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

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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 twenty-first 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).

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

Table 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

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, b). 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 14,044) (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.

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. 8.2c). Broadly said, scopes, corresponding methods and indicators of the life cycle inventory (LCI), life cycle

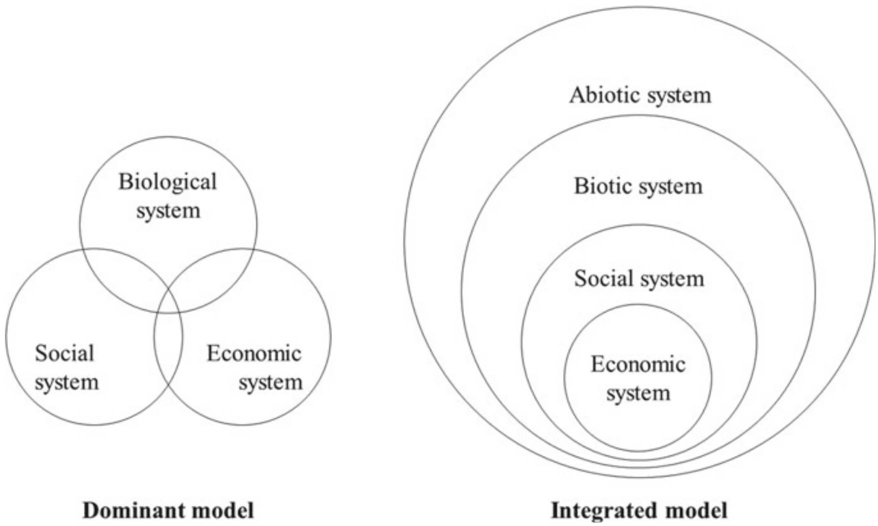

Fig. 8.1 Schemes of sustainability concepts, adopted from (Mebratu 1998, Fig. 1)

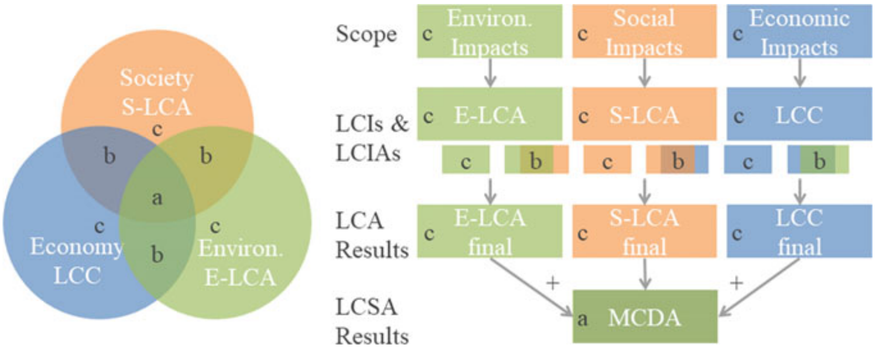

Fig. 8.2 Three-pillar-approach of sustainability and additive scheme of LCSA = ELCA + LCC + SLCA, (**c** separate systems, methods and indicators, **b** intersection between two systems, indicators which cannot be clearly assigned to one system, **a** all dimensions somehow combined, additive combination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

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).

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 (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 Sect. 8.2). 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, 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, 2011; Görg et al. 2017; Hummel et al. 2017; Kramm et al. 2017; Pichler et al. 2020, 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 (Zeug et al. 2019, 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.

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. Sect. 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

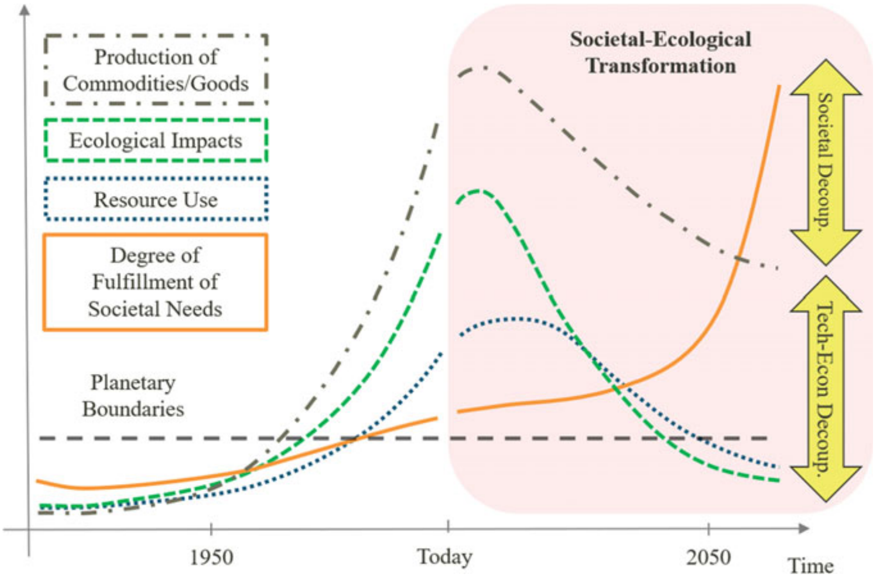

Fig. 8.3 Societal-ecological transformation and double decoupling as qualitative trends

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 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 et al. (2011): to integrate social, ecological and economic sustainability assessment into one unified method instead of additionally combining different methods (see Sect. 8.1.2).

