Transformation Towards a Sustainable Regional Bioeconomy—A Monitoring Approach

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Abstract The concept of the sustainable bioeconomy aims to ensure the well-being of both current and future generations while staying within environmental boundaries. However, achieving this goal will require significant changes to existing resource systems, business models, governance systems, and more. Current approaches to monitoring the transformation towards a sustainable bioeconomy lack a regional perspective that incorporates all three sustainability dimensions. To address this gap, we aim to provide an integrated evaluative framework for assessing regional transformation processes towards a bioeconomy. The recent decision to phase-out coal power in Germany presents a unique opportunity to understand the socio-technical dynamics and implementation options for the transformation to a sustainable bioeconomy region in the current lignite-mining region "Rheinisches Revier".

Keywords Sustainability · Biobased transformation · Bioeconomy · Regional development · Monitoring framework

1 Introduction

To satisfy the growing demand for resources without transgressing environmental limits, a rapid transformation with profound interventions by public and private decision-makers is needed (Te Velde et al. 2012; WBGU 2016). The transformation of an economy predominantly based on fossil resources towards a sustainable bioeconomy is a core cornerstone on this route. However, while an economy largely

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based on biogenic resources offers many attractive options and opportunities, undertaking and governing its implementation process is complex: it requires major transformations of existing resource systems, value networks, business models, infrastructures, and governance systems with diverse interrelations leading to intended and unintended effects. Existing structures have evolved over a long period under a mostly unsustainable management paradigm. Only recently, holistic, integrated, and sustainable transformation approaches have been considered (Eversberg et al. 2023).

During the last decade, climate change and environmental protection have been at the top of global political agendas. Planetary boundaries ensuring the stability of the Earth system (e.g., atmospheric carbon dioxide (CO_2) concentration and levels of phosphorus and nitrogen in freshwater systems) have been surpassed and the achievement of the 1.5 °C global warming goal remains highly questionable (Kopittke et al. 2021; IPCC 2022). Reducing greenhouse gas (GHG) emissions is key to mitigating the impacts of climate change and to achieving the United Nations (UN) Sustainable Development Goals (SDGs) (United Nations 2015). The European Union (EU) assumes a leading role in this process and aims for defossilization and zero net GHG emissions by 2050 (European Commission 2019). The required transformation goes beyond using renewable energy resources like solar, wind, and biomass as basis for the economy. Instead, it calls for a holistic approach to facilitate societal change (European Commission 2019).

Bioeconomy, i.e., the production, conversion and use of renewable biological resources to create value-added products and services, provides suitable mechanisms for this holistic transformation towards resilience (Galanakis et al. 2022). Especially for carbon-intensive regions where mining and refining of fossil resources is a main economic activity, a phasing out of these technologies and a shift towards bioeconomy promise an economically, socially, and ecologically sustainable future.

The collective promotion of both modern technology (i.e. technical know-how) and improved awareness (i.e. social know-how) on the bioeconomy has been identified as a key policy objective (BMBF and BMEL 2020). Research has shown that today's global sustainability challenges cannot be overcome solely by greater scientific and technological understanding, but will instead require also a greater understanding of the role of people and their social systems (Macht et al. 2023; Zander et al. 2022). Thus, closing this gap has been translated into a strong academic mandate to address the question of understanding "how risk, social networks, and governance can influence the pace of transition to a low-carbon future" (Editorial Nature Climate Change 2016). In a similar vein, current research stresses the need to envisage the entire innovation ecosystem as an indispensable perspective to understand the emerging innovation capabilities of individual corporations, industries, and regions (Adner and Kapoor 2010; Marcone et al. 2022).

For more than a decade, the transformation towards a bioeconomy has been discussed in contested terms, highlighting different perspectives and challenges (Bugge et al. 2016; Hausknost et al. 2017; Pfau et al. 2014). Monitoring approaches address sub-sectors of the bioeconomy country level, and comprehensive frameworks are still in development (Thrän 2022). So far, the perceptions and approaches of different stakeholder groups have mostly been analysed individually (Kuckertz et al. 2020; Vandermeulen et al. 2012; Wensing et al. 2019) or at the national level (Dieken and Venghaus 2020; Sturm and Banse 2021). Since bioeconomy activities are often clustered in subnational regions and driven by both national and regional policies (Overbeek et al. 2016), these approaches fall short of the bioeconomic aspiration to provide a holistic perspective based equally on the three sustainability dimensions, which requires an integrated evaluative framework for regional transformation processes. As bioeconomy is a growing research discipline (Dieken and Venghaus 2020) and several international political agents strive towards implementing bioeconomic patterns at different scales (IACGB 2020), this research gap needs to be closed. We propose to close this gap by providing a comprehensive framework for the assessment of regional transformation processes towards bioeconomy, which was developed using the case of the lignite-mining region "Rheinisches Revier" (RR) in the state of North Rhine-Westphalia in western Germany. From a scientific viewpoint, the regionally integrated perspective allows to reduce the complexity of emerging, dynamic, self-organizing, and larger scale systems, such as the bioeconomy (Urry 2005). The recent decision of the German government to phase-out coal power will initiate major transformation processes in the Rheinisches Revier, creating a unique opportunity for understanding the socio-technical dynamics and implementation options towards an entire sustainable bioeconomy region. Against this background, it is crucial to systematically identify and monitor transformation trajectories for the implementation of a strong bioeconomy in the Rheinisches Revier. These transformation routes need to be, at the same time, (a) desirable (from a sustainability perspective), (b) possible (from a techno-economic perspective), and (c) acceptable (from a stakeholder consensus perspective) and cover all three sustainability dimensions.

We begin with a description of the visions and pathways of bioeconomy transformation (Sect. 2) to underscore the need for a holistic perspective, which is based on the three sustainability dimensions and that addresses all relevant stakeholder groups. To identify relevant determinants for bioeconomy transformation, we conduct a structured literature review (Sect. 3) of current bioeconomy monitoring approaches to highlight the importance of local conditions in bioeconomy transformation, followed by the presentation of the regional perspective on bioeconomy transformation monitoring (Sect. 4). Section 5 concludes.

2 Transformation Towards a Sustainable Bioeconomy

Bioeconomy is a comprehensive concept that aims to address global challenges such as resource scarcity, climate change, and population growth by ensuring sustainable use of natural resources while providing adequate food and renewable resources to a growing population (Lewandowski et al. 2018). Although bioeconomy principles are considered a key contribution to the SDGs, the bioeconomic use of natural resources is not inherently sustainable. The production of biogenic materials for material or energetic use requires scarce resources, particularly land and water (Pfau et al. 2014).

The increased demand for biomass in industrialized countries can cause land use change and biodiversity loss, leading to food security issues in developing countries (BÖR 2015). Over the past decade, the number of bioeconomy strategies at regional and national levels has increased worldwide (Haarich and Kirchmayr-Novak 2022; IACGB 2020; Dietz et al. 2018); however, current strategies address sustainability issues vaguely (Kiresiewa et al. 2019).

