product Social Impact Life Cycle Assessment) database as well as a basic LCSA functionality in openLCA is fundamental to this. The LCI in HILCSA entails a set of 109 quantitative and qualitative indicators for HILCSA capable to address societal needs by 21 indicators, economy by 59 indicators and the PB by 29 indicators (Zeug et al. 2021a). Thereby HILCSA is capable of addressing 15 out of 17 SDGs (SDG 10 & 17 missing yet). For the variety of indicators, we combined several established LCIA methods like ReCiPe, Impact World +, EF 3.0, RESPONSA and SoCa. Assessment of indicator values is based on a progressive regulation of SRN and a societal-ecological transformation, e.g. high efficiency and effectiveness, or less working time and a higher average renumeration lead to better assessment scores.

In a first and previous case study (Zeug et al. 2022a) of substituting steel beams with LVL beams (laminated veneer lumber), for each indicator i which is assigned to a specific subgoal SDG $sSDG$, in openLCA we calculate values x for each process of the LVL product system x_{sSDG}^{LVL}, as well as cumulated (total) values for the whole product system of LVL $x_{sSDG,T}^{LVL}$ and the steel beam $x_{sSDG,T}^{SB}$. All cumulated results of all indicators of our BE product system we finally compare to the product which can be substituted (steel beam), to assess their relative rather than absolute impact. Therefore, we calculate a factor f^{sSDG} called substitution-factor of impact of an indicator (Eq. 1), expressing the magnitude of relative sustainability. As aggregation on the SDG level, we calculated weighted mean factors for substitution of impact for each SDG f^{SDG} (Eq. 2). As weighting factors, we used the relevances R^{sSDG} of each of the SDG-subgoals in the context of the German BE-monitoring (Zeug et al. 2019). Analogical as well a total substitution-factor of impacts f is calculated on the level of all SDGs (Eq. 3).

$$f^{sSDG} = \frac{x_{sSDG,T}^{LVL}}{x_{sSDG,T}^{SB}} \qquad \text{(Eq. 1)}$$

$$f^{SDG} = \frac{\sum_{sSDG} R^{sSDG} f^{sSDG}}{\sum_{sSDG} R^{sSDG}} \qquad \text{(Eq. 2)}$$

$$f = \frac{\sum_{SDG} R^{SDG} f^{sSDG}}{\sum_{SDG} R^{SDG}} \qquad \text{(Eq. 3)}$$

According to the assignment of SDGs to societal needs (SDG 1, 2, 3, 4, 5, 11, (16, 17)), economy (SDG 6, 7, 8, 9, 10, 12) and ecology (SDG 13, 14, 15) we calculated substitution factors of impact for social $f_{social} = 0.31$, ecological $f_{ecological} = 1.01$ and economic $f_{economic} = 0.60$ sustainability. LVL seems to have a way better social sustainability, by having a detailed look at the indicator data and inventory, this is mainly due to the less toxicity of materials, immissions on humans and their working environments, but also higher expenditures for social security and education as well as a lower gender wage gap. However, regional analyzes show that the different technical production processes are not the main cause, but the far more global distribution of primary production chains of the steel industry and thereby externalization of social deprivations are worse (Zeug et al. 2022a) (cf. (Backhouse et al. 2021)). Such effects get visible by integrated and holistic methodologies including political economy, and would probably be neglected or falsely allocated to technologies in conventional LCA. Additionally, from a quantitative analysis, we see that the most significant negative impacts of LVL production come from forestry and its effects on land use with a substitution factor $f = 18.15$, e.g. LVL production takes up more than 18 times the land use of steel since steel as a fossil resource was accumulated inside the earth whereas wood has to steadily grow on its surface. However, the potential impact on climate change due to land use change in total is better than that of steel $f = 0.96$ as well as the overall potential negative effects on climate change are far less $f = 0.39$.

In a nutshell, although BE in this case can substitute fossil materials and partly has lower negative impacts (relative decoupling), forestry and agriculture use relatively much more land for primary resource production than fossil resources (Bringezu et al. 2020; O'Brien et al. 2017; Liobikiene et al. 2020). If BE is only seen as a substitution of resources in a capitalist and growing economy, then PB like land use will be transgressed way faster than in a fossil economy. In other words, substituting fossil resources with renewable resources under the same quantitative and qualitative production and consumption patterns will be unsustainable and makes an absolute decoupling seem implausible. Achieving ultimately more sustainability seems to be very unlikely by bioeconomy alone, but when bioeconomy is embedded in a societal-ecological transformation. Processes based on renewable resources in specific regions do not only have a better ecological, but also better social and economic sustainability as synergies. However, the dependency on sustainability from regions does not only apply to fossil industries, but BE can be very unsustainable when renewable material flows reproduce global social and economic inequalities and externalization of effects of sourcing and production (Asada et al. 2020; Backhouse et al. 2021; Eversberg and Holz 2020).

8.3.2 Further Development of HILCSA and LCA

SRN and a societal-ecological transformation as societal and a techno-economical decoupling have far reaching implications on HILCSA and LCA in general, significant for their further development, e.g. identifying seemingly technological problems as embedded problems of political economy and addressing them from a critical and transdisciplinary perspective . Currently, social sustainability in LCA and HILCSA is only measured as potential direct and indirect impacts of production on health, well-fare, education, (gender) equality, etc. of workers and communities in general.

Regarding a techno-economical decoupling, HILCSA currently aims to create an overview of the sustainability of production systems, as complete and concrete as possible. Risks, chances, synergies, trade-offs and hot spots are identified, whereas trade-offs, in particular, are important since they indicate contradictions which are characteristic of capitalists' patterns of regulation and metabolisms and should be avoided in a societal-ecological transformation. As outlined before, surplus and exchange values dominate use value and consequentially monetarization of social, ecological and economic aspects impacts LCA and LCSAs as well. A problem of fundamental character appears, which has not been discussed extensively in the previous research yet: to what extent monetary variables are generally distorted and abstract representations of (non--)material objects, subjects and their relationships in form of exchange values. In contrast to physical quantities, costs and prices are subject to abstract quantities and substantial fluctuations, not only due to fluctuations in market prices due to changing (un-)equilibria of supply and demand. For example, the amount of CO_2 emitted when a certain amount of a fuel is burned and the subsequent effects on the atmosphere and climate change are almost independent of location and, in the short term, time. Most internalized costs, on the other hand, for one and the same commodity can depend both in real and nominal terms on several factors, such as region, currency and time, and show significant differences (Ciroth 2009). As well as accounting procedures themselves are not standardized (Swarr et al. 2011). Besides, solely costs are of secondary importance for the production and marketing of commodities under capitalism; the prospect of a return on capital and profit remains paramount (Ciroth 2009; Postone 1993; Zeug et al. 2020). As well as decisive for most economic decisions are not the absolute balanced costs, but the relative costs of the opportunities (Kuosmanen 2005). For this series of reasons as well as potential future applications (section 4), HILCSA avoids monetarization and relies primarily on material and energy flows as well as working time for balancing. Indicators representing economic sustainability are i.e. water and energy consumption, share of fossil energies, resource efficiency, cascading factor, weekly hours of work per employee, average remuneration level, children in employment, and right of association (Zeug et al. 2021a). In addition, life cycle costs are also implemented as a variable.

A challenge will be that private industrial actors in capitalist societal relations have and must have an intrinsic interest in capital accumulation and increasing output, and by themselves will not embark on a good life for all within PB or cost internalization. Societal decoupling will in particular rely on a decreasing production of material goods and is essentially coherent with techno-economic decoupling not transgressing PB by resource use and environmental impacts is a hard criterion. Consequentially, beyond the importance of regionalized and spatially explicit datasets in order to improve the quality of results (Fauzi et al. 2019), it is just as important to take into account PB and global effects in LCSA by appropriate LCIAs

(Chandrakumar and McLaren 2018a; Chandrakumar and McLaren 2018b; Chandrakumar et al. 2018). In recent years, significant developments were made, especially in the context of the European Commission - Joint Research Centre (EC-JRC) to integrate PB and environmental footprints (EF) into E-LCA to allow meso- and macroeconomic assessments and conclusions by sector and product specific bottom-up approaches (Bjørn et al. 2020; Robert et al. 2020; Sala and Castellani 2019; Sala et al. 2020). Like a majority of LCAs, HILCSA as well entails a relative assessment, e.g. if the observed case is better than a reference of cases and how much it is (substitution factor of impacts). However, there is no information on if it performs ‘well enough’ for ecological sustainability in terms of PB (Bjørn et al. 2020). Whereas absolute sustainability assessment methods (Chandrakumar and McLaren 2018b) compare specific impacts with external environmental carrying capacities (according to PB), e.g. life-cycle climate impacts are related to the 1.5 degree climate goal (Bjørn et al. 2020). In a relative dimension, this comes down to assessing how much kg CO_2 eq. per product can be considered as (un-)sustainable, however, on an absolute dimension it is a question of what quantities of such a product can be produced in general within a specific time frame. Such PB-LCIAs (Ryberg et al. 2018) addressing challenges of relating LCIs and LCIAs to operational definitions of PBs (Robert et al. 2020) are significant for BE, since a sustainable BE requires that the rate of extraction does not exceed the rate of regeneration, and that this regenerativity and the surrounding supporting systems are maintained. However, such absolute sustainability assessment methods are not robustly available in LCA, yet (Alejandrino et al. 2021; Guinée et al. 2022). The major reason and hurdle, besides technical complexity, are so-called problems of sharing principles and distributive justice theories used in diverse political philosophies (i.e. egalitarian, utilitarian, and acquired rights principles) (Ryberg et al. 2020; Ryberg et al. 2018), e.g. the basic question to determine how much products and resources of whole economies can be granted to different social entities (individuals, regions, nations). We consider addressing these questions requires societal and democratic political processes as well as a transdisciplinary scientific perspective for which HILCSA can provide a specific tool, data, information and interpretations.

8.4 Conclusions and Outlook

At this very point, the mutual dependency and relation of societal decoupling and techno-economic decoupling (PB) leads unavoidably to fundamental questions of political economy and political ecology: How to socially organize and normatively analyze the fulfillment of societal needs by economies within PBs? For various previously mentioned reasons, but especially due to the twisted relations of means and ends, this question is unlikely to be solved within capitalists’ societal relations and their intrinsic compulsion to grow, independent of which ‘philosophy’ is applied. On the other hand, in political economy and ecology, a new discourse is rising in the direction of which the approaches of an absolute sustainability assessment and HILCSA point implicitly: new forms of distributed planned economies.

Planning economy means to mentally, organizationally and institutionally shape processes of determining, through assessment and decisions, on which paths, with which steps, in which temporal and organizational sequence, under which framework conditions and finally with which 'costs' and consequences a certain goal seems to be achievable (Nuss and Daum 2021). Of course, planning in this regard, as a mental anticipation of actions, is already immanent for the current economic system, especially in times of large digital platforms but under very different preconditions (Bastani 2019; Morozov 2019; Phillips and Rozworski 2019). Climate change as a relatively new global problem can only be countered by means of collective planning, however, the debate on capitalist market economies versus socialist planned economies has a long tradition and comes down to the question of which societal and technical basis, how and supported by which tools an economy is organized and coordinated (Groos 2021). Against the background of societal decoupling, it would be of particular interest to implement whether and to what extent the product manufactured and evaluated actually meets social needs in terms of effectiveness, sufficiency and justice.

For such future theoretical perspectives as well as current assessment, HILCSA allows an integrative and holistic sustainability analysis and assessment based on aggregated indicators qualitative discussion, retrospective and prospective. At this early stage, the indicator and impact assessment sets are not as detailed as in the stand alone methods, rather the goal is to avoid a piecemeal approach to SD (Taylor et al. 2017) and to deliver a comprehensive picture of trade-offs, synergies, hotspots, significant risks and chances and a fundamental understanding. Currently, the techno-economic dimension of decoupling can be described relatively well, the societal dimension of decoupling only partially with the need for transdisciplinary cooperation and integration. At this point, however, LCSAs can no longer be sharply and meaningfully separated from political and macroeconomic topics, which was proposed in additive LCSA. For further applications in regional production systems and macroeconomic systems, the extension towards multi regional input output methods (MRIO) and hybrid LCSAs is promising (Budzinski et al. 2017; Fröhlich 2009; Jander and Grundmann 2019; Teh et al. 2017).

BE and circular economy as well as sustainability assessments are for both societal-ecological transformations and "green" capitalism necessary and meaningful. Less unsustainable practices even under SRN of capitalism are viable to retain the environmental basis for anything beyond. However, the overall possibilities of achieving sustainability by BE and sustainability assessments are limited as long as social, ecological and economic sustainability are not a central objective of the general economy and its patterns of regulation itself.

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LIFE CYCLE SUSTAINABILITY ASSESSMENT

A framework for implementing holistic and integrated life cycle sustainability assessment of regional bioeconomy

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Abstract

Purpose Currently, social, environmental, and economic risks and chances of bioeconomy are becoming increasingly a subject of applied sustainability assessments. Based on life cycle assessment (LCA) methodology, life cycle sustainability assessment (LCSA) aims to combine or integrate social, environmental, and economic assessments. In order to contribute to the current early stage of LCSA development, this study seeks to identify a practical framework for integrated LCSA implementation.

Methods We select possible indicators from existing suitable LCA and LCSA approaches as well as from the literature, and allocate them to a sustainability concept for holistic and integrated LCSA (HILCSA), based on the Sustainable Development Goals (SDGs). In order to conduct a practical implementation of HILCSA, we choose openLCA, because it offers the best current state and most future potential for application of LCSA. Therefore, not only the capabilities of the software and databases, but also the supported methods of life cycle impact assessments (LCIA) are evaluated regarding the requirements of the indicator set and goal and scope of future case studies.

Results and discussion This study presents an overview of available indicators and LCIAs for bioeconomy sustainability assessments as well as their link to the SDGs. We provide a practical framework for HILCSA of regional bioeconomy, which includes an indicator set for regional (product and territorial) bioeconomy assessment, applicable with current software and databases, LCIA methods and methods of normalization, weighting, and aggregation. The implementation of HILCSA in openLCA allows an integrative LCSA by conducting all steps in a single framework with harmonized, aggregated, and coherent results. HILCSA is capable of a sustainability assessment in terms of planetary boundaries, provisioning system and societal needs, as well as communication of results to different stakeholders.

Conclusions Our framework is capable of compensating some deficits of S-LCA, E-LCA, and economic assessments by integration, and shows main advantages compared to additive LCSA. HILCSA is capable of addressing 15 out of 17 SDGs. It addresses open questions and significant problems of LCSAs in terms of goal and scope, LCI, LCIA, and interpretation. Furthermore, HILCSA is the first of its kind actually applicable in an existing software environment. Regional bioeconomy sustainability assessment is bridging scales of global and regional effects and can inform stakeholders comprehensively on various impacts, hotspots, trade-offs, and synergies of regional bioeconomy. However, significant research needs in LCIAs, software, and indicator development remain.

Keywords Bioeconomy · Sustainability assessment · SDGs · Life cycle assessment · Life cycle sustainability assessment · Life cycle impact assessment · openLCA

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1 Introduction

Decoupling human well-being from environmental impacts as well as the fulfillment of societal needs by a socially just and sustainable provisioning system is and will be the major challenge to avoid a socioecological crisis. We understand the emerging bioeconomy as a provisioning system linking social outcomes and renewable resources by innovative technologies. Bioeconomy comprises both physical and social systems, mediating the relationship between planetary boundaries and societal needs by economic activities of physical infrastructures. Thus, a sustainable bioeconomy should be assessed with regard to its potential to provide a good life for all within planetary boundaries (Zeug et al. 2020; O'Neill et al. 2018). So far, attempts into such assessments are focused on achieving gains in ecotechnological efficiency. However, though improvements in efficiencies are necessary, they are not sufficient in designing a sustainable bioeconomy. Instead, societal and economic transformations entailing bioeconomy are necessary (Ramcilovic-Suominen and Pülzl 2018; Hausknost et al. 2017; Bezama et al. 2019). This consideration actually implies the need for a double decoupling, i.e., decoupling of the increasing satisfaction of societal needs from an otherwise ever greater production of material goods and services as well as decoupling of the production of goods and services from growing negative ecological, social, and economic effects.

In order to accommodate for this complexity of demands on social, ecological, and economic sustainability (holistic sustainability), the Sustainable Development Goals (SDGs) provide measurable and normative objectives for bioeconomy assessments (Zeug et al. 2020, 2019; Linser and Lier 2020; Calicioglu and Bogdanski 2021). By stakeholder participation, we identified and quantified relevances of SDGs for bioeconomy assessments in Germany (in descending order): ending hunger (SDG 2); sustainable consumption and production (SDG 12); terrestrial ecology (SDG 15); oceanic ecology (SDG 14); water and sanitation (SDG 6); climate change (SDG 13); affordable and clean energy (SDG 7); industrialization, innovation, and infrastructure (SDG 9); and no poverty (SDG 1) (Zeug et al. 2019). Nearly all of the named SDGs are developing problematically—hunger is rising again, consumption and productions patterns remain unchanged at a global level, the global material footprint is rapidly growing, and economic output and natural resource use are far from being decoupled (UN 2019; Zeug et al. 2020).

This shows that looking at a specific bioeconomy, in this case Germany, implies to look at its global effects. For this reason, the two depictions of bioeconomy, a new societal and economic development path as well as an improvement in specific products, should be merged and consequently the two main scales of bioeconomy sustainability assessment as well: a territorial (macro) and a product level (micro) (Bracco et al. 2019). However, the SDGs and their individual sub-goals cannot be applied directly to regional bioeconomy, rather they represent a general global political agenda (Zeug et al. 2019; Lyytimaki et al. 2020; UNEP 2020). So, they need to be applied and adapted by means of specific indicators. A particular focus has to be on different kinds of indicators, what bioeconomy aspects they are able to represent, and also how more abstract societal questions, like bioeconomy as a societal change, can be addressed by them. However, although there are no sets of indicators for merging a territorial and product scale to a regional scale (Linser and Lier 2020), a comprehensive review of possible indicators was presented in the FAO Indicators to Monitor and Evaluate the Sustainability of bioeconomy (Bracco et al. 2019). The latter study provides a suitable basis for our analysis.

A measurement and evaluation of sustainability, mainly at product level, is the central motivation of different approaches to life cycle assessments (LCAs). Within the broad spectrum of LCA approaches and methods, LCSAs as the most recent development are a combination or integration of social LCA (S-LCA), environmental LCA (E-LCA), and life cycle costing (LCC). As a relatively new field, LCAs and LCSAs are considered to be used for regional sustainability assessments (Balkau and Bezama 2019). This scope on regional bioeconomy as provisioning systems on a meso level, which we apply in the following, means to take up concrete production processes and imbedding them in their specific regional context with regard to global effects (Zeug et al. 2020). Regions differ in their socioeconomic and environmental conditions, with corresponding differences in strategies, research, and implementation. This implies that in future research we need especially meta- and sector-wide studies of regional and respective global effects and possible interventions (Ingrao et al. 2018; Fröhling and Hiete 2020).

However, LCSAs face the most significant problems, and in terms of indicators, impact assessment methods, normalization, weighting, aggregation as well as harmonization, many questions are open—but they also seem to have the most potential of empirical sustainability assessments (Balkau and Sonnemann 2017; Ingrao et al. 2018; Guinée 2016; Onat et al. 2017; Urban e al. 2018; OECD 2018). Currently, there are two main definitions or understandings of LCSA; on the one hand, the widely known combining and additive scheme (LCSA = E-LCA + LCC + S-LCA) (Klöpffer 2008)—based on the three-pillar approach, three different methods have to be standardized, harmonized, synchronized, and then combined. On the other hand, a far less established vision of an integrative approach (Guinée et al. 2011)—within a common sustainability concept, social, ecological, and economic aspects—should be integrated into a unified assessment and methodical framework. We evaluated the underlying assumptions and sustainability concepts of those two approaches as well as respective consequences for life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Zeug et al. 2020). In this previous work, we discussed extensively a variety of approaches based on existing reviews, as well as their pros and cons, which we not repeat in this study. Due to its more consistent character, we considered integrated LCSA as most appropriate for holistic sustainability assessments (cf. Sala et al. 2012b, a; Keller et al. 2015). We also set the conceptual basis and sustainability framework of our holistic and integrated LCSA (HILCSA), by introducing the SDGs and the transdisciplinary grounded theory of Societal Relations to Nature. Societal needs, provisioning systems, and ecological boundaries are not seen as separate entities, but rather as facets of one and the same object—industrial metabolisms and their provisioning systems, like bioeconomy (Zeug et al. 2020).

Recent comprehensive reviews, however, show that most LCSA approaches more or less follow the additive and not integrated scheme, yet (Costa et al. 2019; D'Amato et al. 2020; Wulf et al. 2019; Fauzi et al. 2019; Zimek et al. 2019; Troullaki et al. 2021). In sustainability concepts and LCSA in general, there are significant gaps regarding indicator sets, frameworks and software for implementation, databases, LCIAs, and applications of integrated but also additive LCSAs. As well as especially S-LCA and LCC are still under development and not robustly applicable (Wulf et al. 2018; Keller et al. 2015), which is likewise true for additive and integrated LCSA. However, integrative LCSA demands for even more consistent and mature methodologies as well as software implementation than the additive scheme does, which might be the main reason why additive LCSA is mainly used. A lack of harmonization and limited comparability is the consequence, and a variety of impact categories differ across studies and methods (Costa et al. 2019). Within S-LCA the selection of indicators, LCIAs and handling of (semi-)qualitative and quantitative indicators and results propose big challenges (Wulf et al. 2019; Guinée 2016). In LCC, questions arise on how to implement socioeconomic, mesoeconomic, and macroeconomic aspects beyond traditional microeconomic LCC (Zimek et al. 2019). In this regard, data availability and moreover existence of applicable databases are major constraints (Costa et al. 2019; Wulf et al. 2019). Which is particularly important, when it comes to more regionalized and spatially explicit datasets in order to improve quality of results (Fauzi et al. 2019). Having said that, it is just as important as taking planetary boundaries and global effects into account in LCSA by appropriate LCIAs (Chandrakumar and McLaren 2018b, a; Chandrakumar et al. 2018). In recent years, significant developments were made, especially in context of the European Commission-Joint Research Centre (EC-JRC) to integrate planetary boundaries and environmental footprints into E-LCA in order to allow mesoeconomic and macroeconomic assessments and conclusions by sector and product-specific bottom-up approaches (Sala and Castellani 2019; Sala et al. 2020; Bjørn et al. 2020; Robert et al. 2020; Fazio et al. 2018). Most of the shown issues go hand in hand with implementation of LCA and LCSA within a software environment, since development of LCA software, databases, and LCIA methods is mutually connected and depends on each other, as well as most LCA practitioners depend on them (Fritter et al. 2020). There are further practical challenges in the operationalization of LCSA and integrated LCSA, e.g., definition of coherent system boundaries, methods to conduct sensitivity and uncertainty analysis (Costa et al. 2019), rebound effects (Guinée 2016), trade-offs, biased decision making between social, economic, and environmental aspects (Fauzi et al. 2019) among others. In this study, we focus on the following research questions for setting up a practical framework for HILCSA:

> What are criteria and aspects for implementation and operationalization of HILCSA for bioeconomy regions? What should a scope, goal, interpretation, and most importantly an LCI and LCIA look like for this?

2 Methodology

First, the methodical point of departure is our previously developed HILCSA sustainability framework (Zeug et al. 2020) (Fig. 1, (1)). In this framework, we extensively discussed the background theory on sustainability and LCA as well as integrated social, ecological, and economic aspects assigned to specific SDGs and their corresponding sub-goals (Table 1). To transfer this theory and sustainability framework to LCA practice, in this study on implementation and operationalization of HILCSA, we followed the integrated LCSA approach, i.e., integration of these aspects and LCA methods in a common goal and scope, LCI, LCIA, results, and interpretation. There are currently two general methodical approaches for linking SDGs and LCA: (i) qualitatively linking existing LCA indicators and midpoints to SDGs as endpoints and (ii) quantitatively linking SDGs as midpoints to LCA indicators and endpoints (Weidema and Goedkoop 2019). For this research, we are following (i) implying to rather use existing LCA indicators and LCIA methods than to develop new LCIA methods and quantify specific cause and effect chains, since (ii) it is beyond the scope and limitations of this paper. The selection criteria for such existing LCA indicators, LCIA methods, software environments, and databases are as follows:

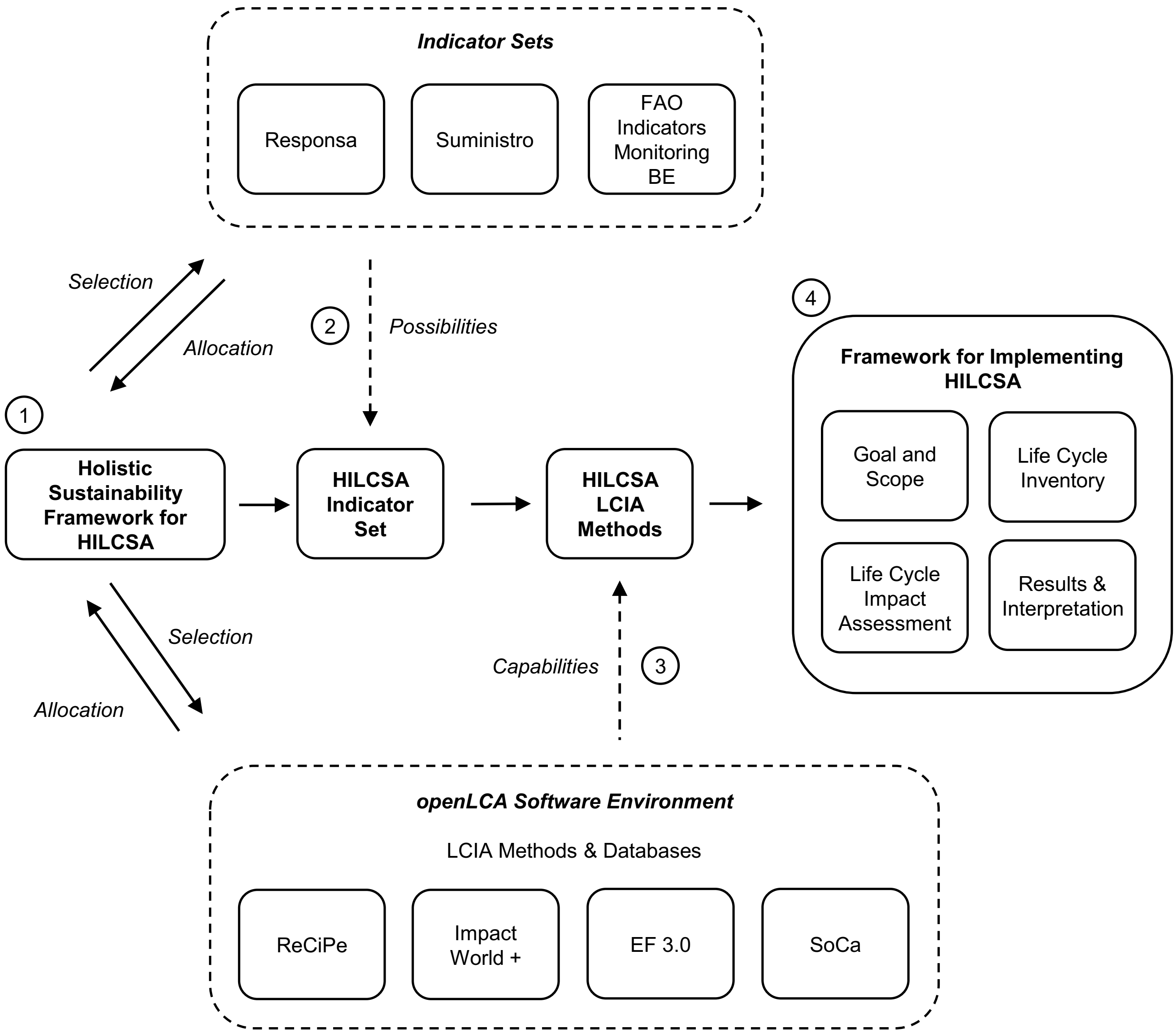

Fig. 1 Methodological steps for developing a framework for implementing holistic and integrated life cycle sustainability assessment (HILCSA) (LCIA life cycle inventory)

(a) Possibility of allocation to relevant SDG sub-goals and our HILCSA sustainability framework.

(b) Capability of the given software environment to operationalize and implement them.

Table 1 Relational entities, aspects, background methodologies, and assigned SDGs of HILCSA (Zeug et al. 2020)

	Relational entity, aspect, background methodology	Assigned SDGs
HILCSA	Societal needs, social, S-LCA	1. No poverty, 2. zero hunger, 3. good health and well-being, 4. Quality education, 5. gender equality, 11. sustainable cities and communities
	Provisioning System, economic LCA	6. Clean water and sanitation, 7. affordable and clean energy, 8. decent work and economic growth, 9. industry, innovation and infrastructure, 10. reduce inequalities, 12. responsible consumption and production, 16. peace, justice and strong institutions, 17. partnership for the goals
	Planetary boundaries, ecological, E-LCA	13. Climate action, 14. life below water, 15. life on land

(c) Maintain consistency and avoid redundancies in models.
(d) Relevance and applicability in regional bioeconomy.
(e) Transparency of methods and potential availability of data.

Thus, our methodology for developing a framework for implementation and operationalization of HILCSA is mainly guided by the relation between possibilities and capabilities of complex sustainability assessments.

2.1 Possibilities of indicator sets

Secondly, we select indicator sets from our previous research as well as a review of literature on indicators for bioeconomy assessment, and allocate them to the HILCSA sustainability framework (Fig. 1, (2)). From previous research, we take our attributional, retrospective RESPONSA S-LCA framework (Siebert et al. 2016, 2018a, b; Jarosch et al. 2020), and the SUMINISTRO framework designed to carry out an E-LCA combined with RESPONSA based on a multi-criteria decision analysis approach (Hildebrandt et al. 2018b; Hildebrandt et al. 2019; Hildebrandt et al. 2018a; Hildebrandt et al. 2020). However, even though E-LCA and S-LCA results in SUMINISTRO were additively combined by MCDA, there is no designated (integrated) LCSA approach. We allocate the indicators from RESPONSA and SUMINISTRO to the SDGs on basis of preliminary work (Jarosch et al. 2020) with some adjustments, thereby criteria a and e are meet.

From the literature review, we consider the FAO indicators to monitor and evaluate sustainability of bioeconomy (Bracco et al. 2019) as the most comprehensive and recent indicator review basis available, in order to expand existing methods. For this reason, we did not conduct any additional review on indicator sets. In Bracco et al. (2019), indicators were categorized as (i) territorial, to measure the impact of bioeconomy at national, regional, or sub-national level (contribution of bioeconomy to overall sustainability on a macro scale) and (ii) product level indicators in product systems (to measure impact at a microscale when replacing fossil fuel resources with biological resources) (Bracco et al. 2019). We allocate all FAO indicators from product and territorial level to the HILCSA sustainability framework (criteria a). For this, we use the already-made assignment by the authors as well as an assignment of all remaining or questionably assigned indicators by their best descriptive capability of addressing an SDG sub-goal. If we cannot assign indicators to a specific sub-goal, we assign them to SDGs which they deliver information on, even if these aspects were not foreseen in the general SDG framework.

As a result of this second step, we gain an extensive indicator set which describes the possibilities of HILCSA (Fig. 1, (2)) (Table 2).

2.2 Capabilities of software environments and LCIAs

A given software environment is a precondition to manage the enormous complexity behind LCA methods and data in order to make them applicable in future case studies (Zeug et al. 2021) in line with our framework. In the course of this work, it becomes clear that due to strong interdependencies, the development of a framework cannot be carried out independently of a specific software. In the third step (Fig. 1, (3)), we choose openLCA as the only software environment capable of incorporating social, ecological, and economic aspects in LCA as well as different functional units and activity variables (Di Noi and Ciroth 2018; Di Noi et al. 2018; Eisfeldt et al. 2017). In openLCA are S-LCA functionalities as well as SoCa and PSILCA as socioeconomic databases implemented and constantly further developed (criteria e). For social indicators, data, and LCIA, the only software implementation available is SoCa. Based on Ecoinvent, simultaneously making Ecoinvent the process database most suitable in this context to avoid incompatibilities (Eisfeldt et al. 2017; Di Noi and Ciroth 2018). Additionally, only openLCA aims explicitly at an implementation of integrated LCSA (Di Noi and Ciroth 2018; Di Noi et al. 2018). Even though there is no LCSA functionality in openLCA or application yet, openLCA was considered for this work as the most promising platform, also regarding a broad set of implemented LCIA methods (criteria b). Especially for environmental impacts, there are a variety of more or less well-established LCIA methods. To compile LCIAs for our indicator set and to define the capabilities, we select LCIA methods from literature and openLCA method database, which are able to address most SDG sub-goals at their midpoint or endpoint level, so we can allocate them to our framework (criteria a): open LCA-SoCa (Eisfeldt et al. 2017), openLCA-ReCiPe 2016 (H-Hierachrist) (Huijbregts et al. 2017), Impact World + (Bulle et al. 2019) and Environmental Footprint 3.0 (Fazio et al. 2018), and CED-Cumulated Energy Demand from openLCA (Table 2).

To finally gain an implemented and operationalized HILCSA framework in step four (Fig. 1, (4)), meeting all the defined criteria, we check for redundancies in the indicator set and LCIAs as well as maintain as much consistency as possible from each of the individual methods (criteria c). In a last step, we sort out all indicators which are not applicable and relevant in regional bioeconomy assessments (criteria d). For this, we use the relevances of corresponding SDGs and sub-goals, which we gained by stakeholder participation (Zeug et al. 2019), and keep all indicators whose SDGs must and may be part of bioeconomy monitoring. Not every

Table 2 Overview on LCA frameworks, indicators, and LCIA methods covering the SDG sustainability framework (coverage given, (x) number of (endpoint/midpoint) indicator coverage)

Sustainability framework (Zeug et al. 2020)	SDG code	RESPONSA (Jarosch et al. 2020)	SUMINISTRO (Hildebrandt et al. 2020)	FAO indicators (Bracco et al. 2019)		open LCA—SoCa and CED	openLCA—ReCiPe 2016 (H-Hierachrist)		Impact World +		Environmental Footprint 3.0
				Product level	Territorial level		Endpoint indicator	Midpoint indicator	Endpoint indicator	Midpoint indicator	
Societal needs	1	✓ (3)	✓ (2)	✓ (3)	✓ (9)	✓ (2)					
	2			✓ (23)	✓ (15)	✓ (2)	✓ (1)		✓ (1)		
	3			✓ (7)	✓ (11)	✓ (6)	✓ (7)	✓ (3)	✓ (7)	✓ (5)	✓ (5)
	4			✓ (3)	✓ (6)	✓ (7)					
	5	✓ (3)		✓ (5)	✓ (5)	✓ (1)					
	11			✓ (5)	✓ (2)						
Provisioning system	6		✓ (1)	✓ (6)	✓ (11)	✓ (2)					
	7		✓ (4)	✓ (4)	✓ (13)	✓ (2)					✓ (1)
	8	✓ (17)	✓ (16)	✓ (28)	✓ (40)	✓ (22)					
	9	✓ (1)	✓ (2)	✓ (1)	✓ (7)						
	10	✓ (1)	✓ (1)		✓ (6)						
	12		✓ (4)	✓ (105)	✓ (55)	✓ (9)	✓ (2)	✓ (3)		✓ (1)	✓ (1)
	16					✓ (2)					
	17				✓ (8)						
Planetary boundaries	13		✓ (1)	✓ (13)	✓ (9)			✓ (4)		✓ (3)	✓ (4)
	14			✓ (17)	✓ (16)		✓ (6)	✓ (5)	✓ (9)	✓ (5)	✓ (5)
	15		✓ (1)	✓ (26)	✓ (35)		✓ (6)	✓ (3)	✓ (5)	✓ (2)	✓ (2)

SDG indicator of global relevance necessarily plays a role in regional bioeconomy assessments, even when external or international effects are considered diligently. Still, LCAs and their indicators have to consider international effects, since first, using local or global indicators depends on the nature of environmental pressures and its causes (global-GHG, local-acidification), and second, a spatial dissociation between places of extraction, production, and consumption distributes social and economic effects globally (Parrique 2019). We furthermore test these tools and develop and apply methods of normalization, weighting, and aggregation to gain a consistent methodology. As a result, a comprehensive LCI and LCIA is set up (Table 4). Such a practical framework for HILCSA within limited capacities is only possible if it builds on existing and appropriate methods and research that to most extent meet the methodological criteria for HILCSA. Consequently, not every assumption of these approaches goes in line with our framework; some technical detail can only be discussed and regarded to a limited extend, and compromises have to be made.

3 Framework for implementation and operationalization of HILCSA

Previously, we discussed a sustainability framework for HILCSA, in contrast to the widely used three-pillar approach (Zeug et al. 2020). We define social sustainability as the long-term and global fulfillment of societal needs and social well-being as an end; ecological sustainability is the long-term stability of our environment as a basis of reproduction within planetary boundaries; economic sustainability stands for technologies and economic structures which are efficient, effective, and just provisioning systems relating societal needs and environment (Fig. 2, i). Basic for implementation and operationalization of this sustainability framework and HILCSA is the integrated approach, inspired by Guinee et al. (2011): HILCSA = f (S-LCA, E-LCA, LCC) as a holistic integration of social, economic, and ecological aspects in a common goal and scope, LCI, LCIA, results, and interpretation (Fig. 2, ii). Integration in this sense means.

- Horizontal holistic integration: integrating different aspects and categories of impacts (social, ecological, economic).
- Vertical integration: integrating scales and scopes (product and territorial into regional level) (Zeug et al. 2020; Sala et al. 2012b).

In the following, we present this framework (Fig. 2, ii), step by step structured likewise to ISO14040—goal and scope, LCI, LCIA, and interpretation.

3.1 Goal and scope

Goal of the HILCSA methodology and its future case studies is the assessment of social, environmental, and economic impacts as risks and chances of regional bioeconomy product systems, their contributions to the SDGs, and a socio-ecological transformation. In specific, this means to quantify and qualify social, environmental, and economic performance of bioeconomy product systems, to identify main hotspots, and when possible to compare this performance and hotspots with fossil product systems to understand the contribution of bioeconomy product systems to regional and global holistic sustainability.

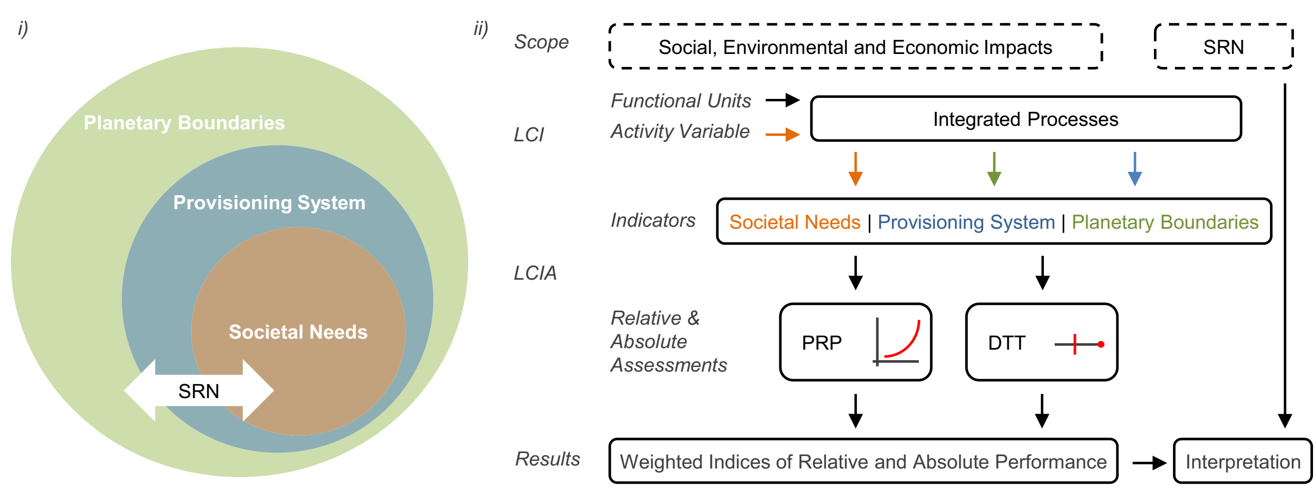

Fig. 2 (i) The integrated model of holistic sustainability in LCSA based on the Societal Relations to Nature and (ii) holistic and integrative scheme of HILCSA = f(S-LCA, E-LCA, LCC) based on (i) (SRN Societal Relations to Nature, PRP relative method of impact assessment by performance reference points, DTT absolute method of impact assessment by distance to target, LCI life cycle inventory, LCIA life cycle inventory) cf. (Zeug et al. 2020)

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Because wood has the greatest economic importance and most versatile use among renewable resources, the specific scope of our methodology and future case studies (Zeug et al. 2021) are regional wood-based bioeconomy product systems of Central Germany as a foreground system and, respectively, international/multi-regional interlinkages as background systems (UNEP 2020). Wood is not produced and used exclusively regional (Weimar 2015; Budzinski et al. 2017). Forests can provide increasing but limited resources for renewable materials, e.g., construction materials as laminated veneer lumber (LVL), and have a significant potential to mitigate climate change due to their capability of sequestering and storing carbon (Sahoo et al. 2019). LVL is an engineered wood product that uses multiple layers of more or less thin wood sheets assembled with adhesives like phenolic resin and manufactured as beams; it can substitute fossil-based construction materials like steel or steel concrete beams. However, when sustainable forest management is applied, a fully substitution of the existing material demand is unlikely, making absolute decreasing, optimal, and circular and/or cascading production and use even more critical (Sahoo et al. 2019; EU 2015). In general, due to the oftentimes decentral occurrence and cultivation of biomass, associated activities and their barriers are also of a regional and decentral character. The climate, soils, and cultivation practices can vary regionally and thus significantly determine biomass production, its regional distribution, and ecological barriers (O'Keeffe et al. 2016).

As usual, we model products and their life cycles as a product system (Fig. 3), reduced to its essential functions, characterized by material flows, and differentiated from the system environment by system boundaries. The product system contains all essential processes associated with the product and interactions with other systems. For describing its regional and global effects, the life cycle must be broken down into its essential process steps and unit processes. Generally, for wood-based products like LVL, the resource and first process step is roundwood—as well as residues from harvesting and processing (e.g., branches and bark) can be used for bioenergy and innovative biomaterials from cellulose (Sahoo et al. 2019)—feeding subsequent processing and conversion industries. Long and broad value-added networks can result from a cascade of utilization, recycling, and integrated bio-refineries entailing thermochemical, biochemical, and physicochemical conversion processes with a possible integration of by-products (Smetana et al. 2016). A simplified, model-based product system which is modularly designed is common in LCAs. Process steps are simplified as linear and chronologically occurring aggregates of unit processes. So, each step consists of at least one unit process as the smallest balancing unit, defined by the characteristic physical intermediate material flows and their qualitative change. In regional LCSA, these unit processes rarely describe specific technical processes, but mostly entire companies and production sites.

The geographical system boundaries are derived from economic boundaries, i.e., the main level of impacts can be regional, national, or global. In this regard, a geographic region is defined as a bioeconomy region when predominant economic activities of biobased production systems are concentrated and the majority of required primary raw materials

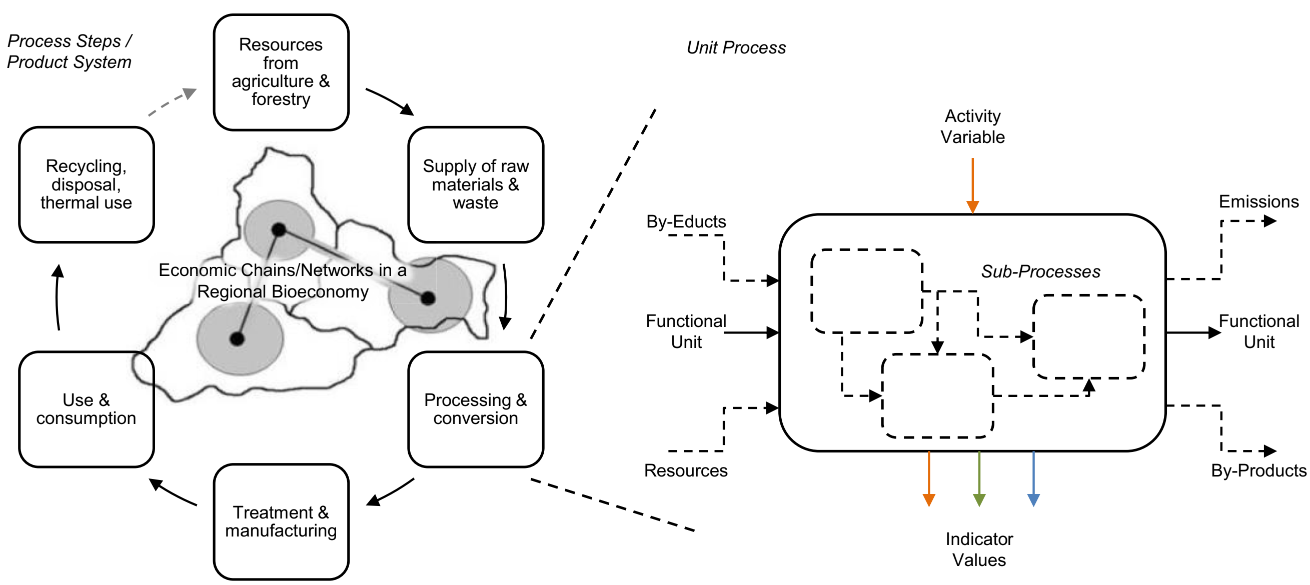

Fig. 3 Product system as process steps and unit processes in holistic and integrated life cycle sustainability assessment (HILCSA) of regional Bioeconomy

are obtained there, as well as social, economic, or ecological correlations with environment or society are significant in this very region (Siebert et al. 2016, 2018b). Because of the sustainability potential and most social impacts within the production sphere, as well as due to data availability, most LCA studies are conducted as cradle to gate (Suwelack 2016). Prospectively, this needs to be overcome in regard to circular economy as a basic principle of sustainable bioeconomy (use and recycling/disposal). Whereby the distribution sphere has not always to be considered, due to its comparatively low effect (despite of transport). As a general criterion, it is important to take all significant interactions with environment and society into account, as well as to make all neglected aspects transparent by cutoff criteria to be set.

