

**Policy-Driven Structural Change – Governance in the Transition
from Coal to Bioeconomy**

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List of Abbreviations

AHP	Analytic Hierarchy Process
BBE	Bio-Based Economy
BMBF*	Federal Ministry of Education and Research
BMEL*	Federal Ministry of Food and Agriculture
BReg*	Federal Government
CAGR	Compound Annual Growth Rate
CBA	Cost–Benefit Analysis
CE	Circular Economy
DM	Decision Maker
EAM	Extent Analysis Method
EGD	European Green Deal
ELECTREE	ELimination and ChoiceExpressingREality
ESG	Environmental-Social-Governance
EC	European Commission
EU	European Union
FAHP	Fuzzy Analytic Hierarchy Process
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GE	Green Economy
GSDS	German Sustainable Development Strategy
IPCC	Intergovernmental Panel on Climate Change
ISBWG	International Sustainable Bioeconomy Working Group
KETs	Key Enabling Technologies
MADM	Multiple Attribute Decision Making
MAMCA	Multi-Actor Multi-Criteria Analysis
MAUT	Multi-Attribute Utility Theory
MCDA	Multiple Criteria Decision Aid (Analysis)
MCDM	Multiple Criteria Decision Making
MCE	Multi-Criteria Evaluation
MODM	Multiple Objective Decision-Making
NGO	Non-Governmental Organizations
NRW	North Rhine-Westphalia
P&C	Principles and Criteria
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluations
RCPs	Representative Concentration Pathways

* These abbreviations refer to the German title or name of organization.

RR	Rheinische Revier
RTPs	Regional Transformation Pathways
SAW	Simple Additive Weighting
SCT	Social Choice Theory
SDGs	Sustainable Development Goals
SMART	Simple Multi Attribute Rating Technique
SMCE	Social Multi-Criteria Evaluation
SMLFA	Systematic Multilevel Filter Approach
SSPs	Shared Socioeconomic Pathways
TFN	Triangular Fuzzy Numbers
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WGBU*	German Advisory Council on Global Change

* These abbreviations refer to the German title or name of organization.

1 Introduction

With the Agenda 2030 and the 17 Sustainable Development Goals (SDGs), the international community has reinforced its commitment to achieving sustainable development in all its facets (UN, 2015). An essential part of the intended transformation and of meeting climate change targets is to reduce dependence on fossil resources (IPCC, 2023). Despite some progress, the current pace is not sufficient to achieve the 2030 targets (UN, 2023). Thus, further efforts are crucial to accelerate the transformation (UN, 2023). While there is general agreement on the overarching goal of striving for sustainability, there is less consensus on what is sustainable and what steps and measures are required to achieve the different goals (Sachs et al., 2019). However, political will and cooperation between stakeholders are key to making progress and taking the necessary steps (FAO, 2024b; UN, 2023).

Efforts for reducing CO₂ emissions and global temperature increase have led to ambitious climate policies (EC, 2019a; UNFCCC, 2015). The transition of the energy system constitutes a central part of these global commitments and climate policies in Germany. In recent decades, German energy policy underwent multiple remarkable shifts and the energy transition has been the subject of contentious debate, with divergent perspectives shaping the discourse on its feasibility, implications and goals (Fischer et al., 2016; Hake et al., 2015; Joas et al., 2016; Leipprand et al., 2017; Renn & Marshall, 2016; Schmidt et al., 2019; Selje, 2022; Wiertz et al., 2023). By phasing out the use of nuclear energy in April 2023, a major step of the energy transition was concluded (Glynos & Scharf, 2024). The political decision to reduce and eventually end coal-fired power generation marks the start of the next important phase of the energy transition (Selje, 2022). Policies and regulations have been the key drivers of the energy system transformation in Germany while technological developments have had only a minor impact (Kappner et al., 2023). The choice of energy technologies was ultimately determined by political decisions (Fischer et al., 2016; Kappner et al., 2023). The transformation process can therefore be seen as policy-driven structural change (Matthes, 2017).

In the years following the decision to phase-out nuclear, increasing awareness of climate change has intensified public and political debates on climate action and

sustainability (EC, 2017, 2019b; Venghaus, Henseleit, & Belka, 2022). The changing focus of energy policy discussions in parliamentary debates reflects shifting priorities over time and can be observed in the case of coal, which constituted an important topic for several decades (Buschmann & Oels, 2019; Leipprand & Flachsland, 2018; Leipprand et al., 2017; Müller-Hansen et al., 2021). Originally, coal was seen as essential to economic prosperity and energy security (Müller-Hansen et al., 2021). Backed also by arguments of affordability and its contribution to energy security, coal has maintained an important position in Germany's energy mix, irrespective of its emissions (Buschmann & Oels, 2019). More recently, however, the debate over coal has shifted and is more frequently discussed in relation to energy system transformation, coal phase-out, and renewable energy expansion (Leipprand & Flachsland, 2018; Müller-Hansen et al., 2021; Müller-Hansen et al., 2022). Despite the shift in debate from if to how to phase-out coal in Germany, the future of coal continued to be disputed and the center of several societal conflicts, which led to a political deadlock situation (Hauenstein et al., 2023). Governance approaches with stakeholder involvement have been proposed as a way to address such societal conflicts (Hauenstein et al., 2023).

Involving stakeholders in energy system transformation policy-making constitutes a central approach to achieving the goals of a democratic sustainability transition (Radtke & Renn, 2024). Previous experiences in the context of the energy transition in Germany illustrated that historically rooted, conflicting objectives influence decision-making and its outcome over time (Hake et al., 2015; Hermwille & Kiyar, 2022; Selje, 2022). Changing stakeholder discourses and power constellations play a crucial role and can influence stakeholders' subjective perception (Buschmann & Oels, 2019; Hake et al., 2015; Hauenstein et al., 2023; Herberg et al., 2024; Leipprand & Flachsland, 2018; Markard et al., 2021; Radtke & David, 2024; Radtke & Löw Beer, 2024). Policy outcomes related to coal phase-out strategies, measures and timelines are thus strongly affected by stakeholder dynamics (Brauers et al., 2020; Jakob et al., 2020; Markard et al., 2021; Radtke & Löw Beer, 2024). Despite similar climate targets and commitment to the Paris Agreement, political decisions and plans to phase-out coal differ notably between countries (Brauers et al., 2020; Gürtler et al., 2021; Steckel & Jakob, 2021; UNFCCC, 2015). Coal phase-outs and related transformation processes are therefore context-

dependent illustrate a challenging governance task for policy makers (Diluiso et al., 2021).

In the case of Germany, an expert commission, namely the *Commission on Growth, Structural Change and Employment*, also referred to as *Coal Commission*, was established to develop a plan and propose measures on how to address the structural change in Germany that is necessitated by energy and climate policy. Expert commissions are a recurring part of the German political landscape and are often set up to provide expert advice and increase the legitimacy of government action (Siefken, 2016). This contributed to end the political deadlock situation and the coal phase-out was scheduled to be completed by 2038 at the latest (Hauenstein et al., 2023). Following subsequent legislation of the German Federal Government in December 2022, the coal phase-out in North-Rhine-Westphalia (NRW) is to be achieved by 2030 and thereby eight years earlier than initially planned.

