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Regional transformation pathways for the bioeconomy

A novel monitoring approach for complex transitions

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Abstract

Addressing the complexities of transitioning to a sustainable bioeconomy, this paper presents a novel approach for developing regional transformation pathways (RTPs) based on narratives derived from the shared socioeconomic pathways. The methodology emphasizes a comprehensive understanding of underlying perspectives and perceptions, incorporating socio-economic, environmental, and political dimensions. The developed indicator framework captures a balanced representation of diverse interests by integrating insights from stakeholder analyses. The case study in the Rheinisches Revier region, Germany, exemplifies the approach's applicability, providing valuable insights for decision-making processes in the context of regional transitions toward a low-carbon economy. The results consist of five developed RTPs, offering a multitude of potential future trajectories of possible directions for regional transformations. Understanding potential pathways and related consequences is crucial for informed decision-making concerning resource use optimization since transformations of that scale influence the composition of supply chains and resource networks. This informed approach contributes to strategic planning and helps ensure resources are utilized efficiently and sustainably. By emphasizing the crucial role of transparency and reflection of assumptions in addressing the complexities of societal transformation processes, our approach seeks to support the implementation of a sustainable and inclusive bioeconomy at the regional level.

KEYWORDS
bioeconomy, circular economy, industrial ecology, low-carbon transition, sustainability indicator, transformation pathway

1 | INTRODUCTION

Governing complex transformations toward a green economy involves accommodating multiple stakeholders and divergent value systems. While broad objectives like the sustainable development goals (SDGs) are generally endorsed, perceptions of sustainability, required regional measures, prioritization of conflicting objectives, and measurement frameworks can notably differ. This poses challenges in tracking progress toward enhanced sustainability.

Circular economy (CE) is one of the concepts broadly conceived as a suitable approach to cope with the above challenges (Johansson & Krook, 2021; Maksymiv et al., 2021). The CE and the bioeconomy are interconnected concepts that complement each other in pursuing sustainable development, resource conservation, and a reduced environmental footprint (European Commission, 2018; von Braun, 2018). Both share a focus on sustainability and resource efficiency while emphasizing different aspects. The CE highlights the necessity to minimize waste and maximize the value of resources by promoting practices such as reducing, reusing, recycling, and recovering (Kirchherr et al., 2017). The bioeconomy encompasses producing and utilizing renewable biological resources, such as crops, forestry, and marine resources, for various sectors, including food, energy, and materials (European Commission, 2018).

Leipold et al. (2023) emphasize the importance of three key research areas meaningful to the growing body of CE knowledge and to facilitate effective communication with policymakers and decision-makers: examining diverse narratives surrounding the CE; incorporating technical, managerial, socio-economic, environmental, and political perspectives; and critically assessing the opportunities and limitations arising from the interaction between CE science and policy. Given the shared characteristics of research on the bioeconomy, we argue that these suggestions apply equally.

Regional transitions and associated changes are crucial given their profound effects on material stocks and flows (van Oorschot et al., 2023). As regions transform, the way resources are produced, distributed, and consumed adjust. These changes in socio-economic systems intertwine resource flows with the nature of economic activities (Font Vivanco et al., 2019). Developing effective policies prioritizing sustainability and resource efficiency requires policymakers to account for how structural changes impact future resource flows and consumption patterns. In this connection, transformation pathways are a valuable tool for understanding policy options and assessing their impacts. They simplify complex concepts, enhancing communication with stakeholders and the public. Pathways also aid in monitoring and evaluating policy progress, allowing for necessary adjustments.

We therefore introduce a novel approach to developing regional transformation pathways (RTPs) for implementing a sustainable bioeconomy based on narratives derived from the shared socioeconomic pathways (SSPs). Building upon the SSPs allows the development of pathways that align with the established accounts within the scientific community while being tailored to and more tangible for decision-makers' requirements in a regional context. This way, we strive to address the challenges stemming from the interaction between science and policy in future bioeconomy policy development. We consider managerial, socio-economic, environmental, and political factors within the developed framework. This holistic approach ensures that our analysis and derived recommendations account for the complexities of transitioning to a sustainable and inclusive bioeconomy.

To demonstrate the applicability of our approach, we operationalize it within the regional transformation process for implementing a sustainable bioeconomy in the Rheinisches Revier (RR) region, Germany. The conceptual approach developed in this paper serves as a valuable groundwork for researchers and decision-makers, providing support in navigating transitions toward a low-carbon economy.

The paper is structured as follows: We first provide an overview of existing bioeconomy monitoring. We then describe the SSP framework and related literature, highlight the core characteristics of the narratives, and introduce the case study. Subsequently, the development of RTP narratives is illustrated and the systematic process for deriving the indicator system is outlined, whereupon the set of transformation trajectories is developed. The next section presents the results obtained from the methodology. We proceed by elaborating on insights gained from the set of RTPs, emphasizing the potential of our approach in informing decision-making processes. Finally, we discuss the implications of our findings, identify limitations, and propose future research directions.