Regarding the general character of the assessment, there is an ongoing debate on whether to assess sustainability in absolute or relative manner, and latest publications on E-LCA argue increasingly strong for an absolute environmental sustainability assessment (Bjørn et al. 2020; Castellani et al. 2016; Robert et al. 2020; Sala and Castellani 2019; Sala et al. 2020). Every relative assessment needs to have a reference on which the results depend in a qualitative and quantitative way, e.g., if the case to be observed is better than a reference of cases and how much it is. For example, within the common E-LCA of SUMINISTRO, an optimal product composition and an optimized feedstock mix for beach fiber laminate boards and LVL were identified to assess the potential mitigation of environmental impact when producing 1 m2 of such product. Such hotspot analyses meet the basic requirements of product system improvement. However, there is no or very limited information, if it performs "well enough" to be part of an environmentally sustainable economy, e.g., what the space for improvement is or has to be (Bjørn et al. 2020). Whereas absolute sustainability assessment methods (Chandrakumar and McLaren 2018b) compare specific impacts with external environmental carrying capacities (according to planetary boundaries) as impact pathways LCIAs (UNEP 2020), e.g., life cycle climate impacts are related to the 1.5° climate goal (Bjørn et al. 2020). However, introducing new parameters such as downscaled planetary boundary and complex cause-effect chains comes with a higher uncertainty due to limited knowledge at the current stage of research. Besides, for social (societal needs and social well-being as an end) and economic aspects (efficient, effective, and just provisioning systems), there are no defined quantitative boundaries, rather there are qualitative development pathways which are quite context specific (Jarosch et al. 2020; Siebert et al. 2018b; Hauschild et al. 2008; Zamagni et al. 2011). The social effects in RESPONSA are directly related to a specific intermediate product with means of an individually developed and context-specific set of indicators and data of federal statistical agencies. For such aspects, a relative sustainability assessment as reference scale LCIA (UNEP 2020) by calculating performance reference points (PRPs) on the basis of a distribution of reference value is applicable, and also the most common method in S-LCA (Jarosch et al. 2020; Siebert et al. 2018b).

3.2 Life cycle inventory

The operational core of HILCSA is integrated processes of regional bioeconomy product systems in the openLCA software environment. The process units are designed following the integrated LCSA approach (cf. Keller et al. 2015) and the openLCA implementation with SoCa. Such an LCI of HILCSA has to integrate a number of indicators of different character, on which we focus first.

3.2.1 Indicator system

From the studies and methods we consider, we identify in total 708 possible indicators for bioeconomy assessment on territorial and product level. The FAO indicator report (Bracco et al. 2019) provides the best overview of possible indicators, 248 on product level and 252 on territorial level, and is a helpful reference for setting up possibilities of an indicator system. While it does not provide directly applicable indicators or methods for HILCSA, taking it as a reference template and allocating LCIAs to it already produces a bioeconomy-specific indicator system. Thereof 566 nonredundant (criteria c) indicators can possibly be applied to regional bioeconomy assessments by allocating them to SDGs and our HILCSA sustainability framework (criteria a). These indicators describe 118 social, 130 ecological, and 318 economic aspects assigned to 74 SDGs and sub-goals (Table 2). For 95 SDG sub-goals, there are no indicators yet, mainly SDG 16, 17, 10, and 3. Especially for SDG 16, there are no direct indicator links in the current literature, and it is more a cross-cutting issue for bioeconomy (Calicioglu and Bogdanski 2021).

In the following, we keep all indicators whose relevance of corresponding SDGs is significant for bioeconomy monitoring (criteria d, "must and may be part of monitoring" (Zeug et al. 2019)), and which are available within LCIA methods and databases of openLCA (criteria b and e). Some of the SDG sub-goals and indicators which are not applicable in a LCSA of bioeconomy are excluded from the LCI (criteria b), e.g., policy coherence in sustainable development (SDG 17.14). As a result, we consider HILCSA capable of 109 indicators (Table 3). RESPONSA contributes 12 practically applicable indicators for the provisioning system and 4 indicators for societal needs (mostly addressing working conditions). Some RESPONSA indicators are left out since there is a redundancy and to high level of detail (Jarosch et al. 2020)

Table 3 Indicators, LCIA methods, and properties in HILCSA

Sustainability framework (Zeug et al. 2020)	SDG code	Source	ID	Indicator name	Data type	Functional unit/ activity variable	Unit of measurement	LCIA normalization	R (Zeug et al. 2019)
Societal needs	1	SoCa	1/1	Social security expenditures	quan	wh	% of GDP	PRP	6.61
	1.2	SoCa/RESPONSA	1.2/1	Payment according to basic wage	qual	wh	y/n	PRP	6.94
	1.4	RESPONSA	1.4/1	Capital participation	qual	wh	y/n	PRP	6.94
	1.4	RESPONSA	1.4/2	Profit-sharing and bonuses	qual	wh	y/n	PRP	
	2	Recipe/Impact World (Endpoint)	2/1	Water consumption—human health	quan	mf	Daly/m3 consumed	DTT	9.33
	2.3	SoCa	2.3/1	Human rights issues faced by indigenous people	quan	wh	Score	PRP	6.39
	2.3	SoCa	2.3/2	Presence of indigenous population	qual	wh	y/n	PRP	
	3.9	SoCa	3.9/1	DALYs due to indoor and outdoor air and water pollution	quan	wh	DALY rate	PRP	8.61
	3.9	SoCa	3.9/2	Pollution level of the country	quan	wh	Index	PRP	
	3.9	Recipe/Impact World (Endpoint)	3.9/3	Global warming—human health	quan	mf	DALY/kg CO2 eq	DTT	
	3.9	Recipe/Impact World (Endpoint)	3.9/4	Stratospheric ozone depletion—human health	quan	mf	DALY/kg CFC11 eq	DTT	
	3.9	Recipe (Endpoint)	3.9/5	Photochemical ozone formation—human health	quan	mf	DALY/kg NOx eq	DTT	
	3.9	Recipe/Impact World (Endpoint)	3.9/6	Ionizing radiation—human health	quan	mf	DALY/kBq Co-60 emitted to air eq	DTT	
	3.9	Recipe/Impact World (Endpoint)	3.9/7	Fine particulate matter formation—human health	quan	mf	DALY/kg PM2.5 eq	DTT	
	3.9	Recipe/Impact World (Endpoint)	3.9/8	Toxicity—human health (cancer)	quan	mf	DALY/kg 1,4-DCB emitted to urban air eq	DTT	
	3.9	Recipe/Impact World (Endpoint)	3.9/9	Toxicity—human health (non-cancer)	quan	mf	DALY/kg 1,4-DCB emitted to urban air eq	DTT	
	4	SoCa	4/1	Public expenditure on education	quan	wh	% of GDP	PRP	4.43
	5.1	SoCa	5.1/1	Gender wage gap	quan	wh	%	PRP	5.83
	5.1	RESPONSA	5.1/3	Rate of female employees	quan	wh	%	PRP	
	5.1	RESPONSA	5.1/6	Measures to improve gender equality	qual	wh	y/n	PRP	

Table 3 (continued)

Sustainability framework (Zeug et al. 2020)	SDG code	Source	ID	Indicator name	Data type	Functional unit/ activity variable	Unit of measurement	LCIA normalization	R (Zeug et al. 2019)
	11.6	Recipe/Impact World (End-point)	11.6/1	If production site is in urban region (annual mean levels of fine particulate matter (e.g., PM2.5 and PM10) in cities (population weighted), see 3.9/7				DTT	9.17
Provisioning System	6.1	SoCa	6.1/1	Drinking water coverage	quan	wh	%	PRP	8.61
	6.2	SoCa	6.2/1	Sanitation coverage	quan	wh	%	PRP	4.44
	6.4	FAO Product	6.4/1	Amount of water used in the whole forestry wood chain (m3) [8]/water consumption	quan	mf	m3/t	DTT	7.22
	7.2	FAO Product	7.2/1	Change in consumption level of fossil fuel resources/ product unit [2]	quan	mf	%	DTT	5.56
	7.2	CED	7.2/2	Share of fossil energies, CED	quan	mf	%	DTT	
	7.3	EF 3.0	7.3/1	Resource use, energy carriers	quan	mf	MJ	DTT	5.83
	7.3	CED	7.3/2	Cumulated energy demand	quan	mf	MJ	DTT	
	8.4	SUMINISTRO	8.4/1	Increasing the resource efficiency of biomass conversion	quan	mf	w/w	DTT	5.83
	8.4	SUMINISTRO	8.4/2	Cascading factor	quan	mf	w/w	DTT	
	8.4	SUMINISTRO	8.4/3	Maximizing land use efficiency (forest biomass, agroforestry and agrarian biomass)	quan	mf	t saw logs/ha, t fiber/ha, t sugar/ha, t pulp/ha, t/ha t/t sucrose	DTT	
	8.4	SUMINISTRO	8.4/4	Increase in material efficiency	quan	mf	e.g., *U* value, tensile modulus	DTT	
	8.5	SoCa/ RESPONSA	8.5/1	Weekly hours of work per employee	quan	wh	h	PRP	5.00
	8.5	RESPONSA	8.5/2	Compensation for overtime	qual	wh	y/n	PRP	
	8.5	RESPONSA	8.5/3	Access to flexible working time agreements	qual	wh	y/n	PRP	
	8.5	RESPONSA	8.5/4	Rate of part-time employees	quan	wh	%	PRP	
	8.5	RESPONSA	8.5/5	Rate of marginally employees (max. 450€)	quan	wh	%	PRP	
	8.5	RESPONSA	8.5/6	Rate of fixed-term employees	quan	wh	%	PRP	
	8.5	RESPONSA	8.5/7	Rate of employees provided by temporary work agencies	quan	wh	%	PRP	

Table 3 (continued)

Sustainability framework (Zeug et al. 2020)	SDG code	Source	ID	Indicator name	Data type	Functional unit/ activity variable	Unit of measurement	LCIA normalization	R (Zeug et al. 2019)
	8.5	RESPONSA	8.5/8	Rate of disabled employees	quan	wh	%	PRP	
	8.5	RESPONSA	8.5/9	Rate of foreign employees	quan	wh	%	PRP	
	8.5	SoCa	8.5/10	Net migration rate	quan	wh	‰	PRP	
	8.5	SoCa	8.5/11	International migrant stock	quan	wh	%	PRP	
	8.5	SoCa/ RESPONSA	8.5/12	Average remuneration level	quan	wh	€	PRP	
	8.5	SoCa	8.5/13	Sector average wage, per month	quan	wh	USD	PRP	
	8.5	SoCa	8.5/14	Unemployment rate in the country	quan	wh	%	PRP	
	8.6	RESPONSA	8.6/1	Rate of vocational trainees	quan		%	PRP	4.72
	8.7/8.8	SoCa	8.7/2	Children in employment, total	quan	wh	% of children	PRP	5.00
	8.7/8.8	SoCa	8.7/5	Trafficking in persons	quan	wh	Tier	PRP	
	8.7/8.8	SoCa	8.7/6	Frequency of forced labor	quan	wh	‰	PRP	
	8.7/8.8	SoCa	8.7/7	Goods produced by forced labor	quan	wh	#	PRP	
	8.7/8.8	SoCa	8.7/8	Right of collective bargaining	quan	wh	Score	PRP	
	8.7/8.8	SoCa	8.7/9	Right of association	quan	wh	Score	PRP	
	8.7/8.8	SoCa	8.7/10	Trade union density	quan	wh	%	PRP	
	8.7/8.8	SoCa	8.7/11	Right to strike	quan	wh	Score	PRP	
	8.7/8.8	SoCa/ RESPONSA	8.7/12	Rate of non-fatal accidents at workplace	quan	wh	#/year and 100 k empl	PRP	
	8.7/8.8	SoCa/ RESPONSA	8.7/13	Rate of fatal accidents at workplace	quan	wh	#/year and 100 k empl	PRP	
	8.7/8.8	RESPONSA	8.7/14	Sick-leave days	quan	wh		PRP	
	8.7/8.8	SoCa/ RESPONSA	8.7/15	Presence of sufficient safety measures	quan	wh	# per 100 k empl	PRP	
	8.7/8.8	RESPONSA	8.7/16	Measures to support older employees	qual	wh	y/n	PRP	
	8.7/8.8	SoCa	8.7/19	Evidence of violations of laws and employment regulations	quan	wh	# per 1 k empl	PRP	
	8.7/8.8	SoCa	8.7/20	Workers affected by natural disasters	quan	wh	%	PRP	
	9.5	RESPONSA	9.5/1	Rate of employees in research and development	quan	wh	%	PRP	5.83

Table 3 (continued)

Sustainability framework (Zeug et al. 2020)	SDG code	Source	ID	Indicator name	Data type	Functional unit/activity variable	Unit of measurement	LCIA normalization	R (Zeug et al. 2019)
	12.2	SoCa	12.2/4	Level of industrial water use (related to total withdrawal)	quan	mf	% of total	PRP	8.89
	12.2	SoCa	12.2/5	Level of industrial water use (related to renewable water resources)	quan	mf	% of renewable	PRP	
	12.2	Recipe/Impact World (Endpoint)	12.2/6	Fossil resource scarcity	quan	mf	USD2013/kg Cu	DTT	
	12.2	SoCa	12.2/7	Extraction of fossil fuels	quan	mf	t/cap	PRP	
	12.2	SoCa	12.2/8	Extraction of biomass (related to population)	quan	mf	t/cap	PRP	
	12.2	SoCa	12.2/9	Extraction of biomass (related to area)	quan	mf	t/km2	PRP	
	12.2	SoCa	12.2/10	Extraction of industrial and construction minerals	quan	mf	t/cap	PRP	
	12.2	SoCa	12.2/11	Extraction of ores	quan	mf	t/cap	PRP	
	12.2	EF 3.0	12.2/12	Resource use, mineral and metals	quan	mf	kg Sb eq	DTT	
	12.2	Recipe (Midpoint)	12.2/13	Ionizing Radiation	quan	mf	Bq C-60 eq. to air	DTT	
	12.5	SUMINISTRO	12.5/1	Reduction of waste from fossil-based auxiliaries	quan	mf	%	DTT	9.17
	12.5	SUMINISTRO /FAO Product	12.5/2	Maximizing the recycled content at the end of its life/% of product is actively being recovered and recycled [5]	quan	mf	%	DTT	
	12.6	SUMINISTRO	12.6/1	Maximizing or guaranteeing high standards of raw material provision	quan	mf		DTT	8.61
	12.6	SoCa	12.6/2	Certified environmental management systems	quan	mf	# per 10 k empl	PRP	
	12.6	SoCa	12.6/3	Presence of anti-competitive behavior or violation of anti-trust and monopoly legislation	quan	mf	# per 10 k empl	PRP	
	16.5	SoCa	16.5/1	Public sector corruption	quan	mf	Score	PRP	7.22
	16.5	SoCa	16.5/1	Active involvement of enterprises in corruption and bribery	quan	mf	%	PRP	

Table 3 (continued)

Sustainability framework (Zeug et al. 2020)	SDG code	Source	ID	Indicator name	Data type	Functional unit/activity variable	Unit of measurement	LCIA normalization	R (Zeug et al. 2019)
Planetary Boundaries	13	EF 3.0	13/1	Climate change	quan	mf	kg CO2 eq	DTT	7.53
	13	EF 3.0	13/2	Climate change (fossil)	quan	mf	kg CO2 eq	DTT	
	13	EF 3.0	13/3	Climate change (biogenic)	quan	mf	kg CO2 eq	DTT	
	13	Recipe (Midpoint)	13/9	Photochemical ozone formation, Ecosystems/photochemical ozone formation, human health	quan	mf	kg NO*x* eq	DTT	
	13	Recipe/Impact World (Midpoint)	13/10	Stratospheric ozone depletion	quan	mf	kg CFC-11 eq	DTT	
	13	EF 3.0	13/20	Climate change (land use change)	quan	mf	kg CO2 eq	DTT	
	14	Recipe (Endpoint)	14/1	Global warming—freshwater ecosystems	quan	mf	Species year/kg CO2 eq	DTT	8.37
	14	EF 3.0	14/2	Eutrophication freshwater	quan	mf	kg P eq	DTT	
	14	EF 3.0	14/3	Ecotoxicity freshwater	quan	mf	CTUe	DTT	
	14	EF 3.0	14/4	Water scarcity	quan	mf	m3 world equiv	DTT	
	14	EF 3.0	14/5	Acidification terrestrial and freshwater	quan	mf	Mole of H + eq	DTT	
	14	Impact World (Endpoint)	14/6	Thermally polluted water	quan	mf	PDF m2 year	DTT	
	14	Impact World (Endpoint)	14/7	Water availability, freshwater ecosystem	quan	mf	PDF m2 year	DTT	
	14.1	Recipe (Endpoint)	14.1/1	Toxicity—marine ecosystems	quan	mf	species•year/kg 1,4-DBC emitted to sea water eq	DTT	8.33
	14.1	EF 3.0	14.1/2	Eutrophication marine	quan	mf	kg N eq	DTT	
	14.3	Impact World (Endpoint)	14.3/1	Marine acidification, long term	quan	mf	PDF m2 year	DTT	6.94
	14.3	Impact World (Endpoint)	14.3/2	Marine acidification, short term	quan	mf	PDF m2 year	DTT	
	15.1	EF 3.0	15.1/1	Land use	quan	mf	Pt	DTT	7.50
	15.1	Recipe (Midpoint)	15.1/2	Terrestrial acidification	quan	mf	kg SO2 eq	DTT	
	15.1	Recipe (Midpoint)	15.1/3	Terrestrial ecotoxicity	quan	mf	kg 1,4-DB eq	DTT	
	15.1	Impact World (Endpoint)	15.1/4	Water availability, terrestrial ecosystem	quan	mf	PDF m2 year	DTT	
	15.1	EF 3.0	15.1/5	Eutrophication terrestrial	quan	mf	Mole of N eq	DTT	
	15.5	Recipe (Endpoint)	15.5/1	Global warming—terrestrial ecosystems	quan	mf	Species year/kg CO2 eq	DTT	8.33

Table 3 (continued)

Sustainability framework (Zeug et al. 2020)	SDG code	Source	ID	Indicator name	Data type	Functional unit/activity variable	Unit of measurement	LCIA normalization	R (Zeug et al. 2019)
	15.5	Impact World (Endpoint)	15.5/2	Ionizing radiation, ecosystem quality	quan	mf	PDF m2 year	DTT	
	15.5	EF 3.0	15.5/3	Land occupation, biodiversity/land transformation, biodiversity	quan	mf	m2 arable land eq year	DTT	
	15.5	Recipe (Endpoint)	15.5/4	Photochemical ozone formation—terrestrial ecosystems	quan	mf	Species.year/kg NOx eq	DTT	
	15.5	Recipe (Endpoint)	15.5/5	Acidification—terrestrial ecosystems	quan	mf	Species.year/kg SO2 eq	DTT	
	15.5	Recipe (Endpoint)	15.5/6	Toxicity—terrestrial ecosystems	quan	mf	species year/kg 1,4-DBC emitted to industrial soil eq	DTT	
	15.5	Recipe (Endpoint)	15.5/7	Water consumption—terrestrial ecosystems	quan	mf	Species year/m3 consumed	DTT	

EF Environmental Footprint, *LCIA* life cycle impact assessment, *PRP* performance reference point, *DTT* distance to target, *R* relevance of SDG and sub-goals, *wh* working hours, *mf* material flow, *qual* qualitative, *quan* quantitative

or SoCa covers them. When indicators are already available within an established LCIA method, we prefer them because of their better practicability and robustness. The same is true for SUMINISTRO, delivering valuable data for later case studies (Hildebrandt et al. 2020; Siebert et al. 2018b) and 7 indicators mainly including technological process characteristics (e.g., efficiencies, cascading factor). All other (midpoint/endpoint) indicators come with the LCIA methods available in openLCA (Acero et al. 2016) and chosen for HILCSA: SoCa, ReCiPe 2016 (H), Impact World +, and EF 3.0.

As a typical consequence in LCSA, this framework is not as detailed as in stand-alone methods (Taylor et al. 2017). Rather, the goal is to avoid a piecemeal approach to sustainable transformation and the capability of delivering a holistic picture on trade-offs, synergies, hotspots, significant risks, and chances as well as a fundamental understanding (Zeug et al. 2020). In addition, more indicators do not necessarily lead to a better quality necessarily, but an adequate impact category coverage is of particular importance (Lindqvist et al. 2019). The 109 possbile indicators are already quite much compared to most other studies and potential data availability.

In Table 3, we allocate all indicators to our sustainability framework (societal needs, provisioning system, planetary boundaries) (Zeug et al. 2020), the SDG subgoals (or SDGs) by the official SDG codes (UN 2015), and gave them a HILCSA-specific ID composed of the SDG code and the sequential number of indicators of this SDG. Indicators have a qualitative (categorical, limited number of values) or quantitative (continuous, unlimited number of values) type of data. Qualitative indicators mostly occur when specific measures (yes/no) in societal needs and the provisioning system are evaluated. We also categorize all indicators by having a physical functional unit (material flow) or an activity variable (working hours) (see Sect. 3.2.2), and their unit of measurement which is the same as from the source of the indicator. As mentioned, the indicators of HILCSA have an absolute (impact pathway) or relative (reference scale) character important for their LCIA (see Sect. 3.3). The relevance of the indicator is derived from the respective relevance of its SDG and sub-goals according to our stakeholder participation process, and shown as a decimal score ranging from 4.43 to 9.33 (Zeug et al. 2019, 2020).

Since all indicators in the LCI are not modified and are integrated in HILCSA as they were presented in their original studies, we will not discuss any indicators individually here, but refer to the relevant literature.

3.2.2 Functional units and activity variables

Only one functional unit or reference material flow is not sufficient for accounting impacts on social, economic, and ecological systems. Rather, additional activity variables need to be used (Costa et al. 2019; Urban et al. 2018; Zamagni et al. 2013). The activity variable for balancing social and some economic impacts has similarities with elementary flows, and is used to represent the impact share of a process step or unit process (UNEP 2020). The crucial difference is that most social as well economic effects of the production of a commodity are not directly related to the amount of physical output of a process, but are mediated through complex socioeconomic relations (Zeug et al. 2020; Dreyer et al. 2006; Benoit et al. 2006). From those can be derived that socioeconomic effects are balanced by the number of working hours required to produce the functional unit (UNEP 2020; Zeug et al. 2020; Siebert et al. 2018b). Nevertheless, working hours are quite indirectly related to some social indicators, e.g., drinking water coverage or displacements of local communities, for which new approaches are under development (Ciroth et al. 2019; UNEP 2020).

In case of material use of wood products generally, a unit, volume, or mass of products (material flow) is used as functional unit (Sahoo et al. 2019), e.g., the production of 1-m3 LVL. When several conversions take place or a complex regional bioeconomy product system is assessed, it is difficult to break everything down to one final product as functional unit, since calculations can easily get unpractical (e.g., properties of wood products and educts such as variable water content result in variable mass and volume as well as a variety of different end-products). Therefore, the resource-related mass of wood fiber equivalent (WFE) of the end products should be considered (Weimar 2015; Budzinski et al. 2017), excluding water and additives and confining the functional unit to the actual mass fraction of lingo celluloses in each process step and unit process.

For our purposes, openLCA with SoCa as software environment for implementation of HILCSA sufficiently supports a variety of functional units (mass, volume, product units, WFE) as well as working hours as activity variable.

3.3 Life cycle impact assessment

Like in LCA and S-LCA, the LCIA aims at calculating, understanding, and evaluating the magnitude and significance of actual or potential impacts of a product system throughout the life cycle (UNEP 2020). Within the LCIA, we link indicators by classification, normalization, weighting, and aggregation to the sustainability framework and the SDGs as well as sub-goals as end point impact categories. From 109 indicators, we assign 20 to societal needs, 60 to the provisioning system, and 29 to planetary boundaries—thereby covering 30 SDGs and sub-goals (Table 3). Only SDG 17 and 10 cannot be addressed at all. The SDG sub-goals 8.7 (worker rights, abolition of forced labor/trafficking/child labor) and 8.8 (worker rights, labor protection rights, promoting safe work environment) were merged, since they differ not significantly in terms of impact categories and a better aggregation and weighting is possible.

As part of the LCIA, in RESPONSA and partly SUMINISTRO, the performance of organizations of the life cycle was compared with a statistical reference and resulting dimensionless PRPs (Siebert et al. 2018b) give an indication on the social performance of a product life cycle (e.g., LVL) (Jarosch et al. 2020; Hildebrandt et al. 2020). For most of the planetary boundaries—indicators and some indicators of societal needs, whose effects have their cause in physical emissions, we follow impact pathway LCIA approaches to assess consequential social impacts through characterizing the cause-effect chain (cf. (UNEP 2020)).

There are a series of heterogeneous and mostly incompatible environmental LCIA methods for the environmental assessment of bioeconomy value-added chains (Cristóbal et al. 2016), but we follow the recommendation of the EC-JRC by using the LCA-based Product Environmental Footprint (PEF) methods (Fazio et al. 2018) (EC and JRC 2010). Environmental Footprint can be seen as the most robust and comparable environmental accounting concept (Manfredi et al. 2015). Environmental Footprint and PEF are most suitable in HILCSA because of two main reasons: They provide a best practice to include global effects into a meso-level assessment such as LCSA, and thereby bridge the gap to global and national goal systems like the SDGs (Wulf et al. 2018) as well as planetary boundaries. The growing importance of planetary boundaries and the finite nature of the environment led to absolute sustainability assessment methods in LCA, recently (Bjørn et al. 2020; Sala et al. 2020). Absolute sustainability assessment methods evaluate if an industrial metabolism on different scales (ranging from products, regions to whole economies) is (un-)sustainable in an absolute sense of regional and global boundaries for a comprehensive set of impact categories (Bjørn et al. 2020). However, there are planetary boundaries, SDGs, and sub-goals not covered by Environmental Footprint (e.g., ozone formation/depletion, loss of biodiversity, terrestrial acidification/toxicity) (Chandrakumar and McLaren 2018b) for which we chose midpoint and endpoint indicators from ReCiPe 2016 (H-Hierachrist) (Huijbregts et al. 2017; Huijbregts 2016) and Impact World + (Bulle et al. 2019). In ReCiPe 2016, the hierarchist perspective is chosen, since it represents the scientific consensus with regard to timeframe and plausibility of impact mechanisms (Huijbregts

2016). For some midpoint indicators which are highly regional specific (e.g., water availability), the Impact World + LCIA is more appropriate, because of country default, and native resolutions (Bulle et al. 2019). However, Impact World + is still to be implemented in openLCA in near future.

Combining several LCIA methods within one framework is necessary to cover all impact categories and not per se problematic (Wulf et al. 2017; Di Noi and Ciroth 2018). Though, a consistent implementation of several LCIA requires a careful analysis of their units, impact factors, and normalization methodologies (e.g., SoCa uses risk levels and specific impact factors which have to be applied to the PRPs and are not comparable and cannot be aggregated with plain results of ReCiPe or Environmental Footprint) as well as to avoid double counting one impact in several LCIAs and impact categories. Nevertheless, in the following case studies (Zeug et al. 2021), a sensitivity analysis is required to cross-check for impact shifting. We do not change the different LCIA methods or characterization factors in order to keep consistency (criteria c). For all other indicators, we do not conduct any impact pathway characterization, but follow directly a reference-scale assessment approach (see Sect. 3.3.1) (UNEP 2020).

Even more important and controversial in LCSA than in LCA are the optional steps of normalization, weighting, and aggregation of impact categories, due to increased complexity of results and how to communicate them to different stakeholders (Wulf et al. 2017; Andreas et al. 2020). At this early stage of overall method development, in future case studies, we will present plain results as well as normalized, weighted, and aggregated results (Valdivia et al. 2012; Wulf et al. 2017).

3.3.1 Normalization

In order to compare different indicators and impact categories with different units with each other, various forms of normalization in LCIA can be performed at midpoint and endpoint levels (Andreas et al. 2020). This is a prerequisite for aggregation as well (Wulf et al. 2017). In general, normalization can be done by internal reference (maximum/minimum values or ratios from within the LCI) or external reference (external data of systems and rankings) (Prado et al. 2012; Wulf et al. 2017). Provided that internal normalization comes with several fundamental methodological issues, we prefer recommended external normalization (ibid.). However, external normalization factors can increase uncertainty of the whole assessment (Wulf et al. 2017), and the choice of reference values plays a vital role (Sala et al. 2012a).

Normalization in HILCSA requires to incoporate two types of LCIAs (Fig. 4): (i) the relative performance of a particular bioeconomy system in relation to a reference system and (ii) the absolute benchmarking of a particular bioeconomy system against planetary boundaries. Therefore, available methods of impact assessment are the following: (i) PRPs as reference scale approach and (ii) distance to target (DTT) as impact pathway approach. On the one hand, measurements of relative performance can compare provisioning systems like bioeconomy at their status quo and do not rely on global models, quantitative goals, or thresholds. This is especially true for impact categories of societal needs and provisioning systems to which (i) relative PRPs are mostly applied. They have accompanied S-LCA methods for a long time in various forms (Traverso et al. 2012; Siebert et al. 2018b). On the other hand, absolute

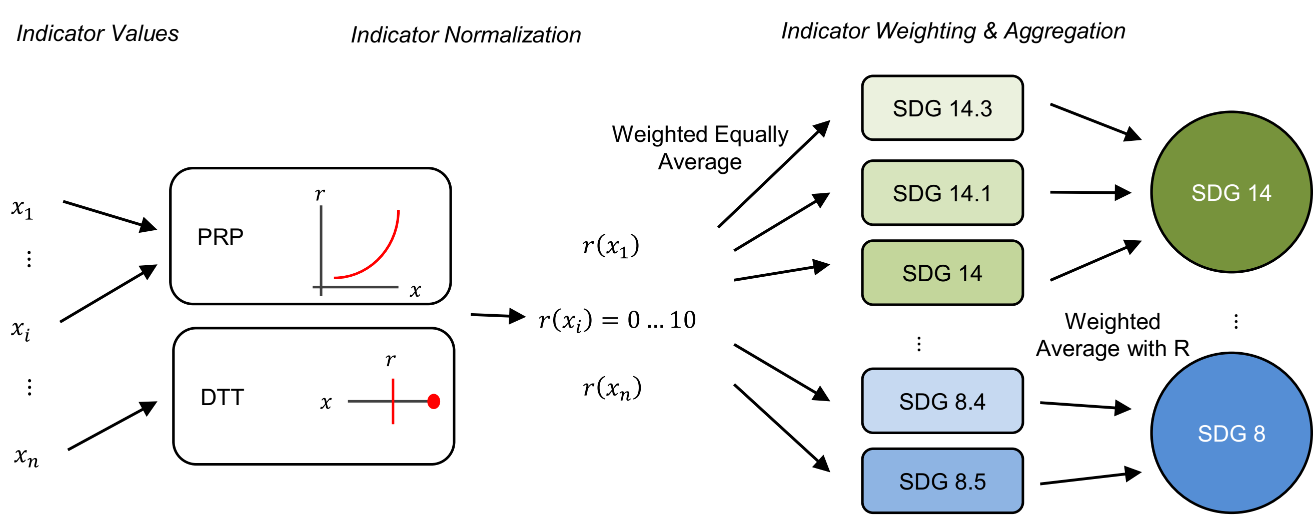

Fig. 4 Scheme of indicator normalization, weighting and aggregation (SDG sustainable development goals, PRP relative method of impact assessment by performance reference points, DTT absolute method of impact assessment by distance to target)

sustainability assessment methods are concerned with the potential transgression of regional and global boundaries (Bjørn et al. 2020). Only absolute measurements can provide information on whether the status quo of even one of these provisioning systems is sufficiently sustainable at all, and if not, how much. Therefore, the impact category planetary boundaries are normalized by (ii) absolute DTT. In the end, integrated LCSAs entail many different indicators, measurements, and units. Thus, dimensionless scores are necessary and practical to allow comprehensibility. We carry out evaluations by calculations, which use distributions, threshold values, benchmarks, or ideals as measurement scales and output result for PRP and DTT in a dimensionless score r ranging from $r_{\min} = 0$ to $r_{\max} = 10$ (Siebert et al. 2016). The score $r_{\min}$ represents the worst performance and $r_{\max}$ the best performance (Siebert et al. 2018b). This approach in general can be applied on a global, national, sectoral, regional, and product-specific level.

3.3.1.1 Performance reference points The normalization method of PRPs for quantitative and qualitative indicators was extensively discussed in our previous studies (Siebert et al. 2016, 2018b, a; Jarosch et al. 2020; Hildebrandt et al. 2020): The reference, against which assessment takes place, is not a singular value, but a spectrum of values we interpret as a distribution of an indicator i. The databases of the SDGs as well as Ecoinvent for ecological and the IAB as well as the Federal Statistical Office for social and economic indicators are sources of these reference data. Especially reference data of context-specific relative indicators have to be differentiated by region and sector of activity in a regional bioeconomy (Siebert et al. 2018b). The valuation, based on the assignment of scores to indicator expressions, is actually an ordinal scale, but treated as a cardinal scale for aggregation calculations (UNEP 2020). For detailed information on PRP methodology, see Appendix 1. Similar to PRP, the SoCa LCIA and its implementation in openLCA apply different scores for qualitative and quantitative indicators which in the end are assigned to risk levels (very low risk; low risk; medium risk; high risk; very high risk) (Eisfeldt 2017). In future case studies, we will combine these two approaches by assigning risk levels to PRPs and vice versa (Zeug et al. 2021).

3.3.1.2 Distance to target The planetary boundaries describe carrying capacities as instrumental values of natural resources and ecosystem services, e.g., in case of bioeconomy as renewable resource use: the maximum persistent impacts environments can sustain, without suffering perceived unacceptable impairment of their functional integrity (Bjørn et al. 2020; Bjørn and Hauschild 2015). These carrying capacities are mostly a combination of policy targets and biophysical (science-based) thresholds (Chandrakumar and McLaren 2018b; Sala et al. 2020). However, LCIA results cannot be compared directly against planetary boundaries (Sala et al. 2020), but they can be downscaled to a specific region, and under certain circumstances to a regional provisioning systems, when a share based on one or more normative sharing principles (e.g., equal per capita) is assigned to them (Ryberg et al. 2020; Bjørn et al. 2020; O'Neill et al. 2018). In principle and analogously to PRP, these targets values can serve as normative best practice in reference and therefor rated with $r_{\max}$ if not transgressed. Although there are huge efforts on EU level towards this promising approach (Sala et al. 2020), currently in context of this very study, it seems not feasible to the authors to operationalize an absolute sustainability assessment methods for planetary boundaries allowing to calculate a product specific environmental threshold, e.g., how much kg CO2 eq. per product or regional bioeconomy network can be considered as (un-)sustainable. Rather, in the meanwhile, the planetary boundaries give us an indication on how much a certain planetary boundary is stressed for a specific region, hence how urgent the reduction of regional impacts in this impact category is. This has been adopted as normalization reference in the Environmental Footprint method (Bjørn and Hauschild 2015; Sala et al. 2020) and as DTT weighting factors (Castellani et al. 2016).

3.3.2 Weighting and aggregation

In contrast to additive LCSA methods—where separate and different results of S-LCA, E-LCA, and LCC are at the end additively combined by MCDA—for our SDG oriented HILCSA, we use the relevances of SDG sub-goals given by stakeholders as exogenous weightings of indices on different levels of aggregation (Table 3, Fig. 4). Aggregations reduce complexity of assessments to easier communicate results and to avoid cherry picking (Schmidt-Traub et al. 2017) (analytical-reductionist approach). However, holistic and integrated assessments should be able to manage these complexities as well (systematic-interactionist approach) (Malik 2015), to simplify without curtailing. There are, however, limits to the extent to which indicators should be aggregated into indices. On the one hand, the degree of aggregation depends on the purpose and addressees of the study, so that a balance must be made between the degree of detail required for the greatest possible significance and when this becomes too complex for general comprehensibility. On the other hand, additive links at a high level of aggregation can only be realized, if they do not exhibit linear dependencies, i.e., collinearities leading to double counting (e.g., when SDGs 8.7 and 8.8 if separate).

If more than one normalized indicator rating is classified to an SDG or sub-goal, which is mostly the case, we conduct a linear aggregation by the method of equally weighted averages (Wulf et al. 2017). Afterwards, each of the SDGs and sub-goals has an own score assigned, and so each impact category is quantitatively represented by an impact category index. The relevancies of the SDG sub-goals for bioeconomy monitoring (Zeug et al. 2019, 2020) determine the endpoint weightings in our LCIA. A weighted average according to the relevance calculates scores for each of the SDGs and in total for societal needs, provisioning system and PB as end point categories.

3.4 Interpretation

In the final phase of interpretation, the aim is twofold: to perform completeness, consistency, sensitivity, and data quality checks (UNEP 2020) as well as to create an as complete and concrete as possible picture of the sustainability of a life cycle. Those results are put in context to an ideal or desirable bioeconomy and the contribution of a regional bioeconomy for implementing the SDGs (Zeug et al. 2020). Risks, chances, synergies, and trade-offs are interpreted and possible conclusions and solutions proposed. It is important to consider that the empirical reality behind indicators can interact with more than one goal, and also can be contradictory to each other or associated with trade-offs. The focus is especially on contradictions and trade-offs between economical, ecological, and social issues; which process steps are relevant for most of the impacts (hotspot analysis and pareto-effects (Halog and Manik 2011)); and to what extent structures of a bioeconomy are sustainable or more sustainable than a (fossil) reference. The data quality of the entire analysis must be considered here with regard to quality of statements, and presented in the results (UNEP 2011).

Dependencies, interlinkages, limitations, and the named shortcomings of LCSAs are discussed and addressed. The previously conducted LCI and LCIA alone leads to a positivist empiricism that alone has very limited ability to address visions and imperatives from a complex sustainability framework. The developed methods, especially the rating and evaluation methods, should be presented to stakeholders to reflect and consolidate them, in particular to calibrate weightings (Suwelack 2016). Moreover, the results should be able to specifically address questions of associated research on governance in context of science-policy interfaces (Gawel et al. 2016), meaning to identify concrete fields of potential action and regulation from the results. The following questions should be addressed by the results and their interpretation: What are the social, economic, and environmental impacts of a regional bioeconomy system? What are the allocated social, economic, and biophysical needs and limits of this bioeconomy system? Which interventions in the system may be able to bring the system within these needs and limits?

By using the SDGs as a framework, it is possible to set the results in context of exiting monitoring activities (Schmidt-Traub et al. 2017), e.g., national bioeconomy monitorings like SYMOBIO (Bringezu et al. 2020) and the EU biomonitor (BioMonitor 2018). Beyond this, the scientific community in LCSA should strive to established more uniform formats of presenting results, e.g., like Life Cycle Sustainability Dashboards (Traverso et al. 2012).

4 Discussion

Regarding the goals and scopes, a regional HILCSA is able of bridging scales (levels): focusing on an assessment of regional bioeconomy as provisioning systems (meso) is able to connect regional (micro) societal needs and the contribution to social SDGs (macro), as well as linking impacts on global environmental and resource systems like planetary boundaries (macro) (micro). This is important, since although strong efforts are made to improve the ecological performance of products at micro level, only a limited to non-existent effect at macro level is achieved yet (Guinée 2016). The environmental-economic significance of LCSAs in this regard can also be shown by the well-known IPAT identity (Common and Stagl 2012). IPAT describes effects on economic growth and environment I (Impact), which are generally dependent on population P (Population), per capita consumption A (Affluence), and production technologies T (Technology). Previous E-LCAs basically focused on environmental pollution per functional unit of a commodity and thus represent no more than a "super micro" analysis by T (Guinée 2016). Regionalized HILCSA extends this microanalysis to A and I. At this point, however, LCSAs can no longer be sharply and meaningfully separated from political and macroeconomic topics, which was proposed for additive LCSA (cf. (Klöpffer 2008)).

This potential can be further unlocked when quantitative environmental cause and effect chains in regard to absolute sustainability assessment methods are further developed and implemented in LCSA. A sustainable bioeconomy requires that the rate of extraction does not exceed the rate of regeneration and that this regenerativity and the surrounding supporting systems are maintained (Lindqvist et al. 2019). Currently under development are planetary boundary LCIAs (Ryberg et al. 2018) addressing challenges of relating LCIs and LCIAs to operational definitions of planetary boundaries (Robert et al. 2020). This can improve the quality of planetary boundary results in (HI)LCSA significantly. Furthermore, comprehensive material flow data of biomass are not available yet (Adler et al. 2015), but there are extensive efforts for sectoral monitoring (SYMOBIO 2018; Bringezu et al. 2020). For the provisioning system and societal needs, quantitative cause and effect chains are less relevant, also because global modelling is far less possible than for environmental impacts. In this case, it is more important to derive qualitative conclusions from a set of quantitative and qualitative indicators and aggregations to support the discussion. Making this linkage of regional assessments and global impacts also clear to regional stakeholders contributes to a more global thinking on a regional level (de Schutter et al. 2019).

It is not only interesting for bioeconomy sector—which is still a marginal sector, especially at the level of consumer goods—to know which specific sustainability a specific product of bioeconomy possesses. Additionally, the sustainability potential that can be tapped by substituting conventional goods with biobased goods, i.e., produced by renewable raw materials and renewable energies, is of strategic interest (Bezama et al. 2017). This is perfectly possible with the presented methods. However, when comparing production systems and their products, the functional unit of mass and volume does not represent the function and use value of products (Sahoo et al. 2019; Zeug et al. 2020). A chair can be made of steel or wood, and we assume that its actual use value is largely independent of the material it is made of. When comparing them in LCSA, the quality of substitution has to be considered: Does a substitute deliver the same use value for the same time? Since a fundamental challenge in provisioning systems is to replace fossil carbon by biogenic carbon (Carus et al. 2020), this substation processes could be assessed by economic-environmental bioeconomy transition indicators currently in development (Jander and Grundmann 2019; Jander et al. 2020; D'Adamo et al. 2020), e.g., fossil resource saving in a sector.

For some readers, it might be remarkable that traditional LCC is not part of HILCSA, instead economic aspects are measured as quality of the provisioning system on a meso and macro scale—mainly by indicators from SoCa, RESPONSA, and SUMINISTRO, covering water, sanitation, energy, working conditions, and mainly consumption and production patterns. Especially for LCC and economic assessments, the goal and scope as well as stakeholders of the study are of decisive importance (Wulf et al. 2017, 2018). Traditional LCC differs notably in conceptual frameworks, terminology, methodology, and content from LCA and has been debated and questioned in sustainability science (Jørgensen et al. 2010; Swarr et al. 2011; Sala et al. 2012a): It focuses on individual costs and benefits of organizations, mostly neglects global perspectives, and there is a systematic bias through monetarization as well as exchange value-constricted valorization (Zeug et al. 2020). We take a systematic and societal approach with a provisioning system addressing society as a whole, taking primarily macro, socio, and ecological economics into account and relating them to the SDGs. Thus, no microeconomic cost accounting like in traditional LCC is adequate.

Additionally, a problem of fundamental character appears in traditional LCC and LCSA, which has not been discussed extensively in previous research yet: to what extent, monetary variables are generally distorted and abstract representations of (non-)material objects, subjects, and their relationships in form of exchange values. In contrast to physical quantities or concrete social outcomes, costs and prices are subject to abstract quantities and substantial fluctuations, not only due to fluctuations in market prices and changing (un-) equilibria of supply and demand. For example, the amount of CO_2 emitted when a certain amount of fuel is burned and subsequent effects on the atmosphere and climate change are almost independent of location and, in the short term, time. Most internalized costs, on the other hand, for one and the same commodity can depend both in real and nominal terms on a number of factors, such as region, currency, and time. They show significant differences (Ciroth 2009), even since accounting procedures themselves are not standardized (Swarr et al. 2011). Besides, solely costs are of secondary importance for production and marketing of commodities in capitalism; instead, the prospect of a return on capital and profit remains paramount (Postone 1993; Zeug et al. 2020; Ciroth 2009), decisive for most economic decisions are not absolute balanced costs, but relative costs of opportunities (Kuosmanen 2005). A challenge will be that not only private industrial actors in capitalist societies have an intrinsic particular interest in capital accumulation and increasing output, and by themselves will not embark to a universal good life for all within planetary boundaries, cost internalization, or the SDGs. Even the SDGs themselves do not deviate from this intrinsic principle (Spangenberg 2017). In this regard and in contrast to the new S-LCA Guidelines (UNEP 2020), we very much question whether "profit" should be a pillar like "people" and "planet" in sustainability assessments (Zeug et al. 2020). Civil society pressuring states are therefore the only entities able to provide the organizational and planning capacity by political coordination necessary for this transition (Hausknost et al. 2017). Corporations are still key actors, but have to be guided by societal rules and strategies in a sustainable bioeconomy. For this, however, a necessary change of patterns of regulation is necessary in a way that states themselves are not depending on abstract economic growth; besides, the latter was identified as a relatively irrelevant objective by stakeholders (Zeug et al. 2019).

In general, we see three main limiting factors in HILCSA:

(i) Data availability: To model the material flows between sectors of a wood fiber-based bioeconomy and so implicitly its products, disaggregation of national flows from I/O models like EXIOBASE (Vendries Algarin et al. 2015; Wood et al. 2014; Lindner et al. 2012; Joshi 1999), EW-MFA, and by hybrid LCA (Budzinski et al. 2017) should be considered. This depends also on further I/O database implementation in SoCa and openLCA. Nevertheless, in case studies, it is necessary to fill crucial data gaps by own data acquisition by questionnaires and stakeholder or expert interviews. Ideally, this goes hand in hand with establishing common standards for data modeling and exchange for interoperability in LCA (Fritter et al. 2020). Limited data availability will lead to less applicable indicators when HILCSA is applied the first times.