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 (Sect. 8.1.2). Instead, we propose an integrated sustainability framework filling the identified research gap of a missing framework for HILCSA (Fig. 8.4i). 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. 8.4ii).

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

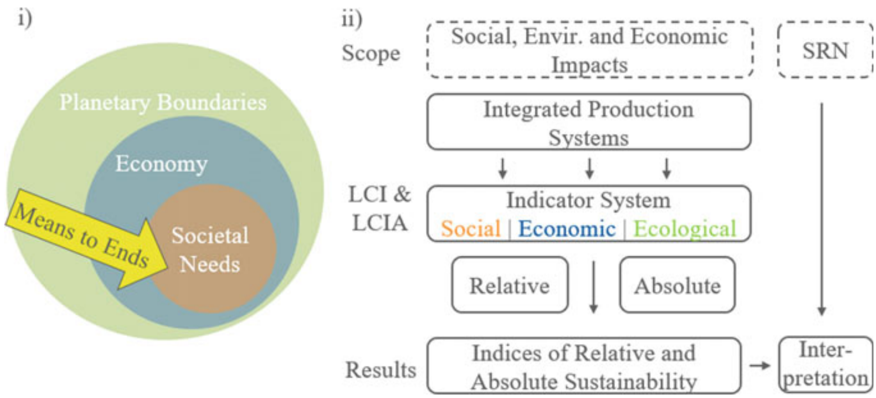

Fig. 8.4 (i) Sustainability model, (ii) Framework of HILCSA = f (S-LCA, E-LCA, LCC) (integrated product and production systems in openLCA entail ecological, social and economic data)

of natural resources, labor and technologies (means). This leads to a model (Fig. 8.4i) 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)

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, 2021a, 2020, 2022a). We built a SDG framework in previous studies (Zeug et al. 2019) as well as developed (Zeug et al. 2021a, 2020) and applied (Zeug et al. 2022a, 2023) 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. 8.4ii). 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. 8.1), 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. 8.2). 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. 8.3).

$$f^{sSDG} = \frac{x_{sSDG,T}^{LVL}}{x_{sSDG,T}^{SB}} \tag{8.1}$$

$$f^{SDG} = \frac{\sum_{sSDG} R^{sSDG} f^{sSDG}}{\sum_{sSDG} R^{sSDG}} \tag{8.2}$$

$$f = \frac{\sum_{SDG} R^{SDG} f^{sSDG}}{\sum_{SDG} R^{SDG}} \tag{8.3}$$

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 (Sect. 8.4), 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 (Chandrakumar and McLaren 2018a, b; 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° 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, 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.

References

Aguilar A, Wohlgemuth R, Twardowski T (2018) Preface to the special issue bioeconomy. New Biotechnol 40:1–4. https://doi.org/10.1016/j.nbt.2017.06.008

Alejandrino C, Mercante I, Bovea MD (2021) Life cycle sustainability assessment: lessons learned from case studies. Environ Impact Assess Rev 87 106517ARTN106517. https://doi.org/10.1016/j.eiar.2020.106517

Amidon KS (2008) Diesmal fehlt die Biologie! Max Horkheimer, Richard Thurnwald, and the Biological Prehistory of German Sozialforschung. New German Critique 103–137

Asada R, Cardellini G, Mair-Bauernfeind C, Wenger J, Haas V, Holzer D, Stern T (2020) Effective bioeconomy? a MRIO-based socioeconomic and environmental impact assessment of generic sectoral innovations. Technol Forecast Soc Change 153:119946. https://doi.org/10.1016/j.techfore.2020.119946

Ashukem J-CN (2020) The SDGs and the bio-economy: fostering land-grabbing in Africa. Rev Afr Polit Econ 1–16. https://doi.org/10.1080/03056244.2019.1687086

Backhouse M, Lehmann R, Lorenzen K, Lühmann M, Puder J, Rodríguez F, Tittor A (2021) Bioeconomy and global inequalities. Springer Nature. https://doi.org/10.1007/978-3-030-68944-5