2 | LITERATURE REVIEW

2.1 | Bioeconomy monitoring

While the bioeconomy has received significant attention in recent years (Mubareka et al., 2023), existing reviews reveal a range of diverse interpretations and perspectives, reflecting the inherent ambiguity and complexity surrounding the topic (Bugge et al., 2016; Dallendörfer et al., 2022; Dieken et al., 2021; Dieken & Venghaus, 2020). Research agendas tend to remain fragmented, focusing on particular aspects rather than embracing a holistic view (Bringezu et al., 2021; Dieken et al., 2021; Egenolf & Bringezu, 2019; Giampietro, 2019; Jander & Grundmann, 2019; Jander et al., 2020). Bioeconomy objectives frequently prioritize countries' competitive advantages, but comprehensive progress measurement and monitoring are often lacking (Bracco et al., 2018). Many nations primarily monitor the bioeconomy's influence on GDP and employment, conceivably leading to an inaccurate perception of overall developments (Bracco et al., 2018; Sturm & Banse, 2021). Moreover, because the social and environmental implications of the bioeconomy are widely predicted but not quantified, a discrepancy between the stated goals and assessment methodologies exists (Bracco et al., 2018). Therefore, a comprehensive and systematic indicator set must inevitably also include environmental and social aspects of sustainability to account for inherent strains on both ecosystems and the well-being of affected communities (Bracco et al., 2018). While specific sectors achieved progress in recent years, strategic objectives as laid out in policy documents often fail to achieve their set goals, indicating a lack of policy-relevant knowledge (Lühmann & Vogelpohl, 2023). This is further underlined by the fact that the essence of transformational strategies is not just restricted to technology development but also covers institutional and behavioral facets (Bracco et al., 2018; von Braun, 2018). Thus, current initiatives to monitor progress toward a sustainable bioeconomy should be improved to track performance related to the SDGs (Bracco et al., 2018).

Recognizing the potential emergence of unintended implications caused by further progress of the bioeconomy, the Food and Agriculture Organization of the United Nations (FAO) established the International Sustainable Bioeconomy Working Group (ISBWG) in 2016 (FAO, 2021). The ISBWG, a multi-stakeholder group within the FAO, assists countries in developing policies and strategies for circularity and sustainability in the bioeconomy (FAO, 2021). It serves as an advisory body for the FAO (FAO, 2021). To derive a normative understanding of sustainability, the ISBWG developed a set of desired principles and criteria for a sustainable bioeconomy (FAO, 2021). In this context, Calicioglu and Bogdanski (2021) argue that these principles can potentially serve as the foundation for monitoring frameworks and support approaches for systemic assessments of the bioeconomy. Based on a meta-analysis of existing literature and technical reports, Calicioglu and Bogdanski (2021) linked SDG indicators to each of the principles laid out by the ISBWG. The stated objective is not just to monitor the bioeconomy itself but explicitly in connection with sustainability (Calicioglu & Bogdanski, 2021). However, this work addresses global developments, whereas bioeconomies are often implemented regionally. Thus, while the works of the ISBWG and Calicioglu and Bogdanski (2021) provide a solid foundation serving as the basis on which this work develops a novel indicator system, further adaptation and development are needed.

2.2 | Transformation pathways and narratives

The SSPs are a central element in the development of RTPs in this paper. The SSPs succeed the special report on emissions scenarios (SRES) and serve as a reference for a range of assessments addressing challenges in climate change and broader sustainability aspects (van Vuuren et al., 2014). Enhancing the representative concentration pathways, the SSPs introduce socio-economic narratives designed to address the challenges of both mitigation and adaptation (van Vuuren et al., 2011; van Vuuren et al., 2014).

As O'Neill et al. (2017) point out, the creation process of the SSP narratives was guided by existing narratives, including the IPCC SRES (Nakicenovic et al., 2000), the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), the Global Environment Outlook scenarios (UNEP, 2002, 2007) as well as further global scenario developments (van Vuuren et al., 2012). Potential foundations for SSP narratives were outlined in several papers, including those by Kriegler et al. (2012), O'Neill et al. (2014), and Schweizer and O'Neill (2014), with van Vuuren and Carter (2014) delving into analogies to SRES scenarios (O'Neill et al., 2017). O'Neill et al. (2017) further highlight the role of the concept of challenges to adaptation (Rothman et al., 2014) and of political economy and governance (Lane & Montgomery, 2014) in shaping the narratives. The SSPs and related narratives are therefore the result of a long-term development process.

Pathways within the SSP framework are intentionally designed without accounting for the impacts of climate change and climate policies (O'Neill et al., 2014). They serve as reference points to assess the effects of different climate change levels and policy choices on baseline conditions (O'Neill et al., 2017; O'Neill et al., 2014). Therefore, the narratives were created utilizing socio-economic and environmental factors (excluding climate) that are essential for addressing these challenges (O'Neill et al., 2017). Consequently, the SSPs can be used to analyze sustainable development, even without explicitly focusing on mitigation and adaptation challenges, although these challenges were the initial inspiration for their creation (O'Neill et al., 2017). Overall, five SSPs resting on divergent assumptions concerning mitigation and adaptation have been developed (Calvin et al., 2017; Fricko et al., 2017; Fujimori et al., 2017; Kriegler et al., 2017; O'Neill et al., 2017; Riahi et al., 2017). These illustrate the starting point for the regional transformation pathways developed in this work.

The SSP narratives provide sufficient information to outline plausible alternative development pathways (O'Neill et al., 2017). However, for an analysis on a sub-national level and a particular sector, extended narratives that are consistent with the SSPs but go beyond them are required (O'Neill et al., 2020; O'Neill et al., 2017). In contrast to the developed bioeconomy pathways conceptualized in this work, the observed period of the SSPs differs and the sectors considered are not targeted predominantly on aspects related to bioeconomy transformations. Still, the framework provides valuable groundwork for comparability between transformation trajectories. It promotes mutual understanding among researchers and decision-makers. Thus, aligning pathways with established SSP narratives facilitates the translation of global developments into a regional context for a low-carbon transition.

To develop the RTP narratives, key aspects of the existing SSP narratives were extracted and summarized (see Figure 1). The focus was primarily on aspects that form the core of the respective transformation path. Consideration was given to which elements are of interest for regional developments and imply interdependencies. An overview of the core elements of the respective SSP narratives, derived from O'Neill et al. (2017), is presented in Table 1.

2.3 | Case study and stakeholder perceptions

The RR was identified as a suitable region for the development of RTPs and the application of the approach developed in this paper. It is Europe's largest connected lignite deposit and is situated in North Rhine-Westphalia (NRW) in the area between Aachen, Bonn, Cologne, and Düsseldorf.