National goals of reducing emissions do not affect regions equally (Diluiso et al., 2021; Gürtler et al., 2021; Reitzenstein et al., 2022). It is therefore crucial to integrate top-down, climate-oriented national energy policies with local and regional conditions for their implementation (Radtke & Renn, 2024). The challenges of structural change in respective coal regions are multifaceted and region-specific, covering political, economic, technical, social and cultural aspects (Reitzenstein et al., 2022). A profound understanding of the regional context is thus vital as it forms the basis for effective interventions and defines the scope of related discourses (Radtke & Renn, 2024). The decision to phase-out coal includes substantial financial compensation for coal companies and funding for the affected regions (Furnaro, 2023; Tiedemann & Müller-Hansen, 2023). However, addressing this transformation process requires more than financial support and compensation (Diluiso et al., 2021; Reitzenstein et al., 2022). It involves key challenges such as fostering a new regional identity through investment in emerging sectors, diversifying the economy and providing sustainable long-term alternatives (Diluiso et al., 2021). A crucial question for policy makers to answer is thus what kind of new, positive future is proposed (Diluiso et al., 2021). The need for such a comprehensive approach is exemplified by the Coal Commission's proposal to implement a sustainable bioeconomy in the Rheinische Revier (RR), which aims to address the region's structural challenges arising from the phase-out of coal.

In the case of the RR, the Coal Commission proposed the implementation of a bioeconomy as a future guiding concept for the structural change in the region (Coal Commission, 2019). Following this far-reaching energy policy decision in the form of the coal phase-out, this regional structural change in the RR affects large sections of society and requires comprehensive governance. This leads to a complex decision-making process driven by the dynamic interplay of stakeholders and the need to balance economic, social, and environmental considerations - and thus often conflicting objectives. Questions concerning the right balance of environmental protection and the use of resources – fossil- as well as bio-based – are essentially political and societal since they affect large parts of society, including workers, companies, regions and entire nations (Geels, 2014; Muttitt et al., 2023; Nacke et al., 2024; Rauner et al., 2020; Spencer et al., 2018). Hence, there are a variety of opinions about what is desirable in relation to low-carbon transitions that influence the path for society as a whole (Baur et al., 2022; Carbajo & Cabeza, 2019; Newell et al., 2022; Ohlendorf et al., 2022).

A profound understanding of stakeholder perceptions in relation to the bioeconomy is thus crucial since underlying visions, interests and political weight differ (Biber-Freudenberger et al., 2020; Bogner & Dahlke, 2022; Devaney et al., 2017; Hausknost et al., 2017; Hoes et al., 2021; Lühmann, 2020; Patermann & Aguilar, 2021; Schlaile et al., 2017; Vivien et al., 2019). Against this background, identifying transformation routes for a sustainable bioeconomy illustrates a complex task since potential regional trajectories must fulfill three conditions simultaneously. First, they need to be desirable from a sustainability perspective. Second, they must be feasible from a techno-economic perspective. And third, they need to be acceptable from a stakeholder perspective.

Moreover, since the structural change process will have an effect across multiple dimensions, a comprehensive monitoring of the bioeconomy beyond individual technologies is necessary (Bracco et al., 2018; Bracco et al., 2019). Monitoring provides vital insights that inform the adaptation and transformation of bioeconomy trajectories. It can thus serve as basis for subsequent transformation of trajectories. Hence, the next section discusses current research concerning bioeconomy, and specifically with respect to monitoring approaches and stakeholder perceptions.

1.1 State of the Art and Research Gap

Research related to the bioeconomy has received considerable attention in recent years (Wei et al., 2022). However, existing reviews point to a number of different interpretations and perspectives, mirroring the inherent ambiguity and complexity of the field (Bugge et al., 2016; Dieken & Venghaus, 2020; Hausknost et al., 2017). Research efforts are often fragmented, with an emphasis on specific aspects, such as individual technologies, rather than a more holistic view (Bogner & Dahlke, 2022; Bringezu et al., 2021; Egenolf & Bringezu, 2019; Giampietro, 2019; Jander & Grundmann, 2019; Jander et al., 2020). Research projects are predominantly technology-driven and often lack stakeholder involvement and participation (Bogner & Dahlke, 2022). Thus, there is an increased necessity for considering normative aspects beyond purely technological or economic issues (Schlaile et al., 2017; Urmetzer et al., 2021). To do this, a profound understanding and comprehensive monitoring of dimensions the bioeconomy encompasses is prerequisite.

1.1.1 Bioeconomy Monitoring

The bioeconomy is not necessarily sustainable (Stark et al., 2022; Vainio et al., 2019). However, the question of sustainability is central to a desirable transformation process (BMBF & BMEL, 2020b). Technological innovations and key enabling technologies play an important role for achieving the goals set out in bioeconomy strategies (BMBF & BMEL, 2020b; Bröring et al., 2020; EC, 2018c; OECD, 2018c; Waßenhoven et al., 2023). And while related technologies obtain potential to contribute towards sustainability, overcoming existing difficulties and supporting the transition to an economy in line with the SDGs, trade-offs frequently occur (Escobar & Laibach, 2021). Several long-term effects of biotechnologies linked to the bioeconomy concept are not predictable and bring along uncertainties, which makes the implementation of a sustainable bioeconomy as one possible transformation trajectory not uncontroversial (Lühmann & Vogelpohl, 2023; Vogelpohl & Töller, 2021). The implications of new technologies become fully visible only as they become embedded in society, while the possibilities for control diminish (Collingridge, 1981). Early assessment of related technological shifts and their implications for sustainable development is thus vital (Siekmann et al., 2023).

However, bioeconomy targets frequently prioritize competitive advantages, but comprehensive ways to measure and monitor progress are often lacking (Bracco et al., 2018). Many states predominantly monitor the impact of the bioeconomy on Gross Domestic Product (GDP) and employment, which may lead to an inaccurate perception of the overall picture (Bracco et al., 2018; Sturm & Banse, 2021). Beyond that, various existing monitoring approaches address, for example, issues at national or European level (Cingiz et al., 2021; Kardung et al., 2021; Robert et al., 2020; Ronzon et al., 2022b; Ronzon & M'Barek, 2018; Zeug et al., 2019), aspects related to material flows (Schweinle et al., 2020), supply chain effects (Lago-Oliveira et al., 2024; Rossi et al., 2024), its overall size within the economy (Efken et al., 2016; Iost et al., 2019; Kuosmanen et al., 2020), individual sectors, products or resources (Antar et al., 2021; Jafari et al., 2023; Ruf et al., 2022; Többen et al., 2024), or with respect to Life Cycle Assessment (D'Amato et al., 2020; Zeug et al., 2021).