(ii) Weighting and aggregation: The relevancies of SDGs are based on a quite broad stakeholder involvement, expectations, framing of questions, and societal perspectives (Zeug et al. 2019). They are value choices and different individuals; organizations and societies may have different preferences (Andreas et al. 2020). However, this weighting and aggregation as well as normalization methods enables us theoretically to calculate single scores, becoming more acceptable within the LCA community (Andreas et al. 2020), if aspects are neither over nor underrepresent and address multiple issues simultaneously avoiding burden shifting (Lindqvist et al. 2019).

(iii) Measuring a societal change: Sustainability assessments of production systems on a meso level alone are not capable of measuring a necessary societal change. Methods like HILCSA can only support larger macro assessments, like national monitoring of bioeconomy (Bringezu et al. 2020), social science studies on changing and persistent mentalities (Eversberg and Holz 2020) as well as political economy and ecology (Pichler et al. 2020).

5 Conclusions

Our analysis shows that the established field of LCAs can be substantially complemented by a HILCSA—which provides a common and integrated sustainability assessment framework applied to regional bioeconomy product systems. Integrating S-LCA, E-LCA, and economic assessments as well as macro and micro approaches is compensating some of their gaps and disadvantages. The proposed set of 109 indicators for HILCSA within the openLCA software environment is capable of addressing societal needs by 21 indicators, the provisioning system by 59 indicators, and the planetary boundaries by 29 indicators. Thereby, HILCSA is capable of addressing 15 out of 17 SDGs (with the exception of SDGs 10 and 17), including all relevant and problematic developing SDGs. In order to achieve this variety of indicators, the LCIA methods ReCiPe, Impact World +, Environmental Footprint 3.0, and SoCa as well as RESPONSA and SUMINISTRO are integrated, and a normalization method by PRP and DTT provides scores which make this variety of different properties and units comparable. Thus, the HILCSA framework addresses to some extend most of the open questions and significant problems of LCSAs in general, in terms of goal and scope, LCI, LCIA, and interpretation. As well as this framework substantiates the idea of an integrated LCSA proposed by Guinée et al. (2011), and shows main advantages compared to additive LCSA, but also makes future research necessary.

As a major value added, we see our LCI and LCIA, which is the first of its kind actually applicable in an existing software environment (openLCA), its linkage to databases, the integration of innovative S-LCA methods as well as overcoming the problem of economic sustainability assessment. In specific and compared to existing rudimentary integrated LCSA approaches, the handling of different kinds of indicators is improved by PRP and DTT methodology, impact categories are unified and comparable by addressing the SDGs, local and global scales are bridged by the SDGs as well as integrating absolute sustainability assessment methods. Not to be neglected as well is the improvement of participation of stakeholders via SDG relevances and further ongoing reflections, in order to ensure their wide recognition and acceptance of their results.

We see important future research needs in validating and applying the HILCSA by case studies on bioeconomy regions, and actual assessments of holistic sustainability and potential of a regional bioeconomy product systems (Zeug et al. 2021). Then, we will be able to address further relevant practical challenges, e.g., detailed definition of system boundaries, sensitivity and uncertainty analyses, and data availability and quality checks. Conducting a series of case studies in HILCSA will not only validate and improve the model itself, but can also help to develop further software environments and databases for LCSA in general. A significant progress will be made, when planetary boundaries are downscaled in a methodically robust manner in the EU to specific regions, provisioning and product systems (Ryberg et al. 2020). The development of a holistic and fully integrated LCIA for LCSA is a promising long-term research objective for meeting possibilities and capabilities of LCSA. But requires extensive cooperation with software developers and LCIA experts, to which as well as to critical discussion, we explicitly invite all interested researchers. Whether transferability of this framework or LCSA in general to other software environments is possible depending on whether basic requirements, such as an activity variable and corresponding databases and LCIAs, are implemented.

Coming back to our point of departure, HILCSA is able to quantify and qualify the (dis-)ability of bioeconomy product systems to address and assess the problem of double decoupling: to achieve as much social outcomes by transgressing as less planetary boundaries as possible, in other words to provide a good life for all within planetary boundaries. By identifying hotspots of unsustainable practices, socioeconomic contradictions and trade-offs when industrial metabolisms are transformed by substitution, specific bioeconomy strategies and action plans can be focused and the subject of governance activities specified. Such sustainability assessments are potentially able to structure the discourse around sustainability concepts, the implementation of SDGs and regional transitions to holistic sustainable bioeconomies. A better understanding of what “social,” “ecological,” and “economic” means can overcome reductionist approaches and epistemological traps and improve the understanding of mutual dependencies and complex interactions. The deployment of local bioeconomies, improving the knowledge base, and linking of local measurements to global goals can support policy makers and underpin policy coherence from a local to international level (European Commission 2018). When advantages of bioeconomies compared to fossil-based economies become clearer, a substitution and transition can be fostered better by all stakeholders, and potential risks can be minimized alongside chances becoming maximized. Such projections thus result in several areas of application, namely the analysis of possible consequences of actions, anticipating problems before they arise, discussing effects of a possible future on the present, and developing an idea of future conditions (Halog and Manik 2011). Additionally, regional bioeconomy practitioner profit from a holistic assessment of their activities and the local and global context they are acting within, when their contribution to global goals gets clear for policymakers and consumers. Beyond that, also civil stakeholders like NGOs and resulting controversial societal discourses profit from an evidence-based method for assessing bioeconomy and establishing a common narrative of a sustainable bioeconomy and sustainable development.

Appendix 1 PRP methodology

For quantitative indicators i with a high-resolution reference database, the deciles $\left\{q_1^{i,ref}; \dots; q_9^{i,ref}\right\}$, a minimum $q_{min}^{i,ref}$, and a maximum $q_{max}^{i,ref}$ of $P^{i,ref}$ are determined and a cumulative distribution function $F(x^{i,ref})$ is generated by regression analyses. This homomorphic representation of the empirical reference is used as a scale. With the determination that $q_{max}^{i,ref}$ is the best-practice case in the *ref* and therefor rated with r_{max}^i, $q_{min}^{i,ref}$ is the worst-practice case rated with r_{min}^i and $q_5^{i,ref}$ (median) as an average rated with $r_{q_5}^i = 5$, a scale can be formed by a direct substitution of the statistical measures with the scale r^i and $x^{i,ref}$ with x^i of the case to be evaluated. Thereby from $F(x^{i,ref})$ the continuous rating function $r^i\left(x^i\right)$ is obtained (Fig. 5). When only partial data is available, then an interpolation and regression is conducted.

In case of qualitative indicators, the shares of its categorical values in the reference, e.g., the percentage of “yes” or “no” answers are applied. Because there is no continuous distribution, it is therefore necessary to develop analogous rating functions from discrete variables. In the simplest case, the presence or non-presence of i in the case is designated as an expression θ, the value of i is θ^i (i.e. $\theta^i = 1$ or $\theta^i = 0$). It is observed in the reference data that there is a share $p_{\theta=1}^i$ of all cases with $\theta^i = 1$ and another share $p_{\theta=0}^i$ with $\theta^i = 0$, interpreted as the probability p_θ^i of θ. The higher p_θ^i ($p_\theta^i \to 1$), the more common θ^i is in reality and therefore to be understood

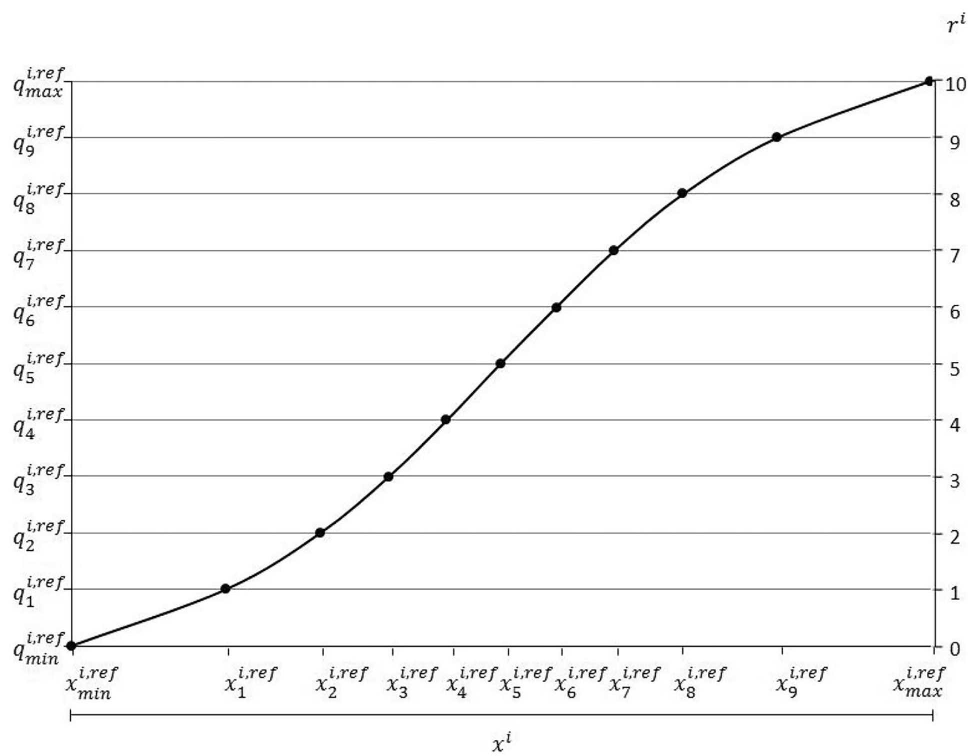

Fig. 5 Deciles, minimum, maximum, and their values in $\boldsymbol{F}(\boldsymbol{x}^{i,ref})$ of $\mathcal{N}\left(\boldsymbol{x}_5^{ref};1\right)$ and rating function $\boldsymbol{r}^i\left(\boldsymbol{x}^i\right)$ of quantitative indicators

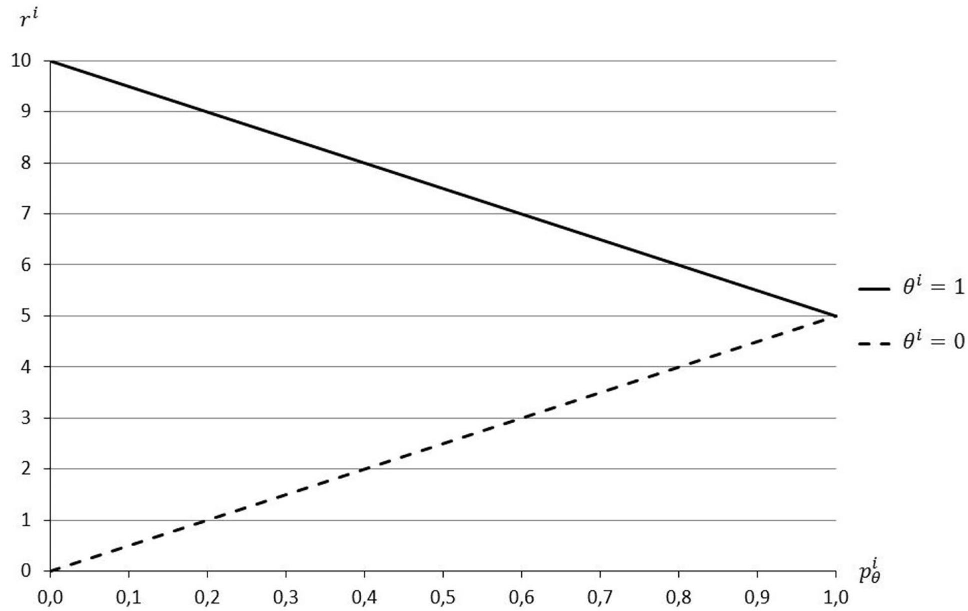

Fig. 6 Rating function $r^i(p^i_\theta;\theta^i)$ of qualitative indicators

as an average. If θ^i is also the case in the surveyed case, due to the previous determinations, a rating $r^i(p^i_\theta \to 1;\theta^i) = 5$ is applied. If $\theta^i = 1$, but p^i_θ is very small, the case represents best practice with $r^i(p^i_{\theta=1} \to 0;\theta^i = 1) = 10$. In contrast, $r^i(p^i_{\theta=1} \to 1;\theta^i = 0) = 0$ represents worst practice. The evaluation and rating of qualitative indicators is thus determined by p^i_θ in the reference and θ^i in the case. In order to obtain rating functions, a linear interpolation between the described characteristic combinations provides the numerical relative (Fig. 6) (Eq. 1)

$$r^i(p^i_\theta) = \begin{cases} 5p^i_\theta & if\theta^i = 0 \\ -5p^i_\theta + 10 & if\theta^i = 1 \end{cases} \tag{1}$$

If indicators behave in such a way that their increase, stronger expression or qualitative presence is read negative with regard to sustainability, then a transformation is necessary: the result of $r^i\left(x^i\right)$ and $r^i\left(p^i_\theta;\theta^i\right)$ must be reversed.

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LIFE CYCLE SUSTAINABILITY ASSESSMENT

Application of holistic and integrated LCSA: Case study on laminated veneer lumber production in Central Germany

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Abstract

Purpose We have to transform our societies and economic systems towards social, ecological, and economic (holistic) sustainability. Bioeconomy (BE) can contribute to sustainable development by substituting fossil-based products with renewable ones; however, sustainability is not intrinsic to BE.

Methods Therefore, we developed a holistic and integrated life cycle sustainability assessment (HILCSA) method containing 91 indicators, implemented in openLCA, using the Ecoinvent and SoCa database, and addressing 15 out of 17 Sustainable Development Goals. We applied it for the first time to show its capabilities by assessing the holistic sustainability of laminated veneer lumber (LVL) relative to hot-rolled steel beams.

Results, discussion Our results indicate that renewable bio-based construction materials can have a better holistic sustainability than fossil-based products for nearly all indicators, by less stressing the environment, having a less negative impact on society and being economically more efficient. However, fossil-based components of LVL such as phenolic resin are main contributors of negative impacts and should be reduced and replaced. Renewable resources from agriculture and forestry have significant impacts on land use (change).

Conclusions HILCSA demonstrates to be able to provide comprehensive sustainability assessments as well as aggregated results. BE substitutes indeed can improve sustainability; however, sustainability assessments and HILCSA need to be further developed to allow conclusions to be drawn about absolute sustainability of BE.

Keywords Bioeconomy · Life cycle assessment · LCA · Life cycle sustainability assessment · LCSA · Sustainable development goals · SDGs · Laminated veneer lumber

1 Introduction

A sustainable bioeconomy (BE) based on renewable resources and entailing a societal ecological transformation can potentially contribute to a good life for all within planetary boundaries (PB) (Zeug et al. 2022, 2021b). PB represent main global ecological limits, e.g., a certain GHG concentration should not be exceeded as well as there is a limit for the use of land, resources, and water (O'Neill et al. 2018). PB are not necessarily constant over time nor a deterministic constant, but most likely are scenarios in which the transgression of one PB leads to even more transgressions of other PB (e.g., climate change induces water scarcity and land degradation) as well as societal impacts (e.g., human health and well-being), which should be avoided (Rockström et al. 2009; Steffen et al. 2018). However, contributing to a good life for all within PB is not necessarily the case for the currently emerging BE and circular economy in general, and to only focus on ecotechnological efficiency is not sufficient, but societal and economic transformations entailing BE are necessary for effectiveness (Eversberg and Holz 2020; Padilla-Rivera et al. 2020; Bezama et al. 2019; Ramcilovic-Suominen and

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Pülzl 2018; Hausknost et al. 2017). This complex problem can be characterized as a need of double decoupling (Zeug et al. 2022): a decoupling of increasing satisfaction of societal needs from an otherwise ever greater production of material goods, as well as a decoupling of production of goods from growing negative ecological, social, and economic effects. However, a necessary absolute decoupling does not exist and also seems implausible under business-as-usual conditions in the future (Parrique et al. 2019). As a promising approach to measure and assess social, ecological, and economic sustainability, life cycle sustainability assessments (LCSA) based on life cycle assessment (LCA) methods are considered as essential for a movement towards global sustainable development by many stakeholders (Balkau and Sonnemann 2017; de Besi and McCormick 2015; Gao and Bryan 2017; OECD 2018; Onat et al. 2017; Urban et al. 2018; Zimek et al. 2019). However, as recent comprehensive reviews show (Costa et al. 2019; D'Amato et al. 2020; Fauzi et al. 2019; Troullaki et al. 2021; Wulf et al. 2019; Zimek et al. 2019), most LCSA approaches more or less follow the additive scheme of LCSA (LCSA = social LCA (S-LCA) + environmental LCA (E-LCA) + life cycle costing (LCC) and lacking a theoretically founded framework of holistic sustainability, which in practical terms leads to different social, economic, and ecological dimensions and indicators which are not integrated (Zeug et al. 2020, 2022). Broadly said, scopes, corresponding methods and indicators of the life cycle inventory (LCI), life cycle impact assessment (LCIA) as well as their individual results only have in common that they relate to the same product or functional unit which is to be assessed (cf. Ekener et al. 2018; Suwelack 2016; Urban et al. 2018)). Following a suggestion from Guinee (Guinee et al. 2011), instead of additive, we developed an integrated and holistic LCSA (HILCSA = f (S-LCA, E-LCA, LCC)) which builds on the integrated and holistic sustainability framework and integrates social, economic, and ecological aspects in a common goal and scope, LCI, LCIA, results, and interpretation (Fig. 1) (for details see our previous research Zeug et al. 2021a, 2020, 2022)). Holistic in this regard means to have a broader transdisciplinary perspective, a critical background theory of political economy and political ecology, but as well to not fall short on the implications which may have and impose fundamental societal transformations. Based on the concept of societal relations to nature (SRN) (Becker et al. 2011; Görg 2011; Hummel et al. 2017), we define social sustainability as a long-term and global fulfillment of societal needs and social well-being as an end; ecological sustainability is a long-term stability of our environment as a basis of reproduction within PB; economic sustainability stands for technologies and economic structures which are efficient, effective and just economies relating societal needs and environment. Integrated stands for an integrated model of sustainability which enables to integrate social, ecological, and economic sustainability assessment into one unified method instead of additionally combine different LCA methods.

However, to our knowledge, neither a holistic nor integrated LCSA in general was applied to BE product systems, yet. In previous studies, we assessed the production of laminated veneer lumber (LVL) in Central Germany (Thuringia, Saxony and Saxony-Anhalt) in a social LCA (S-LCA) using the RESPONSA model (Jarosch et al. 2020) as well as in an technical and environmental LCA (E-LCA) applying the SUMINISTRO tool (Hildebrandt et al. 2019; Bezama et al. 2021): (i) RESPONSA as a context-specific S-LCA focuses on identifying social hotspots and opportunities on the organizational level of foreground activities in the production

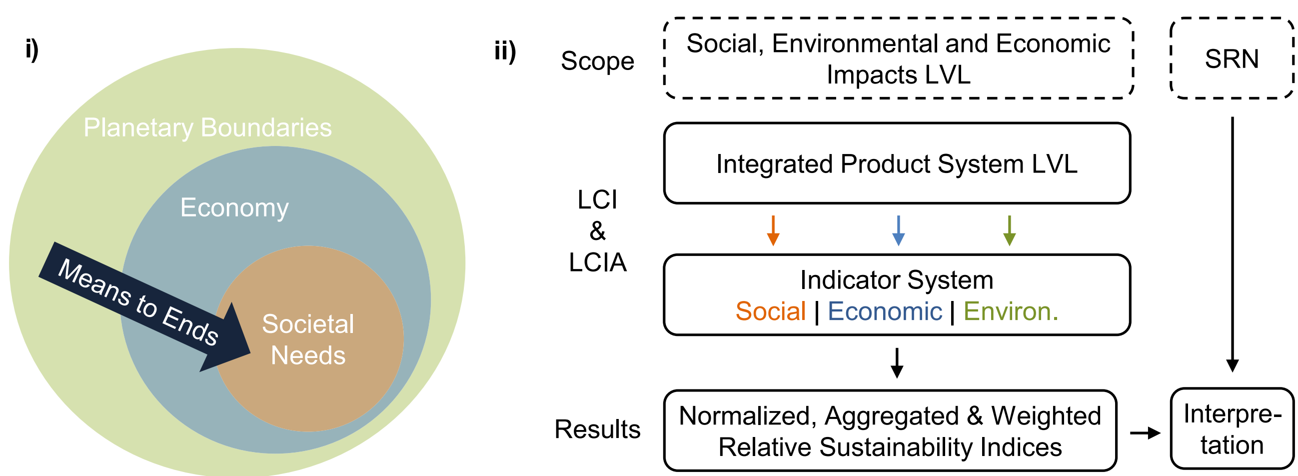

Fig. 1 **i**) Integrated and holistic sustainability framework, **ii**) framework of holistic and integrated life cycle sustainability assessment (HILCSA) (laminated veneer lumber, LVL; societal relations to nature, SRN; life cycle inventory, LCI; life cycle impact assessment, LCIA; integrated product systems in openLCA entail ecological, social and economic inventory data)

chain; (ii) SUMINISTRO assesses an technically and environmentally optimal product and feedstock composition. Thus, a number of relevant social, ecological and economic SDGs are not addressed, background activities are not considered as well as there is no common theoretical background and method of holistic and integrated sustainability assessment (Jarosch et al. 2020; Zeug et al. 2021a, b, 2019).

The case of LVL is important and of interest since any kind of sustainable BE will rely on industrial implementation of increasingly sophisticated and knowledge-intensive biotechnological processes like the wood-based BE, e.g., the efficient and sustainable use of beech wood (Hildebrandt et al. 2019; BMBF 2014). Especially the construction sector respectively the life cycle of buildings is responsible for 50% of extracted materials, 35% of anthropogenic GHG emissions, and consumes 42% of the total energy as well as 30% of the water in Europe (European Commission 2011; Asada et al. 2020). Wood, however, accounts for less than 2% of total material used by weight in the constructions sector (Herczeg et al. 2014), but the replacement of products with high GHG emissions such as steel, concrete, and aluminum with wood-based ones is thus considered as favorable to reduce GHG emissions and important for sustainable development (Asada et al. 2020; Leskinen et al. 2018; IPCC 2018). In the last decades, engineered wood products like LVL are a rapidly growing market, industrially manufactured, standardized, and slowly substituting fossil construction elements like steel beams (Leskinen et al. 2018). But for such a substitution, the potentials of available wood resources are limited and forests are already under pressure and competition for use (Egenolf et al. 2021; Palahí 2021) as well as the European Union already relies on foreign land for its biomass demand (De Laurentiis et al. 2022).

The main goal of this work is to assess how socially, ecologically, and economically sustainable is the LVL production in Central Germany, when compared to conventional building materials, utilizing the proposed HILCSA methodology in order to identify the substitution effects, hotspots, trade-offs, and synergies.

2 Methodology

In general, our methodology follows the standard approach of LCA (Fig. 1) (goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), interpretation and discussion). The methodical point of departure is our previously developed HILCSA sustainability framework (Zeug et al. 2020) as well as the HILCSA indicator and life cycle impact assessment framework (Zeug et al. 2021a). For HILCSA in general and for assessing the case study system, we used openLCA, as it offers not only a S-LCA functionality as well as socio-economic databases like SOCA (Eisfeldt 2017) and PSILCA (Maister et al. 2020), but also because the openLCA structure aims explicitly for a perspective of integration and implementation of LCSA (Di Noi et al. 2018; Di Noi and Ciroth 2018; Zeug et al. 2021a).

To build our LCI LVL-model in openLCA, we adapted the detailed gate-to-gate techno-ecological production system of LVL in Central Germany from the literature of the SUMINSITRO model (Hildebrandt et al. 2020, 2019, 2018), which were validated by participating stakeholders and producers, and made it a foreground system process "LVL manufacturing" in openLCA v.1.10 embodying all activities in the organization manufacturing LVL. For supply with raw materials, transportation, and background processes, we used Ecoinvent v.3.6 APOS (Allocation at the Point of Substitution) processes with social and economic data from SoCa v.1 by Green Delta. APOS integrates the treatment of wastes better than the cut-off system models, and is therefore more suitable for assessing BE and circular economy. For LVL manufacturing, we adopted the data for all social and economic indicators from SoCa by using a comparable LVL manufacturing process (laminated timber element production, for outdoor use | laminated timber element, transversally prestressed, for outdoor use | APOS, U; UUID: cdeab870-22e8-4b0c-9090-99d6595f77a5). From the RESPONSA survey and study (Jarosch et al. 2020), we took the real-world data of RESPONSA indicators for LVL manufacturing and forestry as well as activity variables. However, RESPONSA indicators are gained by surveys to a single company, are only representative for this very case, and consequently could only be applied to the foreground processes (LVL manufacturing, forestry) in this study. Primary data of RESPONSA indicators cannot be shown in this study due to privacy constraints and data protection of involved organizations. The system boundaries of this study are set by the cradle-to-gate product system (Fig. 2), for the LVL manufacturing process system boundaries are given by the primary data from the manufacturer (see chapter "3.2") and all other processes include the up-streams given by Ecoinvent v.3.6. The system boundaries of this study are consistent with the RESPONSA and SUMINSTRO model. The risk of double counting in "LVL manufacturing" is avoided due to the manufacturing and production site only producing this final product, for all other processes we rely on Ecoinvent APOS allocation method.

For the following LCIA, we created an HILCSA-LCIA method in openLCA. Following the HILCSA indicator set (Zeug et al. 2021a), 91 SDGs and SDG subgoals serve as impact categories in openLCA and we quantified each by one mid or endpoint indicator as well as their given normalization factors from the chosen LCIA methods (RESPONSA, SoCa, ReCiPe 2016 End-/Midpoint H and Environmental Footprint (EF)) as well as weightings from stakeholder participation (Zeug et al. 2019). The SDGs are applicable as a commonly agreed on goal and indicator framework which was adapted to BE in previous studies (Bracco et al. 2019). For allocation and weighting of indicators in

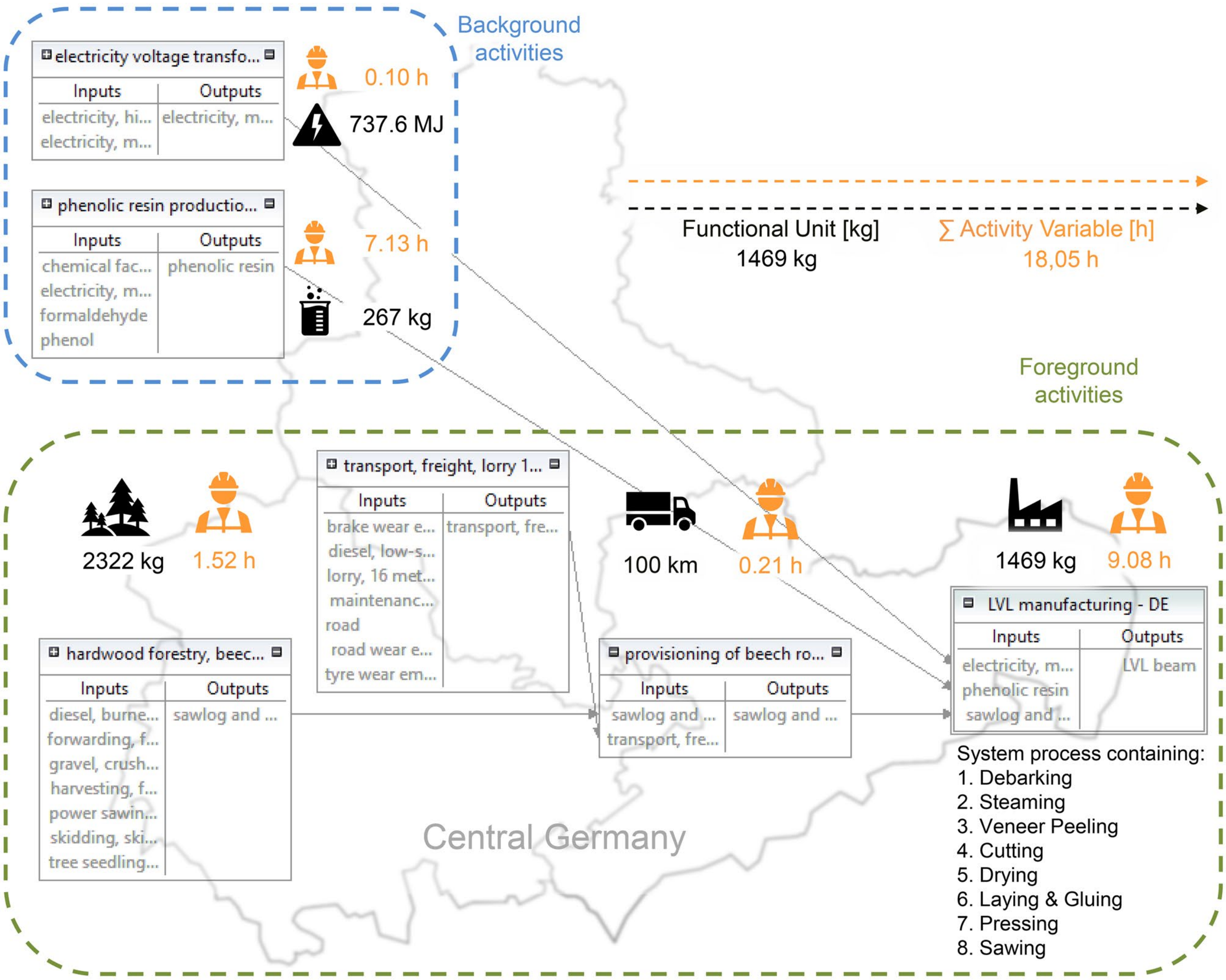

Fig. 2 Product system of LVL production in Central Germany with foreground and background activities, based on openLCA model graph ("+" indicates hidden upstream flows and processes for inputs; position of processes is schematic; all mass given as wet mass)

HILCSA, in Zeug et al. (2020) and Zeug et al. (2021a, b) certain SDGs were assigned to societal needs, economy, and PB; however, a clean analytical distinction is not possible due to the complex interactions to be discussed (de Schutter et al. 2019): societal needs (SDG 1, 2, 3, 4, 5, 11, (16, 17)); economy (SDG 6, 7, 8, 9, 10, 12); PB (SDG 13, 14, 15) (Zeug et al. 2019, 2021a, 2020).

Additionally, we added total and renewable cumulative energy demand (CED) for SDG 7.3/1 respectively SDG 7.2/4 (Table 4 in the Appendix). Since editing data in the openLCA front end can only be done manually and especially the impact factors for each impact category can easily exceed thousand flows, we exported the LCI and LCIA data to the ILCD format, edited it by using a powerful XML editor, and then imported it back to openLCA again.

Afterwards, we checked that the HILCSA-LCIA impact categories produce the same plain impact results as the used stand-alone LCIA methods, as well as for overall consistency of inventory results and impact analysis. Therefore, openLCA also provides a LCIA check, which gives information on flows which are not covered by applied LCIA methods. It is not important that all flows are covered by the LCIA, but rather that all flows with a significant impact are. To validate our inventory model and check for plausibility, we finally applied the HILCA-LCIA to our LVL product system as well as the comparable LVL manufacturing product system mentioned above, and compared the results.

To finally make a relative assumption on the sustainability of LVL production in Central Germany, we applied HILCSA-LCIA to the production system of hot-rolled steel beams (steel production, low-alloyed, hot-rolled|steel, low-alloyed, hot-rolled|APOS, U; UUID 93f61e55-d632-405e-8299-1cac3453ae7e). The functional unit (FU) of our LVL product system is an LVL beam with a mass of $m_{\mathrm{LVL}}^{\mathrm{FU}} = 1469.0\mathrm{kg}$. In order to make LVL and steel beams

(SB) comparable regarding their functionality and the FU, we calculated a comparison factor C_{SB-LVL} on basis of their average bending capacities q (load per unit length) (Pollmeier 2021), according to Eq. 1. As a result, a comparable steel beam with same functionality as our LVL beam has a mass and FU of $m_{SB}^{FU} = 1720.8\mathrm{kg}$.

$$C_{SB-LVL} = \frac{q_{SB}}{q_{LVL}} = \frac{59.72\frac{kg}{m}}{50.98\frac{kg}{m}} = 1.171 \tag{1}$$

Within the framework of this study, for some indicators, we can only present plain results at the level of impact categories without a further LCIA normalization entailing the distance to target (DTT) approach (Zeug et al. 2021a), since absolute sustainability assessment methods and models are still in development and not available as applicable LCIA methods yet (Bjørn et al. 2020; Ryberg et al. 2020; Sala et al. 2020). For each indicator i which is assigned to a specific subgoal SDG sSDG, in openLCA, we calculate values x for each process of the LVL product system x_{sSDG}^{LVL}, as well as cumulated (total) values for the whole product system of LVL $x_{sSDG,T}^{LVL}$ and the steel beam $x_{sSDG,T}^{SB}$. With all cumulated results of all indicators of our BE product system, we finally compare it to the product which can be substituted (steel beam), to assess their relative rather than absolute impact. For this purpose, we calculate a factor f^{sSDG} called substitution factor of impact of an indicator (Eq. 2), expressing the magnitude of relative sustainability. However, in this study, we cannot apply this normalization and aggregation to the 17 indicators from RESPONSA since we could not do a data survey on those indicators for the steel industry. For the remaining 74 indicators, we applied the substitution factors of impact normalization and aggregation. As aggregation on SDG level, we calculated weighted mean factors for substitution of impact for each SDG f^{SDG} (Eq. 3). As weighting factors, we used the relevances R^{sSDG} of each of the SDG subgoals which were gained in stakeholder workshops in context of the German BE-monitoring (Zeug et al. 2019). These weighting factors are dimensionless weightings ranging from 0 to 10 and represent the relevance of SDG subgoals within the Systemic Modelling and Monitoring of the German Bioeconomy (SYMOBIO) (Bringezu et al. 2020). Analogical as well a total substitution factor of impacts f is calculated on the level of all SDGs (Eq. 4).

$$f^{sSDG} = \frac{x_{sSDG,T}^{LVL}}{x_{sSDG,T}^{SB}} \tag{2}$$

$$f^{SDG} = \frac{\sum_{sSDG} R^{sSDG} f^{sSDG}}{\sum_{sSDG} R^{sSDG}} \tag{3}$$

$$f = \frac{\sum_{SDG} R^{SDG} f^{sSDG}}{\sum_{SDG} R^{SDG}} \tag{4}$$

3 Application of HILCSA to LVL

3.1 Goal and scope

Goal of this first HILCSA application is to assess the relative social, environmental, and economic impacts as risks and chances of regional BE product systems, their contributions to the SDGs and a socio-ecological transformation. In the present case, it is the comparison of LVL based on renewable raw materials with steel beams made of fossil raw materials, both having the same functionality per FU. As previously mentioned, HILCSA aims for absolute sustainability assessment methods; however, since applicable absolute LCIAs are not available, we apply HILCSA as relative sustainability assessment.

Beech wood is the main resource for the product system of LVL production in Central Germany and LVL serves as supporting structures in timber construction and also can be processed further to beams, panels, floor, and components for other structural applications (Jarosch et al. 2020; Pollmeier 2018). Most of the companies involved are members or former members of the Leading-Edge Cluster Bio-Economy (BioEconomy Cluster 2019) and connected by diverse regional material flows of (renewable) resources, semi-finished products, chemicals, infrastructure, and knowledge (Hildebrandt et al. 2020). We speak about regional BE, as it is the case here, when a predominant share of resource extraction, semi-finished products, and manufacturing take place within a spatial area of no more than a 100-km radius. Besides, this radius is the average transport distance for roundwood in Germany (Schusser et al. 2019; Obkircher et al. 2013) and the assumed distance of transportation in our study.

Economic system boundaries are defined by the involved organizations performing foreground activities in LVL production, resulting in a cradle-to-gate product system (Fig. 2). In this product systems, as a first foreground activity beech saw and veneer log is provided by the "hardwood forestry, beech, UUID: bd06b5b9-0824-44c6-827b-650c59fbdb5f" process, which is then transported to the LVL manufacturing site by the "provisioning of beech roundwood" and "transport, freight, lorry, UUID: 28b69524-cdef-4d3c-93f8-54a48dc8d51a" processes ("provisioning of beech roundwood" only serves for a separate balancing of the transport service but has no additional inputs nor outputs). Finally, it is processed to a finished LVL beam by the "LVL manufacturing" process. All other processes are background activities and provide foreground processes with energy and ancillary by-educts material flows, such as the "phenolic resin production, UUID: b81f0c27-7ea1-4e3d-bd4c-c4972fd28bdd" process needed for gluing veneer sheets, the "electricity voltage transformation, UUID: 8675c4d1-60e3-40c4-b75c-a93553c86bed." In the background as well, there are a multitude of not displayed processes providing input flows for shown foreground and background activities. These background processes do not necessarily take place in Central Germany and are fully covered by Ecoinvent upstream processes.

The LVL manufacturing process is an aggregated system process derived from a number of processes within the site of LVL manufacturing that was modeled in openLCA: debarking (also providing bark for heat production*), cooking in steam pit*, veneer peeling, cutting and drying*, laying and gluing, pressing in continuous press*, veneer layer sawing gluing with phenolic resin, pressing LVL in batch press). These processes in technical detail were assessed and validated in previous studies (Hildebrandt et al. 2019, 2020; Jarosch et al. 2020). In this study, they are only considered as an aggregated system process, since technical processes per se are not relevant in meso-scale regional LCSA, as long as they do not have a significant impact beyond the organization and especially socio-economic effects cannot be balanced separately (Zeug et al. 2020, 2021a).

3.2 Life cycle inventory

The LCI in this case is founded on the holistic and integrated sustainability framework (Zeug et al. 2020) and indicator system (Zeug et al. 2021a) of HILCSA. Our indicator system entails 91 social, ecological, and economic indicators, which are assigned to 25 SDGs (Table 4 in the Appendix). We derive each indicator from a specific LCIA model: SoCa, RESPONSA, Recipe or EF 3.0. Indicators contain qualitative (mostly social and economic) and/or quantitative (mostly economic and ecological) primary data. For each process of the foreground system, the indicator data is adopted and added from our previous studies (Hildebrandt et al. 2020; Jarosch et al. 2020); however, data for RESPONSA indicators is only available for the forestry process and manufacturing process but not for the transport process or background processes. All other indicator inventory data comes with the processes from Ecoinvent 3.3 with SoCa v.1, especially in case of the background processes as well as the forestry process and transport process. An overview of the main input and output flows is shown in Table 1. Despite the process "LVL manufacturing," all processes come from the SoCa database and are considered with their corresponding up- and downstream flows. LVL manufacturing, however, is a system process compiled from a value chain of unit processes (Debarking–Steaming–Veneer Peeling–Cutting–Drying–Laying and Gluing–Pressing–Sawing) compiled of validated primary data coming from the manufacturer in Central Germany. Due to data protection of process details, we cannot provide quantitative LCI data but an aggregated system process for LVL manufacturing entailing all inputs, outputs, and emissions. Qualitatively, the LVL manufacturing processes are at the technical level of 2010; the thermal energy for steaming, drying, and pressing is provided by a bark-fired steam boiler (bark from roundwood and use of secondary fossil fuels); as well as residues from veneer peeling, cutting, and sawing are further processed to wood pellets for an external market which is not regarded and outside the system boundaries of this study.

For each process, we have material flow (mf) inputs as well as outputs, with one output flow being the reference flow and FU of this very process (e.g., for the forestry process the FU is 1 m3 saw log and veneer log, measured as solid wood under bark, UUID c00cac00-a885-42b0-88f5-fb5dce2a9a6f). We know from our S-LCA results (Jarosch et al. 2020) and the SoCa database that producing our final product FU, an LVL beam with $m_{\mathrm{LVL}}^{\mathrm{FU}}$, requires specific amounts of working time in each upstream process (e.g., 0.72 h for 1 m3 saw log and veneer log, 9.08 h for $m_{\mathrm{LVL}}^{\mathrm{FU}}$). This working time per FU of a specific process is the activity variable (AV) for all social and economic indicators of SoCa and RESPONSA. Such indicators are balanced and handled as output flows of specific risk levels (very low risk; low risk; medium risk; high risk; very high risk; no data) with an AV within a process in openLCA. These risk levels are determined and deposited in the social aspects/assessment tab of a process in openLCA. Processes containing social, economic, and ecological data ready for being further calculated in openLCA with HILCSA are integrated processes. In case of RESPONSA indicators, we assign risk levels to performance reference points (PRPs) according to the evaluation scheme in (Table 4 in the Appendix). PRPs are determined before by using the RESPONSA model (Jarosch et al. 2020; Siebert et al. 2018; Zeug et al. 2021a). All indicators have a unit of measurement at primary data level, in case of social and economic indicators of SoCa and RESPONSA indicator values get dimensionless in the inventory when being transformed to risk levels.

3.3 Life cycle impact assessment

Our LCIA in general aims at calculating, understanding, and evaluating the magnitude and significance of impacts of the LVL product system (Zeug et al. 2021a,

Table 1 Inventory for production of one LVL beam (1469 kg, functional unit), main material and energy input and output flows for functional unit with according working time (activity variable)

Processes	Main material and energy input and output flows		Working time (activity variable)	Data source
	Input	Output		
Hardwood forestry, beech wood (unit process)		2.11 m^3 roundwood (solid m^3 with bark, wet mass = 2322 kg)	1.52 h	Ecoinvent + SoCa (hardwood forestry, beech, sustainable forest management | saw log and veneer log, hardwood, measured as solid wood under bark | APOS, U)
Transportation (unit process)	232 tkm transport service (100 km distance); 2.11 m^3 roundwood (pile at forest)	2.11 m^3 roundwood (pile at factory)	0.21 h	Ecoinvent + SoCa (transport, freight, lorry 16–32 metric ton, EURO5 | transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U), distance (Schusser et al. 2019; Obkircher et al. 2013)
Phenolic resin production (unit process)		267 kg phenolic resin	7.13 h	Ecoinvent + SoCa (phenolic resin production | phenolic resin | APOS, U)
Electricity (unit process)		737 MJ electricity	0.10 h	Ecoinvent + SoCa (electricity voltage transformation from high to medium voltage | electricity, medium voltage | APOS, U)
LVL manufacturing (system process)	2.11 m^3 roundwood; 267 kg phenolic resin; 737 MJ electricity	1469 kg LVL beam (total mass of one module)	9.08 h	Manufacturer, unit processes and detail I/O flows under data protection

b). Each indicator is assigned to SDGs of the sustainability framework as end point impact categories (Table 4 in the Appendix). To some SDGs, a number of indicators are assigned, i.e., SDG 3.9 (reduce pollution of air/water/soil, health protection), SDG 8.7 and 8.8 (worker rights, labor protection rights, promoting safe work environment, abolition of forced labor/trafficking/child labor), SDG 13 (take urgent action to combat climate change and its impacts). However, there is no indicator which is assigned to several impact categories (SDGs) in exactly the same way, only if production sites are in urban regions (SDG 11.6), then indicator ID14 is used there instead.

At this early stage of overall method development, we do not change the different LCIA methods or characterization factors while integrating into LCSA, in order to keep consistency and only present rather plain results. Only in the CED LCIA we excluded the energetic gross calorific value of biomass flows (UUID: 01c12fca-ad8b-4902-8b48-2d5afe3d3a0f). Otherwise, this energy content of wood would be handled as if this energy is already consumed, although it is still contained by the LVL beam.

SoCa, as the socio-economic extension of openLCA, handles the variety of units and characteristics of social and economic indicators by applying common ordinal risks levels and according impact factors to different specific values of each indicator, assessed by its specific context (Social Impacts Weighting Method) (Eisfeldt 2017; Maister et al. 2020). SoCa, as well as our PRP-based social LCIA in RESPONSA, corresponds to an external normalization approach, which is recommended in general in the LCSA literature (Prado et al. 2012; Wulf et al. 2017; Troullaki et al. 2021) and also chosen for HILCSA (Zeug et al. 2021a). However, external normalization factors can increase the uncertainty of the whole assessment (Wulf et al. 2017) and the choice and transparency of the reference values plays a vital role (Sala et al. 2012). Due to the complexity in this regard, we refer in this study to the literature: SoCa relies on the PSILCA data of GreenDelta and its indicator values are based on international conventions and standards, labor laws, expert opinions but also own experience and evaluation (Maister et al. 2020); RESPONSA calculates PRPs as a regional and context-specific LCIA (Jarosch et al. 2020; Siebert et al. 2018; Zeug et al. 2021a). All socio-economic indicators from SoCa and RESPONSA in our HILCSA are comparable on from being transferred to risk levels (normalization) and share the same impact factor of the Social Impact Weighting Method (Table 2). For aggregation and balancing social indicators along the value chain, we use the implemented method of SoCa in openLCA based on the activity variable.

However, as discussed before, absolute sustainability assessment methods in forms of distance to target (DTT) as impact pathway approaches are not robustly available in LCA, yet (Zeug et al. 2021a). But as soon as they are, absolute sustainability assessment methods and DTT will allow to calculate a product system and regional specific environmental threshold in regard to PB, e.g., how much kg CO2 eq. per product or regional BE network can be considered as (un-)sustainable. We are confident that the specific indicator values of mostly environmental indicators can be assigned to the same risks levels as above,

Table 2 Evaluation scheme for HILCSA indicators according to their source, performance and risk assessment, impact factors, substitution factor of impact, and colors of risk indication

RESPONSA Rating in PRP r^{PRP}	**SOCA / RESPONSA Risk levels**	**Impact factors SoCa / RESPONSA**	**Substitution-factors of impact / color f^{sSDG} f^{SDG} f**
$8.0 < r^{PRP} \leq 10$	Very Low	0.01	$f = 0.01$
$6.0 < r^{PRP} \leq 8.0$	Low	0.1	$f = 0.1$
$4.0 < r^{PRP} \leq 6.0$	Medium	1	$f = 1.0$
$2.0 < r^{PRP} \leq 4.0$	High	10	$f = 10$
$0 < r^{PRP} \leq 2.0$	Very High	100	$f = 100$

in regard to the risk of transgressing PB when producing a specific product or operating a regional economy. In the meanwhile, the stress on PB has been adopted as normalization factors in the EF 3.0 method (Bjørn et al. 2020; Bjørn and Hauschild 2015; Sala et al. 2020) and as well as the Recipe Endpoint indicators which are assigned to PB SDGs of our sustainability framework (Zeug et al. 2021a).