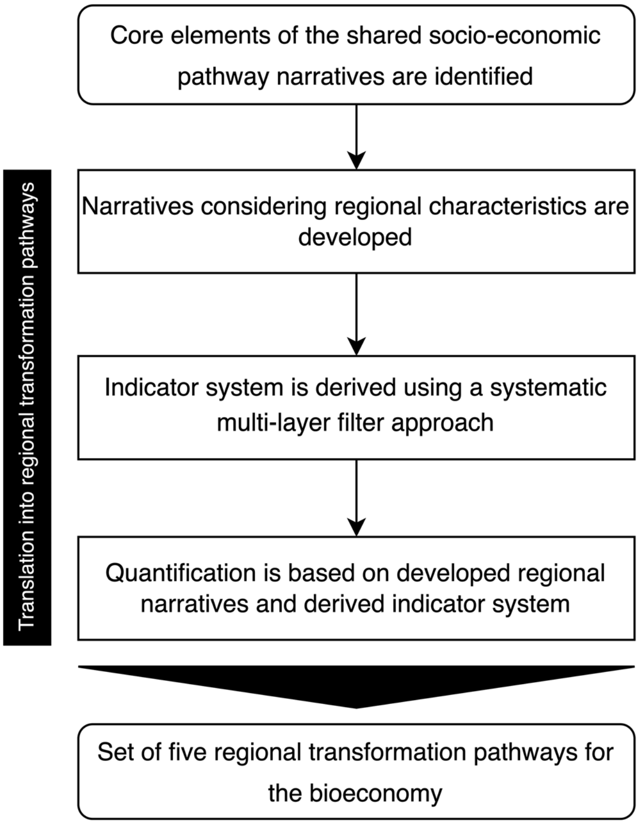

FIGURE 1 Overview of the steps required for developing the regional transformation pathways.

The region is characterized by the presence of both a robust fossil-based economy with well-established food, chemical, and energy industries and a strong bio-based economy. Two pivotal trends strongly influence the RR: the coal phase-out and the concurrent promotion of the RR as a sustainable bioeconomy model region. In this connection, developing decision support systems for aspired transitions was recommended (BMUV, 2019). Decisions concerning future transformation paths in the RR will be contentious and need to consider divergent opinions and value systems (Dallendörfer et al., 2022; Dieken et al., 2021; Dieken & Venghaus, 2020). Therefore, it serves as an ideal case study (see Section 3.1 for further details).

3 | METHODOLOGICAL APPROACH

3.1 | Developing narratives for regional transformation pathways

The process of narrative creation was guided by the development of SSP narratives (O'Neill et al., 2017). Overall, three deliberations played a central role. First, while building upon the SSPs, the RTP narratives consider challenges relevant to bioeconomy transitions. Second, they integrate key characteristics connected to the context of the RR and stakeholder perceptions involved in the transition. Third, while considering regional specificities, they need to remain consistent with the SSP narratives' core elements. These deliberations involved a process that iterated between the set objective of developing SSP-consistent RTP narratives and identifying context-specific narrative components and presuppositions. It is illustrated in Figure 2. This procedure constitutes a solid basis for the following quantification that increases transparency and allows researchers to relate to the underlying main assumptions.

The RTP narratives' content was informed through in-depth familiarization with the case study building upon three steps.

First, in November 2019, a focus group workshop was conducted to gain an initial understanding of existing lines of conflict within the region. Eight people participated, including representatives from the population, business, industry, as well as politics and NGOs. A key insight was that environmental considerations and fair financial burden distribution played a significant role for the participants.

In addition, we conducted a systematic literature analysis on stakeholders' perceptions of the bioeconomy based on the central dimensions of the bioeconomy introduced by Bugge et al. (2016), namely, biotechnology, bioresources, and bioecology. The analysis reveals a prevailing

TABLE 1 Overview of shared socioeconomic pathway (SSP) narratives' core elements.

SSP No.	SSP title	SSP core elements
1	Sustainability—Taking the green road	- Environmental boundaries respected - Investment in health and education - Economic growth as part of a general understanding of human well-being - Inequality reduced - Consumption oriented to lower material, resource, and energy requirements
2	Middle of the road	- Social, economic, and technological trends do not shift - Slow progress toward the SDGs - Overall decrease in the use of resources and energy but degradation of environmental systems - Population growth levels off in the second half of the century - Income inequality persists and the vulnerability of societal groups remains
3	Regional rivalry—A rocky road	- Nationalism and competitiveness play a key role - National and regional security high on the political agenda - No broader-based development but a regional focus - Reduction in education and technological investment - Material-intensive consumption, inequalities increase, and economic development is slow - Population growth is high in low-income and low in high-income countries - Environmental concerns are not addressed internationally - Strong environmental degradation in some regions
4	Inequality—A road divided	- Unequal investments in human capital - Increasing disparities in economic opportunity and political power - Inequality increases - Social cohesion degrades - Fragmented society and a widening gap between societies and sectors - Energy sector diversified—low-carbon as well as carbon-intensive technologies - Environmental policies mainly address issues on the local level and in high-income countries
5	Fossil-fueled development—Taking the highway	- Competitive markets, rapid technological progress - Participatory societies - Global markets integrated - Global population peaks and declines during the 21st century - Substantial investments in health, education, and institutions to enhance social and human capital - Exploitation of fossil resources - Energy-intensive lifestyles - Rapid economic growth - Local environmental problems addressed (e.g., air pollution)

Abbreviation: SDGs, sustainable development goals.

emphasis on biotechnology and resource-related topics, with significant attention directed toward research, policy, and industry stakeholders. However, a notable absence of ecological and societal concerns, coupled with limited research on actors from civil society, indicates a disparity between the bioeconomy as a sustainability concept and stakeholders' perceptions (Dieken et al., 2021). Consequently, there is a pressing need for greater consideration of societal stakeholders' interest in both research and policy endeavors (Dieken et al., 2021).