Yet, current literature reviews highlight the need for multifaceted approaches to improving indicators, including creating a tailored set of indicators for specific case studies (Mesa et al., 2024). Moreover, despite the efforts on the European and national level, policymakers frequently lack information to make informed decisions locally or regionally (Bianchi et al., 2024). While environmental and social indicators are present on monitoring approaches on the macro level, they are mainly addressing employment indicators while neglecting broader societal issues (Bianchi et al., 2024). Furthermore, efforts are required to increase interpretability of indicators and related measurement approaches for stakeholders and policymakers (Mesa et al., 2024).

Additionally, since the social and environmental impacts of the bioeconomy are widely anticipated but not quantitatively assessed, there is a mismatch between stated goals and assessment methodologies (Bracco et al., 2018). Hence, a holistic and systematic set of indicators must necessarily include environmental and social aspects of sustainability to account for the inherent stresses on both the ecosystems and the well-being of impacted communities (Bracco et al., 2018). Although certain sectors have made progress in recent years, the strategic objectives set out in policy documents often fall short of their targets, suggesting a scarcity of policy-relevant knowledge (Lühmann & Vogelpohl, 2023). This is emphasized by the point that the scope of transformational strategies is not limited to technological development, but also includes institutional and behavioral aspects (Bracco

et al., 2018; von Braun, 2018). As such, current initiatives to monitor progress towards a sustainable bioeconomy should be strengthened in order to track performance in relation to sustainability and the SDGs (Bogner & Dahlke, 2022; Bracco et al., 2018; FAO, 2024b).

Thus, bioeconomy strategies have yet to achieve more comprehensive integration with global initiatives like the SDGs and other climate change efforts (Aguilar & Patermann, 2020; FAO, 2024b). On this issue, the work of the Food and Agriculture Organization of the United Nations (FAO) is promising. In 2016, FAO established the International Sustainable Bioeconomy Working Group (ISBWG), acknowledging the potential for unintended consequences as the bioeconomy continues to advance (FAO, 2021). As a multi-stakeholder group within FAO, the ISBWG supports countries in their development of policies and strategies for circularity and sustainability in the bioeconomy (FAO, 2021). It functions as an advisory body to the FAO (FAO, 2021). The ISBWG developed a set of desired principles and criteria (P&C) for a sustainable bioeconomy in order to derive a normative understanding of sustainability (FAO, 2021). With reference to these principles, Calicioglu and Bogdanski (2021) state that these principles can be used as a basis for monitoring frameworks and support approaches for systemic assessments of the bioeconomy. Through a meta-analysis of existing literature and technical reports, Calicioglu and Bogdanski (2021) linked SDG indicators to each of the principles developed by the ISBWG. The declared goal is to monitor not only the bioeconomy per se, but explicitly in the context of sustainability (Calicioglu & Bogdanski, 2021). But this work addresses global developments, while bioeconomies are frequently implemented at the regional level. However, it is frequently challenging to make global sustainability goals more tangible in a regional context. In this context, transformation pathways are a useful tool to contribute to a better understanding of possible options and the assessment of potential impacts. They can simplify complex concepts and improve communication with stakeholders and are used in this work for the development of decision alternatives.

Although the work done by the ISBWG and Calicioglu and Bogdanski (2021) provides a sound underpinning upon which this work builds a new indicator system, further modification and refinement is needed. This dissertation thus builds upon previous efforts in monitoring the bioeconomy in relation to sustainability. The developed monitoring

system will subsequently serve as foundation for developing regional transformation trajectories.

1.1.2 Stakeholder Perceptions

While monitoring systems track the progress of the bioeconomy, it is equally important to consider how various societal actors perceive these changes, as their acceptance and understanding of these policies play a crucial role in their successful implementation. As pointed out, stakeholder perceptions, power dynamics and discourses play a crucial role in energy system transitions. This holds true for transformation efforts in the context of the bioeconomy (D'Amato et al., 2022; Holmgren et al., 2022; Leipold, 2021; Lühmann & Vogelpohl, 2023; Neill et al., 2023; Ramcilovic-Suominen et al., 2022; von Braun, 2022; Wolff, 2022). Yet, integrating stakeholders in decision-making processes is widely regarded as central aspect of related political initiatives (BMBF, 2021; BMBF & BMEL, 2020b; EC, 2018c). Related research indicates the existence of various conflicts within the population regarding bio-based, post-fossil transformations, including tensions between growth and sufficiency perspectives, high-tech and techno-sceptic views, and fossilist and post-fossilist visions (Bugge et al., 2016; Eversberg & Fritz, 2022; Hausknost et al., 2017). Current research indicates that there are indeed differences in the acceptance of bioeconomic technologies, which should be taken into account for a successful transformation (Macht, Klink-Lehmann, & Hartmann, 2023; Macht et al., 2022). However, it is unclear what stakeholders' perceptions concerning the bioeconomy actually are.³

Existing research on stakeholder perceptions focuses mainly on technical aspects such as acceptance or in relation to genetics, chemistry and biotechnology, but lacks a holistic perspective to consider the complex social and economic implications of the bioeconomy (Golembiewski et al., 2015; Sanz-Hernández et al., 2019). It is further indicated that there is a lack of transformative knowledge particularly in terms of education on the bioeconomy (Urmetzer et al., 2020). Moreover, there is a lack of studies from the social sciences and particularly on the bioeconomy's socioeconomic impacts (Sanz-Hernández

³ A comprehensive review of stakeholder perceptions on the bioeconomy is provided in section 6.2.

et al., 2019). In particular, studies related to political science remain scarce (Böcher et al., 2020).

There is a need to integrate more diverse understandings of the bioeconomy and consider the perceptions of actors from various groups of society (Lühmann & Vogelpohl, 2023; Riemann et al., 2022). To address the multifaceted challenges of the bioeconomy, and contribute to addressing resulting problems in decision-making, perspectives of multiple societal actors must be considered (Bogner & Dahlke, 2022; FAO, 2024b). Investigating these perceptions is therefore an important part of this work.

Overall, existing research approaches tend to be fragmented and focus on individual aspects rather than a holistic view. Research gaps remain in understanding stakeholder perceptions and developing comprehensive monitoring systems that address the social, economic, and environmental impacts of the bioeconomy.

1.2 Research Objective

This dissertation is designed precisely to fill the indicated knowledge gaps in the scientific literature. The objective of this work is therefore to combine the perceptions of stakeholders and transformation trajectories in a decision support system to identify sustainable transformation trajectories for the bioeconomy. These regional transition trajectories must fulfill three conditions. First, they need to be desirable from a sustainability perspective. Second, they need to be techno-economically feasible. And third, they need to be acceptable from a stakeholder consensus perspective. To achieve this, an approach is needed to navigate the complexities of bioeconomy transitions. In particular, decision support systems that integrate the multiple dimensions can help by providing a broad foundation for prospective decision-making.