Finally, for all indicators (except of RESPONSA, since RESPONSA inventory data is not available for steel), we compare the values of the LVL to the steel beam to assess their relative rather than absolute impact. For this normalization, we calculate substitution factors of impact f^{sSDG} (Eq. 2) for each indictor. In a following aggregation of these normalized factors, we apply a weighted mean factor f^{SDG} (Eq. 3) for each SDG the f^{sSDG} is assigned to. The weightings are based on the relevance of SDG subgoals, we determined for the German BE-monitoring by stakeholder participation (Zeug et al. 2019). As a highest level of aggregation by aggregating all SDGs, we analogically calculate a total substitution factor of impacts f of all SDGs (Eq. 4). According to the impact factors from the Social Impact Weighting Method from above, we assign them the according risk level and color as described in Table 2. The values of the individual indicators as well as all substitution factors of impact are presented in Table 3.

3.4 Interpretation

The aggregated results of the HILCSA are presented within the HILCSA sustainability framework in Fig. 3 in which the share of areas in the chart of each SDG indicates their relevance R^{sSDG}. Their substituiton factor of impact f^{SDG}, and a total substitution factor of impact f as well as their colors of risk levels are indicated.

At the highest aggregation level over all SDGs, the total substitution factor of impact of this case study of LVL relative to steal beams is $f = 0.61$. Regarding the results of our LCI and LCIA, this means that the holistic risks and impacts of LVL production in Central Germany are considered to be lower according to this factor compared to the production of steel beams. Positive effects of this substitution will especially entail a better social sustainability (societal needs; SDG 1, 2, 3, 4, 5, 11) as well as economic sustainability (economy; SDG 6, 8, 12, 16) and mostly ecological sustainability (PB; SDG 13, 14). For those SDGs, the substituion factors of impact are below 1.0. However, LVL production has some partly significant risks compared to steal production when it comes to SDG 7 (energy) and SDG 15 (life on land) with weighted impacts above 1.0.

To understand these general and relative results in more detail, we need to take a look at the substitution factors of impact on SDG-subgoal level and the openLCA model results with focus on some remarkable ones (Table 3). First to say, out of 74 indicators (excluding RESPONSA, see above) for which we calculated f, for 70 indicators $f^{sSDG} < 1.0$ and for 56 indicators $f^{sSDG} < 0.5$ which means that the LVL production can be considered as reletivley more sustainable and mostly has half of the weighted impacts than steel beam production. Besides overall good relative social sustainability, in other words low risks and low f, there are relatively very low impacts on human health toxicity ($f^{ID15} = 0.02$;$f^{ID16} = 0.09$) which we trace back to the high impacts of mining, treating slag and sulfidic tailings in steel production. On the other side, SDG 7 (energy) as part of economic sustainability in the provisioning sytem, only has a medium risk level and $f^{SDG7} = 0.98$, which means there is no advantage of LVL in this regard. The two relevant indicators are CED (ID25) and Share of fossil energies in CED (sfCED) (ID24) with $f^{ID25} = 0.91$ and $f^{ID24} = 1.05$, respectivley $CED^{LVL} = 36375MJ$ and $CED^{SB} = 39982MJ$ as well as $sfCED^{LVL} = 0.98$ and $sfCED^{SB} = 0.93$. These results show us that the CED of LVL and steel beam production is comparable, although in case of LVL phenolic resin production is accountable for 91% of LVLs CED. Interestingly, the share of fossil energies in LVL production is slightly higher than of steel, since on the one hand they share more or less the same comparable power grids for electricity, but wood is mainly harvested and transported by diesel fuel driven machines with a $sfCED = 0.99$. As it can be expected, most significant negetive impacts of LVL production come from forestry and its effects on land use (ID83) represented in SDG 15 (life on land) with $f^{ID83} = 18.15$ respectivley $f^{SDG15} = 2.14$. However, the climate change due to land use change (ID73) in total is better than of steel $f^{ID73} = 0.96$ as well as the overall negative effects on climate change (ID70) are far less $f^{ID70} = 0.39$. In general, it is striking that phenolic resin production for 70 out of 74 indicators is the main contributer of negative impacts in LVL production (except level of industrial renewable water use (ID57), extraction of biomass related to area (ID61), climate change due to land use change (ID73), land use (ID83)), even thouh its mass fraction of the final product is only 18.2%. Our results suggest that substituting steel beams by LVL beams can make a significant contribution

Table 3 HILCSA results of LVL beam production system and steel beam production (main contributor in LVL products system written in bold)

Sustainability framework and indicator system						LVL beam product system						Steel beam	Substitution-factor of impact		
						Foreground x_{sSDG}^{LVL}			Background x_{sSDG}^{LVL}						
	SDG Code	R^{sSDG}	Source	ID	Indicator Name i	hardwood forestry, beech,	transport, freight, lorry 16-32 tons	LVL manufacturing	phenolic resin production	electricity production and provision	Total $x_{sSDG,T}^{LVL}$	Total $x_{sSDG,T}^{SB}$	f^{sSDG}	SDG	f^{SDG}
Societal Needs	1	6.6	Soca	1	Social security expenditures	10.00	7.60	9.08	**737.71**	19.40	783.78	2160.97	0.36	1	0.36
	1.2	6.94	Responsa	2	Payment according to basic wage	0.02		90.80			90.82	0.00			
	1.4	6.94	Responsa	3	Capital participation	1.52		9.08			10.60	0.00			
	1.4	6.94	Responsa	4	Profit-sharing and bonuses	1.52		9.08			10.60	0.00			
	2	9.33	Recipe (End)	5	Water consumption - HH	9.00E-05	7.04E-05	-1.27E-06	**6.28E-03**	1.01E-03	7.45E-03	5.30E-02	0.14	2	0.25
	2.3	6.39	Soca	6	Human rights issues faced by indigenous people	1.30	0.93		100.25	4.13	106.61	321.04	0.33		
	2.3	6.39	Soca	7	Presence of indigenous population	0.65	0.57		58.09	1.82	61.13	177.57	0.34		
	3.9	8.61	Soca	8	DALYs due to indoor and outdoor air and water pollution	1.20	1.04	0.09	**81.26**	3.69	87.29	284.60	0.31	3	0.33
	3.9	8.61	Soca	9	Pollution level of the country	8.92	6.41	9.08	**800.29**	20.99	845.69	1692.21	0.50		
	3.9	8.61	Recipe (End)	10	Global Warming - HH	2.75E-05	3.57E-05	1.43E-09	**1.21E-03**	1.27E-04	1.40E-03	3.53E-03	0.40		
	3.9	8.61	Recipe (End)	11	Stratospheric ozone depletion - HH	1.31E-08	1.49E-08	2.67E-12	**1.32E-07**	4.20E-08	2.02E-07	5.47E-07	0.37		
	3.9	8.61	Recipe (End)	12	Photochemical ozone formation - HH	1.77E-07	1.10E-07	7.26E-12	**2.45E-06**	1.05E-07	2.85E-06	8.03E-06	0.35		
	3.9	8.61	Recipe (End)	13	Ionizing Radiation - HH	8.84E-09	9.40E-09	1.76E-13	**5.78E-07**	2.29E-07	8.25E-07	1.19E-06	0.69		
	3.9	8.61	Recipe (End)	14	Fine particulate matter formation - HH	2.79E-05	2.67E-05	3.46E-08	**1.37E-03**	4.02E-05	1.47E-03	5.59E-03	0.26		
	3.9	8.61	Recipe (End)	15	Toxicity - HH (cancer)	2.57E-06	2.66E-06	1.93E-10	**1.61E-04**	2.90E-05	1.95E-04	8.55E-03	0.02		
	3.9	8.61	Recipe (End)	16	Toxicity - HH (non-cancer)	2.90E-06	6.38E-06	5.42E-10	**2.77E-04**	4.26E-05	3.29E-04	3.77E-03	0.09		
	4	4.43	Soca	17	Public expenditure on education	10.24	7.39	9.08	**713.46**	37.38	777.55	2126.85	0.37	4	0.37
	5.1	5.83	Soca	18	Gender wage gap	2.50	3.78	9.08	**213.34**	3.54	232.23	566.23	0.41	5	0.41
	5.1	5.83	Responsa	19	Female employees in management positions	0.02		9.08			9.10	0.00			
	5.1	5.83	Responsa	20	Rate of female employees	152.12		9.08			161.20	0.00			
	11.6	9.17	Recipe (End)	21	If production site is in urban, then ID 14	2.79E-05	2.67E-05	3.46E-08	**1.37E-03**	4.02E-05	1.47E-03	5.59E-03	0.26	11	0.26
Economy	6.1	8.61	Soca	22	Drinking water coverage	10.20	8.10	0.91	**779.99**	36.45	835.64	2721.76	0.31	6	0.32
	6.2	4.44	Soca	23	Sanitation coverage	83.47	67.19	9.08	**6945.78**	368.11	7473.63	20920.51	0.36		
	7.2	5.56	CED	24	Share of fossil energies, CED	0.99	0.99		0.99	0.95	0.98	0.93	1.05	7	0.98
	7.3	5.83	CED	25	Cumulative Energy Demand	441.82	627.45		**33125.80**	2180.11	36375.20	39982.60	0.91		
	8.5	5.00	Soca/Responsa	26	Weekly hours of work per employee	0.49	0.33	0.09	**22.08**	0.79	23.79	48.24	0.49	8	0.51
	8.5	5.00	Responsa	27	Compensation for overtime	0.02		0.91			0.92	0.00			
	8.5	5.00	Responsa	28	Access to flexible working time agreements	0.02		90.80			90.82	0.00			

Table 3 (continued)

	8.5	5.00	Responsa	29	Rate of part-time employees	0.02		9.08			9.10	0.00			
	8.5	5.00	Responsa	30	Rate of marginally employees (max. 450€)	0.02		9.08			9.10	0.00			
	8.5	5.00	Responsa	31	Rate of fixed-term employees	0.02		908.00			908.02	0.00			
	8.5	5.00	Responsa	32	Rate of employees provided by temporary work agencies	1.52		908.00			909.52	0.00			
	8.5	5.00	Responsa	33	Rate of disabled employees	0.02		90.80			90.82	0.00			
	8.5	5.00	Responsa	34	Rate of foreign employees	0.02		90.80			90.82	0.00			
	8.5	5.00	Soca	35	Net migration rate	0.05	0.12	0.09	**1.47**	0.09	1.81	4.43	0.41		
	8.5	5.00	Soca	36	International Migrant Stock	26.93	20.78	90.80	**842.38**	43.38	1024.28	2310.23	0.44		
	8.5	5.00	Responsa	37	Average remuneration level	0.02		9.08			9.10	0.00			
	8.5	5.00	Soca	38	Sector average wage, per month	0.04	0.01	0.09	**1.13**	0.05	1.32	3.31	0.40		
	8.5	5.00	Soca	39	Unemployment rate in the country	1.32	1.22	9.08	**89.36**	3.82	104.81	241.46	0.43		
	8.6	4.72	Responsa	40	Rate of vocational trainees	0.15		9.08			9.23	0.00			
	8.7/8.8	5.00	Soca	41	Children in employment, total	13.25	13.15	0.91	**990.66**	37.63	1055.61	3167.98	0.33		
	8.7/8.8	5.00	Soca	42	Trafficking in persons	3.70	2.90	9.08	**264.22**	21.58	301.48	774.90	0.39		
	8.7/8.8	5.00	Soca	43	Frequency of forced labor	10.57	11.86	9.08	**676.53**	26.73	734.76	2470.23	0.30		
	8.7/8.8	5.00	Soca	44	Goods produced by forced labor	0.25	0.11		**8.29**	0.41	9.06	14.91	0.61		
	8.7/8.8	5.00	Soca	45	Right of Collective bargaining	0.30	0.20		**19.62**	2.46	22.58	93.95	0.24		
	8.7/8.8	5.00	Soca	46	Right of Association	0.24	0.14		**21.28**	0.15	21.81	74.56	0.29		
	8.7/8.8	5.00	Soca	47	Trade union density	27.58	19.79	90.80	**896.08**	44.93	1079.18	2482.67	0.43		
	8.7/8.8	5.00	Soca	48	Right to Strike	4.23	2.61		**292.28**	4.76	303.87	1190.51	0.26		
	8.7/8.8	5.00	Soca/Responsa	49	Rate of non-fatal accidents at workplace	8.70	15.21	90.80	**650.03**	24.49	789.24	1733.23	0.46		
	8.7/8.8	5.00	Soca/Responsa	50	Rate of fatal accidents at workplace	82.38	66.60	0.09	**7503.23**	349.57	8001.87	11014.64	0.73		
	8.7/8.8	5.00	Responsa	51	Sick-leave days	0.02		9.08			9.10	0.00			
	8.7/8.8	5.00	Soca/Responsa	52	Presence of sufficient/preventive safety measures	23.33	26.32	9.08	**3378.92**	3.00	3440.64	1594.87	2.16		
	8.7/8.8	5.00	Soca	53	Violations of laws and employment regulations	16.95	1.69	9.08	**119.39**	6.64	153.76	367.91	0.42		
	8.7/8.8	5.00	Soca	54	Workers affected by natural disasters	1.08	0.68	0.91	**84.93**	2.17	89.76	237.61	0.38		
	8.7/8.8	5.00	Responsa	55	Work Council	0.02		90.80			90.82	0.00			
	12.2	8.89	Soca	56	Level of industrial water use (related to total withdrawal)	178.90	45.84	9.08	**1734.39**	58.63	2026.84	2920.84	0.69		
	12.2	8.89	Soca	57	Level of industrial water use (related to renewable water resources)	**154.48**	2.88	9.08	117.16	24.58	308.18	331.57	0.93		
	12.2	8.89	Recipe (End)	58	Fossil resource scarcity	3.76	5.74		**230.73**	3.60	243.83	162.85	1.50	12	0.61
	12.2	8.89	Soca	59	Extraction of fossil fuels	1.68	0.16	0.91	**11.81**	0.81	15.37	31.76	0.48		
	12.2	8.89	Soca	60	Extraction of biomass (related to population)	0.64	0.17	9.08	**15.90**	0.49	26.29	49.54	0.53		

Table 3 (continued)

	12.2	8.89	Soca	61	Extraction of biomass (related to area)	**154.33**	1.20	9.08	114.00	23.36	301.98	329.30	0.92		
	12.2	8.89	Soca	62	Extraction of industrial and construction minerals	2.34	0.98	9.08	**58.45**	2.90	73.76	254.18	0.29		
	12.2	8.89	Soca	63	Extraction of ores	0.08	0.07	0.09	**3.97**	0.10	4.31	25.04	0.17		
	12.2	8.89	EF 3.0	64	Resource use, mineral and metals	6.47E-05	1.04E-04	2.08E-11	**4.31E-03**	2.64E-05	4.51E-03	4.05E-02	0.11		
	12.2	8.89	Recipe (Mid)	65	Ionizing Radiation	1.04	1.11	0.00	**68.13**	26.95	97.23	140.56	0.69		
	12.6	8.61	Soca	66	Certified environmental management systems	41.97	29.84	90.80	**1557.95**	43.24	1763.79	2568.43	0.69		
	12.6	8.61	Soca	67	Presence of anti-competitive behavior or violation of anti-trust and monopoly legislation	10.86	9.15	0.91	**336.83**	16.66	374.41	1220.69	0.31		
	16.5	7.22	Soca	68	Public sector corruption	89.02	73.36	90.80	**7166.29**	370.94	7790.41	21344.48	0.36	16	0.53
	16.5	7.22	Soca	69	Active involvement of enterprises in corruption and bribery	50.79	61.25	9.08	**3529.51**	168.71	3819.34	5459.86	0.70		
Planetary Boundaries	13	7.53	EF 3.0	70	Climate Change	31.26	38.62	0.00	**1312.16**	137.24	1519.29	3868.35	0.39	13	0.55
	13	7.53	EF 3.0	71	Climate Change (fossil)	29.45	38.60	0.00	**1309.80**	136.33	1514.17	3862.49	0.39		
	13	7.53	EF 3.0	72	Climate Change (biogenic)	0.03	0.01		**1.43**	0.71	2.17	2.80	0.77		
	13	7.53	EF 3.0	73	Climate Change (land use change)	**1.78**	0.01		0.94	0.21	2.95	3.06	0.96		
	13	7.53	Recipe (Mid)	74	Photochemical Ozone Formation, Ecosystems/Photochemical Ozone Formation	0.24	0.12	0.00	**3.04**	0.12	3.51	9.24	0.38		
	13	7.53	EF 3.0	75	Ozone depletion	5.89E-06	8.95E-06	2.59E-15	**5.83E-05**	6.39E-06	7.95E-05	2.07E-04	0.38		
	14	8.37	Recipe (End)	76	Global Warming - Freshwater ecosystems	2.26E-12	2.94E-12	1.18E-16	**9.96E-11**	1.05E-11	1.15E-10	2.91E-10	0.40	14	0.25
	14	8.37	EF 3.0	77	Eutrophication freshwater	3.89E-03	2.71E-03	3.53E-06	**4.28E-01**	1.74E-01	6.08E-01	2.96E+00	0.21		
	14	8.37	EF 3.0	78	Ecotoxicity freshwater	294.12	356.78	0.02	**23660.44**	479.51	24790.88	95033.57	0.26		
	14	8.37	EF 3.0	79	Water use	1740.51	1362.23	-24.53	**121409.30**	19613.05	144100.57	1025446.81	0.14		
	14	8.37	EF 3.0	80	Acidification terrestrial and freshwater	0.16	0.16	0.00	**6.14**	0.26	6.72	19.69	0.34		
	14.1	8.33	Recipe (End)	81	Toxicity - Marine ecosystems	6.61E-11	1.25E-10	4.25E-15	**4.33E-09**	7.22E-10	5.24E-09	6.36E-08	0.08		
	14.1	8.33	EF 3.0	82	Eutrophication marine	0.06	0.05	0.00	**0.93**	0.08	1.11	3.51	0.32		
	15.1	7.50	EF 3.0	83	Land Use	**129371.13**	398.21		1963.16	464.79	132197.29	7283.60	18.15	15	2.14
	15.1	7.50	Recipe (Mid)	84	Terrestrial Acidification	0.10	0.10	0.00	**4.24**	0.17	4.61	13.29	0.35		
	15.1	7.50	Recipe (Mid)	85	Terrestrial ecotoxicity	89.19	670.21	0.01	**2722.45**	50.46	3532.33	29324.62	0.12		
	15.1	7.50	EF 3.0	86	Eutrophication terrestrial	0.55	0.50	0.00	**9.47**	0.53	11.04	37.51	0.29		
	15.5	8.33	Recipe (End)	87	Global Warming - Terrestrial ecosystems	8.29E-08	1.08E-07	4.33E-12	**3.65E-06**	3.83E-07	4.22E-06	1.06E-05	0.40		
	15.5	8.33	Recipe (End)	88	Photochemical ozone formation - Terrestrial ecosystems	3.08E-08	1.60E-08	1.65E-12	**3.92E-07**	1.51E-08	4.53E-07	1.19E-06	0.38		
	15.5	8.33	Recipe (End)	89	Acidification - Terrestrial ecosystems	2.07E-08	2.03E-08	4.12E-11	**8.99E-07**	3.66E-08	9.77E-07	2.82E-06	0.35		
	15.5	8.33	Recipe (End)	90	Toxicity - Terrestrial ecosystems	1.02E-09	7.64E-09	1.60E-13	**3.11E-08**	5.75E-10	4.03E-08	3.34E-07	0.12		
	15.5	8.33	Recipe (End)	91	Water consumption - terrestrial ecosystems	5.47E-07	4.28E-07	-7.71E-09	**3.82E-05**	6.16E-06	4.53E-05	3.22E-04	0.14		

Fig. 3 Relative holistic sustainability of LVL compared to steel beam production, presented in form of the holistic sustainability framework for HILCSA of the BE (Zeug et al. 2020) (SDGs are viewed in size according to their relevance for German BE assessments from (Zeug et al. 2019); colors and values represent the substitution factors of impacts (Table 2); white = no data)

towards holistic sustainability and contributing to the SDGs. However, LVL would be even much more sustainable and favorable when fossil components like phenolic resin are substituted by renewable alternatives, which is not only true for ecological (cf. (Hildebrandt et al. 2020)) but also for social and economic sustainability. Nonetheless, it remains of high importance to reduce land use and negative land use change impacts of forestry and to at least only use FSC certified wood is highly recommended.

We consider our results as plausible and consistent within the limits of data quality of Ecoinvent and SoCa as well as cradle-to-gate LCA in general. The LCI of the LVL manufacturing process was validated with the involved organizations (Hildebrandt et al. 2020), and comparing it to the Ecoinvent laminated timber element production produced comparable results of the same magnitude. A LCIA check in openLCA suggests that all relevant flows are covered by our HILCSA-LCIA, only a number of flows with very small fractions are not covered which would also be the case in stand-alone methods like ReCiPe or EF3.0. Our results suggest that the social, economic, and environmental impacts and sustainability of LVL production are very sensitive to the quantity and quality of binder which is applicated, in this case fossil-based phenolic resin, as well as the sustainability of forestry. Within our method, most sensitiveness of aggregated results comes from the weighting factors for SDGs from stakeholder participation, which should be carefully applied in other case studies within the same context and should be revised and newly determined in other regional contexts. A consistent data quality check and methodology cannot be applied in context of this very first case study, but partially data quality indications can be gained from the source of the used data and in further case studies build in data quality checks will be used.

4 Discussion and conclusions

This first case study of HILCSA applied as a relative sustainability assessment to LVL compared to steel beams, asks on the one hand for the holistic sustainability of LVL, and on the other hand for the lessons learned from this first application.

We defined holistic sustainability as ecological, economic and social sustainability in the sense given above on the background of the double decoupling problem and potential trade-offs and synergies. In general, with regard to the weightings, our total factor of substitution aggregated for all SDGs and indicators $f = 0.61$ gives a rough approximation on how much less unsustainable LVL can be, compared to steel. In other words, LVL has only 60% of the negative impacts in terms of social, ecological, and economic sustainability. Of course, such a highly aggregated index provides a limited analytical understanding and primarily a first orientation, as well as it can be discussed and criticized due to a number of assumptions, weightings, data quality issues, and much more. The aggregated substitution factors of impact f and f^{SDG} are more subjective and depend on stakeholder relevances compared to the non-aggregated substitution factors of impact at the level of indicators f^{sSDG} (Table 3).

When the substitution factor of impact is calculated for social $f_{\mathrm{social}} = 0.31$, ecological $f_{\mathrm{ecological}} = 1.01$, and economic $f_{\mathrm{economic}} = 0.60$ sustainability (according to the sustainability framework Table 3, the picture begins to differentiate. LVL seems to have a way better social sustainability, having a look at the indicator data and inventory, this is mainly due to the less toxicity of materials, impacts on humans and their working environments, but also higher expenditures for social security and education as well as a lower gender wage gap. However, backed up by literature (Backhouse et al. 2021), we suggest that the different technical production processes are not the main cause, but the far more global distribution of primary production chains and thereby externalization of social deprivations is much higher in the steel industry, and globalized BE would have such negative externalized effects likewise. When looking at $f_{\mathrm{ecological}} = 1.01$, we expect a quite limited better ecological sustainability, which is foremost because of the high land use (change) effects of forestry in a way compensating the significant GWP savings and much lower ecotoxicity. In terms of economic sustainability and a moderately good $f_{\mathrm{economic}} = 0.60$, we can observe mostly low and very low f in the forestry and manufacturing sector of LVL (except fossil fuel-driven machinery); indeed, the phenolic resin production is responsible for a large share of negative impacts for nearly every indicator. Again, global externalization of fossil raw material production seems to be a major issue and phenol in this case is an example for pareto effects (a relatively small number of causes responsible for a major portion of the effects (Halog and Manik 2011).

In a nutshell, we conclude that bio-based renewable materials in this case can substitute fossil materials and can lead to partially significant lower impacts and increasing sustainability. We also see that processes based on renewable resources in specific regions do not only have a better ecological, but also better social and economic sustainability and that there seem to be synergies between these aspects of sustainability. However, the dependency of sustainability from regions does not only apply to fossil industries, but bioeconomy can be very unsustainable as well when renewable material flows reproduce global social and economic inequalities and externalization of effects of sourcing and production (Backhouse et al. 2021; Eversberg and Holz 2020; Asada et al. 2020). In this regard, we see a high potential for regional, holistic, and integrated HILCSA: to not only identify trade-offs or synergies between different aspects of sustainability but also in shifting them to other regions. Besides, a significant and well known trade-off is striking and mostly independent from regions: forestry and agriculture use relatively much more land than fossil resources (in our case by factor 18) setting a major barrier for bioeconomy and simple substitution (Bringezu et al. 2020; O'Brien et al. 2017; Liobikiene et al. 2020). A sustainable bioeconomy requires that the rate of extraction does not exceed the rate of regeneration and that PB are not transgressed (Lindqvist et al. 2019; Zeug et al. 2021a). As a consequence, we suggest that different strategies for specific sectors on using renewable resources should be put in a common context. This can be done by building up a strategy and sector overarching holistic bioeconomy monitoring on national and European level (cf. Bringezu et al. 2020; BioMonitor 2018)), to avoid the double counting of resources in each strategy and sector as well as to foster synergies and to avoid trade-offs, externalization and overuse of renewable resources.

This leads to the lessons learned, and the potential which can be unlocked when absolute sustainability assessments and PB are covered by HILCSA and LCA in general. As discussed above and in previous research (Zeug et al. 2021a), absolute sustainability assessments can address PB by downscaling them to regions, production systems and products, and thereby not only give us information on absolute sustainability, but also relative sustainability if a substitution in a specific context is feasible and in fact relatively sustainable. Currently, environmental footprint methods as the basis for absolute sustainability assessments and their implementation in LCIAs are in a final transition phase (JRC 2019) and will be applicable in context of SDG frameworks like HILCSA (Sala 2019). As main lessons learned, instead of plain results for ecological indicators, context-specific risk levels like for the other indicators could be applied in future case studies entailing absolute sustainability assessments, resulting in a higher consistency as well. Important in this regard is that such LCIA methods are implemented timely in openLCA and that openLCA is constantly developed further to integrate social and economic aspects. S-LCA specific functionalities should be improved regarding a better documentation, more straight-forward implementation in the LCI and especially more flexible option in creating complex and multi-level LCIA methods. Partly quite inconvenient work flows by lack of automatization, linkage of data and working interfaces (e.g., with Excel) result in using the ILCD format and editing in XML language. Despite some lack of functionalities, e.g., parameters seem not to be supported in ILCD, there are as well no manuals on scripting ILCD and a lack of documentation. The HILCSA sustainability framework and LCSA methodology turned out to be functional and powerful to analyze the social, ecological, and economic impacts of product systems. However, the existing indicators should be further streamlined with the sustainability framework, e.g., to implement more specific indicators for contribution of product systems to fulfill societal needs and their contribution to human well-being or to describe economic effectiveness and justice of allocation of the produced goods. As well the substitution factors of impacts work well for the purpose of relative sustainability assessment of two products, but in the current form not applicable to more complex products systems on a meso- and macro-economic scale. For future developments of HILCSA, the extension to hybrid LCSA entailing multi regional input–output analyses (MRIO) (Asada et al. 2020; Budzinski et al. 2017; Crawford et al. 2018; Teh et al. 2017) as well as implementation of circular economy indicators is aimed at (Calisto Friant et al. 2020; Leipold 2021a, b; D'Amato 2021; Moraga et al. 2019; Padilla-Rivera et al. 2020).

The results of our method are depending on the chosen reference. Not to be neglected neither should be the sensitivity due to the weighting factors on aggregated levels of SDG f^{SDG} and in total f. A small sensitivity analyses, however, shows that the overall aggregated results do not change qualitatively, e.g., when all weightings R^{sSDG} and resulting R^{SDG} are set as equal ($R = 1$), then $f = 0.57$, $f_{social} = 0.33$, $f_{ecological} = 1.02$, and $f_{economic} = 0.59$. Nevertheless, in other regional contexts, the weightings should be newly determined and the indicators set should be revised as well, e.g., when child labor, hunger, or modern forms of slavery play a more significant role. Further participation formats with involved stakeholders would also be necessary to ensure collaborative creation, collaboration, and cooperation. Consequently, performance- and values-based methods can be combined in LCSA application as well as drivers and receivers of impact are regarded (Troullaki et al. 2021). In this sense, in future case studies, the data of RESPONSA indicators has to be collected from all involved stakeholders (organizations, workers, local communities) in foreground activities. Furthermore, future case studies of HILCSA should aim at the full life cycle of products, including use and end-of-life phase, as well as recycling and cascading use. Especially for substitutes, it is important to know, if the same use value can be provided for the same life span (Zeug et al. 2021a).

We emphasize that some methodological approaches in this early stage of holistic and integrated LCSA may vary from traditional LCA and concise established methodologies of environmental LCA, but that transdisciplinary and transformational science calls for less rigidly framed methods as well (Troullaki et al. 2021). In this regard, HILCSA lacks of analyzing structural societal elements of economies, e.g., ownership, control, agency, and power relations (Plank et al. 2021). For the double decoupling problem, such aspects in relation to technologies and systemic interlinkages between societal processes and the biophysical dimensions are decisive (Plank et al. 2021). Though, HILCSA does not aim for integrating everything, but to be a valuable interdisciplinary tool together with social science studies on changing and persistent mentalities (Eversberg and Holz 2020; Eversberg 2021) as well as political economy and ecology (Pichler et al. 2020). Ultimately, bioeconomy will not be successful if it is simply a substitution of resources and impacts, but if it is part of a socio-ecological transformation beyond the existing societal relations to nature (Zeug et al. 2022).

Appendix

Table 4 Sustainability framework and indicator system of HILCSA for regional wood-based BE in Central Germany (R, relevance according to (Zeug et al. 2019); AV, activity variable; FU, functional unit; quan, quantitative; qual, qualitative)

Sustainability framework				Life cycle inventory and life cycle impact assessment in HILCSA of LVL								
	SDG Code	SDG R	SDG Sub-Goal	Source	ID	Name	Description	Data type	AV/FU	Unit of Measurement	Evaluation Scheme/Normalization	Impact Factors/Normalization/Weighting
Societal Needs	1	6.6	End poverty in all its forms everywhere	Soca	1	Social security expenditures	Social security expenditures as a percentage of Gross Domestic Product (GDP)	quan	wh	% of GDP	5 = very low risk; 4 = low risk; 3 = medium risk; 2 = high risk; 1 = very high risk; n.a. = no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	1.2	6.94	Poverty reduction	Responsa	2	Payment according to basic wage	Payment according to collective agreement	qual	wh	y/n	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
	1.4	6.94	Enable economic participation for all people	Responsa	3	Capital participation	Possibility of capital participation	qual	wh	y/n	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
	1.4	6.94	Enable economic participation for all people	Responsa	4	Profit-sharing and bonuses	Possibility of profit-sharing and bonuses	qual	wh	y/n	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
	2	9.33	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Recipe (End)	5	Water consumption - HH	Malnutrition caused by water shortage	quan	mf	Daly/m3 consumed	Recipe	Recipe
	2.3	6.39	Increase agricultural productivity, income (small producers)	Soca	6	Human rights issues faced by indigenous people	Score out of a 5-point scale based on ratification of ILO convention 169, UN declaration and report available (for exact scale see documentation)	quan	wh	Score	5 = very low risk; 4 = low risk; 3 = medium risk; 2 = high risk; 1 = very high risk; n.a. = no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
				Soca	7	Presence of indigenous population	Yes or No	qual	wh	Score	0 = no = no risk; 1 = yes = medium risk	
	3.9	8.61	Reduce pollution of air/water/ soil, health protection	Soca	8	DALYs due to indoor and outdoor air and water pollution	Disability adjusted life years (DALYs) per 1,000 inhabitants in the country	quan	wh	DALY rate	0= no risk; >0-<5 = very low risk; 5-<15 = low risk; 15-<30 medium risk; 30-<50 high risk; >50 very high risk; n.a. = no data	
				Soca	9	Pollution level of the country	Pollution Index based on perceptions	quan	wh	Index	0-20 = very low risk; 20-40 = low risk; 40-60 = medium risk; 60-80 = high risk; >80 = very high risk; n.a. = no data	
				Recipe (End)	10	Global Warming - HH	Years of life lost and disabled related to increased malaria, diarrhea, malnutrition and natural disasters due to increased global mean temperature	quan	mf	DALY/kg CO2 eq.	Recipe	Recipe
				Recipe (End)	11	Stratospheric ozone depletion - HH	Years of life lost and disabled related to increased skin cancer and cataract due to UV-exposure	quan	mf	DALY/kg CFC11 eq.	Recipe	Recipe
				Recipe (End)	12	Photochemical ozone formation - HH	Years of life lost related to an increase in respiratory diseases	quan	mf	DALY/kg NOx eq.	Recipe	Recipe

Table 4 (continued)

							caused by exposure to ozone					
				Recipe (End)	13	Ionizing Radiation - HH	Years of life lost and disabled related to an increase in cancer and hereditary diseases due to exposure to radiation	quan	mf	DALY/kBq Co-60 emitted to air eq.	Recipe	Recipe
				Recipe (End)	14	Fine particulate matter formation - HH	Years of life lost related to an increase in cardiopulmonary and lung cancer caused by exposure to primary and secondary aerosols	quan	mf	DALY/kg PM2.5 eq.	Recipe	Recipe
				Recipe (End)	15	Toxicity - HH (cancer)	Years of life lost and disabled due to cancer effects due to ingestion and inhalation of toxic substances	quan	mf	DALY/kg 1,4-DCB emitted to urban air eq.	Recipe	Recipe
				Recipe (End)	16	Toxicity - HH (non-cancer)	Years of life lost and disabled due to non-cancer effects due to ingestion and inhalation of toxic substances	quan	mf	DALY/kg 1,4-DCB emitted to urban air eq.	Recipe	Recipe
	4	4.43	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Soca	17	Public expenditure on education	Percentage of GDP in a given year	quan	wh	% of GDP	0 - < 2,5% = very high risk; 2,5-<5% = high risk; 5-<7,5% = medium risk; 7,5-<10% = low risk; >=10% = very low risk; n.a. = no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very
	5.1	5.83	Eliminate discrimination against women	Soca	18	Gender wage gap	Difference between male and female median wages divided by the higher median wage*100; expressed in %	quan	wh	%	0% = no risk; 0% - <5% and 0% - >-5%= very low risk; 5% - <10% and -5% - >-10% = low risk; 10% - <20% and -10% - >-20% = medium risk; 20% - <30% and -20% - >-30% = high risk; >=30% and <=-30 = very high risk; n.a. = no data	high risk = 100; no data = 0.1
				Responsa	19	Female employees in management positions	Percentage of female employees in management positions	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	20	Rate of female employees	Percentage of female employees per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
	11.6	9.17	Reduce urban environmental impacts, air quality, waste treatment	Recipe (End)	21	If production site is in urban region, then indicator 14 is used here instead		quan	mf	DALY/kg PM2.5 eq.	Recipe	Recipe
Economy	6.1	8.61	Access to affordable drinking water, food security	Soca	22	Drinking water coverage	Percentage of the population with access to drinking water	quan	wh	%	<=85% = very high risk; >85% - 92% = high risk; >92% - 97% = medium risk; >97% - <100% = low risk; 100% = very low risk; n.a. = no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	6.2	4.44	Sanitation / hygiene	Soca	23	Sanitation coverage	Percentage of the population with access to sanitation facilities	quan	wh	%	<=85% = very high risk; >85% - 92% = high risk; >92% - 97% = medium risk; >97% - <100% = low risk; 100% = very low risk; n.a. = no data	

Table 4 (continued)

	7.2	5.56	Increase share of renewable energies, energy mix	CED	24	Share of fossil energies, CED	CED – CED_renewable; without calorific energy of biomass	quan	mf	MJ	cumulation	1.00
	7.3	5.83	Double rate of increase of energy efficiency	CED	25	Cumulative Energy Demand	CED, without calorific energy of biomass	quan	mf	MJ	cumulation	1.00
	8.5	5.00	Productive full employment, decent work, pay equity	Soca / Responsa	26	Weekly hours of work per employee	Hours of work per employee and week	quan	wh	h	40 - <48 = low risk; 30 - <40 and 48 - <55 = medium risk; 20 - <30 and 55 - <60 = high risk; <20 and >60 = very high risk; n.a.= no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
				Responsa	27	Compensati on for overtime	Compensation measures/financial compensation and free time	qual	wh	y/n	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	28	Access to flexible working time agreements	Availability of flexible working agreements	qual	wh	y/n	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	29	Rate of part-time employees	Percentage of part-time employees per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	30	Rate of marginally employees (max. 450€)	Percentage of employees earning max. 450€ per month per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	31	Rate of fixed-term employees	Percentage of fixed-term employees per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	32	Rate of employees provided by temporary work agencies	Percentage of employees provided by temporary work agencies per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	33	Rate of disabled employees	Percentage of disabled employees per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Responsa	34	Rate of foreign employees	Percentage of foreign employees per total employees	quan	wh	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Soca	35	Net migration rate	Difference between number of emigrants and immigrants during a given year per 1,000 inhabitants	quan	wh	%	0‰ = no risk; 0‰-<∣2,5∣‰ = very low risk; ∣2,5∣‰-<∣5∣‰ = low risk; ∣5∣‰-<∣10∣‰ = medium risk; ∣10∣‰-<∣15∣‰ = high risk; >=∣15∣‰ = very high risk; no data	
				Soca	36	International Migrant Stock	Percentage of the population	quan	wh	%	0% = no risk; 0%-<2,5% = very low risk; 2,5%-<5% = low risk; 5%-<10% = medium risk; 10%-<20% = high risk; >=20% = very high risk; n.a. = no data	
				Responsa	37	Average remuneratio n level	Average payment per month per full-time employee per total employees	quan	wh	€	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Soca	38	Sector average wage, per month		quan	wh	USD	living wage (LW), Sector average wage (S)/LW, minimum wage (MW), S/MW: <1 = very high risk; 1 -< 1.5 = high risk; 1.5 -< 2 = medium risk; 2 -< 2.5 = low risk; >= 2.5 = very low risk; no data	

Table 4 (continued)

				Soca	39	Unemployment rate in the country	Percentage of the population	quan	w h	%	0% - < 3% = very low risk; 3% - <8% = low risk; 8% - <15% = medium risk; 15 - <25 = high risk; >= 25% = very high risk; n.a. = no data	
	8.6	4.72	Increase share of youth employment, education and vocational training	Responsa	40	Rate of vocational trainees	Percentage of trainees per total employees	quan	w h	%	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
	8.7/ 8.8	5.00	Worker rights, labor protection rights, promoting safe work environment, abolition of forced labor / trafficking / child labor	Soca	41	Children in employment , total	Percentage of all children ages 7-14	quan	w h	% of children	0% = no risk; 0%-<2,5% = very low risk; 2,5%-<5% = low risk; 5%-<10% = medium risk; 10%-<20% = high risk; >=20% = very high risk; n.a. = no data	
				Soca	42	Trafficking in persons	Tier placement based on trafficking in persons report	quan	w h	Tier	Tier 1 = very low risk; Tier 2 = medium risk; Tier 2 Watch List = high risk; Tier 3 = very high risk; n.a. = no data	
				Soca	43	Frequency of forced labor	Cases of forced labor per 1,000 inhabitants in the region	quan	w h	‰	1,5 = very low risk; 3,1; 3,3 and 3,4 = medium risk; 4,0 = high risk; 4,2 = very high risk; n.a. = no data	
				Soca	44	Goods produced by forced labor	Number of goods produced by forced labor in the sector	quan	w h	#	0 = no risk; 1 = very low risk; 2 = low risk; 3-4 = medium risk; 5-6 = high risk; >=7 = very high risk; n.a. = no data	
				Soca	45	Right of Collective bargaining	ordinal 4 point scale (0-3)	quan	w h	Score	4 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	
				Soca	46	Right of Association	Freedom of association and collective bargaining	quan	w h	Score	3 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	
				Soca	47	Trade union density	Freedom of association and collective bargaining	quan	w h	%	0-20% = very high risk; >20-40% = high risk; >40-60% = medium risk; >60-80% = low risk; >80% = very low risk	
				Soca	48	Right to Strike	Freedom of association and collective bargaining	quan	w h	Score	5 = no risk; 2 = low risk; 1 = high risk; 0 = very high risk; no data	
				Soca / Responsa	49	Rate of non-fatal accidents at workplace	Number of non-fatal accidents per 100,000 employees and year	quan	w h	#/yr and 100k empl.	0-<750 = very low risk; 750-<1500 = low risk; 1500-<2250 = medium risk; 2250-<3000 = high risk; >3000 = very high risk; no data	
				Soca / Responsa	50	Rate of fatal accidents at workplace	Number of fatal accidents per 100,000 employees and year	quan	w h	#/yr and 100k empl.	0-<7,5 = very low risk; 7,5-<15 = low risk; 15-<25 = medium risk; 25-<40 = high risk; >40 = very high risk; no data	
				Responsa	51	Sick-leave days	Sick-leave days per year per employee	quan	w h	#	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
				Soca / Responsa	52	Presence of sufficient/preventive safety measures	Number of violations of occupational safety and health standards (=OSHA cases) per 100,000 employees in the sector	quan	w h	# per 100k empl.	0 < 100 = very low risk; 100 - < 300 = low risk; 300 - < 600 = medium risk; 600 - < 1000 = high risk; > 1000 = very high risk; no data	
				Soca	53	Violations of laws and employment regulations	Violation cases (of wage and hour compliance) per 1,000 employees in the sector between 2007 and 2014	quan	w h	# per 1k empl.	<0,1 = very low risk; 0,1 - <1 = low risk; 1 - <10 = medium risk; 10 - <100 = high risk; >100 = very high risk; n.a. = no data	

Table 4 (continued)

			Soca	54	Workers affected by natural disasters	Persons affected between 2012 and 2014 as percentage of whole population	quan	w h	%	0-<1 = very low risk; 1-<3 = low risk; 3-<5= medium risk, 5-<10 = high risk; >=10 = very high risk; n.a. = no data	
			Responsa	55	Work Council	Existence of Working Council	qual	w h	y/n	10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data	
			Soca	56	Level of industrial water use (related to total withdrawal)	Industrial water withdrawal as percentage of total withdrawal per year	quan	w h	% of total	0 - <10% = very low risk; 10 - < 20% = low risk; 20 - <30% = medium risk; 30 - <40% = high risk; >= 40% = very high risk; n.a. = no data	
			Soca	57	Level of industrial water use (related to renewable water resources)	Industrial water withdrawal as percentage of total actual renewable water resources	quan	w h	% of renewable	0 - <1% = very low risk; 1 - <3% = low risk; 3 - <7% = medium risk; 7 - <13% = high risk; >= 13% = very high risk; n.a. = no data	
12.2	8.89	Sustainable management of natural resources	Recipe (End)	58	Fossil resource scarcity	Cost increase due to fossil extraction increase	quan	mf	USD2013/kg Cu	Recipe	Recipe
			Soca	59	Extraction of fossil fuels	total extraction in t/capita in 2011	quan	w h	t/cap	0 - <10 = very low risk; 10 - <20 = low risk; 20 - <30 = medium risk; 30 - <50 = high risk; >=50 = very high risk; n.a. = no data	
			Soca	60	Extraction of biomass (related to population)	total extraction in t/capita in 2011	quan	w h	t/cap	0 - <2,5 = very low risk; 2,5 - <5 = low risk; 5 - <10 = medium risk; 10 - <15 = high risk; >=15 = very high risk; n.a. = no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
			Soca	61	Extraction of biomass (related to area)	total extraction in t/km² in 2011	quan	w h	t/km²	n.a.	
			Soca	62	Extraction of industrial and construction minerals	total extraction in t/capita in 2011	quan	w h	t/cap	0 - <2,5 = very low risk; 2,5 - <5 = low risk; 5 - <10 = medium risk; 10 - <15 = high risk; >=15 = very high risk; n.a. = no data	
			Soca	63	Extraction of ores	total extraction in t/capita in 2011	quan	w h	t/cap	0 - <5 = very low risk; 5 - <10 = low risk; 10 -<15 = medium risk; 15 - <20 = high risk; >=20 = very high risk; n.a. = no data	
			EF 3.0	64	Resource use, mineral and metals		quan	mf	kg Sb eq.	EF 3.0	EF 3.0
			Recipe (Mid)	65	Ionizing Radiation	Absorbed dose increase/Ionizing radiation potential (IRP)	quan	mf	Bq C-60 eq. to air	Recipe	Recipe
			Soca	66	Certified environmental management systems	Number of Certified environmental management systems (CEMS) (ISO 14001) in sector per 10,000 employees in the country	quan	w h	# per 10k empl.	n.a.	
12.6	8.61	Reporting on sustainability information	Soca	67	Presence of anti-competitive behavior or violation of anti-trust and monopoly legislation	Number of violations per 10,000 employees in the sector	quan	w h	# per 10k empl.	0 = no risk; >0-<0,05 = very low risk; 0,05-<0,1 = low risk; 0,1-<0,2 = medium risk; 0,2-<0,4=high risk; >=0,4 = very high risk; no data	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
16.5	7.22	Reduction of bribery / corruption	Soca	68	Public sector corruption	Corruption Perceptions Index score of the country	quan	w h	Score	100-85 = very low risk; 84-75 = low risk; 74-65 = medium risk; 64-55 = high risk; < 55 = very high risk; n.a. = no data	

Table 4 (continued)

				Soca	69	Active involvement of enterprises in corruption and bribery	Percentage of sector-related cases out of all registered foreign bribery cases	quan	wh	%	0 - 3% = very low risk; 4 - 7% = low risk; 8 - 11% = medium risk; 12 - 15% = high risk; >=15% = very high risk; n.a. = no data	
Planetary Boundaries	13	7.53	Take urgent action to combat climate change and its impacts*	EF 3.0	70	Climate Change	Infrared radiative forcing increase, Global warming potential (GWP)	quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
				EF 3.0	71	Climate Change (fossil)		quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
				EF 3.0	72	Climate Change (biogenic)		quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
				EF 3.0	73	Climate Change (land use change)		quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
				Recipe (Mid)	74	Photochemical Ozone Formation, Ecosystems/ Photochemical Ozone Formation	Tropospheric ozone increase, Photochemical oxidant formation potential: ecosystems (EOFP)	quan	mf	kg NOx eq.	Recipe	Recipe
				EF 3.0	75	Ozone depletion		quan	mf	kg CFC-11 eq.	EF 3.0	EF 3.0
	14	8.37	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	Recipe (End)	76	Global Warming - Freshwater ecosystems	Fish species loss due to decrease river discharge	quan	mf	Species.year/kg CO2 eq.	Recipe	Recipe
				EF 3.0	77	Eutrophication freshwater		quan	mf	kg P eq.	EF 3.0	EF 3.0
				EF 3.0	78	Ecotoxicity freshwater		quan	mf	CTUe	EF 3.0	EF 3.0
				EF 3.0	79	Water use		quan	mf	m³ world equiv.	EF 3.0	EF 3.0
				EF 3.0	80	Acidification terrestrial and freshwater		quan	mf	Mole of H+ eq.	EF 3.0	EF 3.0
	14.1	8.33	Reduce marine pollution, marine litter / nutrient pollution	Recipe (End)	81	Toxicity - Marine ecosystems	Species loss due to chemical exposure in marine waters	quan	mf	species·yr/kg 1,4-DBC emitted to sea water eq.	Recipe	Recipe
				EF 3.0	82	Eutrophication marine		quan	mf	kg N eq.	EF 3.0	EF 3.0
	15.1	7.50	Preservation / sustainable use of terrestrial and inland freshwater ecosystems	EF 3.0	83	Land Use		quan	mf	Pt	EF 3.0	EF 3.0
				Recipe (Mid)	84	Terrestrial Acidification	Proton increase in natural soils, Terrestrial acidification potential (TAP)	quan	mf	kg SO2 eq.	Recipe	Recipe
				Recipe (Mid)	85	Terrestrial ecotoxicity	Hazard-weighted increase in natural soils, Terrestrial ecotoxicity potential (TETP)	quan	mf	kg 1,4-DB eq.	Recipe	Recipe

Table 4 (continued)

				EF 3.0	86	Eutrophication terrestrial		quan	mf	Mole of N eq.	EF 3.0	EF 3.0
	15.5	8.33	Protecting natural habitats, threatened species, biodiversity	Recipe (End)	87	Global Warming - Terrestrial ecosystems	Species loss related to changing biome distributions due to increased global temperature	quan	mf	Species.year/kg CO2 eq.	Recipe	Recipe
				Recipe (End)	88	Photochemical ozone formation - Terrestrial ecosystems	Loss of plant species due to increase in ozone exposure	quan	mf	Species.year/kg NOx eq.	Recipe	Recipe
				Recipe (End)	89	Acidification - Terrestrial ecosystems	Loss of plant species due to decrease in soil pH	quan	mf	Species.year/kg SO2 eq.	Recipe	Recipe
				Recipe (End)	90	Toxicity - Terrestrial ecosystems	Species loss due to chemical exposure in soils	quan	mf	species*yr/kg 1,4-DBC emitted to industrial soil eq.	Recipe	Recipe
				Recipe (End)	91	Water consumption - terrestrial ecosystems	Decrease in Net Primary Productivity because of water shortage as proxy for total species loss	quan	mf	species.yr/m3 consumed	Recipe	Recipe

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Declarations

Conflict of interest The authors declare no competing interests.