In Europe, the concept of a bioeconomy dates back more than 30 years, with the first bioeconomy strategy adopted in 2012 by the European Commission. It defined the bioeconomy as the production of renewable biological resources and the conversion of these resources and waste streams into value-added products (European Commission 2012; Patermann and Aguilar 2018). While the European definition was based on a biotechnology perspective, it aimed to substitute fossil resources with biobased ones (Birner 2018). The National Bioeconomy Strategy of the German Federal Government emphasizes technological progress and the sustainable, circular use of biobased resources to support the country's transition to a climate-neutral economy, pursuing the goal of becoming a globally leading location for innovation in the bioeconomy (BMBF and BMEL 2020). In addition to its strong technological and economic focus, the strategy recognizes the importance of societal opinions and stakeholder expectations regarding the bioeconomy concept, ensuring a successful and smooth implementation (BMBF and BMEL 2020).

Current developments and actions in the bioeconomy are to a large degree policy-induced and thus motivated by research and technology (MKW 2012). As a consequence, the practical and widespread implementation of the bioeconomy will be strongly driven by the introduction of both biobased substitutes and novel products and production processes (e.g., surfactants and platform chemicals derived from biorefineries). However, this transformation will likely implicate also radical technological innovations, which may disrupt existent business models and entire industry logics, as well as innovations in social processes, governance processes, and individual decision-making. A multitude of interrelated actors with different visions, attitudes, objectives, fears, and roles are involved. They will act on different decision-making levels (policy, industry, consumer, civil society, etc.), in different sectors or policy fields (economy, agriculture, environment, energy, consumer protection, etc.), under consideration of differing temporal scales (short-, mid-, and long-term perspectives), and will simultaneously influence the decision-making processes. In the best case, the decision forces initiate measures that positively reinforce each other. Often, however, unintended side effects with unpredictable and likely negative feedback occur (Stark et al. 2022). A possible reason is that the different stakeholders assess their decisions based on their respective and differing contextual frames of reasoning. Especially in the case of radical technological developments, feedback loops, and unintended consequences are much harder to anticipate, making it difficult to adequately integrate them into decision-making. Stakeholder dynamics, their underlying motivations as well as their effects are often not sufficiently considered in mostly techno-economic assessment approaches and, consequently, policy decision-making (Dyer et al. 1992; Lerche and Geldermann 2015).

Research has shown that such comprehensive transformations towards sustainability proceed very slowly, are strongly impaired by path dependencies and lock-in effects, and can only be successful when technological progress meets social acceptance (Gooyert et al. 2016; Hake et al. 2015). Thus, it is crucial for bioeconomic thinking to consider all three dimensions of sustainability at a transnational level to achieve a holistically sustainable bioeconomy. However, the trade-off between economic growth on the one hand and ecological and social sustainability on the other determines the bioeconomy visions and transformation pathways in the current scientific discourse.

2.1 Dominant Visions and Fragmented Perspectives

In the academic literature, three popular visions of the bioeconomy have been identified (Bugge et al. 2016), that differ in the degree how the three distinct sustainability dimensions (i.e. social, economic, and environmental) are addressed. First, in the biotechnology vision, economic growth depends on sector-specific scientific knowledge, patents, and commercialization of research and development (R&D) results. High funding for biotechnology and pharmaceutical companies leads to concentrated growth in regions with these companies. This vision assumes an implicit contribution of technology to sustainability and, therefore, does not regard resource shortages or increasing waste production as a problem. Second, the bioresource vision builds on research and improvements in naturally biobased sectors, such as agriculture, forestry, or fishery. Efficient land use and the avoidance or reuse of industrial side streams connect economic activities with sustainability. Nevertheless, innovation and new technologies are still dominant in upscaling production and conversion of biological resources into marketable products, ensuring economic growth. However, the focus is on interdisciplinary research and collaboration, while new biobased value chains provide employment opportunities in rural areas. The biotechnology and bioresource vision are similar, with economic growth by new technologies and R&D as their core. Third, the bioecology vision is based on sustainability where unequal access to biological resources and knowledge is regarded critically and self-sustaining, circular production and consumption based on local resources is advocated. Natural constraints are respected to ensure ecosystem conservation and soil fertility. By combining the three dimensions of sustainability, "locally embedded economies" are established in this vision (Bugge et al. 2016).

Overall, bioeconomy research is still very fragmented and analyses different transformation aspects in isolation. Thereby, technology and resource-centred visions dominate (Dieken and Venghaus 2020; Dietz et al. 2018), whereas societal considerations are limited to consumer perspectives (Dieken et al. 2021; Priefer et al. 2017). This imposes further challenges for the already missing holistic and harmonized policies needed for a successful transformation (Gottinger et al. 2020)—especially since different stakeholder groups show different perceptions of the bioeconomy and support different bioeconomy narratives. Dieken et al. (2021) find that primarily political actors and researchers indicate a preference for the biotechnology vision, whereas farmers, forest owners, industrial representatives, and social or environmental initiatives tend to favour the bioresource vision, while citizens and consumers mostly support a bioecology vision. Similar results are found by Hausknost et al. (2017) who identify four bioeconomy narratives and evaluate the support by different stakeholders. However, most bioeconomy research focuses on the "golden triangle" of political, industrial, and scientific stakeholders (Dieken et al. 2021; Mukhtarov et al. 2017). For citizens, farmers, environmental, and societal initiatives, the amount of studies is considerably lower than for the other stakeholder groups and focuses on the assessment of biobased product acceptance or adoption. Studies on bioeconomy in social sciences have either a theoretical or a very narrow, case-study focus on aspects of natural sciences, such as technologies in biotechnology, chemistry, or genetics (Sanz-Hernández et al. 2019). The resulting dominance of a techno-economic perspective in bioeconomy research challenges the principles of sustainability postulated by the concept (Dieken et al. 2021).

While technology, biological resources, and ecology appear to be the dominant visions in current bioeconomy research (e.g., Hempel et al. 2019; Stern et al. 2018; Vivien et al. 2019), it must be noted that these represent political and academic idealizations which partly overlap and can be regarded as complementary and not as mutually exclusive (D'Amato et al. 2020). Nevertheless, the three visions and their relative importance determine the pathway selected for bioeconomy transformations.

2.2 Pathways Towards a Sustainable Bioeconomy

Windows of opportunity can enable different pathways that might lead to similar overall transformations (Grin et al. 2011). In the bioeconomy transformation, the overall aim is to replace fossil with biobased resources while ensuring sustainability safeguards. To achieve this, scholars identified transformation pathways and approaches that reflect the target conflicts and trade-offs between the three sustainability dimensions inherent in the visions discussed above and different stakeholders addressed.