Decision support in the context of the bioeconomy that accounts for ethical and practical issues of policymaking requires a strong conceptual foundation. In this connection, Amartya Sen's work on how societies can better account for the diversity of human interests and values in collective decision-making – particularly in the context of group decision-making and sustainable development – can provide crucial guidance (Sen, 2017a). Therefore, the operationalization of Amartya Sen's work on collective decision-making constitutes the foundation for the development of the decision support system.

The developed approach will be applied in the RR, as this region is particularly affected by the coal phase-out and is being developed as a model region for a sustainable bioeconomy. In doing so, it contributes to an improved understanding of current transformation processes in the context of the transition to a bioeconomy and enables the derivation of policy recommendations. This approach will provide a sound basis for policy analysis and advice by offering insights into actor perceptions and transformation dynamics in the context of a structural change process.

Key components of this work are therefore the research on subjective stakeholder perceptions, the development of a comprehensive monitoring system and regional transformation trajectories, and the integration of these core elements into a decision support system. Thereby, it builds on previous research efforts and contributes to existing knowledge by bridging the gap between global efforts and the regional level.

1.3 Relevance and Actuality

Addressing this gap in research is crucial given the importance of the issue for academia, policymakers and society. This is evident not least from the wide range of research activities and the development of political strategies from the international to the regional level.

Evermore countries globally are adopting policy strategies aimed at implementing a sustainable bioeconomy (Dietz et al., 2024; OECD, 2018c; Proestou et al., 2024; von Braun, 2018). There is a recognizable global trend towards realizing that questions of regional implementation are becoming increasingly relevant (Dietz et al., 2024). In the European Union (EU), achieving a sustainable European bioeconomy is regarded as a necessity to reduce carbon as agreed in the objectives of the Paris Agreement (EC, 2018c). The European Green Deal (EGD) underlined the EU's commitment to strengthen efforts to achieve an economy where economic growth is decoupled from the use of resources and without net emissions of greenhouse gases by 2050 (EC, 2019a). This is also reflected in the increasing number of EU regions adopting fully dedicated bioeconomy strategies at regional level (Haarich et al., 2022).

In the German research landscape, the bioeconomy is equally seen as a central building block in the efforts to achieve the SDGs (BMBF, 2010, 2014, 2017, 2021; Prochaska &

Schiller, 2021). It is specifically emphasized that the complex interactions and unexpected side effects only become apparent in the systemic approach of an overarching social, political and economic perspective (BMBF, 2021). The bioeconomy is explicitly perceived as a societal transformation that will only succeed if it is widely understood, advocated and supported (BMBF, 2021). Addressing and better understanding the normative issues in the context of a political bioeconomy agenda is thus vital (BMBF, 2021). The initiative *Bioeconomy Science Year 2020/21* (Wissenschaftsjahr Bioökonomie 2020/21, in German) by the German Federal Ministry of Education and Research (BMBF) along with several publicly-funded research projects further emphasizes the importance of the matter for science, politics and the general public.

As early as 2013, NRW was the first state in Germany to publish key points of a bioeconomy strategy (Landesregierung NRW, 2013). Progress concerning the implementation of a sustainable bioeconomy has since been a stated goal and was reaffirmed in 2023 (Landesregierung NRW, 2023). Moreover, a bioeconomy council comprising 15 experts was set up in 2024 to begin a two-year process of developing a strategy in collaboration with regional stakeholders (Landesregierung NRW, 2023). In addition, an interministerial bioeconomy working group has been established (Landesregierung NRW, 2023).

A key role in harnessing scientific synergies on a regional level further constitutes the work of the Bioeconomy Science Center (BioSC). The BioSC, formed in 2010, brings together scientific expertise from the universities of Aachen, Düsseldorf and Bonn as well as the Jülich Research Center (BioSC, 2024a). Addressing the various drivers of bio-based social transformations comprehensively also constitutes a vital goal of the BioSC (BioSC, 2024a; Schurr & Slusarczyk, 2022).

The research objective of identifying sustainable transformation trajectories is thus highly relevant to policymaking and situated in a dynamic research and policy environment. Political strategies and academic research initiatives dealing with the implementation of a sustainable bioeconomy – from the European to the regional level – underline the importance of the overall concept as well as the value of societal and participatory approaches in decision-making in order to design acceptable transformation trajectories (BMBF, 2010, 2014, 2017, 2021; EC, 2005, 2012, 2018c; European Council,

2007; Landesregierung NRW, 2013, 2023). The topic of this work is therefore timely and relevant in several respects and across multiple dimensions.

To attain internationally agreed climate goals, the world needs to phase-out coal quickly and effectively (Jakob et al., 2020). Involving major stakeholders in the process is crucial to its success (Jakob et al., 2020). For successful transformation processes in the context of the energy system, it is thus vital to consider issues beyond technology and account for the human dimension (Nature Energy, 2016; Otto et al., 2021; Steg et al., 2021).

Harnessing the technology-based opportunities for sustainable development provided by the bioeconomy requires effective governance approaches (Dietz et al., 2023; Patterson et al., 2017; Stark et al., 2022). A high level of political coordination is therefore an important prerequisite for a sustainable bio-based transformation (Dietz et al., 2023). As multiple regions globally aim to phase-out coal and implement sustainable bioeconomies, insights from the transition process in the RR and the transferability of the approach developed in this thesis hold relevance far beyond the region itself.

1.4 Structure

To achieve the research objective, the following structure is pursued. First, the analytical framework in the form of the decision support system is developed. Second, the developed approach is applied in the context of the RR. And third, the results are discussed and contextualized within the overall research frame.

Subsequent to this introduction, the next chapter will introduce the concept of the bioeconomy in more detail. In particular, the emergence of the concept and how it might contribute to addressing global challenges will be elaborated. Major developments, trends as well as critiques of the concept will be also the subject of discussion. Since the bioeconomy concept is frequently perceived as ambiguous, it will be defined and delineated from related concepts, such as the Green Economy (GE) and the Circular Economy (CE). Furthermore, bioeconomy visions or ideal types of what a bioeconomy comprises will be introduced and strategies that play a key role in shaping bioeconomy policies are addressed. The chapter concludes by distinguishing between bioeconomy and sustainable bioeconomy characteristics and their implications for monitoring approaches.

The following chapter continues by introducing the conceptual foundation necessary for pursuing the research objective and developing the decision support system. A central component in this regard is the concept of sustainability, which serves as a guiding principle for the development of the decision support system and has various implications for the overall research approach, including the methodology, development of the monitoring framework and regional transformation trajectories. Subsequently, vital aspects concerning the governance of the transformation process towards a sustainable bioeconomy, in particular concerning complex problems and stakeholder engagement are discussed. In addition, transformation pathways, namely the Shared Socioeconomic Pathways (SSPs) are introduced, which will subsequently inform the development of regional paths. The aspect of regionalization in the RR is, followed by a section summary, conclude this part.