Barbier EB (1999) Endogenous growth and natural resource scarcity. Environ Resource Econ 14:51–74. https://doi.org/10.1023/a:1008389422019

Bastani A (2019) Fully automated luxury communism. Verso Books

Bauriedl S (2016) Politische Ökologie: nicht-deterministische, globale und materielle Dimensionen von Natur/Gesellschaft-Verhältnissen Geographica Helvetica 71:341–351. https://doi.org/10.5194/gh-71-341-2016

Bell J, Paula L, Dodd T, Németh S, Nanou C, Mega V, Campos P (2018) EU ambition to build the world's leading bioeconomy—uncertain times demand innovative and sustainable solutions. New Biotechnol 40:25–30. https://doi.org/10.1016/j.nbt.2017.06.010

Bennich T, Belyazid S (2017) The route to sustainability—prospects and challenges of the bio-based economy. Sustainability 9:887

Bezama A, Mittelstädt N, Thrän D (2021) A systematic approach for assessing and managing the urban bioeconomy. In: Koukios E, Sacio-Szymańska A (eds) Bio#futures: foreseeing and exploring the bioeconomy. Springer International Publishing, Cham, pp 393–410. https://doi.org/10.1007/978-3-030-64969-2_18

Bioökonomierat (2022) Bioökonomie: Gemeinsam eine nachhaltige Zukunft gestalten - 1. Arbeitspapier des III. Bioökonomierats, Berlin

Birner R (2018) Bioeconomy Concepts. In: Lewandowski I (ed) Bioeconomy: shaping the transition to a sustainable, biobased economy. Springer International Publishing, Cham, pp 17–38. doi:https://doi.org/10.1007/978-3-319-68152-8_3

Bjørn A et al (2020) Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. Environ Res Lett 15:083001. https://doi.org/10.1088/1748-9326/ab89d7

Brand U, Wissen M (2018) The limits to capitalist nature: theorizing and overcoming the imperial mode of living. Rowman & Littlefield International

Bringezu S et al. (2020) Pilotbericht zum Monitoring der deutschen Bioökonomie. Center for Environmental Systems Research (CESR), Kassel. https://doi.org/10.17170/kobra-202005131255

Brundtland G et al (1987) Our common future ('Brundtland report'). Oxford University Press, USA

Brynjolfsson E, Andrew M (2015) The great decoupling

Budzinski M, Bezama A, Thran D (2017) Monitoring the progress towards bioeconomy using multi-regional input-output analysis: The example of wood use in Germany. J Clean Prod 161:1–11. https://doi.org/10.1016/j.jclepro.2017.05.090

Chandrakumar C, McLaren SJ (2018a) Exploring the linkages between the environmental sustainable development goals and planetary boundaries using the dpsir impact pathway framework. In: Benetto E, Gericke K, Guiton M (eds) Designing sustainable technologies, products and policies. Springer International Publishing, Cham, pp 413–423. https://doi.org/10.1007/978-3-319-66981-6_46

Chandrakumar C, McLaren SJ (2018b) Towards a comprehensive absolute sustainability assessment method for effective Earth system governance: defining key environmental indicators using an enhanced-DPSIR framework. Ecol Ind 90:577–583. https://doi.org/10.1016/j.ecolind.2018.03.063