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Holistic and integrated life cycle sustainability assessment of prospective biomass to liquid production in Germany

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Author contributions

Walther Zeug conducted the research, general analysis, conceptualization, writing, management, and submission of this research article. Karla Raquel Gan Yupanqui partially provided social indicator data. The manuscript has been edited by Alberto Bezama and Daniela Thrän and reviewed by all authors.

Data availability

The data generated and analyzed in this study are available from the corresponding author upon request.

Conflicts of interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Holistic and integrated life cycle sustainability assessment of prospective biomass to liquid production in Germany

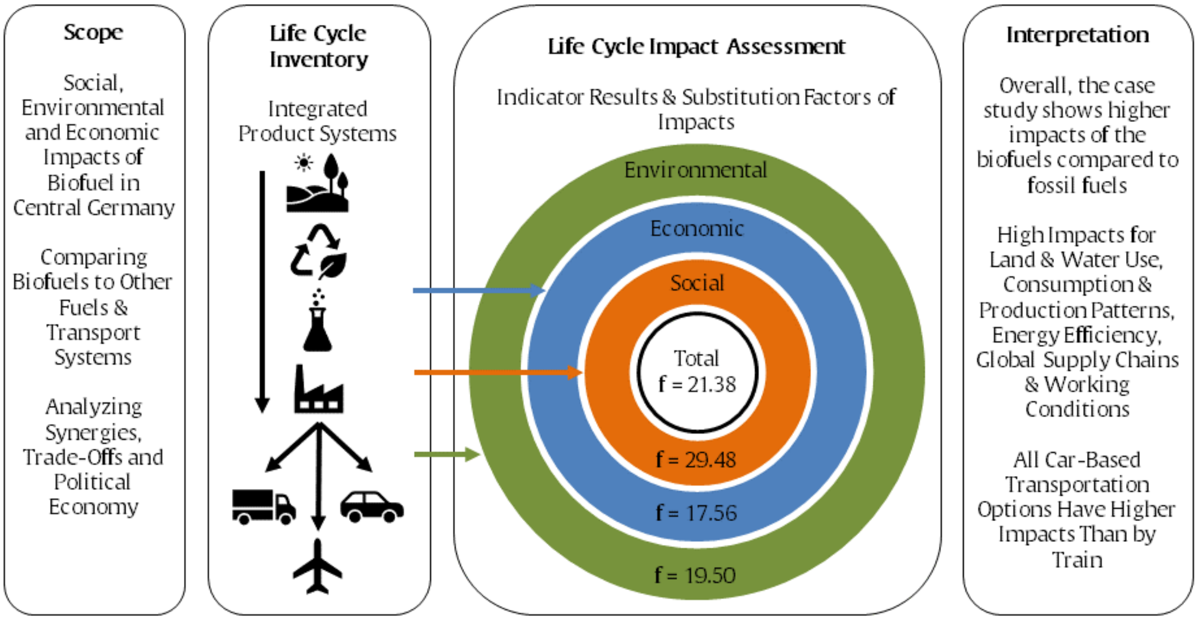
Abstract:

As a part of the developing bioeconomy, liquid biofuels may play an important role for transportation due to the hope for a sustainable drop-in alternative to substitute fossil fuels and maintaining existing economic infrastructures. In this case study we applied Holistic and Integrated Life Cycle Sustainability Assessment to a prospective technical concept for the production of biofuels from wood residues, sorghum and straw via gasification and Fischer-Tropsch synthesis located in the German federal state Brandenburg. Through this quantitative and qualitative sustainability assessment we identified synergies and hot-spots of biofuel production on a detailed and aggregated level, as well as compare the impacts to fossil fuels and other alternative transport systems. 99 social, ecological and economic indicator results addressing 14 out of 17 SDGs show contributions but also sustainability risks of such biofuels for the SDGs. The total substitution factor of impacts (f = 21.38) for all indicators of biofuels compared to fossil fuels indicates significantly higher impacts of biofuels production, in particular for land (SDG 15, f = 30.43), water (SDG 14, f = 125.57), consumption and production patterns (SDG 12, f = 54.11), low energy efficiency and maintaining problematic global supply chains and working conditions. However, the impacts on climate can be lower (SDG 13, f = 0.42), if residual heat is effectively and efficiently used. Comparing the transportation systems and use phases of fuels, all types of car-based individual transportation including fossil fuels (f = 6.50), biofuels (f = 9.16) and electric drive (f = 6.46) had significant higher impacts than transportation by train. Besides technological downsides, such as the high energy demand, biofuels may play a minor role for specific applications with no other alternative energy technologies in the future. In conclusion, it is very questionable whether such liquid biofuels are a suitable drop-in solution to substitute fossil fuels in a significant quantity. In a final discussion we referred to the necessary societal-ecological transformation with structural changes of production, consumption, political economy and global supply chains. In the future, Holistic and Integrated Life Cycle Sustainability Assessment will be further improved by closing indicator and database gaps, including a cost analysis and direct stakeholder participation, as well as absolute sustainability assessments on how much biofuel production is sustainable.

Keywords: bioeconomy; biofuels; sustainability; sustainability assessment; LCSA; transformation

Highlights:

- A Holistic and Integrated Life Cycle Sustainability Assessment analyses impacts, synergies, trade-offs & political economy
- Biofuels can have less CO_2 emissions but more social, ecological & economic risks
- Regional bioeconomy can maintain problems in global supply chains
- Biofuels from this technology are not a drop-in solution to substitute fossil fuels


Scope
Social, Environmental and Economic Impacts of Biofuel in Central Germany
Comparing Biofuels to Other Fuels & Transport Systems
Analyzing Synergies, Trade-Offs and Political Economy
Life Cycle Inventory
Integrated Product Systems
Life Cycle Impact Assessment
Indicator Results & Substitution Factors of Impacts
Environmental
Economic
Social
Total
f = 21.38
f = 29.48
f = 17.56
f = 19.50
Interpretation
Overall, the case study shows higher impacts of the biofuels compared to fossil fuels
High Impacts for Land & Water Use, Consumption & Production Patterns, Energy Efficiency, Global Supply Chains & Working Conditions
All Car-Based Transportation Options Have Higher Impacts Than by Train

1. Introduction

Effectively addressing growing global socio-ecological crises is, and will be, the major challenge of our economic and political systems. Transformation efforts must be twofold, i.e., the decoupling of the fulfillment of societal needs from an ever-increasing production of goods (societal decoupling) combined together with the decoupling of sufficient production from negative environmental, social and economic impacts (technological decoupling) (Zeug et al., 2023). For example, Germanys' environmental footprint is 3.3 times higher than its biocapacity (Bringezu et al., 2021; GFN, 2019; Network, 2019; Schaefer et al., 2006). Sustainable technologies and innovation alone are not sufficient for this transformation, but innovation is one of the prerequisites for sustainable technologies and the necessary substitution of fossil resources. Without a societal decoupling there can only be a relative decoupling (fewer impacts per product) but no absolute decoupling (fewer impacts in total) which is decisive for not further transgressing planetary boundaries (PB) like climate change. Nevertheless, there is no evidence for current or perspective absolute decoupling (Haberl et al., 2017; Parrique T., 2019).

In an effort to address these challenges, more than 50 countries worldwide developed bioeconomy (BE) related policy strategies (Bell et al., 2018; German Bioeconomy Council, 2018; Kleinschmit et al., 2017; Meyer, 2017) to achieve an interpretation of sustainable development. BE is broadly understood as "the production of renewable biological resources and the conversion of these resources, residues, by-products and side streams into value added products, such as food, feed, bio-based products, services and bioenergy within the framework of a sustainable economy" (German Bioeconomy Council, 2018). But a BE and circular economy (CE) (D'Amato, 2021) are not sustainable per se. The expected overall transformation from fossil to renewable resources is a stepwise long-term process and an awareness for synergies but also trade-offs between conflicting aims is present. Over recent years, technological progress and political promotion led to a significant expansion and intensification of the use of bio-based resources both in Germany and worldwide. In congruence with economies as a whole, bio-based value chains are also becoming even more globalized through BE development, which contributes to increasing impacts on land use, environment and income in other countries (SYMOBIO, 2018).

In contrast to fossil resource-based economic activities, BE has an inherent capacity for regeneration, allowing natural or biological resource stocks to both replenish after extraction and typically be in a constant interaction with their surrounding systems (Erb et al., 2022; Lindqvist et al., 2019; Zörb et al., 2018). However, this capacity for regeneration is only sustainable if: [1] the rate of extraction does not exceed the rate of regeneration; [2] the regenerative capacity is not diminished by extraction, processing, and utilization of resources; [3] planetary boundaries are not transgressed; [4] material and energy cycles are increasingly linked; and [5] societal needs are fulfilled as the central objective of the economy itself (Zeug et al., 2023). A societal-ecological transformation would have to change patterns of regulation, societal relations, economic activities, and technologies.

Thus, BE is subject to different and partly contradicting interest groups (Bioökonomierat, 2022a, b; OECD, 2018) and mentalities (Eversberg and Fritz, 2022; Zeug et al., 2019), e.g., BE as a technological solution to enable further growth in 'green capitalism' vs. BE as a socio-ecological transformation. Usually it is seen as a market-based transition pathway, intended as a more sustainable capitalist economy producing fewer greenhouse gases (GHG) and providing 'business-as-usual' approaches to resolving climate change (Birch, 2021). However, from societal

(Eversberg and Fritz, 2022), technological (Parrique T., 2019), and environmental (Bringezu et al., 2021) perspectives the initial promise of unlimited bioeconomic growth was exposed as exaggerated or unfounded, and meanwhile, alternative conceptions of bioeconomic transformation are receiving increasing attention (Birch, 2021; Eversberg and Fritz, 2022).

Biofuels in their liquid form are industrially processed from biomass for use in transport, energy production, or for domestic uses. Liquid biofuels are especially important in transportation as ‘drop-in’ fuels compatible with existing transportation infrastructures built around internal combustion engines, like in aviation and road transportation (Ponte and Birch, 2014; van den Oever et al., 2022). The global transportation sector emitted 5.8 Gt CO_2 in 2000 and 8.2 Gt CO_2 in 2019 (41 % increase), with road transport as the major contributor with 4.3 Gt CO_2 in 2000 and 6.1 Gt CO_2 in 2019 (IEA, 2022), rising at a faster rate than any other energy end-use sector (Mattioli et al., 2020). By becoming a dominant and economic significant ‘carbon-lock in’ technology, car-dependent transport systems are interlocking technological, institutional, social and political forces hindering the mitigation of global climate change (ebd.). Due to these forces, there are partly unrealistic hopes and expectations placed onto bio- or e-fuel technologies to solve the problem with engineering science, without addressing any political-economic dimension and the necessity of deeper transformations (Hornborg, 2017). When liquid biofuels are only seen as drop-in technological problem solvers and more deeply engrained dimensions of the economy remain unchanged, then fossil mentalities still prevail within the BE, i.e., both “the belief that market forces alone regulate the production and distribution of goods without democratic participation, hierarchical dominance over nature and socially disadvantaged groups” and “the strive for extracting more and more natural resources to fuel economic growth etc.” (Fritz, 2022).

Governments around the world push the application of liquid biofuels, i.e. the Renewable Energy Directive (RED) adopted at the European level in 2009, with its 2018 revision (RED II) defining minimum shares of biofuels in the transport sector (RED: 10% by 2020, REDII: 14% by 2030), or the Fuel Quality Directive (FQD) aiming to reduce the lifecycle GHG of fuels (Maier et al., 2021). Additionally, the RED II defines sustainability criteria for biofuels, i.e., biomass cannot be taken from primary forest, nature protection areas, highly biodiverse grassland or land with high carbon stocks. However, the extent and effectiveness of the RED sustainability criteria is questioned due to lacking control instruments and their implementation, not completely excluding unsustainable feedstocks (Mestre, 2021) and low estimations for GHG emissions (Fehrenbach et al., 2023). As a result of such policies, biomass-sourced fuel utilization has changed from 3 out of every annual 50 EJ sourced from biomass being used as transportation fuels in the 1990s to the International Energy Associations (IEA) predicting around 100 EJ of biofuels per year in 2050, and a further increase to 190 EJ per year by 2085 (Sikarwar et al., 2017). The IEA strongly argues for sustainability governance for bioenergy, for which the SDGs could be used as a normative framework (Fritsche et al., 2018).

Liquid biofuels are usually distinguished as conventional (by fermenting, distilling or transesterification of crops and plants) and advanced biofuels (thermochemical or biochemical processes applied to forestry byproducts, crop residues, waste and algae feedstock), where the latter are associated with less negative social and environmental impacts such as food concurrency, land-use change, biodiversity loss, as well as human- and ecotoxic industrial agriculture (Ponte and Birch, 2014; Sikarwar et al., 2017). One way to produce liquid biofuels is to synthesize biomass to liquids (BtL) by using biomass gasification and subsequent Fischer Tropsch synthesis (FT), which is considered as the most developed and mature technology for biofuel production. Within next-generation biofuels and thermochemical technologies, biomass gasification is considered as cost-effective and efficient for liquid biofuels, i.e., processing biomass to synthetic gases by thermal degradation at high temperatures coupled with a chemical and/or catalytic upgrading to liquid fuels such as diesel, petrol, and kerosene (Sikarwar et al., 2017). BtL production is using a surface polymerization reaction in which syngas is converted to a synthetic crude oil (syncrude) at the surface of the catalyst on site (Mahmoudi et al., 2017). However, FT fuel production based on biomass gasification has not reached an industrial scale or market maturity yet, with only some demonstration projects in operation (ETIP, 2022; FNR, 2022; Sikarwar et al., 2017; van den Oever et al., 2022).

Important constraints for biofuels production are threefold: [1] the limited sustainable potentials of available biomass, [2] the preference of CE models to prefer biomass which cannot be materially used and [3] the general overall energy efficiency of biofuels production, oftentimes expressed as the Energy Return on Investment (EROI), e.g., the subtraction of the energy spent on producing, harvesting, and processing from the energy produced as biofuels (see chapter 2). When EROI is very low or even negative, a specific biofuel production not only requires subsidies but is also, in terms of net energy, not technically energy production at all. The legitimization of such technologies is questionable regarding alternative uses of biomass, use of alternative fuels such as direct electricity, and the decisive GHG (Hornborg, 2017). Most renewable energy sources tend to have lower EROI than fossil fuels. In extreme cases very low EROIs can lead to an increased gross energy consumption and the collapse of energy systems in so-called energy-traps (Perez-Valdes et al., 2019). There are mainly concept based studies on GHG emissions from BtLs and some suggest lower emissions of biofuels than for petroleum-derived fuels with overall efficiency and the biomass-to-fuel efficiency between 34%–46% and 34%–50% (Sikarwar et al., 2017; van den Oever et al., 2022). Bioenergy and biofuels can play a crucial role in a transformation towards a more sustainable energy system since they provide GHG emission reductions by using potentially regional renewable resources at comparably lower costs then other technologies, especially when electrification is probably not available like in aviation (Lauer et al., 2022; van den Oever et al., 2022). Modelling results also show that additional costs can be expected when substituting fossil fuels with other renewable alternatives, such as E-fuels (Lauer et al., 2022). However, biofuel and BtL production can generate significant GHG emissions and sustainability risks in the value chain, and therefore, the conduction of life cycle assessments (LCA) is a relevant consideration for analyzing and reducing risks of technologies. The LCAs on BtL (Maier et al., 2021; Sikarwar et al., 2017; Suwelack, 2016; van den Oever et al., 2022) often focus on favorable subjects such as technology, economics and party GHG emissions, but less on social, safety, environmental, and health issues. Thus, future assessments should also consider food security, poverty, land use (especially for lignocellulosic feedstocks), energy security, and working conditions. In general, there is a research gap for sustainability definitions or operationalizations and social, ecological, and economic LCA, which is specifically the case for BE and biofuels (Reijnders, 2022).

The goal of this work is to analyze and assess the social, environmental, and economic impacts of the relevant material and energy flows using the holistic and integrated life cycle sustainability assessment (HILCSA) sustainability framework and impact assessment methodology and embedding these results in ongoing societal discourses. It is not a detailed technical process simulation of BtL production by gasification and FT, but rather an attempt to provide an as complete as possible picture on sustainability risks and chances as well as potentials for improvement of such technologies. For the following case study, we are able to access the technical flow model from the BECOOL research project (Brazil-EU Cooperation for Development of Advanced Lignocellulosic Biofuels) (Dögnitz et al., 2022) of a prospective BtL production in Brandenburg, Germany, using sorghum, wood residues, and straw as regional biomass feedstocks and processing them by gasification, Fischer-Tropsch synthesis (FT), and refinery operation to diesel, petrol and kerosene. The BECOOL project is aimed at finding and optimizing technological and economic aspects of different routes to FT fuels through biomass pyrolysis and gasification.

The guiding research questions are: [1] How socially, ecologically, and economically sustainable would be the BtL production in Germany, when compared to conventional fossil fuels? [2] What would be substitution effects, hotspots, trade-offs, and synergies?

2. Methodology: The HILCSA framework

Beyond traditional environmental and economic LCAs with a very limited set of indictors, life cycle sustainability assessments (LCSA) based on life cycle assessment (LCA) methods are considered as promising approaches to measure and assess social, ecological and economic sustainability and considered as essential for a movement towards global sustainable development by many stakeholders (Balkau and Sonnemann, 2017; de Besi and McCormick, 2015; Gao and Bryan, 2017; OECD, 2018; Onat et al., 2017). However, most LCSA approaches follow an additive scheme of LCSA (LCSA = social LCA (S-LCA) + environmental LCA (E-LCA) + life cycle costing (LCC)) and are lacking a theoretically founded framework of holistic sustainability, as recent comprehensive reviews show (Costa et al., 2019; D'Amato et al., 2020; Fauzi et al., 2019; Troullaki et al., 2021; Wulf et al., 2019; Zimek et al., 2019). In practical terms, this lead to different social, economic and ecological scopes, corresponding methods and indicators of the life cycle inventory (LCI), different life cycle impact assessment (LCIA) and interpretations which are very limited and lacking of identifying the important synergies, trade-offs and relations between social, environmental and economic aspects (Zeug et al., 2021, 2022; Zeug et al., 2023). However, the wider social, ecological and economic impacts as well as synergies, trade-offs and political economy of production systems in general and of BE and BtL in specific, are of particular importance to sustainability assessments of technologies in context of a societal-ecological transformation. To our knowledge no LCSAs were conducted for BtL product systems, yet.

2.1. Holistic and Integrated Life Cycle Sustainability Assessment

For assessing the social, ecological and economic effects and impacts of this prospective BtL value chain in Germany, we used the newly developed holistic and integrated life cycle sustainability assessment (HILCSA) framework. The general methodological approach of HILCSA oriented on LCA and ISO 14040/14044 was developed (Zeug et al., 2021; Zeug et al., 2020; Zeug et al., 2023) and applied in previous studies (Zeug et al., 2022). Holistic in regard to the model means to have the bigger picture in mind, i.e., a transdisciplinary and critical political economy and societal-ecological transformation, where integrated stands for an integrated model of sustainability and integrating social, ecological and economic sustainability assessment into one unified LCA method, instead of additionally combining different methods (Guinée, 2016; Guinee et al., 2011; Zeug et al., 2023). Instead of the typical three-pillar approach we proposed an integrated sustainability framework (Fig. 1, i). In contrast to the additive LCSA (LCSA = S-LCA + E-LCA + LCC), the HILCSA (HLCSA = f (S-LCA, E-LCA, LCC)) integrates social, economic, and ecological aspects in a common goal and scope, i.e., LCI, LCIA, results and interpretation (Fig. 1, ii).

In HILCSA economic systems on a meso scale, such as BtL production, are handled as product- and process-systems in LCA, comprising physical and social systems and mediating the relationship between natural resources and societal needs. The applied sustainability framework is aimed at defining a good life for all within planetary and regional boundaries and societal relations to nature (SRN), which fulfill societal needs (ends) by means of natural resources, labor, and technologies (means). Integrated sustainability is defined as:

- Long-term and global fulfillment of societal needs and well-being as an end (social sustainability),
- Long-term stability of our environment as a basis of societal reproduction within PB (ecological sustainability),
- Technologies and economic structures as efficient, effective, sufficient, and just metabolisms which enable the fulfillment of societal needs within PB (economic sustainability).

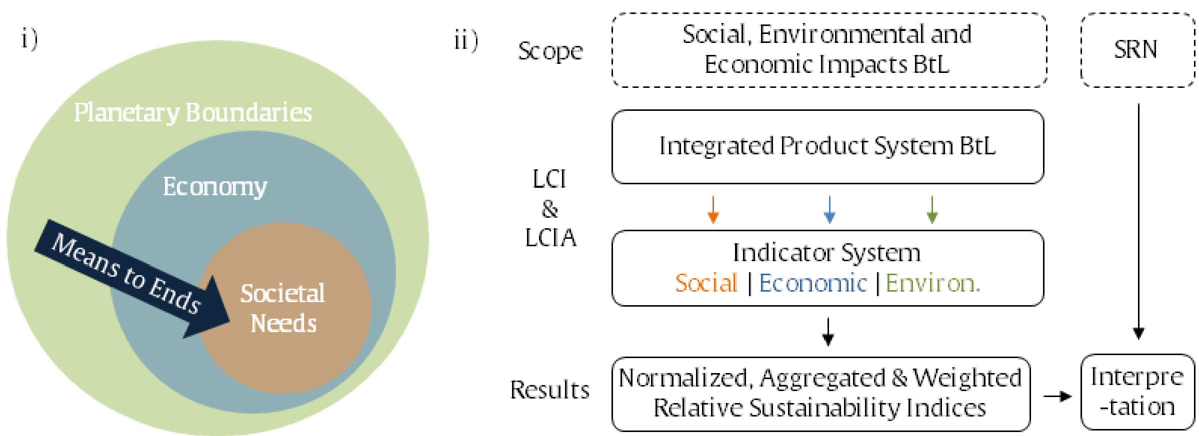


Fig. 1 Sustainability concept and methodological framework of HILCSA (holistic and integrated LCSA) *(color in web and print)*

The operational core of HILCSA for the life cycle inventory (LCI) is integrated production systems and processes entailing social, ecological, and economic data, which is modeled in the software environment of openLCA, mainly using the Ecoinvent database expanded by the SoCa database by GreenDelta (Di Noi et al., 2018; Eisfeldt, 2017) and completed by additional gathering of data for material and energy flows, as well as social data. Essential for integrated LCSA are integrated databases, such as SoCa, which is an add-on combination of the Ecoinvent and PSILCA (Product Social Impact Life Cycle Assessment) database. The first version of HILCSA (Zeug et al., 2021, 2022) entailed a standard set of 109 quantitative and qualitative indicators capable to address societal needs by 21, economy by 59, and the PB by 29 indicators, thereby addressing 14 out of 17 SDGs (SDG 9, 10 & 17 missing).

2.2. *Application of HILCSA for evaluating the case study: BtL sustainability assessment*

For this research we introduced the updated SoCa v2 database (Green Delta, 2021) to HILCSA, which entails updated and new indicators from the PSILCA v3 database (Maister et al., 2020) and Ecoinvent v3.7.1, resulting in a updated second version of HILCSA with updated impact categories as well as updated and new indicators (Table A 2). In the following, applied HILCSA v2 entails a set of 99 quantitative and qualitative indicators capable to address societal needs through 24 indicators, economy by 56 and the PB by 22, as well addressing 14 out of 17 SDGs (SDG 9, 10 & 17 currently not addressed). In this study we introduced EROI related indicators to HILCSA (section 3.2 & 3.3), since an estimation of EROI is of significant importance in generally assessing the sustainability of biofuels and energy systems (Perez-Valdes et al., 2019). In this study 20 socio-economic indicators and their data were gained from the S-LCA RESPONSA methodology and model (Bezama, 2018; Siebert et al., 2018), and as in our previous case study (Jarosch et al., 2020; Zeug et al., 2022), the RESPONSA data was determined in a separate research (Gan Yupanqui and Zeug, Forthcoming). However, RESPONSA data was limited to the BtL production only and not part of the comparison with fossil fuels and final aggregated results.

Like in HILCSA v1, in HILCSA v2 most of the indicators are derived from several established life cycle impact assessment (LCIA) methods, like ReCiPe, Impact World +, EF 3.0, Cumulative Energy/Exergy Demand, RESPONSA, and SoCa v2. All indicator values were assessed against the progressive regulation of SRN and a societal-ecological transformation (Zeug et al., 2023), e.g., high efficiency and effectiveness, or less working time and a higher average renumeration lead to better assessment results in the LCIA. As in the previous case study (Zeug et al., 2022), this case study compared the impacts when substituting a fossil fuel mix (diesel, petrol, kerosene) by the same fuel mix from BtL. For each indicator i, which was assigned to a specific subgoal SDG $sSDG$, in openLCA we calculated values x for each process of the BtL product system x_{sSDG}^{BtL}, as well as cumulated (total) values for the whole product system of BtL $x_{sSDG,T}^{BtL}$ and the fossil fuels $x_{sSDG,T}^{FF}$. Finally, the results of all indicators from BtL and fossil fuels were compared, to assess their relative sustainability. Therefore, we calculated a factor f^{sSDG} called the substitution-factor of the impact of an indicator (Eq. 1), expressing the magnitude of relative sustainability which is a factor that indicates the extent to which the impacts of one product system are larger or smaller than those of the reference system. As an aggregation on the SDG level, we calculated weighted mean factors for substitution of the impact for each SDG f^{SDG} (Eq. 2), according to the assignment of SDGs to societal needs (SDG 1, 2, 3, 4, 5, 11, (16, 17)), economy (SDG 6, 7, 8, 9, 10, 12), and ecology (SDG 13, 14, 15). As weighting factors, we used the relevances R^{sSDG} of each of the SDG-subgoals in the context of German BE-monitoring (Zeug et al. 2019). Calculated analogical, there was a total substitution-factor of impacts f on the level of all SDGs (Eq. 3).

$$f^{sSDG} = x_{sSDG,T}^{BtL} / x_{sSDG,T}^{FF} \qquad \text{(Eq. 1)}$$

$$f^{SDG} = \sum_{sSDG} (R^{sSDG} f^{sSDG}) \,/\, \sum_{sSDG} R^{sSDG} \qquad \text{(Eq. 2)}$$

$$f = \sum_{SDG} (R^{SDG} f^{sSDG}) \,/\, \sum_{SDG} R^{SDG} \qquad \text{(Eq. 3)}$$

This methodology was applied to a product system of BtLs derived from the BECOOL project which is shown in detail in section 3.1. All input and output material and energy flow data were gained from the BECOOL project and no additional detailed technology and process simulations were conducted in this study. The results from BECOOL entail no social or more complex economic data or considerations. The data was then implemented as a product system in openLCA using the Ecoinvent/SoCa database as far as possible. For handling missing data, a series of assumptions were made as described in section 3.2. To finally make a relative sustainability assessment of BtL, we applied HILCSA v2 to the fossil fuel reference production system of the same fuel mix. Both, the functional unit of BtL and the fossil fuel system is a product basket of a total amount of 1 MJ of fuel mix, consisting out of 0.272 MJ ($6.38*10^{-3}$ kg) diesel, 0.399 MJ ($9.18*10^{-3}$ kg) petrol, and 0.330 MJ ($7.66*10^{-3}$ kg) kerosene. Thus, as drop-in fuels, BtLs are qualitatively and quantitatively a full substitute of fossil fuels and no further comparison factors were needed (cf. (Zeug et al., 2022)). Since all further downstream processes in the use phase of such fuels were assumed to be the approximately the same, a cradle to gate approach was sufficient. However, the chemical composition of BtL can differ from fossil fuels resulting in minor differences of emissions in the refinery operation and use phase, which were not regarded in detail in this study. With regards to EROI and further comparability, an extended assessment for the use phase in a personal transport car and a comparison with electric drive was conducted.

Since the BtL production system was a prospective technology modeling and assessment and not yet a real-world practice, we assumed that a practical implementation could be possible by 2030. In this regard, we adopted the Ecoinvent Electricity production system for Germany to 2030 by implementing a current energy scenario for 2030 (Matthes et al., 2022) (see Table A 1) applied for BtL, fossil fuels, electric cars and trains likewise. We limited the adoption to the 2030 scenario to the German electricity production system as the main impact contributor, without making additional changes and adoptions to other foreign energy systems, technologies or socio-economic relations. In order to have practical relevance with a comparison of different transport systems, including not only the production but use phase of fuels, we compared within the electric grid mix of 2030 in Germany in the transport of one person for one kilometer by an electric car (transport, passenger car, electric | transport, passenger car, electric | APOS, U - DE), a diesel car powered by fossil fuel and diesel car powered by BtL (transport, passenger car, medium size, diesel, EURO 5 | transport, passenger car, medium size, diesel, EURO 5 | APOS, U - DE), and average trains in Germany (transport, passenger train | transport, passenger train | APOS, U - DE), applied the same methodology as above. Statistical average values were used in Ecoinvent for the capacity utilization of the respective means of transport. However, the simplified comparison of the different modes of transport was limited to medium and long distances with sufficient infrastructure conditions. For all processes and product systems the boundaries were modelled according to the full background system available in Ecoinvent.

3. Holistic Life Cycle Sustainability Assessment: Results

3.1. Goal and Scope

The goal of this study is to assess the relative social, environmental, and economic impacts of BtL fuel production as a regional BE product system, contributions to the SDGs, and a socio-ecological transformation (Zeug et al., 2023). We rely on the technical, economic, and logistical flow model from the BECOOL project, which is discussed in detail in the BECOOL report (Dögnitz et al., 2022), and the given material and energy flow data of this prospective BtL production, which is assumed to take place in Brandenburg, Germany, with its foreground processes, as a cradle (biomass sourcing) to gate (fuel mix at refinery) life cycle providing 1 MJ fuel mix (40 % petrol, 33

% kerosene and 27 % diesel) as a functional unit (Fig. 2, Table 1). We speak about regional BE, as it is the case here, when a predominant share of resource extraction, semi-finished products, and manufacturing (foreground system) take place within a spatial area of no more than a 100-km radius. As a background system, we describe all other processes, mainly all upstream and downstream flows and processes such as by-educts, by-products (i.e. Electricity, transport, materials and energies), and elementary flows modelled by Ecoinvent.

The biomass sourcing data and reliability of biomass supply comes from field experiments of the BECOOL project to determine sustainable removal rates and logistics in a region. Straw is sufficiently available in the region. Sorghum, however, is not produced yet but considered as a promising future single crop or part of a double cropping system in Central Germany (Dögnitz et al., 2022), which means potential environmental risks due to additional water and land use as well as biodiversity of additional primary plant production. For this case study the crop cultivation model from Ecoinvent is used. Residual wood is available as residual forest wood or residual wood from industry, and in this case, we choose residual soft- and hardwood from industry since this resource base is available in the real world and for modelling in Ecoinvent v3. Biomasses for gasification need to have a moisture content (mc) of maximum 20% (Dögnitz et al., 2022), and in this case sorghum is dried from 68 % mc to 28 % mc in the field, residual soft- and hardwood has 41 % mc and straw 18 % mc after drying in the field. The mc of biomass feedstock is a vital parameter, since every kg of moisture from wet mass (wm) needs to be removed by around 2.3 MJ of unrecoverable energy (Sikarwar et al., 2017).

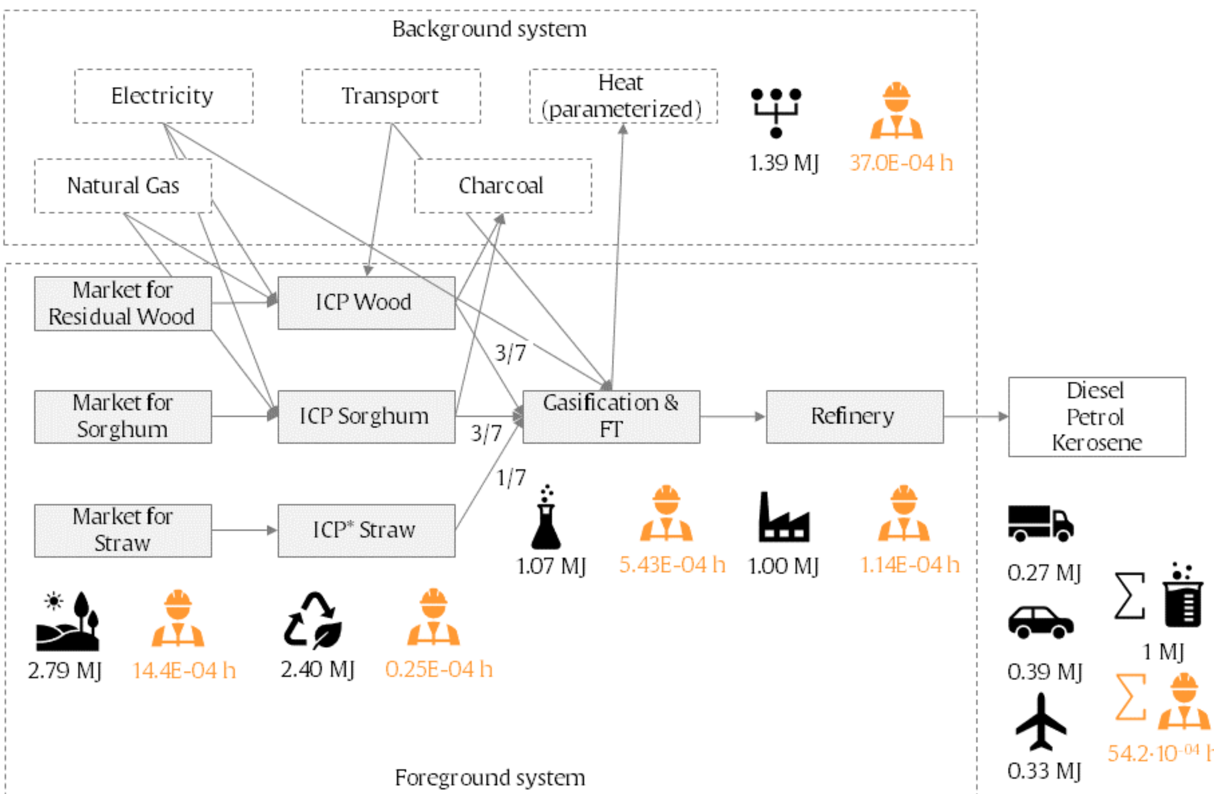


Fig. 2, Product system and flow sheet model for BtL production (Quantities are gross calorific energy of product output in MJ and required working time in h for production of 1 MJ BtL fuel mix (functional unit); FT – Fischer Tropsch synthesis, ICP – intermediate collection point (collection and drying of biomass by slow pyrolysis and support firing), ICP* - intermediate collection point without drying of biomass) *(color in web and print)*

All biomasses have to be collected, as well as residual wood and sorghum additionally dried, at intermediate collection points (ICPs). In the BECOOL project ICPs are small-scale decentralized units containing storage silos for compensation of fluctuations in supply and any necessary pre-drying (in general for residual wood pre-drying from 41 % to 30 % mc, for other biomass when moisture content changes due to weather conditions), as well as multiple moving bed/rotating kiln slow pyrolysis units providing heat from biomass and natural gas for final drying of sorghum and residual wood to 20 % mc. Besides heat, the slow pyrolysis produces char, which theoretically can be fed to gasification, be used as soil amendment or to substitute charcoal. However, the uses of this by-product are assumptions under discussion with no practical evidence (Dögnitz et al., 2022), and so char is not considered for further use and is evaluated as an avoided product in openLCA. Straw is only collected at ICPs and no additional drying by pyrolysis is needed. From the ICPs the biomass is transported 50 km by road to gasification and FT synthesis.

The mix of biomass is determined in BECOOL regarding the technical, economic, and logistic availability for gasification, resulting in a share of 3/7 sorghum, 3/7 residual wood and 1/7 straw of biomass measured as dry mass (dm). In the project gasification is provided by the MILENA technology, heating the biomass to 850°C in the gasification section and thereby degasifying the biomass particles, partially converting them into gas by a exothermic reaction, resulting in a turbulent fluidization of the material, releasing the produced synthetic gas (syngas) at the top of the reactor and sending it to the cooling and gas cleaning section (van der Drift and van der Meijden, 2011). Subsequently, a gas cleaning and FT synthesis (around 100 MWth) is taking place, which is a highly exothermic reaction (H298K = −140 to −160 kJ.mol−1 CO) operating in the temperature range of 150–300 °C (Mahmoudi et al., 2017).

Syncrude from biomass is similar to fossil crude oil (petroleum oil) and thus can be transformed and refined at an average oil refinery into products such as petrol, diesel, oils, kerosene, gas, and naphtha. For transport of syncrude to the refinery it is assumed that there is an average travel distance of 50km by road. The activities end with a mix of refined petroleum products (1 MJ of diesel, petrol and kerosene as functional unit) leaving the refinery.

Due to the limitations of this study, especially its prospective character and building on another study, no additional stakeholder participation is conducted. We point out, however, that this would be absolutely necessary if a real-world implementation of such product systems is considered. All social and economic relations and data involved in the described product system, including working hours (Fig. 2), are gained in the LCI from the SoCa database, literature review, and results from RESPONSA.

3.2. Life Cycle Inventory

In implementing the BtL production system in openLCA we use the SoCa v2 database based on Ecoinvent v3.7 as far as possible and complement non-existing data by creating additional processes and flows. The resulting material and energy flows, as well as required working hours for producing 1 MJ of BtL fuel mix as functional unit in the 2030 energy system, are shown in Table 1.

Table 1, Material and energy flows and working hours for BtL production system of 1 MJ fuel mix (kg as dry mass, MJ as energy gross calorific value, Biom – Biomass, Refi – Refinery, ICP – Intermediate Collection Point, Gasifi – Gasification, Elec – Electricity, NG – Natural Gas, FT – Fischer Tropsch, Sorg – Sorghum, RW – Residual Soft- and Hardwood, I – Input, O – Output)

Category			**Material and Energy**					**Working Hours in $\cdot 10^{-04}$ h**			
			Unit	**Sorg**	**Straw**	**RW**	**Total**	**Sorg**	**Straw**	**RW**	**Total**
Biom	**Biom O / ICP I**	**Biom wet**	kg	0.0695	0.0199	0.0697	0.1591	0.71	0.08	8.73	9.53
			mc	28%	18%	41%					
			MJ	1.1746	0.3335	1.2793	2.7873				
ICPs	**Biom O / Gasifi I**	**Biom dried**	kg	0.0589	0.0195	0.0589	0.1373	0.13		0.13	0.25
			mc	20%	18%	20%					
			MJ	0.9954	0.3258	1.0814	2.4026				
	Energy	**Elec I**	MJ	0.0018		0.0019	0.0038				
		NG I	MJ	0.0075		0.0079	0.0154				
	By-Product	**Char O**	kg	0.0030		0.0031	0.0077				
			MJ	0.0982		0.1023	0.2006				
Gasifi	**Gasifi O / FT I**	**Syn-gas**	m^3	0.3118				1.18			
			MJ	1.6838							
	Energy	**Elec I**	MJ	0.0299							
FT Synt-hesis	**FT O / Refi I**	**Syn-crude**	kg	0.0257				5.08			
			MJ	1.0739							
	Energy	**Elec I**	MJ	0.2095							
		Heat O	MJ	1.0912							
Refi	**Fuel Mix O**	**Petrol**	kg	0.0092				0.65			1.14
			MJ	0.3984							
		Kero-sine	kg	0.0077				0.23			
			MJ	0.3298							
		Diesel	kg	0.0064				0.26			
			MJ	0.2718							
Funct-ional Unit	**Total**		MJ	1.0000					**Foreground**		17.18
									Background		37.00
									Total		54.18

Information on biomass is provided by the SoCa market processes for straw (market for straw | straw | APOS, U - DE), residual soft- (market for residual softwood, wet | residual softwood, wet | APOS, U - DE) and hardwood (market for residual hardwood, wet | residual hardwood, wet | APOS, U), as well as a custom-made sorghum market and production process. Sorghum whole plant production is adopted by combining 7.4% sweet sorghum grain (3860 kg/ha, mc = 9.1%) and 92.6% stem (48263 kg/ha, mc = 73%) from SoCa database as combined flow (68% mc) and additional drying on field (28% mc). Transport distances of biomass supply to the decentral ICPs are included in the Ecoinvent market processes and on this basis assumed as 20 km for the market of sorghum.

As described earlier, ICPs are fictive collection points for storing and drying biomass by slow pyrolysis and natural gas (~300kW), which are not implemented in any database nor do we have specific technological, economic, or social details for this process. In principle, however, ICPs basically correspond to an industrial biomass furnace for heat production which we adopt from SoCa (heat production, softwood chips from forest, at furnace 1000kW | heat, district or industrial, other than natural gas | APOS, U - DE) as an approximation. As a main difference, not all biomass is combusted and we adopt all output flows (emissions, working time for social flows etc.) to the decreased amount of biomass combusted in slow pyrolysis by a factor (biomass combusted pyrolysis / biomass combusted furnace). The input flows are adopted to sorghum and residual wood by including the energetic gross calorific value of biomass, as well as additional heat from natural gas combustion (heat production, natural gas, at industrial furnace >100kW | heat, district or industrial, natural gas | APOS, U) to include these impacts. The energetic conversion efficiency of these ICPs (including energy from biomass, heat and electricity related to the product output) is 85%. Since straw is assumed to already have an appropriate moisture content, the ICP for straw is a collection point only, with no additional input or output flows despite transportation to the gasification facility. All dried biomasses are transported to the gasification facility assuming a transport distance of 50 km (one-way, empty way back included in modelling) by freight lorry on road (market for transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U - RER). Within the ICPs we include an assumed loss of 1.5% dm due to storage and transportation.