Third, to attain additional insights into the public's comprehension of the term "bioeconomy," as well as citizens' knowledge, concerns, and expectations, we conducted a representative survey among the German population. Our findings reveal that the concept of the bioeconomy is not widely familiar among German citizens (Dallendörfer et al., 2022). Still, the underlying principles of the bioeconomy are highly valued. Strong support exists for a sustainable bioeconomy, with expectations centered around environmental and economic benefits (Dallendörfer et al., 2022). Support for the bioeconomy is linked with beliefs reflecting environmental concern and pro-environmental behavior. Measures and principles related to the bioeconomy, such as the use of biogas, biofuels, and renewable materials for everyday products or buildings and the cascading and circular use of resources, are well-received (Dallendörfer et al., 2022). Thus, these aspects are considered in the narratives and related transformation paths.

3.2 | Deriving the indicator framework

The developed indicator framework in this study is designed to encompass not only the bioeconomy itself but also its contributions to sustainability as defined by the SDGs, emphasizing a holistic approach. It is achieved by connecting indicators laid out in the German Sustainable Development

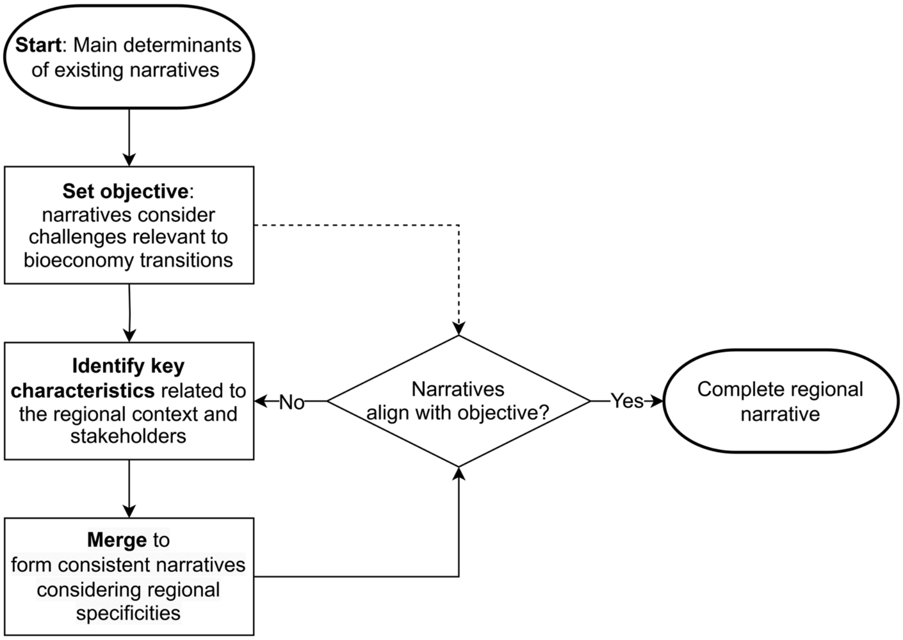

FIGURE 2 Narrative development process for regional transformation pathways illustrated as a flowchart. *Source*: Guided by O'Neill et al. (2017).

Strategy (GSDS) based on their relevance to the concept of the bioeconomy. This allows utilizing a robust data set, including information concerning the current state and corresponding target values for each indicator. Based on the work of Calicioglu and Bogdanski (2021) and the principles and criteria for a sustainable bioeconomy (FAO, 2021), a systematic multi-layer filter approach (SMLFA) to identify a comprehensive indicator set intended to capture relevant aspects of the transformation process is developed. This process demands any indicator to fulfill four requirements until it is included within the resulting framework:

First, it needs to be included in the global SDGs. The SDGs serve as guidance for activities in research and policy and thereby offer a broad and well-established basis often underpinned by widely available data sources. The SDGs further contribute to the possibility of transferring the developed approach to other regions.

The second requirement is that the indicator relates to aspects relevant to a sustainable bioeconomy. The basis for this is identified in the principles and criteria of a sustainable bioeconomy as laid out by the ISBWG (FAO, 2021) and the analysis conducted by Calicioglu and Bogdanski (2021).

Third, an indicator must be represented in national sustainability strategies. The underlying reasoning here is that this allows accounting for national priorities and strengthens the legitimacy of the corresponding aspect measured. In the case of the RR, the relevant policy document is the GSDS (German Federal Government, 2021).

As a fourth criterion, indicators are evaluated with respect to their respective relevance to the decision problem at hand. For example, SDG 14 indicators covering topics related to sustainable fishing practices in the oceans might not be relevant for a transformation process in a landlocked region. The conceptual approach, along with the respective filter layers, is illustrated in Figure 3.

To ensure that the resulting indicator frame captures a balanced representation of the sustainability dimensions of social, economic, and environmental, the indicators are categorized and mapped according to their properties. In addition, the identified indicators can be categorized according to the three central dimensions of the bioeconomy, namely bio-technology, bio-resource, and bio-ecology (Bugge et al., 2016). Mapping indicators along these bioeconomy visions facilitates an overview of potential unintended concentrations on specific perceptions, enhancing transparency and highlighting unbalanced aspects for targeted improvements if needed.

3.3 | Building regional transformation pathways

To complete the RTPs, prior steps must be consolidated. The developed narratives and derived indicator systems form the basis for subsequent quantification. The indicator data that constitute the foundation for the formulation of the RTPs are based on reports from the German Federal Statistical Office that provide information on monitoring the indicators of the GSDS. They are gathered from the publicly available data sources used for the GSDS and are specified, referenced, and laid out for each respective indicator in the Supplementary Information (SI) section.