Dietz et al. (2018) derive four distinct pathways for a transformation towards a bioeconomy that aims at using a country's comparative advantage and creating synergies across economic sectors, which hence are determined by the availability of natural resources, the existence of a strong research sector, pre-established specific technologies in the country and "country-specific development deficits to be overcome". The fossil substitution pathway (TP1) aims at a complete substitution of fossil fuels by biobased resources. High oil prices and new environmental regulations were the point of departure here, but today the negative example of first-generation biofuels causing land use change and monocultures highlights challenges for mere substitution as a long-term strategy. TP2, productivity increase in agriculture, describes the importance of technological innovations in the primary sector for biomass production, yield loss reduction, and unused land development. As land resources are scarce, this pathway threatens biodiversity by claiming land with high ecosystem services for agricultural production. The third pathway (TP3) focuses on efficiency increases in biomass use and processing. The ability to use biomass more efficiently and recycle waste enables the production of biobased products at a large scale. Concerns arise regarding mixed consumer acceptance of biobased products and the occurrence of rebound effects, where overconsumption of biobased products causes an overall increase in biomass use and counteracts efficiency increases. The fourth transformation pathway (TP4), called "value creation and addition", suggests the application of biological principles and knowledge to produce goods independently of biomass availability. By applying new knowledge in combination with technical innovations, this pathway aims for more ecologically sustainable production methods and the development of completely new products (Dietz et al. 2018). Most countries with dedicated bioeconomy strategies rely on a combination of all four pathways to transform into bioeconomies (Dietz et al. 2018).

Priefer et al. (2017) take a broader perspective on bioeconomy transformation, distinguishing two main directions. The *technology-based approach*, a combination of TP2-4 with the biotechnology and bioresource visions, depends on advances in life sciences and biotechnology as enabling technology for the transformation. Political, industrial, and scientific actors, at both national and international levels, cooperate intensively to establish global value chains and ensure overall growth and employment. Efficiency increases in agricultural production, through breeding and genetic engineering, as well as the use of biological knowledge for new product development, e.g., in large biorefineries provide the basis for the transformation. Sustainability is not a concern, and societal actors are not actively participating in the transformation, but are informed about advantages of the new technologies to foster acceptance (Priefer et al. 2017). The *socio-ecological approach*, in line with the bioecology vision of Bugge et al. (2016), postulates that a bioeconomy can be sustainable under certain conditions. Decentralized agriculture, agro-ecological practices (e.g., nutrient cycling and biological pest control), and the avoidance of genetic engineering ensure a sustainable biomass production. Local and tacit knowledge helps to develop regional value chains that follow natural cycles. Sufficiency approaches, the cascade and circular use of resources, combined with social innovations, respect the planetary boundaries. Research combines natural and social sciences and uses inter- and transdisciplinary approaches. Civil society plays an active role in the bioeconomy, its involvement is crucial and ensured at all levels.

These two approaches are extreme examples of bioeconomy transformation pathways, which can also be implemented in a complementary way. Currently, the technology-based pathway is common, with a limited focus on social sciences and low involvement of societal stakeholders. However, a combination of views that addresses all three sustainability dimensions and considers all societal stakeholders is important to fulfil the principle of the bioeconomy as a holistic concept (Priefer et al. 2017). Even though the popularity of bioeconomy strategies increased in the last decade, countries are aware of the risks and trade-offs that a large-scale bioeconomy implementation brings about (Dietz et al. 2018). In particular, land and water availability and use conflicts as well as global food security are concerns which require a clear hierarchy for biomass use to ensure stable, long-term political decisions (Dietz et al. 2018; Meyer 2017). Inequality as well as climate and health risks are less often addressed in national strategies (Dietz et al. 2018). However, positive contributions to these issues are promised by the bioeconomy and non-fulfilment of these expectations will cause disappointment, doubts about the suitability of the bioeconomy concept, and even social opposition (Meyer 2017). Different approaches towards these challenges are mirrored in contrasting positions and visions of the bioeconomy (Bugge et al. 2016; Pfau et al. 2014; Priefer et al. 2017).

3 Monitoring Bioeconomy Transformation

To manage bioeconomy transformations or adjust pathways (i.e. shift from one to another), indicators are required that provide information about the current situation (Ronzon et al. 2022b). Based on the bioeconomy visions, pathways, and barriers, several important aspects for the transformation can be identified: the availability of natural resources, a strong knowledge base and innovation sector, and biomass conversion technologies (Dietz et al. 2018), suitable market conditions for biobased products (Gottinger et al. 2020), the involvement of civil society (Priefer et al. 2017), as well as targeted policies and their implementation measures (Meyer 2017). As bioeconomy in the RR is still in its infancy, a first holistic assessment is needed, where especially qualitative aspects of the transformation provide insights into current developments, structures, and interconnections at the different levels (Geels 2004, 2011).

As a starting point for the development of a monitoring framework, a literature review to identify qualitative factors with an influence on bioeconomy transformations was conducted. Where available, exemplary considerations for a monitoring system are also presented. Due to its comprehensive overview of publishers in the field of natural and social sciences, as well as technology and humanities, the scientific database Scopus was selected as source for the literature review. Scopus was searched for any of the words “monitoring”, “measurement”, “model”, “assessment”, or “framework” in combination with either “bioeconomy”, “bio-economy”, or “biobased economy” and “indicator*” in the title, abstract, or keywords. This search yielded 626 results. Refinement by consideration of open access publications only and the limitation to journals related to environmental, agricultural, earth, and social sciences, as well as economics, management, and energy narrowed the results down to 304 documents. Thereby, the focus was limited to accessible, socio-economic, agricultural, and environmental considerations of the bioeconomy, which are especially important issues (Fritsche and Iriarte 2014). As the RR’s location is in Germany, the scope of the inquiry was limited to Germany, to ensure suitability of the results for the selected case. However, documents mentioning Germany within a European context were also considered. No restriction on the date of publication was applied, yielding documents from 2014 to 2022 leading to a total of 72 documents. The abstracts and the studies were screened for relevant aspects, such as specific sectors or technologies, stakeholder perspectives, or perceived conflicts. Overall, 30 studies dealt with bioeconomy or circular economy approaches, the latter were included due to their important contribution to a sustainable bioeconomy (BMBF and BMEL 2020).

Three studies used expert opinions to assess drivers and barriers of the bioeconomy transformation and provided information on influencing factors. Based on a global expert survey, Issa et al. (2019) highlight the importance of arable land availability for biomass production and yield increases in traditional farming. Beyond this, waste management and side stream use to increase the biogenic resource base, as well as biotechnology and innovations to develop new biobased materials and products are requirements for a successful transformation (Issa et al. 2019). Hagemann et al. (2016) identify clear, long-term political guidance on the use of biobased resources for food, material, or energetic purposes as crucial for the development of bioeconomy sectors (Hagemann et al. 2016). In addition, global economic developments and national policies affect demand for biomass and consumers' willingness to pay for biobased products, shaping investment into biobased value chains. From their point of view, innovation is the most important determining factor as it influences the possible future development and impacts many other aforementioned factors (Hagemann et al. 2016). Using a Delphi study, Hinderer et al. (2021) underline the importance of a common understanding of bioeconomy to develop implementable action plans at a political level (Hinderer et al. 2021). Additionally, stakeholder awareness of the concept is important for legitimization and acceptance of the respective policies.