Biomass gasification applying the MILENA technology is modeled directly by a fluidized bed gasifier for wood from Ecoinvent/SoCa (synthetic gas production, from wood, at fluidized bed gasifier | synthetic gas | APOS, U – DE). This process is scaled for producing 1 Nm^3 or 5.4 MJ synthesis gas output from 7.714 MJ biomass input (70 % energy conversion efficiency). We split the 7.714 MJ (input) / Nm^3 (output) among the biomasses (residual forest wood (3/7), straw (1/7) and sorghum (3/7) measured in dm), resulting in the specific mass and energy quantities (Table 1). Composition (% mol.) of the resulting gas is 15.5% H2, 39.2% CO, 34.9% CO2, 8.7% CH4, and 1.7% other hydrocarbons on a nitrogen and water free basis, where the required heat is supplied by syngas combustion. This gas is not cleaned yet and directly forwarded to the following process steps taking place at the same facility.

This subsequent gas cleaning and FT synthesis of the syngas is associated with the greatest uncertainties in the modeling, since in the data from BECOOL syngas production, gas cleaning, and FT synthesis are accounted as one process and therefore had to be separated for the following model in two processes: the previous Ecoinvent syngas gas production process and a simplified gas cleaning and FT synthesis process. Unfortunately, there are neither FT models in Ecoinvent nor general stand-alone LCAs available of this rather long known technology. For this reason, the modeling of this process is carried out by subtracting the inputs and outputs of the gasification process from the input and output data for the combined process from BECOOL in order to obtain an approximation for the gas cleaning and FT synthesis process. However, the construction of the required process technology (incl. Fe, Co, Ni and Ru) typically used for the catalysts (Sikarwar et al., 2017) or specific direct emissions are not modelled, and social impacts are assumed to be the same as for gasification at the same facility. Our input data, assumptions and results are consistent with the literature (Albers, 2021; Iribarren et al., 2013; Maier et al., 2021; Sikarwar et al., 2017; Tock et al., 2010; van den Oever et al., 2022) and were discussed with experts from the field, in particular the high demand for electric energy for gas cleaning and the significant amount of waste heat from the FT reaction (Table 1). Consequently, the energetic conversion efficiency (incl. syngas input and electricity related to the product output) is relatively poor, with 56%. Above all, the released waste heat of 1.016 MJ per MJ syncrude has to be partially used in order to keep the entire process chain economically and ecologically responsible. However, to determine which share of waste heat can be used is a complex problem, due to numerous dependencies such as temperature level, facility size, and facility location (stand-alone, chemical park, near to residential infrastructures, etc.) determine a realistic assumption. Consequentially, the share of waste heat use is introduced as a parameter in the model ranging from 0 to 100% of waste heat as an avoided product in openLCA for the market for heat. Within the openLCA modelling, avoided products lead to a credit for impacts for the BtL system in the amount of the impacts that would arise if this amount of heat would be generated by the usual heat market. On the one hand, a waste heat use of at least 30% is considered feasible even under comparatively poor conditions by experts, and on the other hand in the LCIA this share results in very low GHG-emissions in BtL production. For this reason, the main results of this research are presented for a 30% share of waste heat use from FT synthesis as well as this value provides a first reference point for the technological conditions under which this BtL production system can be considered desirable, which is in detail discussed in the following sections. As the main product, FT syncrude oil has approximately the same properties as fossil crude oil and is transported 50 km (market for transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U - RER) to a standard refinery.

As the last process step, syncrude oil is refined to 1 MJ fuel mix consisting of specific shares for diesel, petrol, and kerosene given by the data from BECOOL (Table 1). The refinery inventory and model are the updated refinery models from Ecoinvent v3.7, which within the model are able to split refinery operation into several products (petrol production, unleaded, petroleum refinery operation | petrol, unleaded | APOS, U; kerosene production, petroleum refinery operation | kerosene | APOS, U; diesel production, low-sulfur, petroleum refinery operation | diesel, low-sulfur | APOS, U – DE). With an energetic conversion efficiency of 93% the product basket and functional unit of 1 MJ of fuel mix is produced at the end of this cradle to gate LCI.

The fossil fuel product system as reference to compare BtLs to also uses the same refinery processes, product split, and product basket, but it is based on the entire Ecoinvent upstream flow for fossil crude oil instead of syncrude, which is a simplification and e.g., refineries can differ in a real-world implementation or in detail technological study. In the foreground and background system fossil fuel production requires $19.85 \cdot 10^{-04}$ working hours. All data on social indicators for RESPONSA indicators for BtL is determined and adopted from (Gan Yupanqui and Zeug, Forthcoming).

3.3. *Impact Assessment*

The LCIA is based on the holistic and integrated sustainability framework (Zeug et al., 2020; Zeug et al., 2023) and indicator system (Zeug et al., 2021) of HILCSA. Our indicator system in HILCSAv2 entails 99 social, ecological, and economic indicators, which are assigned to 14 SDGs (Table A 2). All indicators, their inventory flows, characterization/impact factors, as well as their normalizations and weightings are used from each established life cycle impact assessment (LCIA) methods and not changed: ReCiPe, Impact World +, EF 3.0, Cumulative Energy/Exergy Demand, RESPONSA, and SoCa v2. Each indicator is assigned to societal needs and social sustainability, economy and economic sustainability, planetary boundaries and ecologic sustainability, as well as an SDG and it's weighting according to the HILCSA framework (Zeug et al., 2021). Furthermore, each indicator has a qualitative or quantitative data type; is allocated by material flows (functional unit) or working time (activity variable); has a unit of measurement which is mostly not quantitatively comparable to other indicators; has an evaluation scheme and impact factors for quantification. To some SDGs a number of indicators are assigned, i.e., SDG 3.9 (Reduce pollution of air/water/ soil, health protection), SDG 8.7 & 8.8 (Worker rights, labor protection rights, promoting safe work environment, abolition of forced labor / trafficking / child labor), SDG 13 (Take urgent action to combat climate change and its impacts). However, there is no indicator which is assigned to several impact categories (SDGs) to avoid double counting.

In Table 2 detailed results of 1 MJ BtL production as well as 1 MJ fossil fuels production are compiled, both in the 2030 electricity grid mix. In general, we account only for negative impacts and in general higher impact values represent a higher risk and less sustainability. The results for all indicators, except of RESPONSA indicators, include all impacts from the foreground and Ecoinvent background system. For specific processes, mainly FT synthesis, indicator values can be negative, which is a result of giving credits by providing an avoided product in openLCA modelling. Avoided products are a feature of openLCA to operationalize a system expansion when two or more products as outputs of one process are produced, but only the flows and impacts of one product (in this case syncrude) are accounted by assuming that the heat produced elsewhere will be substituted via the heat produced of the FT process (Weidema, 2000). The co-generation of heat is thus credited with the avoided impacts of the alternative heat production process with the same amount, i.e., the social, environmental and economic impacts of the process "market for heat, from steam, in chemical industry" are subtracted from the impacts of FT synthesis. However, in a methodologically strict understanding, it must be noted that the avoided burden approach is usually not used in attributional LCA but rather in consequential LCA since e.g., not all emissions are attributed to the product (Brander and Wylie, 2011). The actual impacts of the fuels produced without credits from avoided products, in line with attributional LCA criteria, are according to the impacts of the 0% heat use scenario in Table A 3.

All socio-economic indicators from SoCa and RESPONSA in our HILCSA are comparable on from being transferred to risk levels (normalization) and share the same impact factor of the Social Impact Weighting Method. Finally, we compare the indicator values of BtL to fossil fuels (except for indicators which would lead to double counting and RESPONSA indicators since RESPONSA inventory data is not available for fossil fuels) to assess their relative rather than absolute impact. For this normalization we calculate substitution factors of impact f^{sSDG} (Eq. 1) for each indicator. In a following aggregation of these normalized factors we apply a weighted mean factor f^{SDG} (Eq. 2) for each SDG the f^{sSDG} is assigned to. The weightings are based on the relevance of SDG-subgoals we determine for the German BE-monitoring by stakeholder participation (Zeug et al., 2019). As a highest level of aggregation by aggregating all SDGs, we analogically calculate a total substitution-factor of impacts f of all SDGs (Eq. 3). According to the impact factors from the Social Impact Weighting Method from above, we assign them the according risk level and color of the table in Fig. 3.

Since all impact results are calculated for the functional unit of 1 MJ fuel mix, the indicator values for cumulative energy and exergy demand represent the EROI and EXROI directly. In this case, EROI is applied and the data should be interpreted as standard EROI, including the on-site and offsite energy requirements, energy gross calorific values as well as infrastructures and facilities (Perez-Valdes et al., 2019).

Table 2, Impact assessment results and comparison for BtL production system and fossil fuels, 2030 electric energy grid mix (color scale for each indicator process hot-spot analysis (red - highest risk; green - lowest risk); italic indicators do not account to aggregation to avoid double counting; color scale for substitution factors of impacts according to table in Fig. 3) *(color in web and print)*

Sustainability Framework				BtL product system 1 MJ fuel mix, 30% heat use in FT synthesis with credits									Fossil Fuels 2030, 1 MJ total	Substitution factors of impact		
				Foreground processes incl. background upstream							Background					
	SDG	ID	Indicator Name	Market for residual wood	Market for straw	Market for sorghum	ICPs	Gasification	Gas clean., FT-syn.	Refinery	Electricity	total		f_sSDG	f_SDG	f
Societal needs	1	1	Social security expenditures	$3.17\cdot10^{-02}$	$2.51\cdot10^{-02}$	$4.89\cdot10^{-02}$	$2.97\cdot10^{-02}$	$6.30\cdot10^{-02}$	$-1.71\cdot10^{-03}$	$2.89\cdot10^{-03}$	$7.07\cdot10^{-02}$	$2.00\cdot10^{-01}$	$1.25\cdot10^{-01}$	1.60	1.60	29.48
		2	Payment according to basic wage	$8.73\cdot10^{-03}$	$8.19\cdot10^{-05}$	$7.09\cdot10^{-04}$	$2.51\cdot10^{-04}$	$5.08\cdot10^{-04}$	$1.18\cdot10^{-04}$	$1.14\cdot10^{-04}$	$8.24\cdot10^{-10}$	$1.05\cdot10^{-02}$	no data			
		3	Capital participation	$8.73\cdot10^{-02}$	$8.19\cdot10^{-04}$	$7.09\cdot10^{-03}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-02}$	$1.18\cdot10^{-02}$	$1.14\cdot10^{-02}$	$8.24\cdot10^{-09}$	$1.72\cdot10^{-01}$				
		4	Profit-sharing and bonuses	$8.73\cdot10^{-03}$	$8.19\cdot10^{-05}$	$7.09\cdot10^{-04}$	$2.51\cdot10^{-04}$	$5.08\cdot10^{-02}$	$1.18\cdot10^{-02}$	$1.14\cdot10^{-02}$	$8.24\cdot10^{-10}$	$8.38\cdot10^{-02}$				
	2	5	Water consumption - HH	$5.25\cdot10^{-11}$	$5.16\cdot10^{-10}$	$1.21\cdot10^{-09}$	$2.50\cdot10^{-11}$	$3.27\cdot10^{-10}$	$4.81\cdot10^{-10}$	$1.39\cdot10^{-11}$	$6.43\cdot10^{-10}$	$2.62\cdot10^{-09}$	$2.09\cdot10^{-11}$	125.57	75.25	
		6	Indigenous rights	$1.37\cdot10^{-03}$	$5.35\cdot10^{-04}$	$8.53\cdot10^{-04}$	$6.09\cdot10^{-04}$	$1.23\cdot10^{-03}$	$5.17\cdot10^{-04}$	$4.03\cdot10^{-04}$	$2.34\cdot10^{-03}$	$5.52\cdot10^{-03}$	$3.11\cdot10^{-03}$	1.77		
	3	7	Health expenditure	$1.48\cdot10^{-02}$	$1.12\cdot10^{-02}$	$2.08\cdot10^{-02}$	$1.29\cdot10^{-02}$	$2.74\cdot10^{-02}$	$2.10\cdot10^{-03}$	$2.77\cdot10^{-03}$	$3.39\cdot10^{-02}$	$9.19\cdot10^{-02}$	$5.57\cdot10^{-02}$	1.65	3.69	
		8	Life expectancy at birth	$5.29\cdot10^{-03}$	$3.35\cdot10^{-03}$	$2.95\cdot10^{-03}$	$3.56\cdot10^{-03}$	$7.55\cdot10^{-03}$	$8.06\cdot10^{-03}$	$1.31\cdot10^{-02}$	$2.03\cdot10^{-02}$	$4.38\cdot10^{-02}$	$2.55\cdot10^{-02}$	1.72		
		9	DALYs due to indoor and outdoor air and water pollution	$3.96\cdot10^{-04}$	$3.18\cdot10^{-04}$	$5.52\cdot10^{-04}$	$3.60\cdot10^{-04}$	$7.64\cdot10^{-04}$	$2.97\cdot10^{-04}$	$3.34\cdot10^{-05}$	$1.04\cdot10^{-03}$	$2.72\cdot10^{-03}$	$1.52\cdot10^{-03}$	1.78		
		10	Pollution	$4.93\cdot10^{-03}$	$3.71\cdot10^{-03}$	$6.49\cdot10^{-03}$	$4.16\cdot10^{-03}$	$8.92\cdot10^{-03}$	$4.61\cdot10^{-03}$	$1.64\cdot10^{-03}$	$1.53\cdot10^{-02}$	$3.45\cdot10^{-02}$	$1.81\cdot10^{-02}$	1.90		
		11	Global Warming - HH	$2.95\cdot10^{-09}$	$1.72\cdot10^{-09}$	$1.11\cdot10^{-09}$	$3.97\cdot10^{-09}$	$5.21\cdot10^{-09}$	$-2.37\cdot10^{-08}$	$5.87\cdot10^{-09}$	$8.44\cdot10^{-09}$	$-2.85\cdot10^{-09}$	$1.14\cdot10^{-08}$	-0.25		
		12	Stratospheric ozone depletion - HH	$1.20\cdot10^{-12}$	$1.01\cdot10^{-11}$	$7.05\cdot10^{-12}$	$5.26\cdot10^{-12}$	$2.46\cdot10^{-12}$	$2.78\cdot10^{-12}$	$1.32\cdot10^{-12}$	$7.73\cdot10^{-12}$	$3.02\cdot10^{-11}$	$1.15\cdot10^{-11}$	2.61		
		13	Photochemical ozone formation - HH	$1.62\cdot10^{-11}$	$6.45\cdot10^{-12}$	$3.88\cdot10^{-12}$	$4.12\cdot10^{-11}$	$1.59\cdot10^{-11}$	$-2.63\cdot10^{-11}$	$8.64\cdot10^{-12}$	$1.16\cdot10^{-11}$	$6.61\cdot10^{-11}$	$4.36\cdot10^{-11}$	1.51		
		14	Ionizing Radiation - HH	$2.41\cdot10^{-12}$	$5.44\cdot10^{-13}$	$2.33\cdot10^{-13}$	$6.67\cdot10^{-13}$	$3.02\cdot10^{-12}$	$-5.54\cdot10^{-12}$	$5.45\cdot10^{-14}$	$7.26\cdot10^{-13}$	$1.38\cdot10^{-12}$	$6.20\cdot10^{-12}$	0.22		
		15	Fine particulate matter formation - HH	$2.97\cdot10^{-09}$	$2.45\cdot10^{-09}$	$1.48\cdot10^{-09}$	$1.30\cdot10^{-08}$	$7.18\cdot10^{-09}$	$-1.31\cdot10^{-08}$	$8.39\cdot10^{-09}$	$3.24\cdot10^{-09}$	$2.23\cdot10^{-08}$	$2.22\cdot10^{-08}$	1.01		

		16	Toxicity - HH (cancer)	$1.29\cdot10^{-09}$	$3.98\cdot10^{-10}$	$2.39\cdot10^{-10}$	$1.50\cdot10^{-09}$	$5.24\cdot10^{-09}$	$1.90\cdot10^{-09}$	$1.43\cdot10^{-10}$	$3.85\cdot10^{-09}$	$1.07\cdot10^{-08}$	$1.87\cdot10^{-09}$	5.71		
		17	Toxicity - HH (non-cancer)	$5.16\cdot10^{-10}$	$1.01\cdot10^{-09}$	$-2.20\cdot10^{-10}$	$1.94\cdot10^{-09}$	$1.29\cdot10^{-08}$	$1.03\cdot10^{-09}$	$3.30\cdot10^{-10}$	$2.10\cdot10^{-09}$	$1.75\cdot10^{-08}$	$8.87\cdot10^{-10}$	19.75		
	4	18	Expenditures on education	$3.23\cdot10^{-04}$	$2.54\cdot10^{-04}$	$4.90\cdot10^{-04}$	$3.07\cdot10^{-04}$	$6.84\cdot10^{-04}$	$-7.44\cdot10^{-05}$	$1.90\cdot10^{-05}$	$7.52\cdot10^{-04}$	$2.00\cdot10^{-03}$	$1.25\cdot10^{-03}$	1.60	1.60	
	5	19	Gender wage gap	$7.90\cdot10^{-03}$	$3.27\cdot10^{-03}$	$2.66\cdot10^{-03}$	$3.53\cdot10^{-03}$	$7.89\cdot10^{-03}$	$8.93\cdot10^{-03}$	$1.32\cdot10^{-02}$	$2.09\cdot10^{-02}$	$4.73\cdot10^{-02}$	$2.51\cdot10^{-02}$	1.88	3.56	
		20	Female employees in management positions	$8.73\cdot10^{-02}$	$8.19\cdot10^{-04}$	$7.09\cdot10^{-03}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-02}$	$1.18\cdot10^{-02}$	$1.14\cdot10^{-02}$	$8.24\cdot10^{-09}$	$1.72\cdot10^{-01}$	no data			
		21	Rate of female employees	$8.73\cdot10^{-02}$	$8.46\cdot10^{-08}$	$7.11\cdot10^{-07}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-02}$	$1.18\cdot10^{-02}$	$1.14\cdot10^{-02}$	$8.24\cdot10^{-09}$	$1.64\cdot10^{-01}$				
		22	Men in the sectoral labor force	$8.79\cdot10^{-06}$	$3.93\cdot10^{-06}$	$6.51\cdot10^{-06}$	$7.03\cdot10^{-06}$	$6.16\cdot10^{-05}$	$1.61\cdot10^{-05}$	$2.68\cdot10^{-06}$	$1.69\cdot10^{-05}$	$1.07\cdot10^{-04}$	$2.02\cdot10^{-05}$	5.29		
		23	Women in the sectoral labor force	$1.24\cdot10^{-03}$	$7.83\cdot10^{-04}$	$8.77\cdot10^{-04}$	$1.03\cdot10^{-03}$	$3.27\cdot10^{-03}$	$5.95\cdot10^{-03}$	$1.34\cdot10^{-03}$	$7.85\cdot10^{-03}$	$1.45\cdot10^{-02}$	$4.13\cdot10^{-03}$	3.51		
	11	*24*	*Fine particulate matter ID 15 if production site is in urban region*	*$2.97\cdot10^{-09}$*	*$2.45\cdot10^{-09}$*	*$1.48\cdot10^{-09}$*	*$1.30\cdot10^{-08}$*	*$7.18\cdot10^{-09}$*	*$-1.31\cdot10^{-08}$*	*$8.39\cdot10^{-09}$*	*$3.24\cdot10^{-09}$*	*$2.23\cdot10^{-08}$*	*$2.22\cdot10^{-08}$*	*1.01*	*1.01*	
Provisioning System	6	25	Drinking water coverage	$3.94\cdot10^{-02}$	$3.20\cdot10^{-02}$	$6.13\cdot10^{-02}$	$3.69\cdot10^{-02}$	$7.86\cdot10^{-02}$	$4.01\cdot10^{-02}$	$2.29\cdot10^{-03}$	$1.30\cdot10^{-01}$	$2.91\cdot10^{-01}$	$1.49\cdot10^{-01}$	1.95	2.18	17.56
		26	Sanitation coverage	$5.01\cdot10^{-02}$	$1.29\cdot10^{-02}$	$1.86\cdot10^{-02}$	$1.36\cdot10^{-02}$	$2.57\cdot10^{-02}$	$3.36\cdot10^{-02}$	$1.34\cdot10^{-02}$	$7.09\cdot10^{-02}$	$1.68\cdot10^{-01}$	$6.38\cdot10^{-02}$	2.63		
	7	*27*	*Cumulative Energy Demand, Renewable energies*	*$5.93\cdot10^{-01}$*	*$4.84\cdot10^{-02}$*	*$1.31\cdot10^{-01}$*	*$2.94\cdot10^{-03}$*	*$2.16\cdot10^{-02}$*	*$1.06\cdot10^{-01}$*	*$1.35\cdot10^{-04}$*	*$1.36\cdot10^{-01}$*	*$9.04\cdot10^{-01}$*	*$2.29\cdot10^{-03}$*	*395.45*	0.74	
		28	Cumulative Energy Demand	$6.46\cdot10^{-01}$	$7.05\cdot10^{-02}$	$1.45\cdot10^{-01}$	$6.95\cdot10^{-02}$	$1.04\cdot10^{-01}$	$-3.01\cdot10^{-01}$	$3.69\cdot10^{-03}$	$2.74\cdot10^{-01}$	$7.38\cdot10^{-01}$	$1.26\cdot10^{+00}$	0.59		
		29	Cumulative Exergy Demand	$6.79\cdot10^{-01}$	$8.89\cdot10^{-02}$	$2.05\cdot10^{-01}$	$5.06\cdot10^{-02}$	$1.07\cdot10^{-01}$	$-2.75\cdot10^{-02}$	$1.44\cdot10^{-02}$	$2.37\cdot10^{-01}$	$1.12\cdot10^{+00}$	$1.25\cdot10^{+00}$	0.89		
	8	30	Contribution of the sector to economic development	$6.26\cdot10^{-04}$	$1.94\cdot10^{-04}$	$1.71\cdot10^{-04}$	$2.62\cdot10^{-04}$	$1.08\cdot10^{-03}$	$2.08\cdot10^{-04}$	$2.62\cdot10^{-04}$	$9.74\cdot10^{-04}$	$2.80\cdot10^{-03}$	$1.26\cdot10^{-03}$	2.22	5.33	
		31	Weekly hours of work per employee	$3.63\cdot10^{-03}$	$2.58\cdot10^{-03}$	$4.91\cdot10^{-03}$	$3.34\cdot10^{-03}$	$1.16\cdot10^{-02}$	$3.72\cdot10^{-04}$	$1.92\cdot10^{-04}$	$7.44\cdot10^{-03}$	$2.66\cdot10^{-02}$	$1.27\cdot10^{-02}$	2.09		
		32	Compensation for overtime	$8.73\cdot10^{-05}$	$8.19\cdot10^{-08}$	$7.09\cdot10^{-07}$	$2.51\cdot10^{-07}$	$5.08\cdot10^{-06}$	$1.18\cdot10^{-06}$	$1.14\cdot10^{-06}$	$8.24\cdot10^{-12}$	$9.58\cdot10^{-05}$	no data			
		33	Access to flexible working time agreements	$8.73\cdot10^{-04}$	$8.19\cdot10^{-05}$	$7.09\cdot10^{-04}$	$2.51\cdot10^{-05}$	$5.08\cdot10^{-04}$	$1.18\cdot10^{-04}$	$1.14\cdot10^{-04}$	$8.24\cdot10^{-11}$	$2.43\cdot10^{-03}$				
		34	Rate of part-time employees	$8.73\cdot10^{-04}$	$8.19\cdot10^{-04}$	$7.09\cdot10^{-03}$	$2.48\cdot10^{-07}$	$5.08\cdot10^{-06}$	$1.18\cdot10^{-06}$	$1.14\cdot10^{-06}$	$8.24\cdot10^{-11}$	$8.79\cdot10^{-03}$				
		35	Rate of marginally employees (max. 450€)	$8.73\cdot10^{-02}$	$8.19\cdot10^{-06}$	$7.09\cdot10^{-05}$	$2.48\cdot10^{-05}$	$5.12\cdot10^{-06}$	$1.18\cdot10^{-06}$	$1.14\cdot10^{-06}$	$8.24\cdot10^{-09}$	$8.75\cdot10^{-02}$				
		36	Rate of fixed-term employees	$8.73\cdot10^{-06}$	$8.19\cdot10^{-04}$	$7.09\cdot10^{-03}$	$2.51\cdot10^{-05}$	$5.08\cdot10^{-04}$	$1.18\cdot10^{-04}$	$1.14\cdot10^{-04}$	$8.24\cdot10^{-13}$	$8.69\cdot10^{-03}$				
		37	Rate of employees provided by temporary work agencies	$8.73\cdot10^{-06}$	$8.19\cdot10^{-04}$	$7.09\cdot10^{-03}$	$2.51\cdot10^{-06}$	$5.08\cdot10^{-05}$	$1.18\cdot10^{-05}$	$1.14\cdot10^{-05}$	$8.24\cdot10^{-13}$	$8.00\cdot10^{-03}$				
		38	Rate of disabled employees	$8.73\cdot10^{-02}$	$8.46\cdot10^{-08}$	$7.11\cdot10^{-07}$	$2.18\cdot10^{-06}$	$5.12\cdot10^{-06}$	$1.18\cdot10^{-06}$	$1.14\cdot10^{-06}$	$8.24\cdot10^{-09}$	$8.74\cdot10^{-02}$				

	39	Rate of foreign employees	$8.73\cdot10^{-05}$	$8.19\cdot10^{-08}$	$7.09\cdot10^{-07}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-03}$	$1.18\cdot10^{-03}$	$1.14\cdot10^{-03}$	$8.24\cdot10^{-12}$	$1.00\cdot10^{-02}$			
	40	Net migration	$7.76\cdot10^{-03}$	$6.90\cdot10^{-03}$	$1.27\cdot10^{-02}$	$6.78\cdot10^{-03}$	$1.62\cdot10^{-02}$	$4.86\cdot10^{-02}$	$4.36\cdot10^{-04}$	$5.57\cdot10^{-02}$	$9.93\cdot10^{-02}$	$2.64\cdot10^{-02}$	3.76	
	41	International Migrant Stock	$1.13\cdot10^{-02}$	$9.39\cdot10^{-04}$	$1.44\cdot10^{-03}$	$2.15\cdot10^{-03}$	$1.99\cdot10^{-02}$	$1.75\cdot10^{-02}$	$1.47\cdot10^{-03}$	$1.30\cdot10^{-02}$	$5.47\cdot10^{-02}$	$4.87\cdot10^{-03}$	11.23	
	42	International migrant workers (in the sector/ site)	$1.75\cdot10^{-05}$	$4.48\cdot10^{-06}$	$6.70\cdot10^{-06}$	$7.57\cdot10^{-06}$	$6.41\cdot10^{-05}$	$1.41\cdot10^{-05}$	$2.72\cdot10^{-06}$	$1.79\cdot10^{-05}$	$1.17\cdot10^{-04}$	$2.15\cdot10^{-05}$	5.45	
	43	Migration flows	$4.79\cdot10^{-03}$	$4.97\cdot10^{-04}$	$3.00\cdot10^{-04}$	$3.27\cdot10^{-03}$	$5.51\cdot10^{-02}$	$1.17\cdot10^{-02}$	$1.30\cdot10^{-03}$	$2.43\cdot10^{-03}$	$7.70\cdot10^{-02}$	$4.75\cdot10^{-03}$	16.20	
	44	Average remuneration level	$8.73\cdot10^{-02}$	$8.46\cdot10^{-08}$	$7.11\cdot10^{-07}$	$-7.94\cdot10^{-08}$	$5.08\cdot10^{-04}$	$1.18\cdot10^{-04}$	$1.14\cdot10^{-04}$	$8.24\cdot10^{-09}$	$8.81\cdot10^{-02}$	no data		
	45	Fair salary	$1.42\cdot10^{-01}$	$2.04\cdot10^{-02}$	$1.90\cdot10^{-02}$	$2.47\cdot10^{-02}$	$9.58\cdot10^{-02}$	$3.61\cdot10^{-02}$	$5.09\cdot10^{-02}$	$1.10\cdot10^{-01}$	$3.89\cdot10^{-01}$	$1.13\cdot10^{-01}$	3.46	
	46	Unemployment	$5.04\cdot10^{-03}$	$3.13\cdot10^{-03}$	$2.50\cdot10^{-03}$	$3.30\cdot10^{-03}$	$7.05\cdot10^{-03}$	$8.06\cdot10^{-03}$	$1.31\cdot10^{-02}$	$1.96\cdot10^{-02}$	$4.22\cdot10^{-02}$	$2.44\cdot10^{-02}$	1.73	
	47	Rate of vocational trainees	$8.73\cdot10^{-02}$	$8.19\cdot10^{-04}$	$7.09\cdot10^{-03}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-02}$	$1.18\cdot10^{-02}$	$1.14\cdot10^{-02}$	$8.24\cdot10^{-09}$	$1.72\cdot10^{-01}$	no data		
	48	Child Labor, total	$6.19\cdot10^{-03}$	$3.89\cdot10^{-03}$	$3.76\cdot10^{-03}$	$4.09\cdot10^{-03}$	$8.73\cdot10^{-03}$	$1.21\cdot10^{-02}$	$1.32\cdot10^{-02}$	$2.57\cdot10^{-02}$	$5.19\cdot10^{-02}$	$2.81\cdot10^{-02}$	1.85	
	49	Trafficking in persons	$1.63\cdot10^{-03}$	$1.20\cdot10^{-03}$	$1.08\cdot10^{-03}$	$1.71\cdot10^{-03}$	$2.59\cdot10^{-03}$	$-5.80\cdot10^{-03}$	$1.53\cdot10^{-03}$	$8.77\cdot10^{-03}$	$3.95\cdot10^{-03}$	$6.64\cdot10^{-03}$	0.59	
	50	Frequency of forced labor	$1.12\cdot10^{-02}$	$6.88\cdot10^{-03}$	$1.25\cdot10^{-02}$	$6.83\cdot10^{-03}$	$1.60\cdot10^{-02}$	$4.82\cdot10^{-02}$	$1.53\cdot10^{-03}$	$5.51\cdot10^{-02}$	$1.03\cdot10^{-01}$	$2.55\cdot10^{-02}$	4.04	
	51	Goods produced by forced labor	$1.40\cdot10^{-04}$	$5.73\cdot10^{-05}$	$6.53\cdot10^{-05}$	$9.45\cdot10^{-05}$	$1.70\cdot10^{-04}$	$9.00\cdot10^{-05}$	$2.72\cdot10^{-05}$	$2.45\cdot10^{-04}$	$6.44\cdot10^{-04}$	$2.58\cdot10^{-04}$	2.49	
	52	Association and bargaining rights	$4.09\cdot10^{-04}$	$3.00\cdot10^{-04}$	$2.47\cdot10^{-04}$	$2.98\cdot10^{-04}$	$6.66\cdot10^{-04}$	$-1.45\cdot10^{-03}$	$6.55\cdot10^{-05}$	$7.99\cdot10^{-04}$	$5.38\cdot10^{-04}$	$1.73\cdot10^{-03}$	0.31	
	53	Trade unionism	$3.47\cdot10^{-02}$	$2.54\cdot10^{-02}$	$4.91\cdot10^{-02}$	$3.28\cdot10^{-02}$	$1.18\cdot10^{-01}$	$1.47\cdot10^{-02}$	$2.91\cdot10^{-03}$	$7.53\cdot10^{-02}$	$2.78\cdot10^{-01}$	$1.26\cdot10^{-01}$	2.21	
	54	Non-fatal accidents	$1.53\cdot10^{-04}$	$6.44\cdot10^{-05}$	$7.97\cdot10^{-05}$	$1.13\cdot10^{-04}$	$1.65\cdot10^{-03}$	$1.61\cdot10^{-03}$	$1.90\cdot10^{-05}$	$1.58\cdot10^{-03}$	$3.69\cdot10^{-03}$	$2.36\cdot10^{-04}$	15.66	
	55	Fatal accidents	$4.62\cdot10^{-05}$	$3.19\cdot10^{-05}$	$5.42\cdot10^{-05}$	$3.79\cdot10^{-05}$	$8.70\cdot10^{-05}$	$5.50\cdot10^{-05}$	$1.60\cdot10^{-05}$	$1.42\cdot10^{-04}$	$3.28\cdot10^{-04}$	$1.58\cdot10^{-04}$	2.08	
	56	Sick-leave days	$8.73\cdot10^{-04}$	$8.19\cdot10^{-08}$	$7.09\cdot10^{-07}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-03}$	$1.18\cdot10^{-03}$	$1.14\cdot10^{-03}$	$8.24\cdot10^{-11}$	$1.08\cdot10^{-02}$	no data		
	57	Safety measures	$4.99\cdot10^{-03}$	$3.29\cdot10^{-03}$	$1.90\cdot10^{-03}$	$4.37\cdot10^{-03}$	$1.34\cdot10^{-02}$	$5.25\cdot10^{-02}$	$8.45\cdot10^{-04}$	$5.26\cdot10^{-02}$	$8.13\cdot10^{-02}$	$4.02\cdot10^{-03}$	20.22	
	58	Violations of employment laws and regulations	$5.53\cdot10^{-03}$	$1.67\cdot10^{-03}$	$2.16\cdot10^{-03}$	$1.81\cdot10^{-03}$	$3.74\cdot10^{-03}$	$2.53\cdot10^{-03}$	$1.50\cdot10^{-03}$	$7.92\cdot10^{-03}$	$1.89\cdot10^{-02}$	$1.06\cdot10^{-02}$	1.79	
	59	Workers affected by natural disasters	$1.75\cdot10^{-04}$	$1.18\cdot10^{-04}$	$2.21\cdot10^{-04}$	$1.18\cdot10^{-04}$	$2.64\cdot10^{-04}$	$4.43\cdot10^{-04}$	$2.03\cdot10^{-05}$	$6.70\cdot10^{-04}$	$1.36\cdot10^{-03}$	$5.33\cdot10^{-04}$	2.55	
	60	Work Council	$8.73\cdot10^{-03}$	$8.19\cdot10^{-05}$	$7.09\cdot10^{-04}$	$2.51\cdot10^{-03}$	$5.08\cdot10^{-05}$	$1.18\cdot10^{-05}$	$1.14\cdot10^{-05}$	$8.24\cdot10^{-10}$	$1.21\cdot10^{-02}$	no data		
12	61	Embodied agricultural area footprints	$1.31\cdot10^{-04}$	$2.39\cdot10^{-04}$	$8.25\cdot10^{-04}$	$3.23\cdot10^{-05}$	$5.56\cdot10^{-05}$	$1.19\cdot10^{-04}$	$2.62\cdot10^{-06}$	$1.73\cdot10^{-04}$	$1.40\cdot10^{-03}$	$5.76\cdot10^{-05}$	24.38	54.11
12	62	Embodied biodiversity footprints	$4.72\cdot10^{-02}$	$1.09\cdot10^{-02}$	$1.74\cdot10^{-02}$	$1.11\cdot10^{-02}$	$2.29\cdot10^{-02}$	$4.77\cdot10^{-02}$	$1.25\cdot10^{-02}$	$6.43\cdot10^{-02}$	$1.70\cdot10^{-01}$	$4.93\cdot10^{-02}$	3.44	

		63	Embodied forest area footprints	$3.48\cdot10^{-03}$	$7.37\cdot10^{-06}$	$1.36\cdot10^{-05}$	$1.83\cdot10^{-06}$	$4.63\cdot10^{-06}$	$3.50\cdot10^{-06}$	$2.56\cdot10^{-07}$	$8.98\cdot10^{-06}$	$3.51\cdot10^{-03}$	$5.21\cdot10^{-06}$	674.19		
		64	Embodied water footprints	$7.73\cdot10^{-04}$	$4.49\cdot10^{-04}$	$7.35\cdot10^{-03}$	$3.36\cdot10^{-04}$	$5.33\cdot10^{-04}$	$1.82\cdot10^{-04}$	$1.19\cdot10^{-03}$	$1.10\cdot10^{-03}$	$1.08\cdot10^{-02}$	$3.95\cdot10^{-03}$	2.74		
		65	Embodied GHG footprints	$1.05\cdot10^{-02}$	$4.71\cdot10^{-03}$	$7.49\cdot10^{-03}$	$5.86\cdot10^{-03}$	$1.16\cdot10^{-02}$	$-1.22\cdot10^{-02}$	$1.43\cdot10^{-02}$	$1.80\cdot10^{-02}$	$4.23\cdot10^{-02}$	$4.06\cdot10^{-02}$	1.04		
		66	Industrial water depletion	$4.16\cdot10^{-02}$	$2.82\cdot10^{-03}$	$7.80\cdot10^{-04}$	$3.32\cdot10^{-03}$	$8.52\cdot10^{-03}$	$-9.51\cdot10^{-03}$	$1.16\cdot10^{-02}$	$6.64\cdot10^{-03}$	$5.92\cdot10^{-02}$	$1.61\cdot10^{-02}$	3.67		
		67	Fossil resource scarcity	$4.26\cdot10^{-04}$	$1.74\cdot10^{-04}$	$1.01\cdot10^{-04}$	$5.78\cdot10^{-04}$	$4.76\cdot10^{-04}$	$-3.21\cdot10^{-03}$	$2.49\cdot10^{-05}$	$9.13\cdot10^{-04}$	$-1.43\cdot10^{-03}$	$1.23\cdot10^{-02}$	-0.12		
		68	Fossil fuels consumption	$1.00\cdot10^{-05}$	$4.53\cdot10^{-06}$	$6.86\cdot10^{-06}$	$8.58\cdot10^{-06}$	$6.48\cdot10^{-05}$	$4.85\cdot10^{-06}$	$2.78\cdot10^{-06}$	$2.08\cdot10^{-05}$	$1.02\cdot10^{-04}$	$2.26\cdot10^{-05}$	4.53		
		69	Biomass consumption	$4.07\cdot10^{-02}$	$2.87\cdot10^{-02}$	$5.15\cdot10^{-02}$	$3.68\cdot10^{-02}$	$1.25\cdot10^{-01}$	$1.43\cdot10^{-02}$	$1.48\cdot10^{-02}$	$9.80\cdot10^{-02}$	$3.12\cdot10^{-01}$	$1.53\cdot10^{-01}$	2.04		
		70	Minerals consumption	$1.85\cdot10^{-03}$	$5.08\cdot10^{-04}$	$4.38\cdot10^{-04}$	$5.79\cdot10^{-04}$	$1.20\cdot10^{-03}$	$5.50\cdot10^{-04}$	$1.44\cdot10^{-03}$	$3.29\cdot10^{-03}$	$6.56\cdot10^{-03}$	$3.49\cdot10^{-03}$	1.88		
		71	Resource use, mineral and metals	$1.30\cdot10^{-08}$	$1.71\cdot10^{-08}$	$1.02\cdot10^{-08}$	$1.30\cdot10^{-08}$	$9.47\cdot10^{-08}$	$8.69\cdot10^{-08}$	$5.52\cdot10^{-09}$	$4.43\cdot10^{-08}$	$2.40\cdot10^{-07}$	$1.25\cdot10^{-08}$	19.23		
		72	Ionizing Radiation	$2.84\cdot10^{-04}$	$6.42\cdot10^{-05}$	$2.75\cdot10^{-05}$	$7.86\cdot10^{-05}$	$3.56\cdot10^{-04}$	$-6.53\cdot10^{-04}$	$6.42\cdot10^{-06}$	$8.55\cdot10^{-05}$	$1.63\cdot10^{-04}$	$7.29\cdot10^{-04}$	0.22		
		73	Certified environmental management system	$3.90\cdot10^{-02}$	$2.89\cdot10^{-03}$	$9.12\cdot10^{-03}$	$3.23\cdot10^{-03}$	$2.80\cdot10^{-03}$	$-4.33\cdot10^{-03}$	$1.23\cdot10^{-02}$	$5.67\cdot10^{-03}$	$6.50\cdot10^{-02}$	$2.27\cdot10^{-02}$	2.86		
		74	Anti-competitive behavior or violation of anti-trust and monopoly legislation	$3.65\cdot10^{-02}$	$2.82\cdot10^{-02}$	$5.10\cdot10^{-02}$	$3.29\cdot10^{-02}$	$6.95\cdot10^{-02}$	$3.23\cdot10^{-03}$	$7.92\cdot10^{-03}$	$8.76\cdot10^{-02}$	$2.29\cdot10^{-01}$	$1.56\cdot10^{-01}$	1.47		
		75	Risk of conflicts	$4.03\cdot10^{-03}$	$3.25\cdot10^{-03}$	$5.36\cdot10^{-03}$	$4.22\cdot10^{-03}$	$7.86\cdot10^{-03}$	$-6.16\cdot10^{-03}$	$1.56\cdot10^{-03}$	$1.46\cdot10^{-02}$	$2.01\cdot10^{-02}$	$1.70\cdot10^{-02}$	1.18		
	16	76	Public sector corruption	$7.65\cdot10^{-02}$	$3.27\cdot10^{-02}$	$5.35\cdot10^{-02}$	$3.81\cdot10^{-02}$	$7.45\cdot10^{-02}$	$-1.32\cdot10^{-02}$	$2.63\cdot10^{-02}$	$1.07\cdot10^{-01}$	$2.89\cdot10^{-01}$	$1.75\cdot10^{-01}$	1.65	1.39	
		77	Active involvement of enterprises in corruption and bribery	$6.49\cdot10^{-03}$	$4.17\cdot10^{-03}$	$2.99\cdot10^{-03}$	$5.05\cdot10^{-03}$	$1.15\cdot10^{-02}$	$6.59\cdot10^{-03}$	$6.40\cdot10^{-03}$	$3.00\cdot10^{-02}$	$4.32\cdot10^{-02}$	$3.60\cdot10^{-02}$	1.20		
		78	Climate Change	$3.22\cdot10^{-03}$	$1.86\cdot10^{-03}$	$1.20\cdot10^{-03}$	$4.29\cdot10^{-03}$	$5.63\cdot10^{-03}$	$-2.55\cdot10^{-02}$	$6.33\cdot10^{-03}$	$9.13\cdot10^{-03}$	$-3.02\cdot10^{-03}$	$1.23\cdot10^{-02}$	-0.24		
		79	*Climate Change (fossil)*	$3.17\cdot10^{-03}$	$1.85\cdot10^{-03}$	$1.19\cdot10^{-03}$	$4.26\cdot10^{-03}$	$5.58\cdot10^{-03}$	$-2.57\cdot10^{-02}$	$6.33\cdot10^{-03}$	$8.94\cdot10^{-03}$	$-3.32\cdot10^{-03}$	$1.23\cdot10^{-02}$	*-0.27*		
		80	*Climate Change (biogenic)*	$1.01\cdot10^{-05}$	$3.05\cdot10^{-06}$	$9.16\cdot10^{-07}$	$3.34\cdot10^{-05}$	$3.58\cdot10^{-05}$	$1.34\cdot10^{-04}$	$1.32\cdot10^{-07}$	$1.60\cdot10^{-04}$	$2.18\cdot10^{-04}$	$5.92\cdot10^{-06}$	*36.77*		
Planetary Boundaries	13	*81*	*Climate Change (land use change)*	$4.12\cdot10^{-05}$	$3.60\cdot10^{-06}$	$7.56\cdot10^{-07}$	$1.79\cdot10^{-06}$	$9.24\cdot10^{-06}$	$2.95\cdot10^{-05}$	$1.02\cdot10^{-07}$	$2.69\cdot10^{-05}$	$8.61\cdot10^{-05}$	$2.79\cdot10^{-06}$	*30.83*	0.42	19.50
		82	Photochemical Ozone Formation, Ecosystems/Photochemical Ozone Formation	$1.91\cdot10^{-05}$	$7.21\cdot10^{-06}$	$4.34\cdot10^{-06}$	$4.58\cdot10^{-05}$	$1.78\cdot10^{-05}$	$-2.96\cdot10^{-05}$	$1.02\cdot10^{-05}$	$1.31\cdot10^{-05}$	$7.49\cdot10^{-05}$	$5.09\cdot10^{-05}$	1.47		
		83	Ozone depletion	$6.47\cdot10^{-10}$	$2.45\cdot10^{-10}$	$1.45\cdot10^{-10}$	$8.20\cdot10^{-10}$	$1.47\cdot10^{-09}$	$-2.75\cdot10^{-09}$	$3.10\cdot10^{-11}$	$1.42\cdot10^{-09}$	$6.04\cdot10^{-10}$	$1.93\cdot10^{-08}$	0.03		

		84	Global Warming - Freshwater ecosystems	$2.43 \cdot 10^{-16}$	$1.42 \cdot 10^{-16}$	$9.12 \cdot 10^{-17}$	$3.27 \cdot 10^{-16}$	$4.29 \cdot 10^{-16}$	$-1.95 \cdot 10^{-15}$	$4.84 \cdot 10^{-16}$	$6.96 \cdot 10^{-16}$	$-2.35 \cdot 10^{-16}$	$9.41 \cdot 10^{-16}$	-0.25	
		85	Eutrophication freshwater	$7.22 \cdot 10^{-07}$	$4.62 \cdot 10^{-07}$	$6.36 \cdot 10^{-07}$	$3.29 \cdot 10^{-07}$	$2.74 \cdot 10^{-06}$	$1.35 \cdot 10^{-06}$	$8.26 \cdot 10^{-08}$	$4.51 \cdot 10^{-06}$	$6.31 \cdot 10^{-06}$	$6.74 \cdot 10^{-07}$	9.37	
		86	Ecotoxicity freshwater	$4.21 \cdot 10^{-02}$	$2.48 \cdot 10^{-01}$	$8.21 \cdot 10^{-02}$	$4.50 \cdot 10^{-01}$	$4.73 \cdot 10^{+00}$	$5.97 \cdot 10^{-02}$	$4.31 \cdot 10^{-02}$	$3.41 \cdot 10^{-01}$	$5.65 \cdot 10^{+00}$	$6.01 \cdot 10^{-01}$	9.41	
	14	87	Water use	$9.83 \cdot 10^{-04}$	$9.97 \cdot 10^{-03}$	$2.33 \cdot 10^{-02}$	$4.62 \cdot 10^{-04}$	$6.18 \cdot 10^{-03}$	$8.96 \cdot 10^{-03}$	$2.65 \cdot 10^{-04}$	$1.20 \cdot 10^{-02}$	$5.01 \cdot 10^{-02}$	$3.52 \cdot 10^{-04}$	142.35	25.23
		88	Acidification terrestrial and freshwater	$1.87 \cdot 10^{-05}$	$2.88 \cdot 10^{-05}$	$1.55 \cdot 10^{-05}$	$4.12 \cdot 10^{-05}$	$4.21 \cdot 10^{-05}$	$-8.93 \cdot 10^{-05}$	$5.60 \cdot 10^{-05}$	$2.29 \cdot 10^{-05}$	$1.13 \cdot 10^{-04}$	$1.50 \cdot 10^{-04}$	0.75	
		89	Toxicity - Marine ecosystems	$1.29 \cdot 10^{-14}$	$9.76 \cdot 10^{-15}$	$7.03 \cdot 10^{-15}$	$2.25 \cdot 10^{-14}$	$9.82 \cdot 10^{-14}$	$7.83 \cdot 10^{-14}$	$6.93 \cdot 10^{-15}$	$7.39 \cdot 10^{-14}$	$2.36 \cdot 10^{-13}$	$2.27 \cdot 10^{-14}$	10.39	
		90	Eutrophication marine	$6.53 \cdot 10^{-06}$	$3.47 \cdot 10^{-05}$	$1.53 \cdot 10^{-05}$	$1.74 \cdot 10^{-05}$	$7.91 \cdot 10^{-06}$	$-9.79 \cdot 10^{-06}$	$3.35 \cdot 10^{-06}$	$6.58 \cdot 10^{-06}$	$7.55 \cdot 10^{-05}$	$1.71 \cdot 10^{-05}$	4.42	
		91	Land Use	$1.83 \cdot 10^{+01}$	$1.61 \cdot 10^{-01}$	$1.85 \cdot 10^{-01}$	$3.59 \cdot 10^{-02}$	$8.97 \cdot 10^{-02}$	$1.78 \cdot 10^{-01}$	$9.97 \cdot 10^{-04}$	$2.60 \cdot 10^{-01}$	$1.90 \cdot 10^{+01}$	$1.36 \cdot 10^{-01}$	139.29	
		92	Terrestrial Acidification	$1.10 \cdot 10^{-05}$	$1.83 \cdot 10^{-05}$	$9.83 \cdot 10^{-06}$	$2.22 \cdot 10^{-05}$	$2.85 \cdot 10^{-05}$	$-6.27 \cdot 10^{-05}$	$4.10 \cdot 10^{-05}$	$1.47 \cdot 10^{-05}$	$6.82 \cdot 10^{-05}$	$1.06 \cdot 10^{-04}$	0.64	
		93	Terrestrial ecotoxicity	$4.11 \cdot 10^{-02}$	$1.18 \cdot 10^{-02}$	$6.10 \cdot 10^{-03}$	$6.90 \cdot 10^{-02}$	$1.97 \cdot 10^{-02}$	$-4.29 \cdot 10^{-02}$	$4.08 \cdot 10^{-02}$	$5.71 \cdot 10^{-03}$	$1.46 \cdot 10^{-01}$	$4.52 \cdot 10^{-02}$	3.22	
		94	Eutrophication terrestrial	$6.91 \cdot 10^{-05}$	$1.18 \cdot 10^{-04}$	$6.39 \cdot 10^{-05}$	$1.97 \cdot 10^{-04}$	$7.72 \cdot 10^{-05}$	$-1.10 \cdot 10^{-04}$	$3.69 \cdot 10^{-05}$	$6.39 \cdot 10^{-05}$	$4.53 \cdot 10^{-04}$	$1.87 \cdot 10^{-04}$	2.42	
	15	95	Global Warming - Terrestrial ecosystems	$8.91 \cdot 10^{-12}$	$5.19 \cdot 10^{-12}$	$3.34 \cdot 10^{-12}$	$1.20 \cdot 10^{-11}$	$1.57 \cdot 10^{-11}$	$-7.14 \cdot 10^{-11}$	$1.77 \cdot 10^{-11}$	$2.55 \cdot 10^{-11}$	$-8.62 \cdot 10^{-12}$	$3.44 \cdot 10^{-11}$	-0.25	30.43
		96	Photochemical ozone formation - Terrestrial ecosystems	$2.47 \cdot 10^{-12}$	$9.30 \cdot 10^{-13}$	$5.60 \cdot 10^{-13}$	$5.91 \cdot 10^{-12}$	$2.29 \cdot 10^{-12}$	$-3.81 \cdot 10^{-12}$	$1.31 \cdot 10^{-12}$	$1.68 \cdot 10^{-12}$	$9.66 \cdot 10^{-12}$	$6.56 \cdot 10^{-12}$	1.47	
		97	Acidification - Terrestrial ecosystems	$2.33 \cdot 10^{-12}$	$3.88 \cdot 10^{-12}$	$2.09 \cdot 10^{-12}$	$4.70 \cdot 10^{-12}$	$6.05 \cdot 10^{-12}$	$-1.33 \cdot 10^{-11}$	$8.70 \cdot 10^{-12}$	$3.11 \cdot 10^{-12}$	$1.45 \cdot 10^{-11}$	$2.25 \cdot 10^{-11}$	0.64	
		98	Toxicity - Terrestrial ecosystems	$4.68 \cdot 10^{-13}$	$1.34 \cdot 10^{-13}$	$6.96 \cdot 10^{-14}$	$7.87 \cdot 10^{-13}$	$2.24 \cdot 10^{-13}$	$-4.89 \cdot 10^{-13}$	$4.65 \cdot 10^{-13}$	$6.51 \cdot 10^{-14}$	$1.66 \cdot 10^{-12}$	$5.15 \cdot 10^{-13}$	3.22	
		99	Water consumption - terrestrial ecosystems	$3.20 \cdot 10^{-13}$	$3.14 \cdot 10^{-12}$	$7.33 \cdot 10^{-12}$	$1.52 \cdot 10^{-13}$	$1.99 \cdot 10^{-12}$	$2.92 \cdot 10^{-12}$	$8.42 \cdot 10^{-14}$	$3.91 \cdot 10^{-12}$	$1.59 \cdot 10^{-11}$	$1.27 \cdot 10^{-13}$	125.57	

The total impact assessment results of each product system are aggregated to substitution factors factor f^{SDG} for each SDG and presented in the sustainability framework in Fig. 3. The color scale indicates high sustainability risks in red and significant sustainability potential in green according to the table in Fig. 3. Whereas the size of each SDG represents the relative relevance of this SDG coming from German stakeholder participation (Zeug et al., 2019). White SDGs (9, 10, 17) are not addressed yet and hatched SDGs are based on an insufficient indicator basis and have limited significance, i.e., SDG 2 (nutrition) only entails indicators on water consumption and indigenous rights or SDG 11 (cities) only entails fine particulate matter emissions.