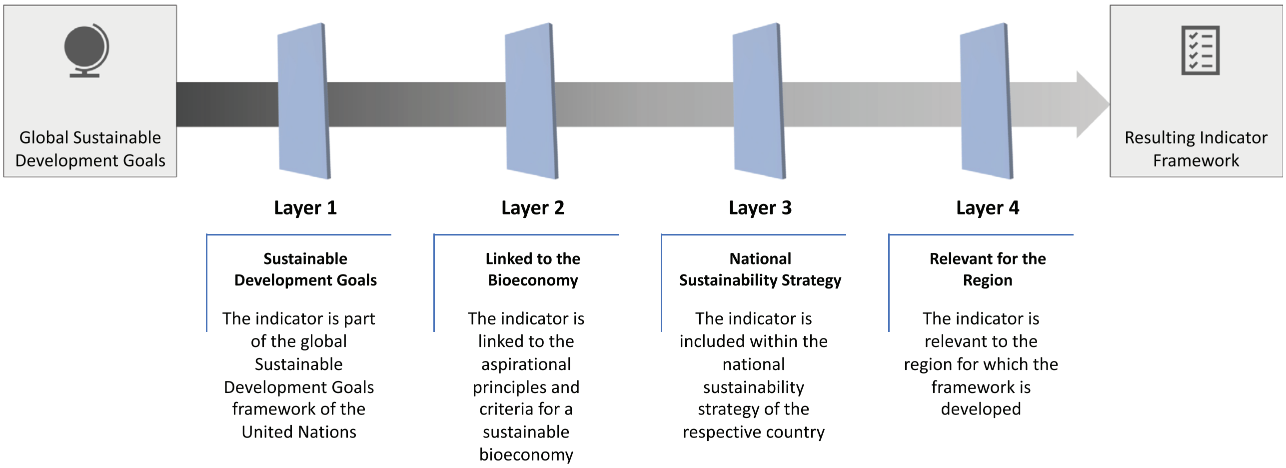

FIGURE 3 Conceptual illustration of the developed systematic multi-layer filter approach. [Color figure can be viewed at wileyonlinelibrary.com]

RTP 1 is conceptualized as the *SDG pathway*. The target data stated within the GSDS are thus the basis for the respective values. By default, the target values for the indicators on the federal and regional levels of NRW were integrated as stated in the GSDS and the NRW SD strategy. The national target value was used in cases without a value for NRW. In instances without an explicitly stated target value, the target value was derived based on the indicator description within the GSDS.

RTP 2 *Incremental progression* is depicted as a pathway achieving half of the SDG target as it, as the name suggests, incrementally progresses but does not fully achieve the intended goals set out in the GSDS.

The narratives associated with the remaining RTPs provide the basis for evaluating the trend of each respective indicator. In the case of an optimistic assumption within the narrative, a positive development was also assumed for the respective indicator, whereas the assumption of a negative development within the narrative is reflected accordingly in the trend of the respective indicator.

We used a four-scale schema to build the remaining RTPs. It consists of much improved (++), improved (+), worse (-), and much worse (–). Individual indicator target values were calculated based on historical data:

- Much improved (++): Historic data were used, and the compound annual growth rate (CAGR) for each year was calculated. Next, the 75th percentile (third quartile) of the resulting CAGRs was used to account for years with exceptionally high CAGRs. This was then assumed as CAGR for the following years until 2030 and applied to the latest available data referring to the status quo.
- Improved (+): Here, we assumed that the incremental progress achieved equals half of the SDG target value. Therefore, the same value as in RTP 2 is derived for the respective value.
- Worse (-): The assumption in these cases reflects the perspective that the current status quo is unsustainable and aligns with the GSDS, which advocates for an urgent and profound transformation (German Federal Government, 2021). In the broader context of the climate crisis and biodiversity loss, maintaining the status quo is seen as a detrimental starting point for the future, with potential limitations on options to avert undesirable developments. Worse can thus be perceived as similar to "business as usual" and worse compared to the SDG-related targets. The value is calculated using the latest available CAGR.
- Much worse (–): Similar to "much improved," historic data were used to calculate the CAGR for each year. The 25th percentile (first quartile) was then used to determine the target value.

The calculations are performed using the future value formula,

$$\mathrm{FV} = \mathrm{PV} \times (1 + r)^{t}, \tag{1}$$

where PV is the present value, r is the interest rate (CAGR in this case), and t is the number of years. The formula provides a valuable tool as it allows for projecting and assessing the long-term consequences of various sustainability-related factors for evidence-based decision-making and planning. It is frequently used for identifying trends and assessment of indicators without quantified targets (eurostat, 2023). The formula is consistently used for all indicators, irrespective of their unit, which includes applying it to indicators that were originally provided as percentages.

TABLE 2 Overview of regional transformation pathway narratives based on shared socioeconomic pathways.