Central to the thesis are Amartya Sen's considerations on collective choice, which will be introduced and discussed in the subsequent chapter. Sen examines how societal decisions can be made that take into account multiple values and perspectives. His work builds on the classical works on social choice theory (SCT) but departs from them in various ways. Related concepts, such as public reasoning and plural grounding, are interpreted and applied in the present work in the context of group decisions and sustainable development.

This requires a methodology that makes it possible to integrate various perspectives into the decision-making process. The methods of the Multiple-Criteria Decision Aid (MCDA) allow for that and will thus serve as the methodological basis for the development of the decision support system. The methods are particularly suitable for complex decision-making processes in which various conflicting objectives must be considered. The application of a multi-criteria approach hence helps to ensure that aspects are included that go beyond a single belief and value system. In the context of this work they provide a useful tool to support coping with complex problems in the context of sustainability transformations and group decision-making situations.

The analytical framework developed is based on the MCDA process and involves four steps, which are applied in the context of the transformation process in the RR. In *Step I*, the decision problem is defined, and the relevant stakeholders are identified. *Step II*

consists of structuring the decision problem by identifying the relevant criteria and decision alternatives. For this purpose, a new systematic approach to developing a monitoring system and regional transformation trajectories is developed. The core of *Step III* is determining the subjective criteria weightings of the stakeholders. Finally, in *Step IV* the previous steps are merged in that the subjective stakeholder assessments, which are expressed as weighted decision criteria, are brought together with the developed transformation trajectories to arrive at ranking of decision alternatives. To consider not only the individual rankings but also the group perspective, a group decision support system is used, which combines the individual results of all stakeholders into a joint ranking. The rankings are not to be understood as predetermined solutions. Instead, they are intended to serve as a starting point and to enrich a constructive discussion in order to find compromises and promote mutual understanding.

The results are discussed, contextualized and based on the analysis, key political implications are derived and the overall research approach is evaluated. To conclude, key aspects, such as the approach's transferability and potential starting points for future research, are highlighted to guide further exploration and practical application.

1.5 Delimitation

While this work pursues a comprehensive approach towards the bioeconomy, certain aspects fall outside its scope. Those concern aspects of SCT as well as elements with regard to the bioeconomy.

Questions dealing with group decision-making attracted the interest of researchers and scholars for centuries (Suzumura, 2002). As an approach to reach collective decisions, SCT has been applied in various contexts and across several different disciplines, including political science and welfare economics (Chambers & Echenique, 2016; Dryzek & List, 2003; Feldman & Serrano, 2006; Patty & Penn, 2019). It can be traced back to the period of the European Enlightenment and builds upon the works of the French mathematicians Borda and Condorcet (Condorcet, 1994; Sen, 2017a). Motivated to develop a framework for democratic and rational decisions while considering the interests and preferences of a group of people, their approaches towards social problems were primarily mathematically – even though Condorcet also discussed several

possibilities of how individual, as well as collective reasoning, can impact social decisions (Condorcet, 1994; Lukes & Urbinati, 2012; Sen, 2017a). And while Condorcet's work regarding the importance of reasoning and education were less prominent in the recent development of social choice theory, Amartya Sen recognizes in the "belief in the reach of human reasoning" the connecting element between the earlier writings during the period of Enlightenment and modern SCT (Sen, 2017a, p. 466). Our current understanding of modern SCT is thus deeply embedded in an axiomatic structure based on democratic values (Sen, 2017a). The mathematical approaches related to formal social choice mainly applied axiomatic requirements to strive for an *optimal* solution. Yet, in the context of societal transformation processes, it is reasonable to reflect on this aspiration and the related axiom system, which is normative in its nature.

SCT and its mathematical foundations, along with related impossibility results, have been intensively studied for several decades by various scholars, among them Kenneth Arrow, Eric Maskin and Kotaro Suzumura. Thus, exhaustive and well-established academic literature exists dealing with the formal and mathematical properties of SCT (Arrow et al., 2011; Arrow, 2012; Maskin et al., 2014; Sen, 2017a; Suzumura, 2016). Therefore, this thesis will not conduct an analysis of the formal mathematical proofs and related impossibility results. Instead, emphasis lies on the constructive parts of normative SCT based on the foundation of related works by Amartya Sen on collective choice.

A further delimitation concerns the concept of the bioeconomy. While the bioeconomy will be a central part of this dissertation, it is not an objective of this work to examine biotechnological products or processes in detail. Instead, the focus lies on the development of regional transformation trajectories and stakeholder perceptions concerning the bioeconomy.

This work integrates a multitude of partly very extensive concepts. In order to maintain argumentative clarity, not all of them can be fully discussed. Therefore, further references are given in the form of footnotes at the appropriate places. These are frequently literature reviews.

As a general remark, the policy recommendations derived in this work are not intended to be understood as imperatives. They offer alternatives for potential courses of action that must be debated since they commonly necessitate prioritizing certain perceptions and

interests. Yet, given the profound policy challenges and urgency resulting from climate change, the difficulties associated with transformations in the context of the energy system, complexity of concepts as the bioeconomy, but also great opportunities that surround the subject, broadening informational space for decision-makers in the highly relevant and dynamic landscape of the bioeconomy is vital to contribute towards informed, balanced, and forward-looking policies.

2 Contextualizing Bioeconomy

To navigate the complex decision environment in the context of the bioeconomy, a profound understanding of the bioeconomy itself is prerequisite. Thus, this chapter proceeds by illustrating the foundation and emergence of the concept. This includes its major developments and trends as well as its linkage to global challenges and related expectations. In addition, drivers, opportunities and critical perspectives towards the bioeconomy are laid out. The concept is then differentiated and delineated from related concepts. Subsequently, major definitions are assessed and a working definition is determined.

To facilitate a deeper understanding, existing, underlying visions associated with the bioeconomy within academic literature are introduced. These represent a useful analytical tool for differentiation in the course of this thesis. Furthermore, since strategies are an important tool for guiding policy in various cross-sectoral policy fields, vital developments on the European, National, and regional levels in relation to the adoption of coherent bioeconomy strategies are discussed. Finally, general aspects relating to bioeconomy monitoring in connection with the SDGs are addressed and a chapter summary is provided.

2.1 Foundations

2.1.1 Fossil and Bio-Based Resources

To lay the groundwork for exploring the fundamental aspects of the bioeconomy, it is important to first understand its role in the global transition from fossil-based systems to sustainable alternatives. Respecting the planetary boundaries is an essential part of related transformation processes intended to direct development towards a more sustainable path (Folke et al., 2011; Steffen et al., 2015). Since the Industrial Revolution, fuels based on fossil resources have played a vital role in the global economy and contributed notably to shifting from societies based on agriculture towards new forms of urban settlements (see e.g., Landes, 1969). However, their widespread utilization causes severe problems and the overall reserves are limited (see e.g., IPCC, 2019; IPCC, 2021). The substitution or reduction of fossil resources, for example through the improvement of technical, chemical

or biological processes, is essential. The use of bio-based resources can reduce or, in some cases, even replace them. The distinction between resource types is crucial. Thus, the following section illustrates the main differences.