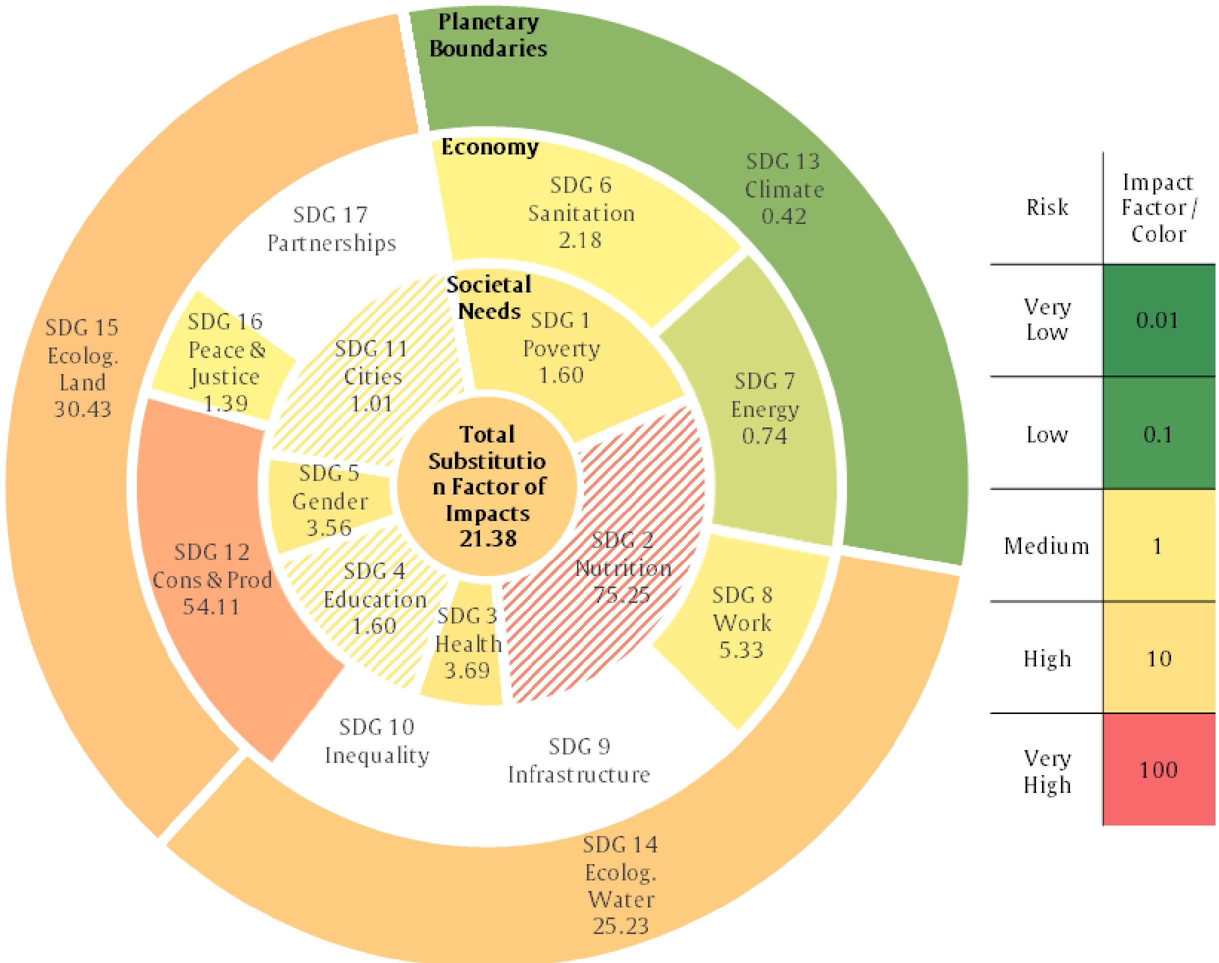


Fig. 3, Relative sustainability of BtL compared to fossil fuels, presented in form of the holistic sustainability framework for HILCSA of the BE (Substitution factor of impact and color aggregated for each SDG according to the table; SDGs are viewed in size according to their relevance for German stakeholders; white SDGs are not addressed yet, hatched SDGs have insufficient indicators) *(color in web and print)*

Since the amount of heat use from waste heat in FT-synthesis is a quite uncertain technology parameter with high sensitivity for some indicators (global warming and other emissions, cumulative energy demand, human trafficking, association and bargaining rights, risk of conflicts, working hours), we include a table with total f and indicator f^{sSDG} factors of substitution for heat use ranging from 0 to 100 % in Table A 3. Especially for the impacts of FT-synthesis, but for the whole product system as well, the impacts from electricity consumption are significant and the electric energy grid mixes result in 589 g CO_2 eq. / kWh (electricity) for 2017 and 163 g CO_2 eq. / kWh (electricity) for the prospective grid mix in 2030 (Table A 1).

For the practical relevance of comparing different transport systems, the results as f^{SDG} of transport of one person for one kilometer by electric car, diesel car powered by fossil fuel, and diesel car powered by BtL compared with train (Fig. 4) are respectively total factors of substitution of 6.50 for the diesel car powered by fossil fuel, 9.16 for the car powered by BtL, and 6.46 for the electric car (Table A 4).

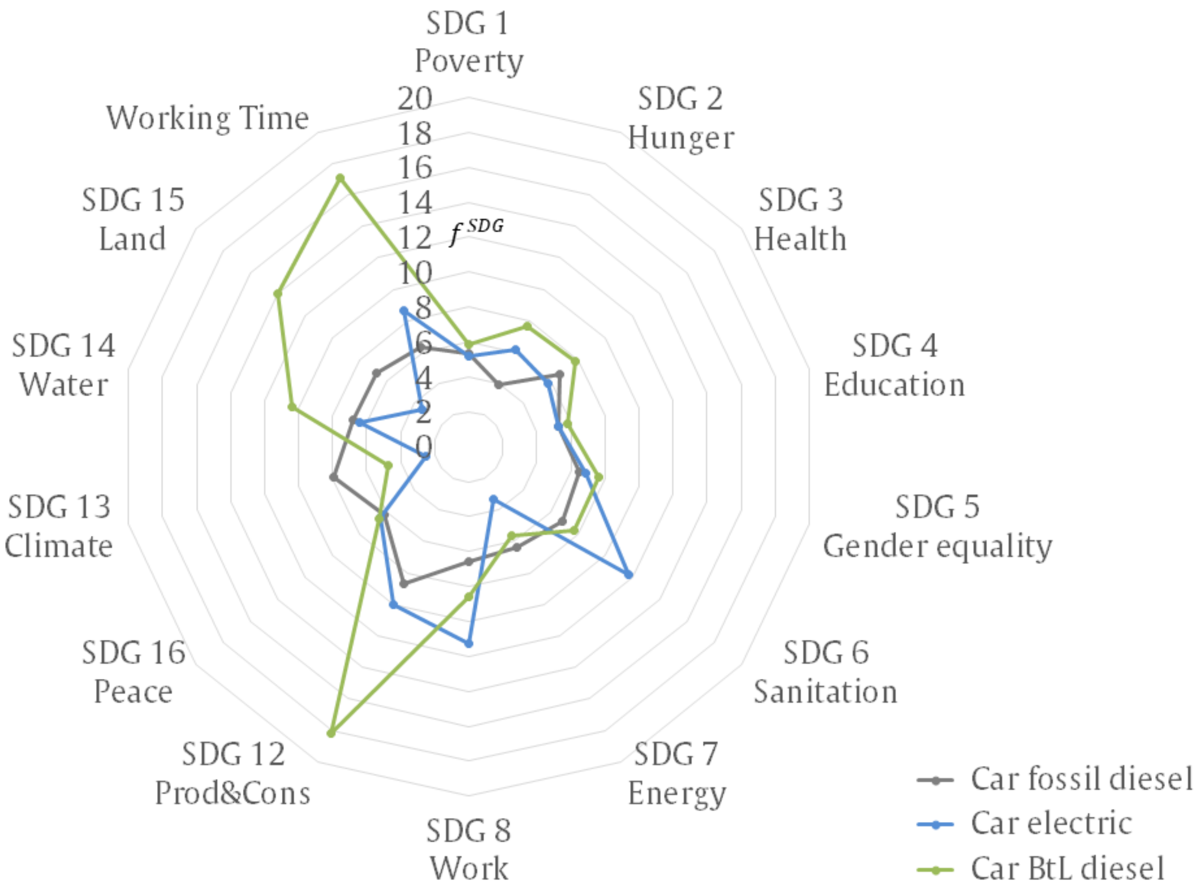


Fig. 4, Relative sustainability of transport of one person for one kilometer by electric car, diesel car powered by fossil fuel and diesel car powered by BtL with train (electric grid mix of 2030 in Germany) *(color in web and print)*

3.4. *Interpretation*

Under the main assumptions of this study (30% heat use in FT-synthesis and electricity grid mix for 2030 in Germany), the total substitution factor of impacts of BtL compared to fossil fuels of $f = 21.38$ indicates significant higher impacts of BtL production. This is the case for social sustainability with $f^{SN} = 29.48$, economic sustainability with $f^{ECO} = 17.56$, and ecological sustainability with $f^{PB} = 19.50$. At the aggregation level of SDGs (Fig. 3) there are sustainability potentials for climate change (SDG 13, $f^{SDG13} = 0.42$) and energy (SDG 13, $f^{SDG13} = 0.72$). However, these impacts are traded-off by all other SDGs and significant risks for $f^{SDG2} = 75.25$ sustainable consumption and production (SDG 12, $f^{SDG12} = 54.11$), ecology in water (SDG 14, $f^{SDG14} = 25.23$), and on land (SDG 15, $f^{SDG15} = 30.43$).

Especially high risks result for human health and indigenous rights (SDG 2, $f^{ID5} = 125.57$) (Table 2) and sustainable use of water resources (SDG 14, $f^{ID87} = 142.35$) in terms of water consumption for sorghum and straw production; for sustainable consumption and production (SDG 12) due to the embodied forest area footprint of residual wood ($f^{ID63} = 674.19$); as well as for terrestrial ecosystems (SDG 15) due to land use ($f^{ID91} = 139.29$) of wood and high water consumption of sorghum and electricty production ($f^{ID99} = 125.57$). We note that high impacts for SDG 2 nutrition do not result from direct use or land use of resources for potential food production, but indirectly by indirect land use changes and water use putting additional pressure on ecological and agricultural systems. There are additional significant high risks ($f^{ID} > 10$) for pollution of air, water, soil, and human health (SDG 3.9) as a result of wood ash treatment from gasification ($f^{ID17} = 19.75$); a high number of migrant workers and migration flows under tendentially bad conditions in sectors with low qualification (SDG 8.5, $f^{ID41} = 11.23$, $f^{ID43} = 16.20$); non-fatal accidents and safety measures (SDG 8.7, $f^{ID54} = 15.66$, $f^{ID57} = 20.22$), increased use of minerals and metals (SDG 12.2, $f^{ID71} = 19.23$) and marine toxicity (SDG 14.1, $f^{ID89} = 10.39$) accounted to gasification coming from the high electricity demand and its background system; and a high embodied agricultural area footprint from biomass cultivation (SDG 12, $f^{ID61} = 24.38$). In total, for 76 out of 99 indicators in HILCSA, the BtLs with 30 % heat use have a worse sustainability performance than fossil fuels ($f^{ID} > 0$), which improves to 51 out of 99 when 70% heat is used. Main contributors are the high demand for electricity for 39 indicators in case of 30% heat use and 27 indicators in case of 70% heat use, which represents a case of low EROI resulting in disadvantageous aspects followed by residual wood with 22 and sorghum production with 8 indicators.

Additionally, we would like to point out the relations between working time and socio-economic risks, which theoretically can lead to higher socio-economic impact results when there is more working time associated to a product system. However, the risk levels themselves are low, and vice versa, there can be low socio-economic impact results when relatively less working time is required but risk levels in general are high. In our case, for BtL the working hours are distributed to flows with very high (13.5 %), high (15.6 %), low (17.4 %) and very low (22.2 %) risks, in a comparable manner as in fossil fuel production with very high (12.8 %), high (17.4 %), low (12.8 %) and very low (23.6 %) risk flows. Consequently, the risk levels are comparable, but overall socio-economic impacts are higher in BtL production since more working time is required in total. In other words, qualitative working conditions in both production systems are similar due to a widely common background system incorporating most working time (e.g., global supply chains in industrial material goods production for educts, energy production, services, waste treatment, etc.) but they quantitatively occur more often in BtL production resulting in higher impacts.

In the case of 16 out of the 99 indicators BtL production has less impacts than fossil fuel production in terms of less ionizing radiation effecting human health (SDG 3.9, $f^{ID14} = 0.22$) and climate (SDG 12.2, $f^{ID72} = 0.22$); less cumulative energy and exergy demand (SDG 7.3, $f^{ID28} = 0.59$, SDG 7.3, $f^{ID29} = 0.89$); less trafficking of persons (SDG 8.7, $f^{ID49} = 0.59$); better association and bargaining rights (SDG 8.7, $f^{ID52} = 0.31$); and less acidification of water SDG 14, $f^{ID88} = 0.75$ and terrestrial ecosystems (SDG 15.5, $f^{ID95} = f^{ID97} = 0.64$). For 6 out of 99 indicators the impacts of BtL production are negative ($0 > f > -0.27$) due to negative GHG emissions in BtL production of -3.0 g CO_2 eq. / MJ (fuel mix) compared to 12.4 g CO_2 eq. / MJ (fuel mix) for fossil fuel production, effecting human health (SDG 3.9, $f^{ID11} = -0.25$), fossil resource scarcity (SDG 12.2, $f^{ID67} = -0.12$) climate change (SDG 13, $f^{ID78} = -0.24$), freshwater ecosystems (SDG 14, $f^{ID84} = -0.25$) and terristral ecosystems (SDG 15.5, $f^{ID95} = -0.25$).

However, in the case of all indicators with less impact ($1 > f$) the positive effects result mainly from credits given by heat use in FT-synthesis and avoiding conventional heat production. All indicator results improve with a further increasing heat use. In particular, some additional indicators reach better sustainability than fossil fuels when heat use exceeds 70 % (Table A 4).

However, there is no scenario in which increased heat use would lead to a better performance than fossil fuels in terms of total factor of substitution.

We explicitly point out that these results relate only to the production phase and not to the use phase of fuels. The production of each MJ FT-BtL fuel, without credits from heat use, would emit 30.95 g CO_2eq (REDII background data for FT diesel from wood: 13.5 – 20.9 g CO_2eq per MJ). With credits from heat use, the combustion of 1 MJ of fuel releases around 72 g CO_2 (calculation of internal diesel combustion from Ecoinvent), the use of every MJ BtL fuel results in the emission of around 69 g CO_2, which is 19 % less than fossil fuels (cf. Fig. 4, SDG 13 Climate change). Furthermore, the production of such BtLs cannot be carbon neutral since in this case already the provision of biomass (before ICPs) is related to 7.6 g CO_2 eq. emissions for the 0.16 kg(dm) of biomass needed to produce 1 MJ of BtL due to transportation, energy for harvesting, machines, and cultivation contributing 7.5 g CO_2 eq. from fossil origin.

Finally, when comparing the transportation systems and use phases of fuels, Fig. 4 shows that all types of car-based individual transportation have significant higher impacts than transportation by train. When translating this general result into the regional case study, transportation by train should be favored and its availability improved, individual transportation should be reduced and electrified as well as BtLs should be marginally used for purposes where electrification is not available for technologic or economic reasons, such as limited aviation, special commercial vehicles and agricultural machinery, a limited number of older cars etc. In case of BtL powered diesel cars the significant risks are rooted in comparable processes, work, material, and energy flows as described before for BtL (Table A 4). Not surprisingly, electric cars have a comparable good performance in terms of energy efficiency and GHG emissions. However, the battery production entails major risks for workers, communities, and environment in global supply chains. Contrarily, fossil diesel powered cars entail most GHG emissions and air pollution.

4. Discussion

First it is important to reflect on the methodological aspects. As mentioned before, this study does not entail a detailed modelling of the technical aspects of BtLs, relying instead on data collected from an external research project. This means that it is highly probable that specific technological parameters can vary, have progressed in the meanwhile, turn out to be different in other locations, or fail to include potential unknown, additional impacts. In particular, the emissions of BtLs in the refinery and use phase can in detail differ from fossil fuels as well as a modelling a global energy system in a 2030 scenario may lead to other results. However, in our opinion, the collected information on the technical aspects reflects the state-of-the-art. Additionally, HILCSA like any other LCA relies on comprehensive databases such as Ecoinvent and the data quality of HILCSA depends on the data quality of Ecoinvent. Whereas the quality of environmental indicators in LCA is good and their application largely mature, there is significant potential for improvement of social and economic indicators in Ecoinvent, SoCa and how to apply and allocate them in HILCSA. Our aggregated results on level of SDGs and sustainability framework depend on the context specific weighting factors from stakeholders for the German BE monitoring. A small sensitivity analysis, however, shows that the overall aggregated results do not change fundamentally, e.g., when all weightings R^{sSDG} and resulting R^{SDG} are set as equal ($R = 1$), then $f = 14.83$, $f_{R=1}^{SN} = 14.77$, $f_{R=1}^{PB} = 18.77$, and $f_{R=1}^{ECO} = 12.52$. Nevertheless, in other regional contexts the weightings should be newly determined and the indicator set should be revised as well, e.g., when child labor, hunger, land grabbing, repressive working conditions, or modern forms of slavery play a more significant role. Especially for such prospective technology assessments further participation formats in Brandenburg with involved stakeholders would be necessary to ensure collaborative creation, collaboration, and cooperation.

Second, regarding technological aspects, usually the biomass provision and properties (e.g., moisture content, transport, ICPs, origin, and trade) are sensitive as well as significant for impacts. However, in this case the sensitivity and significance of biomass is relatively low (partly except of residual wood) since we did not conduct an additional feedstock optimization and due to the high efforts and impacts of biomass conversion. Biomass gasification contributes comparably high environmental impacts and consumes 30% of input biomass energy. Nonetheless, gasification is robustly modeled in Ecoinvent and a fully developed technology. Therefore, from a technological perspective, FT-synthesis is the most volatile, sensitive and high-risk process step. Mainly, because of the very high electric energy demand of 0.195 MJ / MJ (syncrude), the FT-synthesis comes with high impacts, as well as an energetic conversion efficiency of only 56%, which is responsible for increased impacts in all upstream processes. The resulting significant amount of 1,02 MJ / MJ (syncrude) waste heat and its potential use is decisive for the ecological, economic, and social sustainability as well as overall feasibility of the BtL production. As discussed, there is no certain parameter for the percentage of heat use due to a dependency on multiple factors. However, our parameterized results show that for the entire range from 0 to 100 % there are high risks and few chances for sustainable fuel production with this technology. The only reasons why gas cleaning and FT-synthesis do not contribute the most negative impacts of all the processes is because of the assumed 30% heat use and the resulting credits from avoided heat production on the market for heat. This mainly fossil market for heat is modeled as the heat production in chemical industry in 2010, thus the given credits on impacts for each avoided MJ are very high, and would decrease in a 2030 scenario when less unsustainable heat production would be assumed.

Third, in terms of ecological sustainability, we have to say clearly that the production of BtLs is not carbon neutral or even negative, as a misinterpretation of the results from Table 2 could wrongly suggest. The production of each MJ BtL fuel results in 30.95 g CO_2 eq, which is 2.51 times more than in the case of the production of MJ of fossil fuels, and so have all along the life cycle a reduction potential of 66% (when using the RED II comparator of 89 gCO2 eq emission in the use phase for fossil diesel). Of course, the emissions can decrease when process parameter and especially when external conditions improve, such as a higher degree of local waste heat use and lower emissions in upstream and background system flows due to more sustainable electricity and heat production. For all non-GHG related indicators our results suggest that BtLs entail significantly more ecological risks than fossil fuels ($f^{SDG14} = 25.23$, $f^{SDG15} = 30.43$), independently of the degree of heat use. This is mainly due to the higher use of water, land, materials, and toxic emissions at land ecosystems and of course the need for energy and related impacts. In our study seemingly low or negative substitution factors of impact, especially for GHG emissions, are due to the credits given by heat use and not due to biomass as a carbon sink (Table A 3, Impact assessment results and comparison for BtL production system and fossil fuels for heat use (HU) as parameter, 2030 electric energy grid mix (color scale for each indicator process hot-spot analysis (red - highest risk; green - lowest risk); color scale for total impacts over all indicators hot-spot analysis (red - highest risk; green - lowest risk))Table A 3). However, as the assessment presented in this work is significantly dependent on the regional conditions, the ecological impacts can change significantly if the production would take place in other regions, which are e.g., dryer, have higher biodiversity, etc.

Fourth, for economic sustainability, the highest risks and factors of substitutions are again related to agricultural and forest area footprints as well as use of minerals and materials. The main negative economic impacts result from less good working conditions in the agricultural and forestry sector in Germany as well as significant externalized risks in working conditions in global supply chains for the high energy demand. Electricity production is the biggest single sector in terms of working time, contributing about 35% of total required working time and thereby allocating significant impacts to this sector. We have shown that the actual working conditions are not worse than those related to fossil fuel. However, they sum up to a higher risk since significantly more working time is required in these working conditions for BtL production. Although costs are not a focus of this sustainability assessment, we know from the BECOOL data that gasification, gas cleaning, and FT synthesis make up to 57% of the overall production costs and that profits from surplus heat are not relevant (Dögnitz et al., 2022).

Fifth, regarding social sustainability the required working time of BtL production and its allocation over processes, economic sectors, and regions determines social impacts. When looking at regions our openLCA data suggests that, besides Germany, significant social and economic impacts are located and related to India, South Africa, Russia, China, and Chile. These impacts are due to resources and production of the entire background systems, from metals and rare earths to hard coal, chemicals, and food to produce wind turbines, factories, by-educts, electronics, harvesters and so on. Only about $15 \cdot 10^{-04}$ h working time per MJ (28 %) takes place in Germany and the remaining $39 \cdot 10^{-04}$ h (72 %) around the globe. With around $19 \cdot 10^{-04}$ h (35 %) India is the biggest contributor, with nearly this entire workflow relating to hard coal mining, which is not surprising since India is the world's second largest coal producer. Once again, electricity production and agriculture due to water and land use are the hot-spots on a process level, illustrating that the German BE shows a high concentration of unskilled workers and low quality (e.g., high risk) jobs, i.e., twice more than the German average and as well more compared to other European BEs (Fritz, 2022).

However, as bioeconomy policymakers are increasingly aware of, any kind of sustainable bioeconomy will require a reduction of resource and energy use and a societal ecological transformation. Thus, the biggest challenges are not expected to be only technological ones; instead, the challenge of society overcoming the deep structural entrenchment in mindsets of political economy, 'fossilism', and growth oriented capitalism shall also be equally considered (Eversberg and Fritz, 2022). Such a need of change in patterns of regulation in political economy is demonstrated by the so-called fuel versus food debate of bioenergy, i.e., hunger and malnutrition as a consequence of increased use of biomass and land use for bioenergy is not primarily a problem of the applied (first generation bioenergy) technologies, but of their regulation, and consequentially cannot be overcome by only technological means. Even if enough food is produced worldwide to end hunger, the pattern of regulation of our economies requires ending poverty first. Societal needs alone (use value), sufficient resources and means do not lead to their fulfillment as long as those basic needs are not coupled with enough purchasing power (exchange and surplus value). Land or crops will be used for the purpose with the highest expected surplus value (e.g. fuels), instead of the fulfillment of more basic societal needs with a higher use but lower exchange value (e.g. nutrition) (cf. (Ashukem, 2020) (Zeug et al., 2023).

The limitations of this study and of the following conclusions do not allow an in-depth elaboration on some structural elements, such as ownership, control, agency, power relations, and political legislation (Plank et al., 2021), which would be very relevant for social, ecological, and economic impacts when this BtL production would be put into actual practice. Furthermore, in this study we cannot determine the overall potential of any biofuel production to address the double decoupling problem within planetary boundaries, i.e., how much biofuels could be produced sustainably. A missing cost analyses in HILCSA makes a classic economic classification of the results more difficult, but can be supplemented in joint projects. Especially, in future further development of HILCSA methodology, the missing SDGs and SDGs with a weak and insufficient indicators basis should be improved by more and refined indicators, as well as the indicator set and methodology should be updated and improved constantly. Furthermore, bioeconomy-related and innovative cultivation methods, secondary renewable resources and conversion technologies should be better considered in Ecoinvent to improve variability, accuracy and system boundaries of such production systems.

5. Conclusions

This case study and application of HILCSA on BtL aims on the one hand to indicate the sustainability as well as which substitution effects, hotspots, trade-offs, and synergies a BtL production in Brandenburg (Germany) when compared to conventional fossil fuels. On the other hand, the study aims to distinguish which technical, economic, and social conditions would make such technologies environmentally, socially, and economically desirable.

In particular, our results suggest that if this BtL production concept would be put into practice, at least 70% of heat use should be achieved to minimize sustainability risks. The possibility of high waste heat utilization is given when the process steps of the synthesis are close to a year-round heat sink (van den Oever et al., 2022), e.g., industrial parks with a need for low-temperature process heat, public swimming pools, etc..

Besides technological implications, the results illustrate a specific problematic configuration of the bioeconomy and the employed technologies, i.e., resources are comparably cheap and the technologies are expensive, which is in contrast to fossil energy where technology is cheap but feedstock expensive (Birch, 2021; Calvert et al., 2017). Using cheap resources like residues (residual wood and partly straw in this case) does not automatically have fewer negative impacts, not in processing nor in biomass resourcing, especially when it comes to mismanagement and false declarations, as when primary vegetable oils are imported as used cooking oils (Mestre, 2021). While first generation biofuel production competes with food production, second generation biofuels compete with an environmentally and economically favorable material use of biomass (Albers, 2021). In this case, straw, sorghum and residual wood as feedstock result in a combination of first- and second-generation biofuel production entailing both downsides, i.e., a high land and water use as well as competition to material use due to non-existing cascades. Second generation or advanced biofuels may be an option for biomass at the very end of a material cascade use. Whereas sorghum production could have sustainability potentials by improving crop rotation systems. However, in a circular economy, biofuels could play a minor but important role (Bioökonomierat, 2022b) since their use and production in principle is not circular but needed for specific applications. Strategically, the most limiting planetary boundary for liquid biofuels (Fehrenbach et al., 2023) and the bioeconomy in general is the availability of land (Bringezu et al., 2021), since land is already a very contested and limited resource for various uses, such as reservations with functions for ecosystems and biodiversity, the production of food and feed crops, infrastructure and settlements. This is true for using biomass residues as well, due to their dependencies on primary biomass cultivation as well. Furthermore, a sustainable bioeconomy would need additional land to regrow more than it is harvested.

Even when most biomass is regionally produced in Germany, global fossil-based supply chains (e.g. steel, electronics, textiles, plastics, preliminary products, wastes) externalize most of the negative social, economic, and partly ecologic effects to countries in the periphery, which we know well from other economic sectors. Less human labor is required in Germany, where technology and added value is concentrated, and downsides and trade-offs are exported, especially when the German BE relies on increasing biomass imports (Backhouse et al., 2021; Brand and Wissen, 2018). In line with the conclusions reported by (Fritz, 2022), this case study illustrates and witnesses that even when progressive impulses of BE would mostly be expected in technology and resource substitution, a general transformation of working conditions and global political economy is nowhere in sight.

The production of BtL as envisaged in this case study entail social, ecological, and economic risks to such an extent that a large-scale substitution of fossil fuels as a drop-in solution should not be followed from a sustainability perspective. If this would be fostered, the risk is high for a continued lock-in effect in car dependency (Mattioli et al., 2020), non-sustainable biomass use paths over a long period of time (Aktionsforum Bioökonomie, 2022), as well as delays to structural transformations (Eversberg and Fritz, 2022), especially since there are better alternatives in the form of electricity driven public and individual transport, e.g. only 2.5% of the cropland is needed for the electric alternative compared to biofuels (Fehrenbach et al., 2023). As well as liquid fuels that can be produced without biomass directly from CO2 and energy (Treyer et al., 2021) that don't have additional impacts on land use and water. In our limited comparison of transport services, public transport based on electricity entails the lowest social, ecological and economic impacts, as well due to additional effects visible from Ecoinvent such as less land use for public transport infrastructure compared to many roads needed for individual transport.

By its holistic and integrated character, this study shows that only focusing on GHG, for example, could lead to severely abbreviated or incorrect results on sustainability with the risks of misguided conclusions and policy mismanagement. Second- and third-generation biofuels are expected to have lower risks and to be better alternatives, since utilizing wastes and other materials is connected to less land, water, and energy use as well as concurrencies (Sikarwar et al., 2017). In the RED II already insufficient sustainability criteria were defined which will probably be expanded and intensified in its upcoming revision (REDIII). We conclude that future biofuel policies do not only focus on GHG emissions reduction, tightened sustainability criteria of primary resource production and making cascading use of biomass a criteria (Smailagic, 2023), but should include regulations for water and land use, social supply chain effects and energetic efficiency and effectiveness (EROI) as well.

Taken together, the results of this study point out at two main problems, on the one hand that biofuels may be able to sustainably substitute fossil fuels in very specific applications and in relatively small quantities when there is no alternative available. However, biofuels in specific and BE in general will not be able to sustainably substitute the production and consumption of fossil resources in total. On the other hand, production processes using materials and energy cannot be carbon neutral, however, carbon neutrality of production is becoming a dangerous and popular ideological modern myth. Misinterpretations of carbon neutrality or negative substitution factors for GHG in our study lead to the invisibility of emissions and may even trigger more emissions and a loss of precious time and action to implement measures of actual radical GHG reductions.

As a general conclusion, (carbon negative) technologies alone are not able to overcome the transformation problem and only partly switching the resource base of economies will maintain fundamental political problems of sustainability. Both aspects are very well known to most people, scientists and politicians, but remain an ideological fantasy, which means that social-ecological transformations are not demanded and fostered and instead one remains stuck in the currently dominant patterns of political economy. The socio-ecological crisis is not primarily a crisis of knowledge, but a crisis of practice: "even if we do not take things seriously, even if we keep an ironic distance, we are still doing them" (Žižek, 1989). A societal-ecological transformation would have to entail sufficiency, effectiveness, efficiency, equality and justice instead of promises of unlimited growth. In fact, we need this societal-ecological transformation as an democratic, participatory, and adaptive process (Eversberg and Fritz, 2022) to be able to make responsible and reasonable use of renewable resources without overusing them and continue negative societal impacts of established global supply chains and their political economy.

We see the added value of the HILCSA methodology compared to all other existing LCA and LCSA methodologies through its integrated and holistic character, i.e., on the one hand, integrated LCSA [1] allows consistent and comparable data on social, ecological, and economic indicators, [2] identifies synergies and trade-offs between different aspects, [3] traces down impacts to regions in the fore-and background systems, [4] as well as allocates and aggregates them to the SDGs to make complexity communicable. On the other hand, holistic LCSA on the basis of integrated LCSA data takes social sciences and political economy into account from the beginning with clear definitions on sustainability and societal relations to nature, interpretation and discussion of results relating to social, ecological, and economic impacts not only to technologies but also to societal, economic, and political questions; as well as methods for drawing conclusions beyond the status quo, with a perspective on societal-ecological transformations.

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Appendix

Table A 1, Elec production system for Ecoinvent v3 and adopted to 2030 by (Matthes et al., 2022), Fig. 3-7, Scenario KoaP

Electric energy source	Share in kWh / 1 kWh grid mix	
	Ecoinvent v3 (2014)	Scenario 2030
Biogas, heat & power	0.058	0.052
Blast furnace, power	$1.71\cdot10^{-06}$	0.000
Coal gas, power	$3.46\cdot10^{-04}$	0.000
Deep geothermal	$2.73\cdot10^{-04}$	0.000
Hard coal, power	0.129	0.000
Hard coal, heat & power	0.024	0.020
Hydro pumped	0.011	0.000
Hydro reservoir	0.006	0.000
Hydro river	0.031	0.030
Import AT	0.007	0.000
Import CH	0.003	0.000
Import CZ	0.010	0.000
Import DK	0.010	0.000
Import FR	0.013	0.000
Import LU	0.002	0.000
Import NL	0.003	0.000
Import PL	0.000	0.000
Import SE	0.004	0.000
Lignite, heat & power	0.007	0.007
Lignite, power	0.241	0.000
Natural gas, heat & power	0.068	0.146
Natural gas, heat & power combined cycle	0.001	0.000
Natural gas, power	0.013	0.000
Natural gas, power combined cycle	0.021	0.000
Nuclear boiler, power	0.028	0.000
Nuclear, power	0.104	0.000
Oil, heat & power	0.000	0.000
Oil, power	0.002	0.000
Photovoltaic, big	0.000	0.132
Photovoltaic, small	0.000	0.132
Wind, < 1 MW onshore	0.026	0.000
Wind, > 3 MW onshore	0.016	0.000
Wind, 1 - 3 MW offshore	0.006	0.146
Wind, 1 - 3 MW onshore	0.145	0.334
Woodchips, heat & power	0.011	0.000

Table A 2, Sustainability framework and indicator system of HILCSAv2 for BtL production in Germany (R, relevance according to (Zeug et al., 2019); AV, activity variable; FU, functional unit; quan, quantitative; qual, qualitative; PRP Eval. Scheme: 10-8 PRP = very low risk; 8-6 PRP = low risk; 4-6 PRP = medium risk; 2-4 PRP = high risk; 0-2 PRP = very high risk; n.a. = no data)

Sustainability Framework				**Indicator System**								
	SDG Code	**SDG R**	**SDG Sub-Goal**	**Source**	**ID**	**Indicator Name**	**Description**	**Data type**	**AV /FU**	**Unit of Measurement**	**Evaluation Scheme**	**Impact Factors**
Societal needs	1	6.60	End poverty in all its forms everywhere	SoCa v2	1	Social security expenditures	Social security expenditures in % of GDP	quan	wh	SS med risk hours/h	Soca	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	1.2	6.94	Poverty reduction	Responsa	2	Payment according to basic wage	Payment according to collective agreement	qual	wh	y/n	PRP Eval. Scheme	
	1.4	6.94	Enable economic participation for all people	Responsa	3	Capital participation	Possibility of capital participation	qual	wh	y/n		
	1.4	6.94	Enable economic participation for all people	Responsa	4	Profit-sharing and bonuses	Possibility of profit-sharing and bonuses	qual	wh	y/n		
	2	9.33	End hunger, achieve food security and improved nutrition and promote sustainable agriculture	Recipe (End)	5	Water consumption - HH	Malnutrition caused by water shortage	quan	mf	Daly/m3 consumed	Recipe	Recipe
	2.3	6.39	Increase agricultural productivity, income (small producers)	SoCa v2	6	Indigenous rights	Indigenous People Rights Protection Index	quan	wh	IR med risk hours/h	Soca	no risk = 0.0; very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	3	2.15	Ensure healthy lives and promote well-being for all at all ages	SoCa v2	7	Health expenditure	Health expenditure in % of GDP	quan	wh	HE med risk hours/h	Soca	
	3	2.15		SoCa v2	8	Life expectancy at birth	Life expectancy at birth in years	quan	wh	LE med risk hours/h	Soca	

	3.9	8.61	Reduce pollution of air/water/ soil, health protection	SoCa v2	9	DALYs due to indoor and outdoor air and water pollution	DALYs per 1,000 inhabitant in the country	quan	wh	DALY med risk hours/ h	Soca	
	3.9	8.61		SoCa v2	10	Pollution	Pollution Index based on perceptions	quan	wh	P med risk hours/ h	Soca	
	3.9	8.61		Recipe (End)	11	Global Warming - HH	Years of life lost and disabled related to increased malaria, diarrhea, malnutrition and natural disasters due to increased global mean temperature	quan	mf	DALY/ kg CO2 eq.	Recipe	Recipe
	3.9	8.61		Recipe (End)	12	Stratospheric ozone depletion - HH	Years of life lost and disabled related to increased skin cancer and cataract due to UV-exposure	quan	mf	DALY/ kg CFC11 eq.	Recipe	Recipe
	3.9	8.61		Recipe (End)	13	Photochemical ozone formation - HH	Years of life lost related to an increase in respiratory diseases caused by exposure to ozone	quan	mf	DALY/ kg NOx eq.	Recipe	Recipe
	3.9	8.61		Recipe (End)	14	Ionizing Radiation - HH	Years of life lost and disabled related to an increase in cancer and hereditary diseases due to exposure to radiation	quan	mf	DALY/ kBq Co-60 emitte d to air eq.	Recipe	Recipe
	3.9	8.61		Recipe (End)	15	Fine particulate matter formation - HH	Years of life lost related to an increase in cardiopulmonary and lung cancer caused by exposure to primary and secondary aerosols	quan	mf	DALY/ kg PM2.5 eq.	Recipe	Recipe
	3.9	8.61		Recipe (End)	16	Toxicity - HH (cancer)	Years of life lost and disabled due to cancer effects due to ingestion	quan	mf	DALY/ kg 1,4-DCB emitte	Recipe	Recipe

							and inhalation of toxic substances			d to urban air eq.		
	3.9	8.61	Reduce pollution of air/water/ soil, health protection	Recipe (End)	17	Toxicity - HH (non-cancer)	Years of life lost and disabled due to non-cancer effects due to ingestion and inhalation of toxic substances	quan	mf	DALY/ kg 1,4-DCB emitted to urban air eq.	Recipe	Recipe
	4	4.43	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	SoCa v2	18	Expenditures on education	Expenditures on education in % of GDP	quan	wh	EE med risk hours/ h	Soca	no risk = 0.0; not applicable = 0.0; very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	5.1	5.83	Eliminate discrimination against women	SoCa v2	19	Gender wage gap	Difference between male and female median wages	quan	wh	GW med risk hours/ h	Soca	
	5.1	5.83		Responsa	20	Female employees in management positions	Percentage of female employees in management positions	quan	wh	%	PRP Eval. Scheme	
	5.1	5.83		Responsa	21	Rate of female employees	Percentage of female employees per total employees	quan	wh	%	PRP Eval. Scheme	
	5.1	5.83		SoCa v2	22	Men in the sectoral labor force	Men in the sectoral labor force as ratio	quan	wh	M med risk hours/ h	Soca	
	5.1	5.83		SoCa v2	23	Women in the sectoral labor force	Women in the sectoral labor force as ratio	quan	wh	W med risk hours/ h	Soca	
	11.6	9.17	Reduce urban environmental impacts, air quality, waste treatment	Recipe (End)	24	If production site is in urban region (Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted) [5])	3.9/7	quan	mf	DALY/ kg PM2.5 eq.	Recipe	Recipe