RTP no.	RTP title	RTP narrative
1	SDG pathway	Overall, the availability of sustainable resources and environmental protection improves. Biodiversity and landscape quality are respected and preserved to a greater extent, including a higher share of farmers opting for organic farming and less pollution in rivers and groundwater. Investment in research and development, inclusive of sustainable technologies and production processes, accelerates and is introduced to the market by successful start-ups and companies. Forward-looking policy decisions allow for a transition that generates new employment options and reduces inequality across the region. Consumption patterns in the RR are increasingly centered around more sustainable alternatives, including a higher willingness to pay for more regional and ecologically friendly products. Materials, predominantly based on biological resources and energy, mainly generated using renewable energy sources, are used more efficiently in new value creation networks, allowing for overall high raw material and energy productivity.
2	Incremental progression	As current patterns in the region's development persist, agriculture continues to be unsustainable, with a low share of organic farming and limited environmental protection causing nitrate levels in the groundwater to rise. New key enabling technologies in biotechnology increase the productivity of biobased raw materials at reduced energy consumption. Society and consumers are aware of the required changes toward more sustainability, but the willingness to pay for regional products and the acceptance of novel, biobased products are growing only slowly. Overall, social inequality increases, and regulations for more sustainability are executed hesitantly by federal and regional political institutions.
3	Strained cooperation	Regionalization and competition for local resources reduce the region's integration into the network of surrounding cities. Cooperation between the different districts composing the RR is reduced, as political institutions base the transformation on exploiting the fertile soils for food and energy and investing less in biotechnological innovations and education. The productivity of biobased raw materials decreases as large amounts are required for biomass-based energy production. Societal bioeconomy acceptance and willingness to pay for regional, ecological products decrease as the lack of new biobased value creation networks in the industry causes unemployment and higher inequality, especially income-per-capita. Environmental protection is low, causing a decrease in biodiversity quality as nitrate pollution of groundwater increases.
4	Transformational divide	Unequal opportunities and one-sided political influence and investments lead to disparities between those engaging with the structural change in the region and a knowledge-based bioeconomy and those left behind. While technological progress occurs, only a small fraction of companies and members of society can adopt new technologies, limiting the overall potential of positive effects. Fossil resources continue to play an essential role for the RR and are only gradually complemented by low-carbon energy sources. Environmental issues are addressed but mainly within wealthy communities and high-income areas within the region.
5	Technology pathway	Rapid technological progress based on key enabling technologies, competitive and internationally integrated markets, as well as increased investments in education along with the politically well-managed structural change in the region, allow for a robust economy, reduced inequalities, and continued prosperity in the RR. However, progress in the economic and social sphere comes at the expense of a resource-intensive lifestyle, consumption patterns, and overall higher energy and resource consumption. In this connection, economic growth in the region is high, and environmental problems, such as air pollution and clean groundwater and rivers, are controlled.

Abbreviations: RR, Rheinisches Revier; RTP, regional transformation pathway; SDG, sustainable development goal.

4 | RESULTS

Based on the SSPs and familiarization with regional conditions and stakeholder expectations in the region, five narratives were developed. The complete overview of the developed RTP narratives can be found in Table 2.

The next step consists of the derivation of the indicator system. Following the procedure laid out in Section 3.2, it was possible to reduce the 231 unique indicators contained within the global SDG framework and the 72 within the GSDS framework to 18. Table 3 illustrates the resulting indicator framework and the mapping along the sustainability dimensions and bioeconomy visions.

Applying the SMLFA leads to a balanced indicator set comprising 18 indicators: six associated with the economic dimension, six with the environmental dimension, and six with the social dimension. In alignment with the bioeconomy visions introduced by Bugge et al. (2016), these indicators are further categorized into six related to the technology perspective, six to the ecology perspective, and six to the resource perspective. It further entails indicators linked to 12 goals from the national GSDS and 11 from the global SDG framework. The discrepancy arises from indicator 5.1.a, which is linked to SDG 8 in the global framework but listed under SDG 5 in the GSDS.

Following the methodology outlined in Section 3.3, building the remaining RTPs involved consolidating previous work steps and utilizing narratives associated with each indicator. These narratives formed the basis for evaluating the trend of each indicator, reflecting either optimistic or

TABLE 3 Derived indicator system and categorization according to sustainability dimensions and bioeconomy visions.

GSDS	SDG	Description	Dimension	Vision
1.1.a	1.2.2	Material deprivation	Social	Resource
1.1.b	1.2.2	Severe material deprivation	Social	Resource
2.1.b	2.4.1	Organic farming	Environmental	Ecology
2.2	2.a.2	Support for good governance in attaining appropriate nutrition worldwide	Social	Resource
5.1.a	8.5.1	Gender pay gap	Social	Technology
6.1.a	6.3.2	Phosphorus in flowing waters	Environmental	Ecology
6.1.b	6.3.2	Nitrate in groundwater	Environmental	Ecology
7.1.a	7.3.1	Final energy productivity	Economic	Technology
7.1.b	7.3.1	Primary energy consumption	Economic	Ecology
7.2.a	7.2.1	Share of renewable energies in gross final energy consumption	Environmental	Technology
8.1	8.4.2	Raw material input productivity	Economic	Technology
8.4	8.1.1	Gross domestic product per capita	Economic	Technology
9.1.a	9.5.1	Private and public expenditure on research and development	Economic	Technology
10.2	10.2.1	Gini coefficient of income after social transfers	Economic	Resource
11.2.c	11.2.1	Accessibility of medium-sized and large cities by public transport	Social	Resource
12.2	12.6.1	EMAS eco-management	Environmental	Ecology
15.1	15.5.1	Biodiversity and landscape quality	Environmental	Ecology
17.3	17.11.1	Imports from least developed countries	Social	Resource

Abbreviations: GSDS, German Sustainable Development Strategy 2021; SDG, sustainable development goal; SDG indicator, global SDG reference indicators.

pessimistic assumptions. The quantification of the RTPs was carried out using a four-scale schema, which includes much improved (++), improved (+), worse (–), and much worse (—). Table 4 presents the results.

RTP 1 is formulated based on the GSDS target values, aligning with respective sustainability objectives. RTP 2 pursues a middle-ground approach, achieving half of the GSDS target values, thereby being less ambitious concerning progress in the pursuit of sustainability.

Concerning RTP 3, the results depict indicators with varying degrees of improvement and decline. Notably, indicators reflecting a significantly worse performance (occurrences of [—]: 6) highlight areas of concern, whereas indicators with a negative evaluation (occurrences of [–]: 7) indicate potential challenges. On the positive side, several indicators show improvement (occurrences of [+]: 5), demonstrating progress in certain aspects. However, there were no indicators evaluated as "much improved" (occurrences of [++]: 0) within this pathway.