Fossil resources are natural resources, such as coal, oil, and natural gas, formed millions of years ago from the remains of plants and animals (Lewandowski et al., 2018, p. 6; Ritchie & Rosado, 2017). These resources are considered non-renewable because they cannot be replenished on a human time scale and will eventually be depleted. Fossil fuels have been and are still widely used as energy sources for transportation, heating, and electricity generation due to their high energy content and ease of use (Pirani, 2018; Ritchie & Rosado, 2017).

Bio-based resources, on the other hand, are derived from renewable biological sources such as plants, microorganisms, and animals (Kircher, 2022b; Lewandowski et al., 2018, pp. 9, 10; Pillen et al., 2022; Tursi, 2019; Windisch & Flachowsky, 2022). These resources can potentially be sustainably produced and can include crops, forestry, and waste materials such as agricultural residues, food waste, and municipal solid waste (Brosowski et al., 2016; Lewandowski et al., 2018, pp. 9, 10; Schüch & Hennig, 2022; Tursi, 2019). They can be used to produce a range of products, including biofuels, biochemical and bioplastics, as well as food and feed (Dahiya et al., 2020; Lewandowski et al., 2018, p. 14; Ramchuran et al., 2023).

The central difference between fossil and bio-based resources lies in their origin and renewability. Fossil resources are non-renewable and finite, while bio-based resources are renewable and can be produced sustainably. Using fossil resources has substantial environmental consequences, such as greenhouse gas emissions and pollution (IPCC, 2019, 2021). In contrast, utilizing bio-based resources can offer ecological benefits by reducing greenhouse gas emissions, waste, and dependence on non-renewable resources (Kaup & Selbmann, 2013; Musonda et al., 2021). Yet, as with utilizing fossil resources, the sustainable production of bio-based resources requires careful management to avoid negative impacts on land use, water use, and biodiversity (Tursi, 2019; Wang & Azam, 2024).

While bio-based resources are renewable, they are not infinite since they ultimately rely on natural resources, such as land, water and soil (Erb & Gingrich, 2022;

Lewandowski et al., 2018, p. 12). Therefore, a conscious use of available resources is imperative. A targeted allocation is desirable since, in this way, the greatest possible advantages can be achieved regarding sustainable development (see e.g., Musonda et al., 2021). The objective is not to increase agricultural production merely for the bioeconomy. Instead, the focus is on utilizing existing waste and leftover resources and products that already exist in a different setting. Consequently, designing more efficient resource networks and value chains is crucial for further developing the bioeconomy (Lago-Oliveira et al., 2024).

A central resource for the bioeconomy is biomass, including waste materials, crops and forestry products, such as wood and residuals (Lewandowski et al., 2018, p. 10; Szarka et al., 2021; Tursi, 2019). Residuals, in particular, gain significant relevance if regarded as part of a circular economic system (Casau et al., 2022). These often form the basis for the development and production of biofuels, biochemical platform materials and further bio-based products (Kim et al., 2023; Lee et al., 2022; Takkellapati et al., 2018; Tursi, 2019). Moreover, microorganisms and enzymes are also essential in the bioeconomy, as they are used in industrial biotechnology to produce a wide range of products (Birner, 2018, p. 28; Kim et al., 2023; Tursi, 2019). Another important aspect is the energetic use of biomass and bio-based raw materials (Szarka et al., 2021). However, all of that relies on energy and natural resources, especially land and soil, as those are required for any production process related to bio-based products. The quantities of biomass required for the products, process chains and future visions are limited (Fleischmann et al., 2024). Conflicting objectives concerning the best-possible biomass allocation, for instance, will thus also play a role within Germany and need to be addressed (Lubjuhn & Venghaus, 2024; Musonda et al., 2021; Szarka et al., 2021).

Understanding how a sustainable bioeconomy can contribute to effectively addressing the challenges and opportunities resulting from the shift from fossil- to bio-based resources necessitates an understanding of the historical roots and conceptual evolution of the bioeconomy.

2.1.2 Emergence of the Concept

It is commonly assumed that the first use of the terms *bioeconomics* originated in the context of scientists discussing the potential industrial consequences of progress in

biology (Birner, 2018, pp. 18,19; Bonaiuti, 2014, p. 54). In this connection, *bioeconomics* was coined in the late 1960s to describe an economic system that acknowledges the biological foundation of economic pursuits in general (Birner, 2018, pp. 18,19; Bonaiuti, 2014, p. 54). An integral aspect of adopting the term *bioeconomics* was the concern that unrestricted growth would conflict with the fundamental laws of nature (Birner, 2018, pp. 18,19; Bonaiuti, 2014, p. 54). This fear became known to a broader public at the latest with the publication of the report *The Limits to Growth* (Meadows et al., 1972). On the other hand, the term 'bioeconomy' seems to have emerged in a different context, namely in relation to industrial and commercial domains (Birner, 2018, p. 19; Gottwald, 2016, p. 11; von Braun, 2014, p. 7).

The intentional promotion of the bioeconomy concept by staff members of the European Commission (EC) was the primary reason for its emergence as an influential policy concept in Europe (Birner, 2018, p. 19). According to Christian Patermann, who served as Program Director of Biotechnology, Agriculture and Nutrition in the *Directorate General for Research, Science and Education of the European Commission* at the time, it became apparent that by embracing the concept of the bioeconomy, the EU can capitalize on emerging options for future development (Birner, 2018, p. 19; Kircher et al., 2022; Patermann & Aguilar, 2018). One major opportunity illustrated by adopting the concept is utilizing the new potential offered by biotechnologies (Birner, 2018, p. 19). Another possibility is substituting fossil-derived resources with bio-based ones for material and energy applications (Birner, 2018, p. 19).

During the development of the bioeconomy concept in the EU, the term *knowledge-based* was appended to create the *knowledge-based bioeconomy*, consistent with the prevailing EU innovation policy (Birner, 2018, p. 19). The notion of a knowledge-based economy aligns with the objective of attaining economic progress via high-tech industries, necessitating investments in innovation and a proficient workforce (Birner, 2018, p. 19). Following several workshops and conferences to further develop the concept, the Cologne Paper was published and highlighted two central aspects regarding the EU's understanding of the bioeconomy (Birner, 2018, p. 19; European Council, 2007).

According to the report, biotechnology is expected to play a vital role in Europe's economy by 2030 as a substantial pillar essential for sustainable economic growth,

employment generation, energy supply, and upholding living standards (European Council, 2007, p. 4). Moreover, it emphasized the utilization of crops as a renewable source of industrial feedstock to manufacture biofuels, biopolymers, and chemicals (European Council, 2007, p. 4). It also envisioned that enzymatic hydrolysis and gasification technologies would become a standard practice for converting lignocellulosic biomass by 2020, thereby providing extensive access to feedstock supplies for bioprocesses and the production of transportation fuels (European Council, 2007, p. 4). These central aspects of the concept still influence the current debate concerning future directions of bioeconomy implementations.