Chandrakumar C, McLaren SJ, Jayamaha NP, Ramilan T (2018) Absolute Sustainability-Based Life Cycle Assessment (ASLCA): a benchmarking approach to operate agri-food systems within the 2 °C global carbon budget. J Ind Ecol 23:906–917. https://doi.org/10.1111/jiec.12830
Ciroth A (2009) Cost data quality considerations for eco-efficiency measures. Ecol Econ 68:1583–1590. https://doi.org/10.1016/j.ecolecon.2008.08.005
Common M, Stagl S (2012) Ecological economics. Cambridge University Press, Cambridge. https://doi.org/10.1017/cbo9780511805547
Costa D, Quinteiro P, Dias AC (2019) A systematic review of life cycle sustainability assessment: current state, methodological challenges, and implementation issues. Sci Total Environ 686:774–787. https://doi.org/10.1016/j.scitotenv.2019.05.435
Costanza R, Cumberland J, Daly H, Goodland R, Norgaard R (1997) An introduction to ecological economics. CRC Press
D'Amato D, Gaio M, Semenzin E (2020) A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. Sci Total Environ 706:135859. https://doi.org/10.1016/j.scitotenv.2019.135859
D'Amato D (2021) Sustainability narratives as transformative solution pathways: zooming in on the circular economy. Circ Econ Sustain 1:231–242. https://doi.org/10.1007/s43615-021-00008-1
de Besi M, McCormick K (2015) Towards a bioeconomy in Europe: national regional and industrial strategies. Sustainability 7:10461–10478. https://doi.org/10.3390/su70810461
de Schutter L, Giljum S, Hayha T, Bruckner M, Naqvi A, Omann I, Stagl S (2019) Bioeconomy transitions through the lens of coupled social-ecological systems: a framework for place-based responsibility in the global resource system. Sustainability 11:5705. https://doi.org/10.3390/su11205705
Demirovic A (2003) Vorwort. In: Demirovic A (ed) Modelle kritischer Gesellschaftstheorie. J.B. Metzler, Stuttgart, pp 1–9
Di Noi C, Eisfeldt F, Ciroth A, Bizarro D (2018) Complementarity of social and environmental indicators and risks. An example of the mining industry. Paper presented at the S-LCA 2018, Pescara, September 2018
Egenolf V, Bringezu S (2019) Conceptualization of an indicator system for assessing the sustainability of the bioeconomy. Sustainability 11:443
Eisfeldt F (2017) Soca v.1 add-on—adding social impact information to ecoinvent. GreenDelta GmbH, Berlin
Ekener E, Hansson J, Larsson A, Peck P (2018) Developing life cycle sustainability assessment methodology by applying values-based sustainability weighting—tested on biomass based and fossil transportation fuels. J Clean Prod 181:337–351. https://doi.org/10.1016/j.jclepro.2018.01.211
Elkington J (1998) Partnerships fromcannibals with forks: the triple bottom line of 21st-century business. Environ Qual Manage 8:37–51. https://doi.org/10.1002/tqem.3310080106
Erb K-H, Haberl H, Le Noe J, Tappeiner U, Tasser E, Gingrich S (2022) Changes in perspective needed to forge "no-regret" forest-based climate change mitigation strategies. GCB Bioenergy 14. https://doi.org/10.1111/gcbb.12921
Eversberg D, Fritz M (2022) Bioeconomy as a societal transformation: mentalities, conflicts and social practices. Sustain Prod Consum 30:973–987. https://doi.org/10.1016/j.spc.2022.01.021
Eversberg D, Holz J (2020) Empty promises of growth: the bioeconomy and its multiple reality checks. In: Working paper #2 of the BMBF Junior Research Group "Mentalitites in Flux" (flumen). Friedrich-Schiller-Universität Jena, Jena. https://doi.org/10.13140/RG.2.2.30275.84007
Fauzi RT, Lavoie P, Sorelli L, Heidari MD, Amor B (2019) Exploring the current challenges and opportunities of life cycle sustainability assessment. Sustainability 11:636. https://doi.org/10.3390/su11030636
Fedrigo-Fazio D, Schweitzer J-P, Ten Brink P, Mazza L, Ratliff A, Watkins E (2016) Evidence of absolute decoupling from real world policy mixes in Europe. Sustainability 8. https://doi.org/10.3390/su8060517