Regarding RTP 4, results reveal indicators reflecting a significantly worse performance (occurrences of [—]: 4) in several areas that require attention. Additionally, indicators with an unfavorable evaluation (occurrences of [–]: 6) suggest potential challenges to address. On a positive note, several indicators demonstrate improvement (occurrences of (+): 8), indicating progress in certain areas. However, similar to RTP 3, no indicators were evaluated as "much improved" (occurrences of [++]: 0) within this pathway.

Results for RTP 5 display indicators with varying degrees of improvement. Notably, indicators reflecting a remarkably worse performance (occurrences of [—]: 3) and indicators with a negative evaluation (occurrences of [–]: 4) are less prevailing. Encouragingly, several indicators demonstrate improvement (occurrences of [+]: 1), indicating positive developments. Furthermore, RTP 5 stands out with a significant number of indicators evaluated as "much improved" (occurrences of [++]: 10), displaying its potential for substantial positive impact.

Finally, the quantified values for the RTPs are determined, following the procedure described in Section 3.3. The total set of five developed RTPs with respective indicators and their categorization is provided in Table 5.

5 | DISCUSSION

Integrating multiple aspects, including managerial knowledge, political perspectives, socio-economic considerations, and environmental perspectives, is vital for contributing meaningfully to related research (Leipold et al., 2023). By recognizing the cross-sectoral and interlinked impacts captured in the indicator system, incorporating transparent baseline assumptions, and acknowledging the relevant socio-economic impacts for policy design, the developed pathways contribute to action-oriented knowledge for sustainability. This avoids compartmentalization and silo thinking.

TABLE 4 Narrative-based trend evaluation for regional transformation pathways indicators.

GSDS	SDG	Description	RTP 1	RTP 2	RTP 3	RTP 4	RTP 5
1.1.a	1.2.2	Material deprivation	SDG	1/2 SDG	–	–	++
1.1.b	1.2.2	Severe material deprivation	SDG	1/2 SDG	–	–	++
2.1.b	2.4.1	Organic farming	SDG	1/2 SDG	+	–	–
2.2	2.a.2	Support for good gov. in attaining appropriate nutr. worldw.	SDG	1/2 SDG	–	–	–
5.1.a	8.5.1	Gender pay gap	SDG	1/2 SDG	–	–	++
6.1.a	6.3.2	Phosphorus in flowing waters	SDG	1/2 SDG	–	+	++
6.1.b	6.3.2	Nitrate in groundwater	SDG	1/2 SDG	–	+	++
7.1.a	7.3.1	Final energy productivity	SDG	1/2 SDG	–	+	+
7.1.b	7.3.1	Primary energy consumption	SDG	1/2 SDG	–	+	–
7.2.a	7.2.1	Share of renewable energies in gross final energy consumption	SDG	1/2 SDG	–	+	–
8.1	8.4.2	Raw material input productivity	SDG	1/2 SDG	+	+	++
8.4	8.1.1	Gross domestic product per capita	SDG	1/2 SDG	+	+	++
9.1.a	9.5.1	Private and public expenditure on research and development	SDG	1/2 SDG	–	+	++
10.2	10.2.1	Gini coefficient of income after social transfers	SDG	1/2 SDG	–	–	++
11.2.c	11.2.1	Accessibility of medium-sized and large cities by public transport	SDG	1/2 SDG	–	–	–
12.2	12.6.1	EMAS eco-management	SDG	1/2 SDG	+	–	–
15.1	15.5.1	Biodiversity and landscape quality	SDG	1/2 SDG	+	–	–
17.3	17.11.1	Imports from least developed countries	SDG	1/2 SDG	–	–	++

Abbreviations: GSDS, German Sustainable Development Strategy 2021; RTP, regional transformation pathway; SDG, sustainable development goal; SDG indicator, global SDG reference indicators.

Our systematic approach provides multiple benefits and is based on key features designed to provide pathways that help address current research challenges. It contributes to transparent decision-making processes through the use of a well-defined methodology. Regarding transferability, the narrative development based on the SSPs' key aspects is flexible and applicable to different regional settings. Similarly, the SMLFA, which is used to create a balanced indicator system, is adaptable to different contexts. The quantification of values for transformation pathways using SDG data further ensures a transferable framework that can be applied beyond the initial case.

The use of SSPs enables a thorough examination and reflection of the underlying narratives and ensures robust RTPs that take regional specificities into account. This enhances comparability across regions and conditions and makes the pathways accessible to stakeholders and researchers. The approach acknowledges different value systems and provides a balanced representation by integrating insights from stakeholder analysis, including social, environmental, and technological aspects. This enhances transparency by mapping sustainability dimensions and bioeconomy visions, identifying over- and under-representations of stakeholder interests. The application in a region undergoing a dynamic transition demonstrates its adaptability. The RTPs demonstrate a range of potential future paths, presented in an organized manner with both narratives and data, making it easy to comprehend potential directions. The indicator framework is based on a solid normative foundation aligned with the global SDG framework through the SMLFA. The link to the principles for a sustainable bioeconomy ensures that the indicators used to monitor corresponding developments are relevant and suitable. In addition, their integration into the GSDS increases their relevance in the specific context. The use of the SDGs and national sustainability strategies can help achieve data access, traceability, and transparency while incorporating different sustainability dimensions. The familiarity of decision-makers with the SDG framework facilitates communicability. However, transferability can be constrained by the fact that not all national sustainability strategies are structured for straightforward derivation.

Limitations exist concerning the SMLFA. First, while deriving the indicator system from the SDGs and national sustainability strategies offers advantages, it also presents potential limitations linked to the preselection of indicators. Second, the connection of indicators to aspects relevant to a sustainable bioeconomy can be interpreted differently, potentially leading to the inclusion or exclusion of individual indicators. Applying the SMLFA can thus lead to divergent outcomes (see, e.g., Bringezu et al., 2021; Egenolf & Bringezu, 2019; Jander & Grundmann, 2019; Jander et al., 2020; Sturm & Banse, 2021). To address this, incorporating context-specific indicators identified through participatory or expert-based approaches can illustrate feasible options.