From the 30 studies, 19 dealt especially with technological and/or economic aspects of the bioeconomy or with the importance of specific economic sectors. While the bioeconomy sectors discussed are diverse and range from large volume primary biomass production to low bulk, but high-value biologization of processes, most studies deal with the availability of biobased input materials as well as related economic and technological efficiency issues. Efken et al. (2016) for example use employment and gross value added as indicators to determine the contribution of the bioeconomy to the German economy, which accounted for 6% of the gross national product in 2010. In 2017, using labour productivity in addition to employment and value added, (Ronzon et al. 2022b) see the bioeconomy transformation in Germany still at its beginning, but identify agriculture and the food industry as main non-service contributors. More recently, scientists also consider services as an important contributor to the bioeconomy transformation (Ronzon et al. 2022a). In 2017, wholesale, retail of biobased products, as well as services in the food and beverage sector provided more than 60% of employment and value-added of all bioeconomy services in the EU (ibid.). Regarding the sectors addressed in the analysed studies, many evaluate the forest sector or wood-based value chains as main contributors to the bioeconomy (e.g., Budzinski et al. 2017; Jarosch et al. 2020). Thereby, physical requirements for the input material, adequate product design for recycling, and political regulations create central challenges (Jarre et al. 2020). At the global level, land use change (Haddad et al. 2019) and precarious societal conditions (Siebert et al. 2018) are issues often associated with an increasing use of woody biomass.

Biogenic residues, for example agricultural or forestry by-products, municipal and industrial waste, as well as sewage sludge, can increase resource availability and ease pressure on arable land (Brosowski et al. 2019; Kircher 2022). Considering the use of agricultural by-products, Donner et al. (2021) identify biomass storage and logistics, efficient conversion technologies and economies of scale as main techno-economic criteria to ensure price competitiveness of biobased products (Donner et al. 2021). New technologies require joint R&D investments by the public and private sector and subsidies for biobased processes (ibid.). Such technologies like biorefineries for material or energetic purpose and their integration into local value chains are expected to shape the future agricultural side streams valorization (Gontard et al. 2018; Theuerl et al. 2019). However, clear and transparent policies and their communication are needed to avoid sustainability conflicts in the bioeconomy and ensure sufficient availability of food, material, and energy (Horschig et al. 2020; Thrän et al. 2020). Generally, economic and financial aspects are most important for the use of side streams, e.g., by avoiding costs for waste disposal (Klein et al. 2022). In the chemical industry, expectations about contributing to the bioeconomy by shifting from fossil to biobased resources are high (Lokesh et al. 2018; Thormann et al. 2021). Especially bioplastics (Spierling et al. 2020) and biopolymers are subject to studies, where design for recycling plays a key role to ensure sustainability (Hildebrandt et al. 2017).

Overall, eight studies focused on sustainability conflicts caused by the implementation of a bioeconomy. Several underline the importance of a holistic sustainability approach, where economic, environmental, and social dimensions are considered equally (e.g., Fritsche and Iriarte 2014; Kardung et al. 2021). Bringezu et al. (2021) go a step further and consider international implications of domestic production and consumption, showing that for example, the agricultural land used for German consumption is higher than the national availability, causing land use change in other countries. These transnational resource footprints of the national bioeconomy can be calculated for the used agricultural land, forest, water, material (biotic and abiotic), and emitted GHGs (Egenolf and Bringezu 2019). Thereby, the resources consumed or emitted during national production add to the resources consumed or emitted for the production of imported goods, while the resources consumed or emitted for exported goods are subtracted providing the net resource use or emissions (ibid.). Other scientists postulate that the consideration of ecosystem services is important to ensure staying within the recovery capacity of nature (D'Amato et al. 2020; Kircher 2022). In this context, efficiency strategies, e.g., due to innovation and technological developments play a fundamental role for a "smart, innovative, and sustainable bioeconomy" (O'Brien et al. 2015). Moreover, standardization and harmonization of sustainability certificates for biobased products can help manage the scarce resources and increase transparency in the bioeconomy (Majer et al. 2018).

Figure 1 provides a summary of the results from the literature review. Grouped according to the three sustainability dimensions, the relevant factors show the need for a holistic approach, in which efficiency increases and circularity have to go hand in hand with innovations, clear communication, and political action implementation. The economic dimension is dominant, as shown by the higher number of words (8)

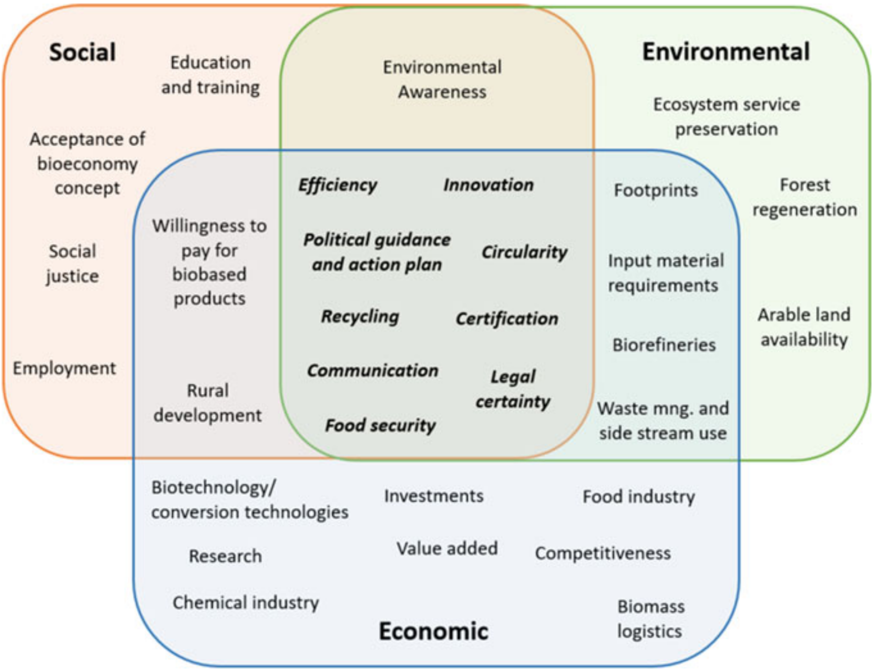

Fig. 1 Determining factors for a holistically sustainable bioeconomy transformation. *Source* Based on 30 studies from literature review. Graphical design inspired by Egenolf and Bringezu (2019)

in the blue square compared to the social (4) and green (3) dimension. However, the latter two have gained importance in recent years and are not regarded as optional anymore, but as required to ensure long-term economic success (O'Brien et al. 2015).

In their study on indicator conceptualization for a sustainable bioeconomy, Egenolf and Bringezu (2019) suggest, among others, developments in consumer food prices, the gender income gap, the number of trade union employees and in-company employees as well as access to public transportation in rural areas as indicators for social sustainability (Egenolf and Bringezu 2019). Environmental sustainability is usually measured by land cover and land use changes, the substitution rate of fossil energy and material with biobased resources, emitted GHGs, and different ecological footprints (Kardung et al. 2021). Average monthly income and value added of bioeconomy sectors, the number of bioeconomy-related R&D projects in SMEs, patents or investments in waste avoidance and recycling are frequently cited indicators for economic sustainability of the bioeconomy (Egenolf and Bringezu 2019).