Provisioning System	6.1	8.61	Access to affordable drinking water, food security	SoCa v2	25	Drinking water coverage	Population with access to drinking water	quan	wh	DW med risk hours/h	Soca	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	6.2	4.44	Sanitation / hygiene	SoCa v2	26	Sanitation coverage	Population with access to sanitation facilities	quan	wh	SC med risk hours/h	Soca	
	7.2	5.56	Increase share of renewable energies, energy mix	CED	27	Cumulative Energy Demand, Renewable energies	Renewable energy biomass, solar, wind, geo, water CED	quan	mf	MJ	cumulation	
	7.3	5.83	Double rate of increase of energy efficiency	CED	28	Cumulative Energy Demand	Cumulative Energy Demand	quan	mf	MJ	cumulation	
	7.3	5.83		EROI	29	Cumulative Exergy Demand	Cumulative Exergy Demand for ExROI	quan	mf	MJ	cumulation	
	8.1	2.78	Per capita economic growth, GDP increase	SoCa v2	30	Contribution of the sector to economic development	Contribution of the sector to economic development	quan	wh	CE med risk hours/h	Soca	no opportunity = 0.0; low opportunity = 0.1; medium opportunity = 1.0; high opportunity = 10; no data = 0.1
	8.5	5.00	Productive full employment, decent work, pay equity	SoCa v2	31	Weekly hours of work per employee	Hours of work per employee and week in h	quan	wh	WH med risk hours/h	Soca	
	8.5	5.00		Responsa	32	Compensation for overtime	Compensation measures/financial compensation and free time	qual	wh	y/n	PRP Eval. Scheme	
	8.5	5.00		Responsa	33	Access to flexible working time agreements	Availability of flexible working agreements	qual	wh	y/n		
	8.5	5.00		Responsa	34	Rate of part-time employees	Percentage of part-time employees per total employees	quan	wh	%		
	8.5	5.00		Responsa	35	Rate of marginally employees (max. 450€)	Percentage of employees earning max. 450€ per	quan	wh	%		

							month per total employees					
	8.5	5.00		Responsa	36	Rate of fixed-term employees	Percentage of fixed-term employees per total employees	quan	wh	%		
	8.5	5.00		Responsa	37	Rate of employees provided by temporary work agencies	Percentage of employees provided by temporary work agencies per total employees	quan	wh	%		
	8.5	5.00		Responsa	38	Rate of disabled employees	Percentage of disabled employees per total employees	quan	wh	%		
	8.5	5.00		Responsa	39	Rate of foreign employees	Percentage of foreign employees per total employees	quan	wh	%		
	8.5	5.00		SoCa v2	40	Net migration	Net migration rate ‰ (= per 1,000 persons)	quan	wh	NM med risk hours/h	Soca	
	8.5	5.00		SoCa v2	41	International Migrant Stock	International Migrant Stock % (of total population)	quan	wh	IMS med risk hours/h	Soca	
	8.5	5.00		SoCa v2	42	International migrant workers (in the sector/ site)	International migrant workers (in the sector/ site)	quan	wh	IMW med risk hours/h	Soca	
	8.5	5.00		SoCa v2	43	Migration flows	Migration flows as score	quan	wh	MF med risk hours/h	Soca	
	8.5	5.00		Responsa	44	Average remuneration level	Average payment per month per full-time employee per total employees	quan	wh	€	PRP Eval. Scheme	
	8.5	5.00		SoCa v2	45	Fair salary	SOCA Sector average wage, Minimum wage, Living wage, Upper & lower bound in USD	quan	wh	FS med risk hours/h	Soca	
	8.5	5.00		SoCa v2	46	Unemployment	Unemployment % of the population	quan	wh	U med risk	Soca	

										hours/ h		
	8.6	4.72	Increase share of youth employment, education and vocational training	Responsa	47	Rate of vocational trainees	Percentage of trainees per total employees	quan	wh	%	PRP Eval. Scheme	
	8.7/8.8	5.00	Worker rights, labor protection rights, promoting safe work environment, abolition of forced labor / trafficking / child labor	SoCa v2	48	Child Labor, total	Child Labor, % of all children employed ages 7-14	quan	wh	CL med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	49	Trafficking in persons	Trafficking in persons as tier placement	quan	wh	Trafficking in persons/h	Soca	
	8.7/8.8	5.00		SoCa v2	50	Frequency of forced labor	Frequency of forced labor as number of cases per 1,000 inhabitants in the country	quan	wh	FL med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	51	Goods produced by forced labor	Number of goods produced by forced labor in the sector	quan	wh	GFL med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	52	Association and bargaining rights	Association and bargaining rights as score	quan	wh	ACB med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	53	Trade unionism	% of employees organized in trade unions	quan	wh	TU med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	54	Non-fatal accidents	Number of non-fatal accidents per 100,000 employees and year	quan	wh	NFA med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	55	Fatal accidents	Number of fatal accidents per 100,000 employees and year	quan	wh	FA med risk hours/h	Soca	
	8.7/8.8	5.00		Responsa	56	Sick-leave days	Sick-leave days per year per employee	quan	wh	#	PRP Eval. Scheme	

	8.7/8.8	5.00		SoCa v2	57	Safety measures	OSHA cases per 100,000 employees in the sector	quan	wh	SM med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	58	Violations of employment laws and regulations	Number of violations of employment laws and regulations	quan	wh	VL med risk hours/h	Soca	
	8.7/8.8	5.00		SoCa v2	59	Workers affected by natural disasters	Workers affected by natural disasters in %	quan	wh	ND med risk hours/h	Soca	
	8.7/8.8	5.00		Responsa	60	Work Council	Existence of Working Council	qual	wh	y/n	PRP Eval. Scheme	
	12	9.15		SoCa v2	61	Embodied agricultural area footprints	Embodied agricultural area footprints in ha/$	quan	wh	EAF med risk hours/h	Soca	
	12	9.15		SoCa v2	62	Embodied biodiversity footprints	Embodied biodiversity footprints in ha/$	quan	wh	EBF med risk hours/h	Soca	
	12	9.15	Ensure sustainable consumption and production patterns	SoCa v2	63	Embodied forest area footprints	Embodied forest area footprints in ha/$	quan	wh	EFA med risk hours/h	Soca	
	12	9.15		SoCa v2	64	Embodied water footprints	Embodied water footprints in m³/$	quan	wh	EWF med risk hours/h	Soca	
	12	9.15		SoCa v2	65	Embodied GHG footprints	Embodied GHG footprints in CO2eq/$	quan	wh	EWF med risk hours/h	Soca	
	12.2	8.89		SoCa v2	66	Industrial water depletion	Industrial water depletion in % of total water withdraw	quan	wh	WU med risk hours/h	Soca	
	12.2	8.89	Sustainable management of natural resources	Recipe (End)	67	Fossil resource scarcity	Cost increase due to fossil extraction increase	quan	mf	USD2013/kg Cu	Recipe	Recipe
	12.2	8.89		SoCa v2	68	Fossil fuels consumption	Fossil fuels consumption t/cap	quan	wh	FF med	Soca	very low risk = 0.01;

										risk hours/ h		low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	12. 2	8.89		SoCa v2	69	Biomass consumption	Biomass consumption t/cap	quan	wh	BM med risk hours/ h	Soca	
	12. 2	8.89		SoCa v2	70	Minerals consumption	Minerals consumption t/cap	quan	wh	MC med risk hours/ h	Soca	
	12. 2	8.89		EF 3.0	71	Resource use, mineral and metals		quan	mf	kg Sb eq.	EF 3.0	EF 3.0
	12. 2	8.89		Recipe (Mid)	72	Ionizing Radiation	Absorbed dose increase/Ionizing radiation potential (IRP)	quan	mf	Bq C-60 eq. to air	Recipe	Recipe
	12. 6	8.61	Reporting on sustainability information	SoCa v2	73	Certified environmental management system	Certified environmental management system	quan	wh	CMS med risk hours/ h	Soca	
	12. 6	8.61		SoCa v2	74	Anti-competitive behavior or violation of anti-trust and monopoly legislation	Cases per 10,000 employees in the sector	quan	wh	AC med risk hours/ h	Soca	
	16	2.61	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	SoCa v2	75	Risk of conflicts	Global peace index score as score	quan	wh	ROC med risk hours/ h	Soca	very low risk = 0.01; low risk = 0.1; medium risk = 1.0; high risk = 10; very high risk = 100; no data = 0.1
	16. 5	7.22	Reduction of bribery / corruption	SoCa v2	76	Public sector corruption	Corruption Perceptions Index score of the country	quan	wh	C med risk hours/ h	Soca	
	16. 5	7.22		SoCa v2	77	Active involvement of enterprises in corruption and bribery	Active involvement of enterprises in corruption and bribery in %	quan	wh	AI med risk hours/ h	Soca	

Planetary Boundaries	13	7.53	Take urgent action to combat climate change and its impacts*	EF 3.0	78	Climate Change	Infrared radiative forcing increase, Global warming potential (GWP)	quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
	13	0.00		EF 3.0	79	Climate Change (fossil)		quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
	13	0.00		EF 3.0	80	Climate Change (biogenic)		quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
	13	0.00		EF 3.0	81	Climate Change (land use change)		quan	mf	kg CO2 eq.	EF 3.0	EF 3.0
	13	7.53		Recipe (Mid)	82	Photochemical Ozone Formation, Ecosystems/Photochemical Ozone Formation	Tropospheric ozone increase, Photochemical oxidant formation potential: ecosystems (EOFP)	quan	mf	kg NOx eq.	Recipe	Recipe
	13	7.53		EF 3.0	83	Ozone depletion		quan	mf	kg CFC-11 eq.	EF 3.0	EF 3.0
	14	8.37	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	Recipe (End)	84	Global Warming - Freshwater ecosystems	Fish species loss due to decrease river discharge	quan	mf	Species.year/ kg CO2 eq.	Recipe	Recipe
	14	8.37		EF 3.0	85	Eutrophication freshwater		quan	mf	kg P eq.	EF 3.0	EF 3.0
	14	8.37		EF 3.0	86	Ecotoxicity freshwater		quan	mf	CTUe	EF 3.0	EF 3.0
	14	8.37		EF 3.0	87	Water use		quan	mf	m^3 world equiv.	EF 3.0	EF 3.0
	14	8.37		EF 3.0	88	Acidification terrestrial and freshwater		quan	mf	Mole of H+ eq.	EF 3.0	EF 3.0
	14.1	8.33	Reduce marine pollution, marine litter / nutrient pollution	Recipe (End)	89	Toxicity - Marine ecosystems	Species loss due to chemical exposure in marine waters	quan	mf	Species·yr/kg 1,4-DBC emitted to sea water eq.	Recipe	Recipe
	14.1	8.33		EF 3.0	90	Eutrophication marine		quan	mf	kg N eq.	EF 3.0	EF 3.0
	15.1	7.50	Preservation / sustainable use of terrestrial	EF 3.0	91	Land Use		quan	mf	Pt	EF 3.0	EF 3.0
	15.1	7.50		Recipe (Mid)	92	Terrestrial Acidification	Proton increase in natural soils,	quan	mf	kg SO2 eq.	Recipe	Recipe

			and inland freshwater ecosystems				Terrestrial acidification potential (TAP)					
	15.1	7.50		Recipe (Mid)	93	Terrestrial ecotoxicity	Hazard-weighted increase in natural soils, Terrestrial ecotoxicity potential (TETP)	quan	mf	kg 1,4-DB eq.	Recipe	Recipe
	15.1	7.50		EF 3.0	94	Eutrophication terrestrial		quan	mf	Mole of N eq.	EF 3.0	EF 3.0
	15.5	8.33	Protecting natural habitats, threatened species, biodiversity	Recipe (End)	95	Global Warming - Terrestrial ecosystems	Species loss related to changing biome distributions due to increased global temperature	quan	mf	Species.year/kg CO2 eq.	Recipe	Recipe
	15.5	8.33		Recipe (End)	96	Photochemical ozone formation - Terrestrial ecosystems	Loss of plant species due to increase in ozone exposure	quan	mf	Species.year/kg NOx eq.	Recipe	Recipe
	15.5	8.33		Recipe (End)	97	Acidification - Terrestrial ecosystems	Loss of plant species due to decrease in soil pH	quan	mf	Species.year/kg SO2 eq.	Recipe	Recipe
	15.5	8.33		Recipe (End)	98	Toxicity - Terrestrial ecosystems	Species loss due to chemical exposure in soils	quan	mf	Species.year/kg 1,4-DBC emitted to industrial soil eq.	Recipe	Recipe
	15.5	8.33		Recipe (End)	99	Water consumption - terrestrial ecosystems	Decrease in Net Primary Productivity because of water shortage as proxy for total species loss	quan	mf	Species.year/m3 consumed	Recipe	Recipe

Table A 3, Impact assessment results and comparison for BtL production system and fossil fuels for heat use (HU) as parameter, 2030 electric energy grid mix (color scale for each indicator process hot-spot analysis (red - highest risk; green - lowest risk); color scale for total impacts over all indicators hot-spot analysis (red - highest risk; green - lowest risk))

Sustainability Framework				**BtL product system 1 MJ fuel mix, heat use in FT synthesis with credits**										
	SDG	**ID**	**Indicator Name**	**0% HU**	**10% HU**	**20% HU**	**30% HU**	**40% HU**	**50% HU**	**60% HU**	**70% HU**	**80% HU**	**90% HU**	**100% HU**
Total Substitution Factor of Impacts				23.00	22.61	22.22	21.83	21.44	21.05	20.66	20.27	19.88	19.50	19.11
Societal needs	1	1	Social security expenditures	2.16	1.97	1.78	1.60	1.41	1.22	1.03	0.85	0.66	0.47	0.29
	2	5	Water consumption - HH	129.63	128.27	126.92	125.57	124.21	122.86	121.50	120.15	118.80	117.44	116.09
		6	Indigenous rights	2.38	2.18	1.98	1.77	1.57	1.37	1.17	0.96	0.76	0.56	0.36
	3	7	Health expenditure	2.21	2.02	1.84	1.65	1.47	1.28	1.10	0.91	0.72	0.54	0.35
		8	Life expectancy at birth	2.11	1.98	1.85	1.72	1.59	1.45	1.32	1.19	1.06	0.93	0.79
		9	DALYs due to indoor and outdoor air and water pollution	2.31	2.14	1.96	1.78	1.61	1.43	1.25	1.08	0.90	0.72	0.55
		10	Pollution	2.50	2.30	2.10	1.90	1.70	1.50	1.30	1.11	0.91	0.71	0.51
		11	Global Warming - HH	2.51	1.59	0.67	-0.25	-1.17	-2.09	-3.01	-3.92	-4.84	-5.76	-6.68
		12	Stratospheric ozone depletion - HH	3.00	2.87	2.74	2.61	2.49	2.36	2.23	2.10	1.97	1.85	1.72
		13	Photochemical ozone formation - HH	2.37	2.09	1.80	1.51	1.23	0.94	0.66	0.37	0.08	-0.20	-0.49
		14	Ionizing Radiation - HH	1.26	0.91	0.57	0.22	-0.12	-0.47	-0.81	-1.16	-1.51	-1.85	-2.20
		15	Fine particulate matter formation - HH	1.74	1.50	1.25	1.01	0.76	0.52	0.27	0.03	-0.22	-0.46	-0.71
		16	Toxicity - HH (cancer)	6.66	6.34	6.03	5.71	5.40	5.08	4.76	4.45	4.13	3.82	3.50
		17	Toxicity - HH (non-cancer)	21.17	20.70	20.23	19.75	19.28	18.81	18.33	17.86	17.38	16.91	16.44
	4	18	Expenditures on education	2.24	2.03	1.81	1.60	1.38	1.16	0.95	0.73	0.52	0.30	0.08
	5	19	Gender wage gap	2.29	2.15	2.02	1.88	1.75	1.61	1.47	1.34	1.20	1.07	0.93
		22	Men in the sectoral labor force	5.94	5.73	5.51	5.29	5.08	4.86	4.64	4.42	4.21	3.99	3.77
		23	Women in the sectoral labor force	4.09	3.89	3.70	3.51	3.32	3.12	2.93	2.74	2.54	2.35	2.16
	11	24	*Fine particulate matter ID 15 if production site is in urban region*	1.74	1.50	1.25	1.01	0.76	0.52	0.27	0.03	-0.22	-0.46	-0.71
Provisioning System	6	25	Drinking water coverage	2.56	2.36	2.15	1.95	1.74	1.53	1.33	1.12	0.92	0.71	0.50
		26	Sanitation coverage	3.29	3.07	2.85	2.63	2.41	2.19	1.97	1.75	1.53	1.31	1.09
	7	27	*Cumulative Energy Demand, Renewable energies*	401.04	399.17	397.31	395.45	393.59	391.73	389.87	388.01	386.15	384.29	382.43
		28	Cumulative Energy Demand	1.02	0.88	0.73	0.59	0.44	0.30	0.15	0.01	-0.14	-0.28	-0.43
		29	Cumulative Exergy Demand	1.08	1.02	0.95	0.89	0.83	0.76	0.70	0.64	0.57	0.51	0.45
	8	30	Contribution of the sector to economic development	2.93	2.69	2.46	2.22	1.99	1.75	1.51	1.28	1.04	0.81	0.57

	31	Weekly hours of work per employee	2.72	2.51	2.30	2.09	1.88	1.67	1.46	1.25	1.04	0.83	0.62
	40	Net migration	4.25	4.09	3.92	3.76	3.60	3.44	3.28	3.11	2.95	2.79	2.63
	41	International Migrant Stock	12.28	11.93	11.58	11.23	10.88	10.53	10.18	9.83	9.48	9.13	8.78
	42	International migrant workers (in the sector/ site)	6.20	5.95	5.70	5.45	5.20	4.95	4.69	4.44	4.19	3.94	3.69
	43	Migration flows	16.83	16.62	16.41	16.20	15.99	15.79	15.58	15.37	15.16	14.95	14.74
	45	Fair salary	4.33	4.04	3.75	3.46	3.17	2.88	2.59	2.30	2.01	1.72	1.43
	46	Unemployment	2.12	1.99	1.86	1.73	1.60	1.47	1.34	1.21	1.08	0.95	0.82
	48	Child Labor, total	2.28	2.14	1.99	1.85	1.71	1.56	1.42	1.28	1.13	0.99	0.85
	49	Trafficking in persons	2.67	1.98	1.29	0.59	-0.10	-0.79	-1.48	-2.18	-2.87	-3.56	-4.26
	50	Frequency of forced labor	4.54	4.37	4.21	4.04	3.88	3.71	3.55	3.38	3.22	3.05	2.89
	51	Goods produced by forced labor	3.08	2.89	2.69	2.49	2.29	2.10	1.90	1.70	1.51	1.31	1.11
	52	Association and bargaining rights	1.68	1.22	0.77	0.31	-0.14	-0.60	-1.06	-1.51	-1.97	-2.42	-2.88
	53	Trade unionism	2.79	2.60	2.40	2.21	2.02	1.82	1.63	1.44	1.24	1.05	0.86
	54	Non-fatal accidents	16.69	16.35	16.00	15.66	15.32	14.98	14.63	14.29	13.95	13.61	13.26
	55	Fatal accidents	2.64	2.46	2.27	2.08	1.89	1.70	1.51	1.32	1.13	0.94	0.76
	57	Safety measures	21.62	21.15	20.69	20.22	19.75	19.29	18.82	18.36	17.89	17.42	16.96
	58	Violations of employment laws and regulations	2.36	2.17	1.98	1.79	1.60	1.41	1.21	1.02	0.83	0.64	0.45
	59	Workers affected by natural disasters	3.09	2.91	2.73	2.55	2.37	2.19	2.01	1.83	1.64	1.46	1.28
12	61	Embodied agricultural area footprints	25.15	24.89	24.64	24.38	24.12	23.86	23.60	23.35	23.09	22.83	22.57
	62	Embodied biodiversity footprints	3.88	3.73	3.59	3.44	3.29	3.14	3.00	2.85	2.70	2.55	2.40
	63	Embodied forest area footprints	675.71	675.21	674.70	674.19	673.69	673.18	672.68	672.17	671.67	671.16	670.66
	64	Embodied water footprints	3.03	2.93	2.83	2.74	2.64	2.55	2.45	2.36	2.26	2.16	2.07
	65	Embodied GHG footprints	1.81	1.55	1.30	1.04	0.79	0.53	0.28	0.02	-0.24	-0.49	-0.75
	66	Industrial water depletion	4.91	4.50	4.09	3.67	3.26	2.85	2.44	2.02	1.61	1.20	0.79
	67	Fossil resource scarcity	0.21	0.10	-0.01	-0.12	-0.23	-0.33	-0.44	-0.55	-0.66	-0.77	-0.88
	68	Fossil fuels consumption	5.78	5.36	4.95	4.53	4.11	3.70	3.28	2.86	2.45	2.03	1.62
	69	Biomass consumption	2.65	2.44	2.24	2.04	1.83	1.63	1.43	1.22	1.02	0.82	0.61
	70	Minerals consumption	2.64	2.38	2.13	1.88	1.63	1.37	1.12	0.87	0.62	0.36	0.11
	71	Resource use, mineral and metals	20.03	19.77	19.50	19.23	18.96	18.69	18.43	18.16	17.89	17.62	17.36
	72	Ionizing Radiation	1.26	0.92	0.57	0.22	-0.12	-0.47	-0.82	-1.16	-1.51	-1.85	-2.20
	73	Certified environmental management system	3.28	3.14	3.00	2.86	2.72	2.58	2.43	2.29	2.15	2.01	1.87
	74	Anti-competitive behavior or violation of anti-trust and monopoly legislation	1.98	1.81	1.64	1.47	1.30	1.12	0.95	0.78	0.61	0.44	0.27
16	75	Risk of conflicts	2.34	1.95	1.57	1.18	0.79	0.41	0.02	-0.36	-0.75	-1.14	-1.52
	76	Public sector corruption	2.31	2.09	1.87	1.65	1.43	1.21	0.99	0.77	0.55	0.33	0.11

		77	Active involvement of enterprises in corruption and bribery	1.81	1.61	1.40	1.20	1.00	0.80	0.59	0.39	0.19	-0.01	-0.22
Planetary Boundaries	13	78	Climate Change	2.51	1.59	0.67	-0.24	-1.16	-2.08	-2.99	-3.91	-4.83	-5.74	-6.66
		79	*Climate Change (fossil)*	2.48	1.57	0.65	-0.27	-1.19	-2.10	-3.02	-3.94	-4.85	-5.77	-6.69
		80	*Climate Change (biogenic)*	37.83	37.47	37.12	36.77	36.41	36.06	35.71	35.35	35.00	34.65	34.29
		81	*Climate Change (land use change)*	32.49	31.93	31.38	30.83	30.27	29.72	29.17	28.62	28.06	27.51	26.96
		82	Photochemical Ozone Formation, Ecosystems/Photochemical Ozone Formation	2.30	2.03	1.75	1.47	1.20	0.92	0.64	0.37	0.09	-0.19	-0.46
		83	Ozone depletion	0.28	0.20	0.11	0.03	-0.05	-0.14	-0.22	-0.30	-0.39	-0.47	-0.55
	14	84	Global Warming - Freshwater ecosystems	2.51	1.59	0.67	-0.25	-1.17	-2.09	-3.01	-3.92	-4.84	-5.76	-6.68
		85	Eutrophication freshwater	13.58	12.18	10.77	9.37	7.96	6.56	5.15	3.74	2.34	0.93	-0.47
		86	Ecotoxicity freshwater	9.84	9.70	9.55	9.41	9.27	9.12	8.98	8.83	8.69	8.55	8.40
		87	Water use	146.75	145.28	143.81	142.35	140.88	139.41	137.94	136.47	135.00	133.53	132.06
		88	Acidification terrestrial and freshwater	1.49	1.25	1.00	0.75	0.50	0.26	0.01	-0.24	-0.48	-0.73	-0.98
		89	Toxicity - Marine ecosystems	11.63	11.22	10.81	10.39	9.98	9.57	9.16	8.75	8.33	7.92	7.51
		90	Eutrophication marine	5.37	5.05	4.74	4.42	4.11	3.80	3.48	3.17	2.86	2.54	2.23
	15	91	Land Use	139.80	139.63	139.46	139.29	139.12	138.95	138.78	138.61	138.43	138.26	138.09
		92	Terrestrial Acidification	1.37	1.13	0.89	0.64	0.40	0.16	-0.08	-0.33	-0.57	-0.81	-1.05
		93	Terrestrial ecotoxicity	4.32	3.95	3.59	3.22	2.85	2.48	2.11	1.74	1.38	1.01	0.64
		94	Eutrophication terrestrial	3.34	3.04	2.73	2.42	2.12	1.81	1.51	1.20	0.89	0.59	0.28
		95	Global Warming - Terrestrial ecosystems	2.51	1.59	0.67	-0.25	-1.17	-2.09	-3.01	-3.92	-4.84	-5.76	-6.68
		96	Photochemical ozone formation - Terrestrial ecosystems	2.30	2.03	1.75	1.47	1.20	0.92	0.64	0.37	0.09	-0.19	-0.46
		97	Acidification - Terrestrial ecosystems	1.37	1.13	0.89	0.64	0.40	0.16	-0.08	-0.33	-0.57	-0.81	-1.05
		98	Toxicity - Terrestrial ecosystems	4.32	3.95	3.59	3.22	2.85	2.48	2.11	1.74	1.38	1.01	0.64
		99	Water consumption - terrestrial ecosystems	129.63	128.27	126.92	125.57	124.21	122.86	121.50	120.15	118.80	117.44	116.09
Working hours in h $\cdot 10^{-03}$				6.77	6.35	5.93	5.51	5.08	4.66	4.24	3.82	3.39	2.97	2.55

Table A 4, Impact assessment results and comparison for different transportation systems, 2030 electric energy grid mix (color scale for each indicator process hot-spot analysis (red - highest risk; green - lowest risk; color scale for total impacts over all indicators hot-spot analysis (red - highest risk; green - lowest risk; color scale for substitution factors of impacts according to table in Fig. 3)

Sustainability Framework				Impacts of transportation systems for one person going one kilometer				Substitution factors of impacts f_sSDG compared to train		
	SDG	ID	Indicator Name	Car diesel fossil	Car electric	Train	Car BtL diesel	Car diesel fossil	Car electric	Car BtL diesel
Societal needs	1	1	Social security expenditures	$5.96\cdot10^{+00}$	$5.80\cdot10^{+00}$	$1.11\cdot10^{+00}$	$6.49\cdot10^{+00}$	5.35	5.21	5.83
		2	Payment according to basic wage	no data	no data	no data	no data	no data	no data	no data
		3	Capital participation	no data	no data	no data	no data	no data	no data	no data
		4	Profit-sharing and bonuses	no data	no data	no data	no data	no data	no data	no data
	2	5	Water consumption - HH	$2.39\cdot10^{-09}$	$4.21\cdot10^{-09}$	$1.25\cdot10^{-09}$	$9.63\cdot10^{-09}$	1.91	3.37	7.71
		6	Indigenous rights	$1.39\cdot10^{-01}$	$2.09\cdot10^{-01}$	$2.02\cdot10^{-02}$	$1.54\cdot10^{-01}$	6.90	10.34	7.62
	3	7	Health expenditure	$2.65\cdot10^{+00}$	$2.81\cdot10^{+00}$	$4.83\cdot10^{-01}$	$2.91\cdot10^{+00}$	5.50	5.82	6.02
		8	Life expectancy at birth	$9.50\cdot10^{-01}$	$6.15\cdot10^{-01}$	$1.15\cdot10^{-01}$	$1.02\cdot10^{+00}$	8.27	5.35	8.91
		9	DALYs due to indoor and outdoor air and water pollution	$8.44\cdot10^{-02}$	$1.15\cdot10^{-01}$	$1.35\cdot10^{-02}$	$9.23\cdot10^{-02}$	6.26	8.51	6.85
		10	Pollution	$8.00\cdot10^{-01}$	$9.98\cdot10^{-01}$	$1.56\cdot10^{-01}$	$8.98\cdot10^{-01}$	5.14	6.41	5.77
		11	Global Warming - HH	$2.81\cdot10^{-07}$	$1.02\cdot10^{-07}$	$3.44\cdot10^{-08}$	$2.48\cdot10^{-07}$	8.19	2.97	7.21
		12	Stratospheric ozone depletion - HH	$7.05\cdot10^{-11}$	$4.51\cdot10^{-11}$	$1.62\cdot10^{-11}$	$1.21\cdot10^{-10}$	4.34	2.78	7.46
		13	Photochemical ozone formation - HH	$1.01\cdot10^{-09}$	$3.60\cdot10^{-10}$	$2.08\cdot10^{-10}$	$1.08\cdot10^{-09}$	4.85	1.73	5.19
		14	Ionizing Radiation - HH	$8.51\cdot10^{-11}$	$5.63\cdot10^{-11}$	$9.79\cdot10^{-12}$	$7.52\cdot10^{-11}$	8.70	5.75	7.69
		15	Fine particulate matter formation - HH	$2.33\cdot10^{-07}$	$1.29\cdot10^{-07}$	$3.73\cdot10^{-08}$	$2.40\cdot10^{-07}$	6.26	3.46	6.43
		16	Toxicity - HH (cancer)	$1.67\cdot10^{-07}$	$1.31\cdot10^{-07}$	$2.39\cdot10^{-08}$	$1.94\cdot10^{-07}$	7.00	5.48	8.12
		17	Toxicity - HH (non-cancer)	$7.21\cdot10^{-08}$	$1.18\cdot10^{-07}$	$7.70\cdot10^{-09}$	$1.19\cdot10^{-07}$	9.36	15.33	15.51
	4	18	Expenditures on education	$5.94\cdot10^{-02}$	$5.86\cdot10^{-02}$	$1.12\cdot10^{-02}$	$6.47\cdot10^{-02}$	5.30	5.23	5.77
	5	19	Gender wage gap	$9.37\cdot10^{-01}$	$7.74\cdot10^{-01}$	$1.10\cdot10^{-01}$	$1.02\cdot10^{+00}$	8.49	7.01	9.25
		20	Female employees in management positions	no data	no data	no data	no data	no data	no data	no data

		21	Rate of female employees	no data	no data	no data	no data	no data	no data	no data
		22	Men in the sectoral labor force	$9.97\cdot10^{-04}$	$1.37\cdot10^{-03}$	$1.59\cdot10^{-04}$	$1.28\cdot10^{-03}$	6.29	8.65	8.09
		23	Women in the sectoral labor force	$1.77\cdot10^{-01}$	$1.89\cdot10^{-01}$	$3.86\cdot10^{-02}$	$2.18\cdot10^{-01}$	4.59	4.89	5.63
	11	24	*Fine particulate matter ID 15 if production site is in urban region*	$2.33\cdot10^{-07}$	$1.29\cdot10^{-07}$	$3.73\cdot10^{-08}$	$2.40\cdot10^{-07}$	6.26	3.46	6.43
Provisioning System	6	25	Drinking water coverage	$8.36\cdot10^{+00}$	$1.20\cdot10^{+01}$	$1.40\cdot10^{+00}$	$9.26\cdot10^{+00}$	5.97	8.58	6.61
		26	Sanitation coverage	$3.73\cdot10^{+00}$	$7.74\cdot10^{+00}$	$4.37\cdot10^{-01}$	$4.25\cdot10^{+00}$	8.54	17.71	9.72
	7	27	*Cumulative Energy Demand, Renewable energies*	$1.35\cdot10^{-01}$	$7.71\cdot10^{-01}$	$2.91\cdot10^{-01}$	$2.72\cdot10^{+00}$	0.47	2.65	9.37
		28	Cumulative Energy Demand	$4.74\cdot10^{+00}$	$2.39\cdot10^{+00}$	$8.12\cdot10^{-01}$	$3.62\cdot10^{+00}$	5.84	2.94	4.45
		29	Cumulative Exergy Demand	$5.47\cdot10^{+00}$	$2.90\cdot10^{+00}$	$7.86\cdot10^{-01}$	$5.38\cdot10^{+00}$	6.96	3.68	6.84
	8	30	Contribution of the sector to economic development	$5.40\cdot10^{-02}$	$9.05\cdot10^{-02}$	$5.63\cdot10^{-03}$	$6.05\cdot10^{-02}$	9.60	16.08	10.75
		31	Weekly hours of work per employee	$6.16\cdot10^{-01}$	$6.27\cdot10^{-01}$	$1.13\cdot10^{-01}$	$6.88\cdot10^{-01}$	5.46	5.56	6.10
		32	Compensation for overtime	no data	no data	no data	no data	no data	no data	no data
		33	Access to flexible working time agreements	no data	no data	no data	no data	no data	no data	no data
		34	Rate of part-time employees	no data	no data	no data	no data	no data	no data	no data
		35	Rate of marginally employees (max. 450€)	no data	no data	no data	no data	no data	no data	no data
		36	Rate of fixed-term employees	no data	no data	no data	no data	no data	no data	no data
		37	Rate of employees provided by temporary work agencies	no data	no data	no data	no data	no data	no data	no data
		38	Rate of disabled employees	no data	no data	no data	no data	no data	no data	no data
		39	Rate of foreign employees	no data	no data	no data	no data	no data	no data	no data
		40	Net migration	$2.48\cdot10^{+00}$	$6.33\cdot10^{+00}$	$2.91\cdot10^{-01}$	$2.87\cdot10^{+00}$	8.52	21.76	9.85
		41	International Migrant Stock	$3.52\cdot10^{-01}$	$7.83\cdot10^{-01}$	$8.46\cdot10^{-02}$	$5.06\cdot10^{-01}$	4.17	9.26	5.98
		42	International migrant workers (in the sector/ site)	$1.07\cdot10^{-03}$	$1.50\cdot10^{-03}$	$1.66\cdot10^{-04}$	$1.39\cdot10^{-03}$	6.45	9.02	8.34
		43	Migration flows	$1.10\cdot10^{-01}$	$1.23\cdot10^{-01}$	$1.07\cdot10^{-02}$	$3.05\cdot10^{-01}$	10.22	11.47	28.44
		44	Average remuneration level	no data	no data	no data	no data	no data	no data	no data
		45	Fair salary	$5.43\cdot10^{+00}$	$8.81\cdot10^{+00}$	$5.71\cdot10^{-01}$	$6.44\cdot10^{+00}$	9.51	15.42	11.27

	46	Unemployment	$8.96 \cdot 10^{-01}$	$5.64 \cdot 10^{-01}$	$1.05 \cdot 10^{-01}$	$9.66 \cdot 10^{-01}$	8.52	5.36	9.18
	47	Rate of vocational trainees	no data	no data	no data	no data	no data	no data	no data
	48	Child Labor, total	$1.15 \cdot 10^{+00}$	$1.26 \cdot 10^{+00}$	$1.35 \cdot 10^{-01}$	$1.25 \cdot 10^{+00}$	8.54	9.35	9.32
	49	Trafficking in persons	$2.30 \cdot 10^{-01}$	$2.54 \cdot 10^{-01}$	$3.97 \cdot 10^{-02}$	$2.33 \cdot 10^{-01}$	5.79	6.39	5.87
	50	Frequency of forced labor	$2.51 \cdot 10^{+00}$	$6.25 \cdot 10^{+00}$	$2.88 \cdot 10^{-01}$	$2.91 \cdot 10^{+00}$	8.70	21.67	10.09
	51	Goods produced by forced labor	$1.22 \cdot 10^{-02}$	$1.13 \cdot 10^{-02}$	$3.53 \cdot 10^{-03}$	$1.38 \cdot 10^{-02}$	3.47	3.20	3.90
	52	Association and bargaining rights	$6.29 \cdot 10^{-02}$	$8.75 \cdot 10^{-02}$	$1.05 \cdot 10^{-02}$	$6.45 \cdot 10^{-02}$	5.97	8.30	6.12
	53	Trade unionism	$5.98 \cdot 10^{+00}$	$6.59 \cdot 10^{+00}$	$1.14 \cdot 10^{+00}$	$6.72 \cdot 10^{+00}$	5.23	5.76	5.88
	54	Non-fatal accidents	$1.35 \cdot 10^{-02}$	$2.35 \cdot 10^{-02}$	$4.53 \cdot 10^{-03}$	$2.40 \cdot 10^{-02}$	2.99	5.18	5.30
	55	Fatal accidents	$7.34 \cdot 10^{-03}$	$7.70 \cdot 10^{-03}$	$1.40 \cdot 10^{-03}$	$8.24 \cdot 10^{-03}$	5.23	5.49	5.87
	56	Sick-leave days	no data	no data	no data	no data	no data	no data	no data
	57	Safety measures	$3.12 \cdot 10^{-01}$	$8.72 \cdot 10^{-01}$	$1.78 \cdot 10^{-01}$	$5.97 \cdot 10^{-01}$	1.75	4.89	3.34
	58	Violations of employment laws and regulations	$4.57 \cdot 10^{-01}$	$1.12 \cdot 10^{+00}$	$5.58 \cdot 10^{-02}$	$5.07 \cdot 10^{-01}$	8.19	20.10	9.08
	59	Workers affected by natural disasters	$3.52 \cdot 10^{-02}$	$1.41 \cdot 10^{-01}$	$4.38 \cdot 10^{-03}$	$3.91 \cdot 10^{-02}$	8.03	32.15	8.92
	60	Work Council	no data	no data	no data	no data	no data	no data	no data
	61	Embodied agricultural area footprints	$8.08 \cdot 10^{-03}$	$8.26 \cdot 10^{-03}$	$9.36 \cdot 10^{-04}$	$1.18 \cdot 10^{-02}$	8.64	8.83	12.62
	62	Embodied biodiversity footprints	$1.79 \cdot 10^{+00}$	$2.78 \cdot 10^{+00}$	$3.41 \cdot 10^{-01}$	$2.23 \cdot 10^{+00}$	5.24	8.16	6.55
	63	Embodied forest area footprints	$4.55 \cdot 10^{-04}$	$5.06 \cdot 10^{-04}$	$7.76 \cdot 10^{-05}$	$9.82 \cdot 10^{-03}$	5.86	6.52	126.43
	64	Embodied water footprints	$5.58 \cdot 10^{-02}$	$8.98 \cdot 10^{-02}$	$6.30 \cdot 10^{-03}$	$7.73 \cdot 10^{-02}$	8.86	14.26	12.27
	65	Embodied GHG footprints	$1.17 \cdot 10^{+00}$	$1.55 \cdot 10^{+00}$	$1.79 \cdot 10^{-01}$	$1.24 \cdot 10^{+00}$	6.53	8.67	6.92
12	66	Industrial water depletion	$5.62 \cdot 10^{-01}$	$2.95 \cdot 10^{-01}$	$4.22 \cdot 10^{-02}$	$6.91 \cdot 10^{-01}$	13.31	6.98	16.36
	67	Fossil resource scarcity	$3.93 \cdot 10^{-02}$	$9.32 \cdot 10^{-03}$	$3.68 \cdot 10^{-03}$	$3.02 \cdot 10^{-03}$	10.68	2.53	0.82
	68	Fossil fuels consumption	$1.23 \cdot 10^{-03}$	$1.59 \cdot 10^{-03}$	$1.92 \cdot 10^{-04}$	$1.52 \cdot 10^{-03}$	6.41	8.27	7.90
	69	Biomass consumption	$6.85 \cdot 10^{+00}$	$6.45 \cdot 10^{+00}$	$1.25 \cdot 10^{+00}$	$7.63 \cdot 10^{+00}$	5.48	5.16	6.10
	70	Minerals consumption	$1.38 \cdot 10^{-01}$	$1.62 \cdot 10^{-01}$	$1.65 \cdot 10^{-02}$	$1.51 \cdot 10^{-01}$	8.38	9.82	9.16

		71	Resource use, mineral and metals	$4.66\cdot10^{-06}$	$1.36\cdot10^{-05}$	$4.18\cdot10^{-07}$	$5.63\cdot10^{-06}$	11.13	32.48	13.46
		72	Ionizing Radiation	$1.00\cdot10^{-02}$	$6.64\cdot10^{-03}$	$1.15\cdot10^{-03}$	$8.86\cdot10^{-03}$	8.70	5.76	7.69
		73	Certified environmental management system	$6.32\cdot10^{-01}$	$6.66\cdot10^{-01}$	$3.70\cdot10^{-02}$	$7.55\cdot10^{-01}$	17.07	18.00	20.41
		74	Anti-competitive behavior or violation of anti-trust and monopoly legislation	$6.58\cdot10^{+00}$	$6.29\cdot10^{+00}$	$1.20\cdot10^{+00}$	$7.13\cdot10^{+00}$	5.46	5.22	5.92
	16	75	Risk of conflicts	$7.21\cdot10^{-01}$	$7.21\cdot10^{-01}$	$1.33\cdot10^{-01}$	$7.67\cdot10^{-01}$	5.44	5.44	5.78
	16	76	Public sector corruption	$9.31\cdot10^{+00}$	$1.14\cdot10^{+01}$	$1.28\cdot10^{+00}$	$1.00\cdot10^{+01}$	7.26	8.90	7.80
	16	77	Active involvement of enterprises in corruption and bribery	$8.32\cdot10^{-01}$	$6.94\cdot10^{-01}$	$1.54\cdot10^{-01}$	$8.81\cdot10^{-01}$	5.39	4.50	5.71
Planetary Boundaries	13	78	Climate Change	$3.04\cdot10^{-01}$	$1.11\cdot10^{-01}$	$3.73\cdot10^{-02}$	$2.68\cdot10^{-01}$	8.16	2.97	7.19
	13	*79*	*Climate Change (fossil)*	$3.04\cdot10^{-01}$	$1.10\cdot10^{-01}$	$3.70\cdot10^{-02}$	$2.67\cdot10^{-01}$	8.22	2.97	7.22
	13	*80*	*Climate Change (biogenic)*	$2.43\cdot10^{-04}$	$7.98\cdot10^{-04}$	$2.45\cdot10^{-04}$	$8.25\cdot10^{-04}$	0.99	3.26	3.38
	13	*81*	*Climate Change (land use change)*	$1.92\cdot10^{-04}$	$2.58\cdot10^{-04}$	$6.73\cdot10^{-05}$	$4.23\cdot10^{-04}$	2.85	3.84	6.29
	13	82	Photochemical Ozone Formation, Ecosystems/Photochemical Ozone Formation	$1.14\cdot10^{-03}$	$4.65\cdot10^{-04}$	$2.32\cdot10^{-04}$	$1.21\cdot10^{-03}$	4.90	2.00	5.23
	13	83	Ozone depletion	$5.91\cdot10^{-08}$	$1.48\cdot10^{-08}$	$5.49\cdot10^{-09}$	$1.01\cdot10^{-08}$	10.77	2.71	1.85
	14	84	Global Warming - Freshwater ecosystems	$2.32\cdot10^{-14}$	$8.41\cdot10^{-15}$	$2.83\cdot10^{-15}$	$2.04\cdot10^{-14}$	8.19	2.97	7.21
	14	85	Eutrophication freshwater	$4.44\cdot10^{-05}$	$7.79\cdot10^{-05}$	$1.17\cdot10^{-05}$	$6.18\cdot10^{-05}$	3.80	6.66	5.29
	14	86	Ecotoxicity freshwater	$5.98\cdot10^{+00}$	$6.36\cdot10^{+00}$	$9.13\cdot10^{-01}$	$1.96\cdot10^{+01}$	6.55	6.96	21.45
	14	87	Water use	$4.38\cdot10^{-02}$	$7.75\cdot10^{-02}$	$2.31\cdot10^{-02}$	$1.82\cdot10^{-01}$	1.90	3.36	7.89
	14	88	Acidification terrestrial and freshwater	$1.49\cdot10^{-03}$	$6.07\cdot10^{-04}$	$2.44\cdot10^{-04}$	$1.41\cdot10^{-03}$	6.08	2.48	5.78
	14	89	Toxicity - Marine ecosystems	$4.94\cdot10^{-12}$	$6.29\cdot10^{-12}$	$3.04\cdot10^{-13}$	$5.68\cdot10^{-12}$	16.25	20.72	18.71
	14	90	Eutrophication marine	$4.30\cdot10^{-04}$	$1.42\cdot10^{-04}$	$9.08\cdot10^{-05}$	$5.90\cdot10^{-04}$	4.73	1.57	6.50
	15	91	Land Use	$2.40\cdot10^{+00}$	$2.34\cdot10^{+00}$	$8.68\cdot10^{-01}$	$5.28\cdot10^{+01}$	2.77	2.70	60.83
	15	92	Terrestrial Acidification	$9.13\cdot10^{-04}$	$4.01\cdot10^{-04}$	$1.40\cdot10^{-04}$	$8.31\cdot10^{-04}$	6.51	2.86	5.92
	15	93	Terrestrial ecotoxicity	$1.48\cdot10^{+00}$	$7.23\cdot10^{-01}$	$1.17\cdot10^{-01}$	$1.83\cdot10^{+00}$	12.59	6.16	15.63
	15	94	Eutrophication terrestrial	$4.65\cdot10^{-03}$	$1.38\cdot10^{-03}$	$9.75\cdot10^{-04}$	$5.41\cdot10^{-03}$	4.77	1.41	5.55
	15	95	Global Warming - Terrestrial ecosystems	$8.49\cdot10^{-10}$	$3.08\cdot10^{-10}$	$1.04\cdot10^{-10}$	$7.47\cdot10^{-10}$	8.19	2.97	7.21

96	Photochemical ozone formation - Terrestrial ecosystems	$1.47 \cdot 10^{-10}$	$5.99 \cdot 10^{-11}$	$2.99 \cdot 10^{-11}$	$1.56 \cdot 10^{-10}$	4.90	2.00	5.23
97	Acidification - Terrestrial ecosystems	$1.94 \cdot 10^{-10}$	$8.51 \cdot 10^{-11}$	$2.98 \cdot 10^{-11}$	$1.76 \cdot 10^{-10}$	6.51	2.86	5.92
98	Toxicity - Terrestrial ecosystems	$1.68 \cdot 10^{-11}$	$8.24 \cdot 10^{-12}$	$1.34 \cdot 10^{-12}$	$2.09 \cdot 10^{-11}$	12.59	6.17	15.63
99	Water consumption - terrestrial ecosystems	$1.45 \cdot 10^{-11}$	$2.56 \cdot 10^{-11}$	$7.60 \cdot 10^{-12}$	$5.86 \cdot 10^{-11}$	1.91	3.37	7.71
	Working time in h	0.099	0.135	0.016	0.267	6.32	8.66	17.08

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