Regarding the narratives and RTPs, it is important to note that the RTPs developed are not to be interpreted as predictions of the future, but rather as solution spaces for possible developments. The future is seen as a realm of opportunities to be shaped and influenced. Formulating a basic concept of the desired outcome is essential before deriving relevant measures.

TABLE 5 Complete overview of regional transformation pathways, including sustainability dimension, bioeconomy vision, and indicator values.

GSDS	SDG	Description	Dimension	Vision	SQ_0	RTP 1	RTP 2	RTP 3	RTP 4	RTP 5
1.1.a	1.2.2	Material deprivation	Social	Resource	8.8	4.16	5.48	7.14	12.90	3.50
1.1.b	1.2.2	Severe material deprivation	Social	Resource	5.6	1.63	2.115	7.14	9.84	1.71
2.1.b	2.4.1	Organic farming	Environmental	Ecology	5.7	20	12.79	12.79	11.97	11.97
2.2	2.a.2	Support for good governance in attaining appropriate nutrition worldwide	Social	Resource	18.3	31.69	25.025	18.3	18.3	31.69
5.1.a	8.5.1	Gender pay gap	Social	Technology	17	10	14	13.62	13.62	11
6.1.a	6.3.2	Phosphorus in flowing waters	Environmental	Ecology	41.7	100	71.4	25.24	71.4	75.15
6.1.b	6.3.2	Nitrate in groundwater	Environmental	Ecology	86.1	100	94.25	79.43	94.25	98.39
7.1.a	7.3.1	Final energy productivity	Economic	Technology	119.3	158	139.1	144.85	139.1	139.1
7.1.b	7.3.1	Primary energy consumption	Economic	Ecology	86.5	70	79.65	89.40	79.65	89.40
7.2.a	7.2.1	Share of renewable energies in gross final energy consumption	Environmental	Technology	7.94	30	18.42	16.29	18.42	16.29
8.1	8.4.2	Raw material input productivity	Economic	Technology	126	160	144	144	144	191.95
8.4	8.1.1	Gross domestic product per capita	Economic	Technology	36.5	43.13	40.315	40.315	40.315	44.63
9.1.a	9.5.1	Private and public expenditure on research and development	Economic	Technology	2.19	3.5	2.845	1.89	2.845	2.90
10.2	10.2.1	Gini coefficient of income after social transfers	Economic	Resource	0.309	0.283	0.29	0.313	0.381	0.258
11.2.c	11.2.1	Accessibility of medium-sized and large cities by public transport	Social	Resource	17.8	15.74	16.4	17.07	17.07	17.07
12.2	12.6.1	EMAS eco-management	Environmental	Ecology	220	531	381.5	381.5	188	170.38
15.1	15.5.1	Biodiversity and landscape quality	Environmental	Ecology	70.5	100	85.25	85.25	69.22	52.60
17.3	17.11.1	Imports from least-developed countries	Social	Resource	1.03	1.43	1.2055	0.98	1.58	3.03

Note: Calculations based on Federal Statistical Office (Destatis), 2023.

Abbreviations: GSDS, German Sustainable Development Strategy 2021; RTP, regional transformation pathway; SDG, sustainable development goal; SDG indicator, global SDG reference indicators; SQ, status quo, refers to the last value available in the data set.

Designed for decision-makers, this framework is intended to guide decisions based on stakeholder interests, including societal concerns, and offer orientation for future policymaking. In particular, it is aimed to inform key stakeholders in policy, industry, and research who play a pivotal role in shaping transformation processes (Dieken et al., 2021). Often, there is a prevailing technical understanding of the bioeconomy and a lack of ecological and societal concerns in these domains, which may not align with the expectations of the broader population (Dallendörfer et al., 2022; Dieken & Venghaus, 2020).

Modern sustainability science strives to generate actionable knowledge for societies to transition toward more sustainable development pathways, but limited quantitative methods are available to evaluate these trajectories (Topf et al., 2023). The developed approach informs strategic processes concerning the transformation of bioeconomy regions through three key avenues. First, it supports the establishment of monitoring and evaluation mechanisms to track the regional progress of the bioeconomy transformation. This entails deriving indicator frameworks to assess the success of implemented strategies. Second, the approach informs policy development at various levels (local, regional, national) to design supportive frameworks that encourage sustainable practices and, third, in formulating communication strategies aimed at raising awareness, engaging communities by providing information, involving them in decision-making, and ensuring fair benefit distribution while considering local perspectives.

Future research should focus on integrating the developed pathways into existing evaluation methods and exploring novel methodological approaches. A promising next step involves utilizing the pathways within a decision support system, particularly in a multi-stakeholder group decision-making context, to visualize diverse stakeholder perspectives and facilitate consensus finding.

6 | CONCLUSIONS

In this paper, we propose an alternative way to develop transformation pathways at a regional scale, taking the SSPs as a starting point to formulate regional interpretations of respective narratives. The SMLFA we employ incorporates an indicator framework that is linked to both the SDGs and the principles of a sustainable bioeconomy, forming the basis of our methodology. Our approach follows a structured and comprehensible process that allows for application in other contexts and offers the flexibility of tailoring it to the specific needs of the intended use case. Thus, gaining insights from countries operating under various socio-economic and political contexts would provide additional valuable perspectives. The application in the RR further illustrates the possibilities of applying the developed approach within the context of a regional transformation process.

Exploring potential transformation pathways early on is instrumental in shaping foresighted resource allocation strategies. This paper presents a valuable methodology that facilitates the implementation of a sustainable bioeconomy and supports key stakeholders in policy, industry, and research in making informed decisions.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supporting information of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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