Overall, the information from the reviewed literature shows the complexity of the bioeconomy transformation and highlights the importance of a holistic monitoring. However, no internationally standardized monitoring framework for this purpose has been developed so far (Bracco et al. 2019). Nevertheless, different institutions develop approaches to determine key influencing indicators and derive monitoring systems (ibid.). To ensure that the results from the literature review are in accordance with these international approaches, an additional targeted revision of national and international bioeconomy principles and monitoring frameworks with relevance for the RR was conducted.

The Food and Agriculture Organization (FAO) of the UN mentions ten principles for a sustainable bioeconomy (FAO 2021). From a societal perspective, (1) food and nutrition security at all levels are the most important criteria. Together with (9) sustainable consumption patterns, they increase (4) social and economic resilience, especially in rural areas. To ensure (3) competitive and inclusive growth, the use of (7) existing knowledge and the promotion of new technologies, in line with (8) sustainable trade practices, is crucial. Regarding ecological sustainability, the FAO highlights the need for (5) efficiency increases and circularity as well as (2) conservation and protection of ecosystems. The achievement of these sustainability aims depends on the implementation of (6) harmonized, inclusive, and transparent governance practices that promote (10) collaboration and cooperation at regional, national, and international level (FAO 2021).

To monitor the bioeconomy, the FAO identifies a dual approach including indicators at the territorial, and product or value chain level as suitable (Bracco et al. 2019). Territorial indicators (e.g., changes in food prices, GHG emissions, turnover in biobased sectors, or primary energy consumption) aim to measure the transformation towards bioeconomy. They are available for all three sustainability dimensions at national, European, and international institutions. If statistical measurement is missing, the FAO suggests the use of good practices as proxies, indicating, for example, the presence of certain strategies. At the level of biobased products and value chains, indicators (e.g. the used amount of water, the amount of biomass produced on protected land or human toxicity and cancer effects) focus especially on the social and environmental dimension (Bracco et al. 2019). Data availability, accessibility, and quality is limited, because every biobased product is different and its sustainability impact depends on the respective producer. Therefore, available, more generic data at product category level or from certifications and labels is often only of limited use (ibid). Thus, the FAO emphasizes the need for more bottom-up information at individual producer level. Indicators or proxies should be specific, measurable, achievable, relevant, and time-bound, as well as in line with the respective bioeconomy strategy and the SDGs (Bracco et al. 2019). To identify indicators and develop a bioeconomy monitoring scheme, the FAO suggests the following steps (ibid):

(1) Stakeholder engagement (iterative),
(2) Choice of relevant territorial level or key products/value chains,
(3) Relevant indicator selection,
(4) Discussion and selection of reference value for each indicator,
(5) Decision on data collection methodology and data availability assessment,
(6) Selection of good practices as additional indicators or proxies (optional),
(7) Sustainability assessment and evaluation of contribution to objectives of bioeconomy strategy, and

(8) Effective communication of results.

At the global level, common indicators and a monitoring design still need to be developed in international agreement, to provide guidance and ensure comparability (FAO 2016). However, flexibility for specific local circumstances has to be maintained. Therefore, the combination of top-down and bottom-up approaches is recommended (ibid.).

The updated Bioeconomy Strategy of the European Union identifies the following five strategic objectives: (1) insurance of food and nutrition security, (2) sustainable management of natural resources, (3) reduction in dependence on (nationally and foreign-sourced) non-renewable resources, (4) mitigation and adaptation to climate change, as well as (5) increasing competitiveness and job creation in the EU (European Commission 2018). These objectives are present in the national bioeconomy strategies of the different member states. A first assessment across member states to identify indicators used or desired in the national strategies, showed similarities for the consideration of the primary sectors as belonging to the bioeconomy, while variations in the inclusion of hybrid sectors were identified (Lier et al. 2018). For example, some countries consider the fraction of the textile or chemical industry using biobased resources a part of the bioeconomy. However, quantification of these parts is difficult, because EU statistics do not segregate biobased from fossil inputs in these sectors (Ronzon and M'Barek 2018).

To monitor the contribution of the EU bioeconomy to all three dimensions of sustainability, the five objectives were mapped to the respective SDGs (Robert et al. 2020). To ensure coherence with other monitoring approaches and strategies, the FAO's ten principles and their criteria were aggregated and mapped to the objectives as well (Giuntoli et al. 2020). Based on the EU's bioeconomy definition, the framework covers primary sectors, value chains in the bioeconomy including recycling and reuse, as well as production processes using biotechnology (independent of the feedstock) (Robert et al. 2020). In accordance with the SDGs, the FAO's principles, the indicator assessment by Lier et al. and further European and international frameworks on bioeconomy-related topics, the five EU objectives were filled with available indicators, to avoid reinventing the wheel (ibid.). For example, objective 1 is assessed using the FAO's indicators on food security, objective 2 is based on indicators from the EU initiative "Mapping and Assessment of Ecosystem Services", while objective 4 on climate change mitigation and adaptation uses data from the IPCC. Indicators from different sources using macroeconomic analysis and Life Cycle Assessment compose objectives 3 and 5 (Robert et al. 2020). Each indicator's suitability was evaluated based on data availability, geographical coverage, methodology, and length of time series (Giuntoli et al. 2020). Identified data gaps were closed with proxies and the selected, basic indicators were processed through harmonization across different scales. With Life Cycle Assessment and footprint calculations, the overall impact of the EU's bioeconomy was calculated to identify synergies and trade-offs and derive expressive system-level indicators that are used for policy decision-making (ibid). The current indicators of the European bioeconomy monitoring are available in dashboard format on the website of the Knowledge Centre for Bioeconomy.[1]

In 2019, Wackerbauer et al. (2019) developed a first attempt to conceptualize a monitoring framework for the German bioeconomy. As in the EU system, they include the primary sector and parts of the industrial sectors using biobased resources as main determinants for the bioeconomy (Wackerbauer et al. 2019). Furthermore, they use information on innovation and education, as well as on cascade use and side stream availability to account for the importance of biological knowledge and circularity in the bioeconomy. Combining top-down and bottom-up data, they assessed the biobased fraction of the oleo chemistry in Germany and verified their results with expert interviews, showing the correctness of their model. However, data availability remains the main obstacle for the bottom-up assessment (Wackerbauer et al. 2019). Bringezu et al. (2020), who provided the first German bioeconomy monitoring report in 2020, agree, concluding that gross value added of the German bioeconomy was €165–265 bn. in 2017, depending on data and calculation methods used (Bringezu et al. 2020). They identify the primary sectors as well as sectors where at least 10% of the input is biobased as belonging to the bioeconomy. The report provides socio-economic (value added, turnover, employment) indicators, which are complemented by various footprints of the German bioeconomy. Based on trends, e.g., organic farming and a reduction in meat demand, broad future developments and their impacts are described (Bringezu et al. 2020).