Concurrently with the EU institutions' efforts to develop the bioeconomy concept, attempts were made to introduce it within the EU member states (Mubareka et al., 2023). Overall, the EU has been an important driver and often provides the blueprint for bioeconomy developments worldwide (Kircher et al., 2022; Patermann & Aguilar, 2018). Moreover, the EU continues to exert notable influence, with its decisions and developments affecting bioeconomy strategies and implementations globally (Kircher et al., 2022; Patermann & Aguilar, 2018).

2.1.3 Global Trend Towards Bioeconomy

The bioeconomy also gained in relevance beyond the EU. In the past decades, there has been a global trend towards adopting bioeconomy-related policies, with more than 50 countries implementing new policies and strategies worldwide (FAO, 2024a; Global Bioeconomy Summit, 2018; von Braun, 2018). As the importance of establishing a sustainable economic system and adopting a sustainable lifestyle increases, the necessity for such transformation becomes more pressing and recognizing this challenge has become a major driver of the bioeconomy concept (Abigail Muscat et al., 2021; von Braun, 2018). It is important to note that focusing on the bioeconomy does not automatically imply sustainable resource use, for instance, due to the possibility of policy and market failures (Gawel et al., 2019; Klauer & Schindler, 2022; von Braun, 2018). Instead, the concept must be intentionally shaped to play a vital role in addressing some of the most consequential challenges faced by society (Aguilar & Patermann, 2020; Aguilar et al., 2019; von Braun, 2018).

Bioeconomy strategies are being developed and implemented by both high and middle-income countries worldwide (Birner, 2018; Proestou et al., 2024; von Braun, 2018). The degree to which policies and strategies concentrate explicitly on the bioeconomy varies considerably, with some countries emphasizing related elements such as biotechnology or renewable energy (FAO, 2024a; Meyer, 2017). In order to facilitate global collective action, it is essential to share new bioeconomic knowledge generated in developed economies with developing economies and support adapting these strategies to local circumstances (Issa et al., 2019; von Braun, 2018).

To understand the concept of the bioeconomy, it is crucial to consider the broader societal, technological, and economic transformations and challenges that are interconnected with it (Aguilar & Patermann, 2020; Aguilar et al., 2019; von Braun, 2018). For this purpose, the global challenges in the context of which the bioeconomy is embedded must first be considered.

2.1.4 Challenges and Expectations

Climate change, the loss of biodiversity, rising resource consumption and questions of land limitation constitute global challenges that require attention (FAO, 2024b; IPBES, 2019; IPCC, 2019, 2021, 2023; UN DESA, 2022; UNCCD, 2022; UNEP IRP, 2019). Actions and transformations of multiple systems are needed to contribute in addressing global challenges (FAO, 2024b; Sachs et al., 2019; UN, 2015). The bioeconomy is commonly mentioned as a potential way to address several global challenges, including food security, population growth, resource scarcity, and climate change (Aguilar & Twardowski, 2022; BMBF & BMEL, 2020b; EC, 2018c; FAO, 2024a; Patermann & Aguilar, 2021).

For instance, it is discussed that strengthening the bioeconomy can help increase food security through sustainable agricultural practices and the development of novel food sources (Biber-Freudenberger et al., 2020, pp. 3-4; FAO, 2024a, 2024b; Gomez San Juan et al., 2022). By leveraging biotechnology and precision agriculture, the bioeconomy can increase crop yields and reduce food waste, thereby ensuring that people have access to adequate and nutritious food (Biber-Freudenberger et al., 2020, pp. 3-4). In this regard, the growing demand for resources through population growth can be met by developing innovative technologies and materials (Aguilar et al., 2019; Biber-Freudenberger et al.,

2020, pp. 3-4; BMBF & BMEL, 2020a). Further, it is frequently claimed that by adopting circular economy (CE) principles and reducing waste, the bioeconomy aims to conserve natural resources and prevent further environmental degradation in striving to respect planetary boundaries (Biber-Freudenberger et al., 2020, pp. 3-4). Another notable benefit often associated with bioeconomic transformation pathways is the critical role it can play in mitigating climate change (Lubjuhn & Venghaus, 2024; Többen et al., 2024). Through sustainable land use practices, renewable energy production, and the development of low-carbon materials, the bioeconomy can contribute to reducing greenhouse gas emissions and promote a more sustainable future (Aguilar & Twardowski, 2022; Biber-Freudenberger et al., 2020, pp. 3-4).

Thus, overall, a sustainable bioeconomy is often mentioned as a potential approach and transformation option. However, related shifts do not take place in isolation and will have an impact on sectors and aspects of life that are not originally intended. While trade-offs occur in any interrelated, complex system, monitoring and assessing them is crucial to minimize or, if possible, prevent indirect or unintended negative impacts. Given the interdependent nature of the SDGs and the far-reaching influence of the bioeconomy, this aspect is of particular relevance (Calicioglu & Bogdanski, 2021; Maksymiv et al., 2021). Hence, despite the potential, a sustainable bioeconomy will not solve all problems simultaneously. Moreover, numerous factors need to be taken into account.

It is important to recognize that the bioeconomy is part of a larger societal, technological, and economic shift toward sustainability (BMBF, 2010; BMBF & BMEL, 2020a; EC, 2018c; von Braun, 2018, p. 83). This transformation requires new scientific and behavioral approaches and institutional changes that provide long-term incentives for sustainable farming, sound bio-resource management, and industrial development. International collaboration is important, particularly in sharing knowledge and best practices between different regions (Aguilar et al., 2019; Bößner et al., 2021; Schütte, 2018; von Braun, 2018, p. 83).

It is crucial to establish a comprehensive evaluation of the impact of bioeconomy on economic growth, development, and food security, especially for the disadvantaged (Braun, 2015; Thompson, 2012). Further, it is essential to assess trade-offs between various objectives. Overusing biomass for bioenergy, for instance, could lead to a

reduction in food availability and may have adverse environmental effects (Braun, 2015; Jordan et al., 2024; Jordan et al., 2023; Thompson, 2012; Tomei & Helliwell, 2016).

Biomass is traded globally, and Germany imports large quantities of biomass (Domnik et al., 2016). Thus, effects on trading partners should also be considered when striving for a sustainable bioeconomy. That specifically applies in relation to resource-rich countries or developing economies (OECD, 2018d). Bioeconomy investments in these countries have the potential to provide multiple benefits, including agricultural growth, energy security, and employment opportunities (Braun, 2015). However, a balance between food and industrial demand for biomass is essential to avoid the risk of positive outcomes in some countries causing negative impacts in others (OECD, 2018d).