Fröhlich N (2009) Die Aktualität der Arbeitswerttheorie - Theoretische und empirische Aspekte vol 128. Hochschulschriften. Metropolis, Marburg
Future Earth (2016) The contribution of science in implementing the sustainable development goals. German Committee Future Earth, Stuttgart
Gawel E, Pannicke N, Hagemann N (2019) A path transition towards a bioeconomy—the crucial role of sustainability. Sustainability 11:3005. https://doi.org/10.3390/su11113005
Georgescu-Roegen N (1971) The entropy law and the economic process
Gerhardt P (2018) Bioökonomie – die neue Nebelwand aus der PR-Abteilung. denkhaus-bremen. https://denkhausbremen.de/biooekonomie-die-neue-nebelwand-aus-der-pr-abteilung/. Accessed 19 Novemvber 2018
German Bioeconomy Council (2018a) http://biooekonomierat.de/en/
German Bioeconomy Council (2018b) Update report of national strategies around the world—bioeconomy policy (Part III). Bioeconomy Council, Berlin
GFN GFN (2019) Ecological deficit/reserve. https://data.footprintnetwork.org. Accessed 05 September 2019
Görg C (2003) Dialektische Konstellationen. Zu einer kritischen Theorie gesellschaftlicher Naturverhältnisse. In: Demirovic A (ed) Modelle kritischer Gesellschaftstheorie. J.B. Metzler, Stuttgart, pp 39–62
Görg C (2004) The construction of societal relationships with nature. Poiesis & Praxis 3:22–36. https://doi.org/10.1007/s10202-004-0066-5
Görg C (2011) Societal Relationships with nature: a dialectical approach to environmental politics. In: Biro A (ed) Critical ecologies. University of Toronto Press, Toronto
Görg C (2015) Planetarische Grenzen. In: Bauriedl S (ed) Wörterbuch Klimadebatte, vol 82. transcript Verlag
Görg C, Brand U, Haberl H, Hummel D, Jahn T, Liehr S (2017) Challenges for social-ecological transformations: contributions from social and political ecology. Sustainability 9:1045
Groos J (2021) Distributed planned economies in the age of their technical feasibility. BEHEMOTH A J Civil 14. https://doi.org/10.6094/behemoth.2021.14.2.1061
Guinée J (2016) life cycle sustainability assessment: what is it and what are its challenges? In: Clift R, Druckman A (eds) Taking stock of industrial ecology. Springer International Publishing, Cham, pp 45–68. https://doi.org/10.1007/978-3-319-20571-7_3
Guinee JB et al (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45:90–96. https://doi.org/10.1021/es101316v
Guinée JB et al (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45:90–96. https://doi.org/10.1021/es101316v
Guinée JB, Koning A, Heijungs R (2022). Life cycle assessment-based absolute environmental sustainability assessment is also relative. J Ind Ecol n/a. https://doi.org/10.1111/jiec.13260
Haberl H, Steinberger JK, Plutzar C, Erb K-H, Gaube V, Gingrich S, Krausmann F (2012) Natural and socioeconomic determinants of the embodied human appropriation of net primary production and its relation to other resource use indicators. Ecol Ind 23:222–231. https://doi.org/10.1016/j.ecolind.2012.03.027
Halog A, Manik Y (2011) Advancing integrated systems modelling framework for life cycle sustainability assessment
Harvey D, Braun B (1996) Justice, nature and the geography of difference, vol 468. Blackwell Oxford
Hauff M, Jörg A (2013) Nachhaltiges Wachstum. Oldenbourg Verlag, München
Hausknost D, Schriefl E, Lauk C, Kalt G (2017) A transition to which bioeconomy? an exploration of diverging techno-political choices. Sustainability 9:669. https://doi.org/10.3390/su9040669
Hector D, Christensen C, Petrie J (2014) Sustainability and sustainable development: philosophical distinctions and practical implications, vol 23. https://doi.org/10.3197/096327114X13851122268963
Holmberg J, Environment IIf, Development (1992) Policies for a small planet: from the international institute for environment and development. Earthscan

Hopwood B, Mellor M, O'Brien G (2005) Sustainable development: mapping different approaches. Sustain Dev 13:38–52. https://doi.org/10.1002/sd.244

Hummel D, Jahn T, Keil F, Liehr S, Stieß I (2017) Social ecology as critical, transdisciplinary science—conceptualizing. analyzing and shaping societal relations to nature. Sustainability 9:1050

Ingrao C et al. (2018) The potential roles of bio-economy in the transition to equitable, sustainable, post fossil-carbon societies: findings from this virtual special issue. J Clean Prod 204:471–488. https://doi.org/10.1016/j.jclepro.2018.09.068

IPCC (2022) Climate change 2022—impacts adaption and vulnerability. UNEP

Jahn T, Bergmann M, Keil F (2012) Transdisciplinarity: between mainstreaming and marginalization. Ecol Econ 79:1–10. https://doi.org/10.1016/j.ecolecon.2012.04.017

Jander W, Grundmann P (2019) Monitoring the transition towards a bioeconomy: a general framework and a specific indicator. J Clean Prod 236:117564. https://doi.org/10.1016/j.jclepro.2019.07.039

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

Karabarbounis L, Neiman B (2013) The global decline of the labor share. National Bureau of Economic Research Working Paper Series No. 19136. https://doi.org/10.3386/w19136

Keller H, Rettenmaier N, Reinhardt GA (2015) Integrated life cycle sustainability assessment—a practical approach applied to biorefineries. Appl Energy 154:1072–1081. https://doi.org/10.1016/j.apenergy.2015.01.095

Klein JT (2008) Evaluation of interdisciplinary and transdisciplinary research: a literature review. Am J Prev Med 35:S116-123. https://doi.org/10.1016/j.amepre.2008.05.010

Kleinschmit D, Arts B, Giurca A, Mustalahti I, Sergent A, Pulzl H (2017) Environmental concerns in political bioeconomy discourses. Int Forest Rev 19:41–55. https://doi.org/10.1505/146554817822407420

Kloepffer W (2008) Life cycle sustainability assessment of products. Int J Life Cycle Assess 13:89–95. https://doi.org/10.1065/lca2008.02.376

Knierim A, Laschewski L, Boyarintseva O (2018) Inter- and transdisciplinarity in bioeconomy. In: Lewandowski I (ed) Bioeconomy: shaping the transition to a sustainable, biobased economy. Springer International Publishing, Cham, pp 39–72. https://doi.org/10.1007/978-3-319-68152-8_4