A stakeholder survey, where the majority (53%) of participants belonged to the science group, evaluated the report as moderately satisfying (Zeug et al. 2021). The stakeholders perceived a tendency towards economic indicators and a lack of consideration of social and environmental aspects, such as gender inequality, working conditions, renewable energy availability and biodiversity (ibid.). In addition, stakeholders criticized the limited alignment of the German monitoring with the National Sustainability Strategy, the SDGs and the European bioeconomy monitoring framework. The results reveal an overall discrepancy between the stakeholders' support for a socio-ecological vision of bioeconomy and their perception of the German and European bioeconomy strategies as "business-as-usual capitalism using additional renewable resources" (Zeug et al. 2021). However, the stakeholders confirmed the need for an annual bioeconomy assessment, where the focus should be on the analysis of synergies and trade-offs together with recommendations for political action (ibid.).

In conclusion, the relevant determining factors for the bioeconomy transformation, identified through the literature review, are in line with the indicators postulated by the EU and FAO. The evaluation of the German monitoring framework highlights the importance of coherence and integration between the different monitors, while underlining development challenges due to complexity. Overall, stakeholders demand a sustainable bioeconomy characterized by food security, production and consumption within the planetary boundaries, innovation, political guidance and societal participation (Hinderer et al. 2021; Zeug et al. 2021).

[1] https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en.

4 Bioeconomy Transformation: A Regional Perspective

Practically, all modern bioeconomy strategies rely on innovation as the central driving force for sustainable transformation processes. Accordingly, the literature on regional innovation systems argues that innovation and networks often occur in regional clusters because some forms of knowledge may be limited to specific regions. The reasons lie in face-to-face interaction and the advantages of norms, codes, language or even historical background, which are usually only prevalent in a certain region. The region is seen as the crucial level where innovation arises through knowledge linkage, clusters, and the mutual fertilization of research institutes. Empirical studies show that the emergence, growth, maturity, decline, and possible revival of clusters are determined by the peculiarities of the knowledge infrastructure, supporting organizations, institutional structure, cultural aspects, and policy measures of a particular region.

Regional or territorial development is a long-established approach in development geography, which deals with the dynamics of local development and structural change processes and their determining factors. The role of decentralized decision-making processes in locally diverse development potentials (e.g., availability of natural resources, quality of natural resources, human capital) is of great importance. Following an understanding of bioeconomy as an economic sector and future concept, the question arises as to what role regional differences should play in shaping bioeconomic development strategies. It should be noted that modern bioeconomy concepts generally assume that knowledge-based approaches to biobased value creation will become increasingly important and will increasingly merge with traditional biobased primary sectors (e.g., agriculture and forestry).

This means that for the development of a bioeconomy strategy, strategic objectives and the corresponding funding instruments should be oriented towards regionally diverse development potentials (Stark et al. 2021). For example, the "State Bioeconomy Strategy" of Baden-Württemberg plans to occupy innovative economic sectors "whose added value largely lies in the regions themselves" (Landesregierung BW 2019, p. 40).

4.1 A Sustainable Bioeconomy in North Rhine-Westphalia

In many regions of North Rhine-Westphalia (NRW), there are now bioeconomic visions and projects. Many projects and clusters have been initiated over the last two years, which are partly implemented across district and county borders in various sectors and bring together a large number of actors from agriculture, industry, and science (Stark et al. 2021). The structural and economic characteristics of the regions are also important in this context. For example, in the Arnsberg administrative district, which is characterized by a relatively high percentage of forest area, projects in the field of forestry, wood and paper production are primarily named, while in agriculturally dominated regions such as the Detmold and Münster administrative districts, the agricultural sector is in the foreground and in the Rhein/Ruhr metropolitan region, the chemical and pharmaceutical industry is highlighted (Stark et al. 2021). Although there are already initiatives in many districts and cities to close biobased material cycles, there is still much unused potential in the use of biogenic residual materials. In particular, there are untapped material flows in waste and construction industries, as well as in the agriculture, forestry, and food industries. The exploitation of untapped potential is also reflected in the priority areas (Stark et al. 2021). The promotion of circular-based material utilization and recycling should be implemented more intensively in future. Networking of actors in the region and the development of partnerships between politics, science, and (agricultural) industry have been found to be just as crucial as knowledge transfer, education, and acceptance by civil society, which must contribute to the development of a regional, sustainable bioeconomy in NRW through sustainable consumption behaviour (Stark et al. 2021).

4.2 From Lignite-Mining to a Bioeconomy Region: The Rheinisches Revier

Major transition processes will be initiated by the recent decision of the German government to phase-out coal mining—a decision with considerable effects on the Rheinisches Revier, Europe's largest connected lignite deposit. The impending, large-scale structural change process provides a unique opportunity for developing options to implement important structural and institutional foundations within a regionalization approach towards a sustainable bioeconomy in an entire region and for understanding the underlying socio-technical dynamics.

In 2016, the German government adopted its Climate Action Plan, a strategy for the long-term reduction of GHG emissions focusing especially on the economic sectors energy, industry, buildings, transport, and agriculture (BMUB 2016). The restructuring of the energy sector was identified as a main aim, as it is the key contributor to German GHG emissions (82.8% in 2020) (UBA 2021). Lignite mining, refining, and power generation are the most GHG intensive ways of energy generation, producing 49% of GHG emissions in the energy sector in 2018 (Öko-Institut 2022). Therefore, in 2018, the German government established a Commission for Growth, Structural Change, and Employment which assessed economic development possibilities for affected regions and political instruments to manage the accompanying structural change (BMWK 2022). In its final report published in January 2019, the commission advocated a phase-out of coal-fired power generation by 2038 (Kommission Wachstum Strukturwandel und Beschäftigung 2019). Following this recommendation, the German government decided in 2020 to phase out lignite mining and electrification by 2038 (Federal German Government 2020). The federal government elected in October 2021 aims to speed up this process and complete the phase-out by 2030 (SPD, Bündnis 90/Die Grünen und FDP, 2021).

The implementation of this political decision especially affects the three remaining lignite-mining regions in Germany: Lausitzer Revier (East), Mitteldeutsches Revier (Centre) and Rheinisches Revier (RR) (West) (Öko-Institut, 2022). In these relatively rural regions, the rich supply of cheap energy gave rise to strong supply chains in the chemical and plastics industry that shape both people's identity and regional landscapes (Kommission Wachstum Strukturwandel und Beschäftigung 2019). Consequently, the lignite-mining phase-out is not only an economic challenge but also drives structural changes that extend beyond the borders of the lignite-mining regions (Kempermann et al. 2021). To guide this transformation, the Coal Phase-out Act and the Structural Development Act were adopted by the German government in 2020, detailing how the budgeted €40 billion (bn.) of funding (to be disbursed until 2038) will be distributed across the three regions (Kempermann et al. 2021). The funding shall ensure a smooth and efficient transformation towards a bioeconomy, maintaining the regions' attractiveness for the local population, by creating new jobs, and for companies, by facilitating the creation of new values, rooted in bioeconomic principles, such as resource efficiency, circular economy and technological innovations based on renewable resources (Kommission Wachstum Strukturwandel und Beschäftigung 2019).

To reduce the complexity of such transformation processes and to consider their context dependence, it is useful to evaluate them at regional level (Nielsen et al. 2020). Furthermore, a long-term perspective is required, because societal changes extend over several generations and provide improvement opportunities and trade-offs at different scales that need to be considered to ensure a just transition (Reitzenstein et al. 2021). A key determinant for a successful transformation is therefore the active contribution of all stakeholders (Banse et al. 2020; Bringezu et al. 2020; Leipold et al. 2021). At the regional level, main stakeholders to be considered for the transformation process towards bioeconomy include local and federal governments and political actors, industry and commerce, farmers and forest owners, research, media, social and environmental citizens' initiatives and non-governmental organizations, as well as citizens and consumers (Dieken et al. 2021). Consideration and balancing of all these perspectives is required to facilitate a smooth and inclusive transformation.

4.3 A Monitoring Framework for Regional Transformation

The literature review and especially the revision of the bioeconomy monitoring approaches highlight the transformation's dependence on local conditions. The assessment of the bioeconomy transformation in the RR therefore requires a regional approach (Nielsen et al. 2020). As the transformation in the RR is still in an early phase, quantitative data, for example on SDGs, environmental footprints and a clear attribution of industry sectors to the bioeconomy is not available. Research in statistical databases of the Federal State of North Rhine-Westphalia shows that disaggregation to the district levels of the RR is difficult for many topics, e.g., agricultural practices, due to strict data protection laws (Kuhn and Schäfer 2018). Therefore, a qualitative approach was chosen to obtain in-depth information on the current trends and underlying conditions that influence the transformation in the RR.

To assess the regional transformation, a monitoring framework was developed. It combines Geels' socio-technical perspective, where technology development and diffusion are crucial, with Göpel's (2016) contribution on the importance of mind-shifts. Information on key determining factors and considerations regarding the structural conditions in the RR are also included. The frame for these different contributions provide the Shared Socio-economic Pathways (SSPs) developed by O'Neill et al. (2014). Combinations of socio-economic drivers and the IPCC's representative concentration pathways show possible pathways for societal development and their impacts on climate change mitigation and adaptation (O'Neill et al. 2017). The SSPs' approach is widely used to calculate, e.g., land use change and GHG emissions (Riahi et al. 2017), carbon reduction due to sewage sludge availability (Zhang et al. 2022), developments in wind energy generation (Martinez and Iglesias 2021), changes in forest management and bioenergy supply (Daigneault and Favero 2021), or population developments (Samir and Lutz 2017), associated with the respective pathway. The selected categories and socio-economic drivers by O'Neill et al. (2014) have therefore proven suitable to assess transformations. Besides, the general nature of the indicators facilitates assessments at varying geographic scales. Overall, their application in this manuscript ensures conceptual alignment with global transformation assessments and increases transparency.

To assess the trends in the RR's transformation, a comprehensive framework was developed that captures crucial aspects related to the transformation and considers regional specificities. It serves to identify trends, challenges, and opportunities for a further bioeconomy transformation, which are the basis for forward-looking and comprehensible political decisions. O'Neill et al. (2014) group the socio-economic drivers they use into six categories. The categories can be distinguished into three social ones, including demographics (e.g., population growth, urbanization, and migration), human development (e.g., education, gender equality, social cohesion, and participation), and policies and institutions (e.g., international cooperation, policy orientation, institutions) (O'Neill et al. 2017). Additional categories encompass economy and lifestyle (e.g., growth, globalization, international trade and consumption), technology (e.g., technology development and transfer, renewable energy technologies), as well as environment and natural resources (e.g., fossil constraints, land use and agriculture) (ibid.). Under consideration of the regional context and the importance of technological innovations and mindsets, the SSP categories were renamed to allow for a holistic transformation monitoring in the RR.

A combination of the socio-economic drivers of the SSPs, the identified determining factors, and information on the transformation aims in the RR filled the framework categories with qualitative considerations. A large number of indicators allows for detailed insights while a reduced number is appropriate for providing an overview (Egenolf and Bringezu 2019). To arrive at an intermediate perspective, allowing for details that can be grouped to give an overview, the six categories are

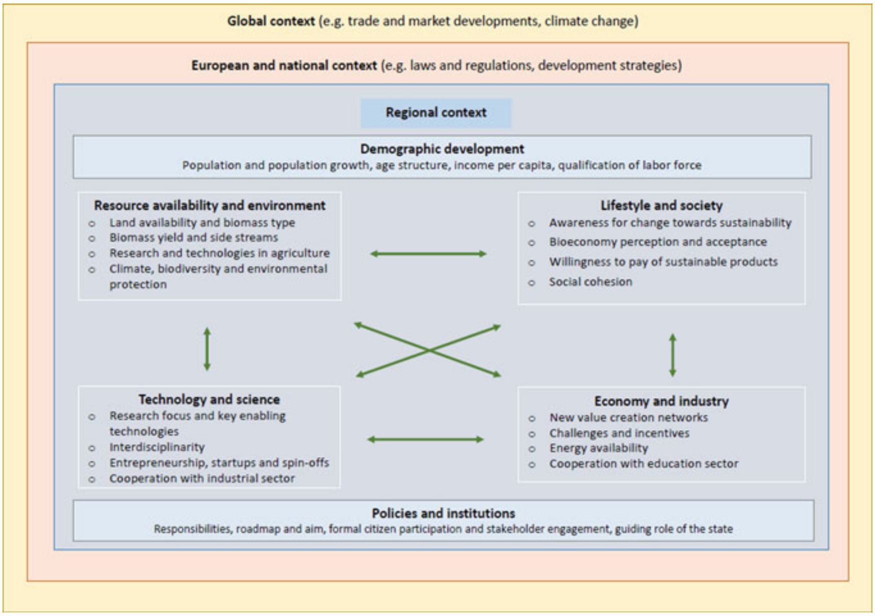

Fig. 2 Assessment framework for the regional bioeconomy transformation in the RR. *Source* Based on BioSC (2022)

represented by four qualitative characteristics each. The developed framework for the assessment of the bioeconomy transformation in the RR is depicted in Fig. 2.