Kramm J, Pichler M, Schaffartzik A, Zimmermann M (2017) Societal relations to nature in times of crisis—social ecology's contributions to interdisciplinary sustainability studies. Sustainability 9:1042

Kuosmanen T (2005) Measurement and analysis of eco-efficiency—an economist's perspective. J Ind Ecol 9:15–18. https://doi.org/10.1162/108819805775248025

Lamont M, Mallard G, Guetzkow J (2006) Beyond blind faith: overcoming the obstacles to interdisciplinary evaluation. Res Evaluat 15:43–55. https://doi.org/10.3152/147154406781776002

Lindqvist AN, Broberg S, Tufvesson L, Khalil S, Prade T (2019) Bio-based production systems: why environmental assessment needs to include supporting systems. Sustainability 11:4678. https://doi.org/10.3390/su11174678

Liu J et al (2015) Systems integration for global sustainability. Science 347:1258832. https://doi.org/10.1126/science.1258832

Lubchenco J, Barner AK, Cerny-Chipman EB, Reimer JN (2015) Sustain Rooted Sci Nat Geosci 8:741. https://doi.org/10.1038/ngeo2552

Meadowcroft J (2007) Who is in charge here? governance for sustainable development in a complex world. J Environ Policy Plan 9:299–314. https://doi.org/10.1080/15239080701631544

Mebratu D (1996) Sustainability as a scientific paradigm. Lund: Int Inst Ind Environ Econ

Mebratu D (1998) Sustainability and sustainable development: historical and conceptual review. Environ Impact Assess Rev 18:493–520. https://doi.org/10.1016/S0195-9255(98)00019-5

Menton M, Larrea C, Latorre S, Martinez-Alier J, Peck M, Temper L, Walter M (2020) Environmental justice and the SDGs: from synergies to gaps and contradictions. Sustain Sci. https://doi.org/10.1007/s11625-020-00789-8

Meyer R (2017) Bioeconomy Strategies: Contexts. Visions, guiding implementation principles and resulting debates. Sustainability 9:1031

Michel P, Rotillon G (1995) Disutility of pollution and endogenous growth. Environ Resour Econ 6:279–300. https://doi.org/10.1007/bf00705982

Morozov E (2019) Digital socialism? The calculation debate in the age of big data. New Left Rev 33–67

Mustalahti I (2018) The responsive bioeconomy: the need for inclusion of citizens and environmental capability in the forest based bioeconomy. J Clean Prod 172:3781–3790. https://doi.org/10.1016/j.jclepro.2017.06.132

Nerini F et al (2019) Connecting climate action with other sustainable development Goals. Nat Sustain 2:674–680. https://doi.org/10.1038/s41893-019-0334-y

Network GF (2019) Global footprint network glossary. https://www.footprintnetwork.org/resources/glossary/. Accessed 27 November 2019

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

Norström AV (2013) Social change vital to sustainability goals. Nature 498:299. https://doi.org/10.1038/498299c. https://www.nature.com/articles/498299c#supplementary-information

Nuss S, Daum T (2021) The invisible hand of the plan—coordination and calculation in digital capitalism [Die unsichtbare Hand des Plans - Koordination und Kalkül im digitalen Kapitalismus]. Dietz, Berlin

O'Neill DW, Fanning AL, Lamb WF, Steinberger JK (2018) A good life for all within planetary boundaries. Nat Sustain 1:88–95. https://doi.org/10.1038/s41893-018-0021-4

OECD (2018) Meeting policy challenges for a sustainable bioeconomy. OECD Publishing, Paris. https://doi.org/10.1787/9789264292345-en

Olsson O et al. (2016) Cascading of woody biomass: definitions, policies and effects on international trade. IEA Bioenergy

Palahí M (2021) Is forest harvesting increasing in Europe? European Forest Institute. https://efi.int/articles/nature. Accessed 15 June 2022

Panoutsou C, Manfredi S, Kavalov B (2013) Biomass resource efficiency for the biobased industries. Joint Research Centre (JRC), Ispra

Parrique TBJ, Briens F, Kerschner C, Kraus-Polk A, Kuokkanen A, Spangenberg JH (2019) Decoupling Debunked - Evidence and arguments against green growth as a sole strategy for sustainability. The European Environmental Bureau, Brussels

Perdomo Echenique EA, Ryberg M, Vea EB, Schwarzbauer P, Hesser F (2022) Analyzing the consequences of sharing principles on different economies: a case study of short rotation coppice poplar wood panel production value chain. Forests 13:461

Pfau SF, Hagens JE, Dankbaar B, Smits AJM (2014) Visions of sustainability in bioeconomy research. Sustainability 6:1222–1249. https://doi.org/10.3390/su6031222

Phillips L, Rozworski M (2019) The people's republic of Walmart: how the world's biggest corporations are laying the foundation for socialism. Verso Books

Pichler M, Brand U, Görg C (2020) The double materiality of democracy in capitalist societies: challenges for social-ecological transformations. Env Polit 29:193–213. https://doi.org/10.1080/09644016.2018.1547260

Pichler M, Schaffartzik A, Haberl H, Görg C (2017) Drivers of society-nature relations in the Anthropocene and their implications for sustainability transformations. Curr Opin Environ Sustain 26–27:32–36. https://doi.org/10.1016/j.cosust.2017.01.017

Piketty T (2014) Capital in the twenty-first century. Harvard University Press

Postone M (1993) Time, labor, and social domination. Cambridge University Press, New York

Purvis B, Mao Y, Robinson D (2019) Three pillars of sustainability: in search of conceptual origins. Sustain Sci 14:681–695. https://doi.org/10.1007/s11625-018-0627-5
Ramcilovic S, Pülzl H (2018) Sustainable development—a 'selling point' of the emerging EU bioeconomy policy framework? J Clean Prod 172:4170–4180. https://doi.org/10.1016/j.jclepro.2016.12.157
Redclift MR, Benton T (1994) Social theory and the global environment. Routledge
Robert N et al (2020) Development of a bioeconomy monitoring framework for the European Union: an integrative and collaborative approach. N Biotechnol 59:10–19. https://doi.org/10.1016/j.nbt.2020.06.001
Rockström J et al (2009) A Safe operating space for humanity nature 461:472. https://doi.org/10.1038/461472a
Rockström J, Sukhdev P (2016) How food connects all the SDGs. Stockholm Resilience Centre. http://www.stockholmresilience.org/research/research-news/2016-06-14-how-food-connects-all-the-sdgs.html. Accessed 01 November 2017
Rosenfield PL (1992) The potential of transdisciplinary research for sustaining and extending linkages between the health and social sciences. Soc Sci Med 35:1343–1357. https://doi.org/10.1016/0277-9536(92)90038-R
Roser M (2022) Our world in data, published online at OurWorldInData.org. Global Change Data Lab. https://ourworldindata.org/
Ryberg MW, Andersen MM, Owsianiak M, Hauschild MZ (2020) Downscaling the planetary boundaries in absolute environmental sustainability assessments—a review. J Clean Prod 276:123287. https://doi.org/10.1016/j.jclepro.2020.123287
Ryberg MW, Owsianiak M, Richardson K, Hauschild MZ (2018) Development of a life-cycle impact assessment methodology linked to the Planetary Boundaries framework. Ecol Ind 88:250–262. https://doi.org/10.1016/j.ecolind.2017.12.065
Sala S, Castellani V (2019) The consumer footprint: monitoring sustainable development goal 12 with process-based life cycle assessment. J Clean Prod 240:118050. https://doi.org/10.1016/j.jclepro.2019.118050
Sala S, Crenna E, Secchi M, Sanye-Mengual E (2020) Environmental sustainability of European production and consumption assessed against planetary boundaries. J Environ Manage 269:110686. https://doi.org/10.1016/j.jenvman.2020.110686
Sala S, Farioli F, Zamagni A (2012a) Life cycle sustainability assessment in the context of sustainability science progress (part 2). Int J Life Cycle Assess 18:1686–1697. https://doi.org/10.1007/s11367-012-0509-5
Sala S, Farioli F, Zamagni A (2012b) Progress in sustainability science: lessons learnt from current methodologies for sustainability assessment: Part 1. Int J Life Cycle Assess 18:1653–1672. https://doi.org/10.1007/s11367-012-0508-6
Schaefer F, Luksch U, Steinbach N, Cabeça J, Hanauer J (2006) Ecological footprint and biocapacity—the world's ability to regenerate resources and absorb waste in a limited time period. European Commission, Luxembourg
Schleyer C, Lux A, Mehring M, Görg C (2017) Ecosystem services as a boundary concept: arguments from social ecology. Sustainability 9:1107
Šimunović N, Hesser F, Stern T (2018) Frame analysis of ENGO conceptualization of sustainable forest management: environmental justice and neoliberalism at the core of sustainability. Sustainability 10:3165
Smulders S (1995) Entropy, environment, and endogenous economic growth. Int Tax Pub Finance 2:319–340. https://doi.org/10.1007/bf00877504
Staffas L, Gustavsson M, McCormick K (2013) Strategies and policies for the bioeconomy and bio-based economy: an analysis of official national approaches. Sustainability 5:2751–2769. https://doi.org/10.3390/su5062751
Steffen W et al (2018) Trajectories of the earth system in the anthropocene. Proc Natl Acad Sci U S A 115:8252–8259. https://doi.org/10.1073/pnas.1810141115