The transformation in the RR is embedded in a wider context of national, European, and global developments, such as environmental policies, market developments, and the impacts of climate change (Hagemann et al. 2016). For reasons of complexity reduction, these aspects are assumed to be external. Looking at the regional context, demographic developments, and policies and institutions establish the frame for the transformation. They are relatively stable in the short and medium term and influence the other categories. Demographic development composed of population growth, age structure, income, and the qualification of the labour force determines the composition of locally available human resources that can take part in the transformation and, e.g., demand biobased goods (O'Neill et al. 2017). Political institutions at regional and national level shape the transformation by identifying the overall aim and managing its achievement (Dietz et al. 2018). Therefore, they need to involve all responsible actors from the different hierarchical levels, which have to coordinate their actions to provide guidance for societal stakeholders (Herberg et al. 2020). Overall, citizen participation and stakeholder engagement are important to raise awareness of the bioeconomy concept, identify concerns and opportunities, and finally to legitimize future political decisions (Hinderer et al. 2021). The category lifestyle and society addresses this aspect and highlights the importance of societal support for a successful transformation (Leipold et al. 2021). The awareness that a shift towards a more sustainable lifestyle is needed marks the first step to communicate the bioeconomy concept to society (Banse et al. 2020). The perception and acceptance of the concept determine societal support for the transformation towards a bioeconomy (Macht et al. 2022), while the willingness to pay for sustainable products, e.g., biobased goods, is important for the implementation of a bioeconomy (Wackerbauer et al. 2019). The transformation in the RR should not lead to a further segregation between employees of the lignite-mining sector and academics in the area of innovation, but instead increase social cohesion (Zukunftsagentur Rheinisches Revier 2021). From an economic and industrial perspective, the success of the bioeconomy transformation depends on the creation of value added in new, circular networks (Banse et al. 2020). An implementation of this change requires different knowledge and skills which need to be taught in schools and training programs, making cooperation between industry and the education sector important (Region Aachen Zweckverband 2019). As many energy intensive companies are located in the RR, ensuring energy availability after the coal phase-out is crucial for the regional economy (Zukunftsagentur Rheinisches Revier 2021). Path-dependencies impose challenges for companies to shift from fossil resources to biogenic inputs. Therefore, incentives and support from the political level are key to a change in the industrial sector (Banse et al. 2020). Innovations and technological developments open up new transformation pathways, so the regional research focus and the identification of key enabling technologies (KETs) shapes the transformation (Egenolf and Bringezu 2019). This requires interdisciplinarity in research teams (Leipold et al. 2021) and cooperation with the industrial sector (BMBF and BMEL 2020) to find practical solutions and implement them through spin-offs and start-ups (Kuckertz et al. 2020). Resource availability and environmental conditions provide boundaries for the regional bioeconomy transformation. Thus, climate, biodiversity, and environmental protection are fundamental to ensure overall sustainability (D'Amato et al. 2020). Due to the strong agricultural focus in the RR, land availability, the selection of suitable crops and adequate biomass yields for the various uses in a bioeconomy determine the transformation's speed and direction (Bringezu et al. 2021). In this context, technologies in agriculture play an important role (Region Aachen Zweckverband 2019). Even though demographics, policies, and institutions frame the developments in the RR, all categories influence each other and are mutually dependent. Only jointly can they contribute to a successful bioeconomy transformation in the RR.

5 Outlook and Discussion

As part of its Climate Action Plan, the German Government implemented the "Commission for Growth, Structural Change, and Regional Development" to prepare the phase-out of coal power in Germany with a proposal for a mix of policy instruments under special consideration of its economic, environmental, and social aspects. In its final report from January 2019, the commission formally proposes the implementation of a bioeconomy as one core element to positively steer the structural change process in the three German lignite-mining regions. As a promising concept for Germany's transformation to sustainability and as an alternative of natural resource management, the sustainable bioeconomy falls naturally into the debate on enabling and shaping system transformations, including the phase-out of coal power. It requires ambitious and far-reaching changes to use biogenic instead of fossil raw materials—biomass and biotechnology instead of coal, oil, natural gas, and petrochemicals. Like the energy transition, the bioeconomy transformation will have to meet a wide range of demands. It will have to bridge the gap between (a) environmental sustainability, (b) techno-economic feasibility, and (c) social acceptance. The negative experiences with the first generation of biofuels illustrate how difficult this balance is to strike. Overall, there is a lack of clear understanding of the possible developments—especially with regard to society's expectations of the bioeconomy.

For the Rheinisches Revier, the commission recommends the development of biomass-based and circular supply chains in cooperation with regional research institutes and universities based on the strong position of the BioSC and local businesses in order to capitalize on existing research and economic structures beyond the coal exit (Kommission Wachstum Strukturwandel und Beschäftigung 2019). The Rheinisches Revier builds on a traditionally strong regional agriculture, already emerging small- and medium-sized enterprises specializing in biomass-based products, process, and services, and the proximity of economic and science organizations located in the region.

Such comprehensive transformations towards sustainability proceed very slowly, are strongly impaired by path dependencies and lock-in effects, and can only be successful when technological progress meets social acceptance. Thus, it is crucial for bioeconomic thinking to consider all three sustainability dimensions to achieve a holistically sustainable bioeconomy. Transformation towards a bioeconomy has been discussed in contested terms, highlighting different perspectives and challenges. Perceptions and approaches of different stakeholder groups have usually been analysed individually or at the national level. Since bioeconomy activities are often clustered in subnational regions and driven by both national and regional policies, these approaches fall short of the bioeconomic objective to provide a holistic perspective based equally on the three sustainability dimensions, which requires an integrated evaluative framework for regional transformation processes. Bioeconomy research is still very fragmented and analyses different transformation aspects in isolation. Technology and resource-centred visions dominate, whereas societal considerations are limited to consumer perspectives. This imposes further challenges for the already missing holistic and harmonized policies needed for a successful transformation. Moreover, current approaches to monitoring the transformation towards a sustainable bioeconomy lack a regional perspective that incorporates all three sustainability dimensions.

To address this gap, we developed an integrated evaluative framework for assessing regional transformation processes towards a bioeconomy. Based on a structured literature review, we first identified determining factors for a holistically sustainable bioeconomy transformation. In a second step, a comprehensive framework was developed that captures crucial aspects related to the transformation and considers regional specificities. Based on a combination of the socio-economic drivers of the Shared Socio-economic Pathways, the identified determining factors, and information on the transformation aims in the Rheinisches Revier filled the framework categories with qualitative considerations. As bioeconomy in the Rheinisches Revier is still in its infancy, our monitoring framework enables a first holistic assessment, where especially qualitative aspects of the transformation can provide insights into current developments, structures, and interconnections at different levels.

In the long term, monitoring of the transformation requires specific and measurable quantitative indicators to assess developments over time (Kardung et al. 2021). However, data protection laws and top-down approaches in national and environmental economic accounting in Germany prevent the evaluation of the current state of bioeconomy development based on publicly available data on NUTS-3 level. Hence, a quantitative assessment of a prospective bioeconomy region must begin with the collection of primary data. The developed framework can serve as a blueprint for this endeavour. The category "Lifestyle and society" requires a representative sample of households to estimate the willingness to pay for sustainable products (e.g., through discrete choice experiments). Societal awareness for change towards sustainability as well as bioeconomy perception and acceptance could be inspired by the outline of the study on environmental awareness conducted by the Federal Environment Agency in Germany (BMUV and UBA 2023). Similarly, the categories "Economy and industry" and "Resource availability and environment" require dedicated surveys addressing both representatives of the biobased industry and the agricultural sector to derive supply and demand of biobased materials and to identify the potential of unused material flows and waste streams. Research and technologies in agriculture as well as relevant indicators in the category "Technology and science" could be derived from secondary sources, e.g., patent and publication data.

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