Stegemann L, Ossewaarde M (2018) A sustainable myth: a neo-Gramscian perspective on the populist and post-truth tendencies of the European green growth discourse. Energy Res Soc. Sci 43:25–32. https://doi.org/10.1016/j.erss.2018.05.015

Stern T, Ploll U, Spies R, Schwarzbauer P, Hesser F, Ranacher L (2018) Understanding perceptions of the bioeconomy in austria—an explorative case study. Sustainability 10:4142

Suwelack K (2016) Conversion technology and life cycle assessment of renewable resources. Hohenheim University, Hohenheim

Swarr TE, Hunkeler D, Klopffer W, Pesonen HL, Ciroth A, Brent AC, Pagan R (2011) Environmental life-cycle costing: a code of practice. Int J Life Cycle Ass 16:389–391. https://doi.org/10.1007/s11367-011-0287-5

Taylor PG, Abdalla K, Quadrelli R, Vera I (2017) Better energy indicators for sustainable development. Nat Energy 2:17117. https://doi.org/10.1038/nenergy.2017.117

Teh SH, Wiedmann T, Schinabeck J, Moore S (2017) Replacement scenarios for construction materials based on economy-wide hybrid LCA. Procedia Eng 180:179–189. https://doi.org/10.1016/j.proeng.2017.04.177

Traverso M, Finkbeiner M, Jorgensen A, Schneider L (2012) Life cycle sustainability dashboard. J Ind Ecol 16:680–688. https://doi.org/10.1111/j.1530-9290.2012.00497.x

Troullaki K, Rozakis S, Kostakis V (2021) Bridging barriers in sustainability research: a review from sustainability science to life cycle sustainability assessment. Ecol Econ 184:107007. https://doi.org/10.1016/j.ecolecon.2021.107007

Trzyna TC, Osborn JK, Nature IUfCo, Resources N (1995) A sustainable world: defining and measuring sustainable development. Published for IUCN—the World Conservation Union by the International Center for the Environment and Public Policy, California Institute of Public Affairs

UNEP (2011) Towards a life cycle sustainability assessment—making informed choices on products. UNEP/SETAC Life Cycle Initiative

UNEP (2020) Guidelines for social life cycle assessment of products and organizations. United Nations Environment Programme (UNEP)

Urban K et al (2018) Markets, sustainability management and entrepreneurship. In: Lewandowski I (ed) Bioeconomy. Springer International Publishing, Cham, pp 231–286. https://doi.org/10.1007/978-3-319-68152-8_8

Valdivia S et al (2021) Principles for the application of life cycle sustainability assessment. Int J Life Cycle Assess 26. https://doi.org/10.1007/s11367-021-01958-2

Verdier T (1995) Environmental pollution and endogenous growth. In: Boston MA (ed) Control and game-theoretic models of the environment. Birkhäuser Boston, pp 175–200

Victor TYH, Chang P, Blackburn K (1994) Endogenous growth, environment and R&D. In: Carraro C (ed) Trade, innovation, environment. Springer Netherlands, Dordrecht, pp 241–258. https://doi.org/10.1007/978-94-011-0948-2_10

Ward JD, Sutton PC, Werner AD, Costanza R, Mohr SH, Simmons CT (2016) Is decoupling GDP growth from environmental impact possible? PLoS ONE 11:e0164733. https://doi.org/10.1371/journal.pone.0164733

Wittmer H et al (2022) Transformative change for a sustainable management of global commons—biodiversity, forests and the ocean. Recommendations for international cooperation based on a review of global assessment reports and project experience. https://doi.org/10.57699/7s83-7z35

Wulf C, Werker J, Ball C, Zapp P, Kuckshinrichs W (2019) Review of sustainability assessment approaches based on life cycles. Sustainability 11:5717. https://doi.org/10.3390/su11205717

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

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, Thran D (2021a). 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

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

Zeug W, Bezama A, Thrän D (2023) Holistic and integrated life cycle sustainability assessment of prospective second generation biofuel production in Germany Forthcoming

Zeug W, Kluson F, Mittelstädt N, Bezama A, Thrän D (2021b) 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

Zimek M, Schober A, Mair C, Baumgartner RJ, Stern T, Füllsack M (2019) The third wave of LCA as the "decade of consolidation. Sustainability 11:3283. https://doi.org/10.3390/su11123283

Zörb C, Lewandowski I, Kindervater R, Göttert U, Patzelt D (2018) Biobased resources and value chains. In: Lewandowski I (ed) Bioeconomy: shaping the transition to a sustainable, biobased economy. Springer International Publishing, Cham, pp 75–95. https://doi.org/10.1007/978-3-319-68152-8_5