Expectations concerning a sustainable bioeconomy are manifold. Through the use of biological science, technology and innovation for the responsible production and use of biological resources, it is expected that environmental and social benefits for society can be realized (FAO, 2024a; Gomez San Juan et al., 2022; Patermann & Aguilar, 2021). It is assumed that technology and innovation thus hold the potential to address and reduce sustainability trade-offs (FAO, 2024a). This is underlined by the widespread incorporation of science, technology and innovation into bioeconomy strategies (BMBF & BMEL, 2020a; EC, 2018c; FAO, 2024a). It is therefore useful to explore related sectors and drivers of the bioeconomy.

2.1.5 Sectors, Drivers and Opportunities

As the bioeconomy is a cross-sectional topic and not limited to any particular sector only, comparable to digitalization, effects across various dimensions are expected, but challenging to measure (von Braun, 2018, p. 82). Which parts of the economy and which sectors are considered to be part of the bioeconomy differ between countries (Lier et al., 2018; Wackerbauer, 2022). In the case of Germany, full or partly included sectors involve agriculture, the food industry, forestry, the pulp and paper industry, pharmaceutical industry and the chemical industry (Kuosmanen et al., 2020; Lier et al., 2018). However, exact estimations are frequently challenging, as is the case in the chemical or pharmaceutical industry since the share of bio-based materials used is difficult to assess and calculate (Kuosmanen et al., 2020; Lier et al., 2018).

The key drivers of the bioeconomy relate to aspects concerning organizations, questions of social behavior, policies, market design and technology (Abigail Muscat et al., 2021). Especially technological progress is considered as important (BMBF & BMEL, 2020a; EC, 2018c; FAO, 2024a; OECD, 2018a). Around a third of the measures set out in the specific strategies are closely linked to technological development and the promotion of innovation (FAO, 2024a).

Biotechnology is thus key to the scientific and innovative underpinnings of bioeconomy policies developed in many countries (Aguilar et al., 2019). A central difference between traditional forms of the bioeconomy and modern approaches is the link towards and integration of novel technologies (Aguilar et al., 2019; OECD, 2018c). Therefore, technology, research and innovation play a pivotal role in achieving these objectives (Aguilar et al., 2019; OECD, 2018c). Related bioeconomy innovations can be categorized into four types, namely substitute products, new products, new processes, and new behavior (Bröring et al., 2020). Moreover, Key Enabling Technologies (KETs) could play an important part in contributing to progress towards the SDGs (Heiden & Lucas, 2022; Laibach et al., 2019). KETs are characterized as multidisciplinary and knowledge-intensive technologies that are driving profound transformations for the modernization of industries (Waßenhoven et al., 2023). For the bioeconomy, initial studies suggest that those could include, for instance, genetic modification of plants, bioinformatics, advanced materials and bio-refineries (Laibach et al., 2019; Waßenhoven et al., 2023).

In the case of the bioeconomy, an emerging interindustry business ecosystem, especially with respect to the food and chemical industry, can be observed (Waßenhoven et al., 2021). Policy approaches towards these innovation ecosystems differ between countries, as does success (Philp, 2018; Philp & Winickoff, 2019; Schütte, 2018; Stadler & Chauvet, 2018). Similarly, the success of shifting towards or implementing sustainable and economically attractive value chains and associated innovation ecosystems varies notably (Philp & Winickoff, 2019). Regional characteristics play a crucial role here since the availability of resources, infrastructure but also aspects such as waste management or acceptance among the respective populations can differ considerably (Philp & Winickoff, 2019).

Policies are generally considered an essential driver for progress in relation to a sustainable bioeconomy (Devaney et al., 2017; El-Chichakli et al., 2016; Abigail Muscat et al., 2021). The importance of international coordination and harmonization of respective policy approaches is repeatedly emphasized (Aguilar & Patermann, 2020; Dietz et al., 2023; El-Chichakli et al., 2016). To move towards the SDGs and goals stated in current policies, however, additional effort is required (Heimann, 2019). Yet, policymakers at regional or local level frequently face difficulties since current approaches for measuring focus predominantly on the macro scale (Bianchi et al., 2024). This further strengthens the need for the approach developed in this thesis.

Human behavior further constitutes a crucial factor and potential driver for successful transformation processes (Abigail Muscat et al., 2021; Nature Energy, 2016; Steg et al., 2021). To ensure sustainable consumption and waste reduction, for instance, socio-economic behavior must be taken into consideration alongside bioeconomy policies (von Braun, 2018, p. 83). To promote healthy lifestyles, education, information, and nudging are potential options to try influencing consumer behavior (Abigail Muscat et al., 2021; von Braun, 2018, p. 83). This is vital since questions of consumer acceptance of biobased products will play an important role in implementing a sustainable bioeconomy (Macht, Klink-Lehmann, & Hartmann, 2023; Macht, Klink-Lehmann, & Venghaus, 2023). The investigation of subjective stakeholder perceptions in this work contributes to improved understanding of this human factor as part of the transition.

The transformation towards a sustainable bioeconomy presents an opportunity and a challenge for various actors, including governments, farmers, scientists, businesses of all sizes and society as a whole (Moesenfechtel, 2022; von Braun, 2018, p. 83; Wensing et al., 2019; Wilde & Hermans, 2024). The transformational strategies required to achieve a sustainable bioeconomy will involve not only technological and behavioral changes but also institutional shifts (OECD, 2018b; Wilde & Hermans, 2024). That includes the development of regulatory frameworks and long-term incentives to encourage sustainable practices among industry, consumers, and resource managers (Abigail Muscat et al., 2021; von Braun, 2018, p. 83; Wilde & Hermans, 2024).

Despite the widespread expectations and opportunities, the bioeconomy is not a solution for all problems humanity faces. Thus, the concept and associated developments are not uncontroversial.

2.1.6 Limitations and Criticism

In addition to the positive perception of the concept and its adaptation in policy and funding schemes, there was considerable criticism relatively early on (Allain et al., 2022). In this regard, Birner (2018, p. 24) distinguishes two main categories of criticism.

The first type of criticism concerns the foundation of the entire concept. Proponents of this view contend that the bioeconomy essentially represents the neoliberalization of nature and critics of this view criticize the dominant neoliberal ideology that has shaped its development (Birch, 2006; Birch et al., 2010; Birner, 2018). It is also argued that the bioeconomy concept reflects a neoliberal regime, which imposes market values as the primary ethical standard in society, thereby subjecting all facets of life to market rule (Birch, 2006; Birch et al., 2010; Birner, 2018). Likewise, the powerful influence of these paradigms on research policy is criticized (Levidow et al., 2012, 2013). In this connection, Giampietro (2019, p. 154) argues that there is still confusion concerning respective terms and underlying narratives used in relation to the bioeconomy that illustrates an obstacle for an informed discussion. Additionally, Giampietro (2019, p. 154) points out that various resource models and narratives presented indicate that the current EU narratives explicitly promote the neoclassical economists' claim of substituting any limiting production factor with technological innovation. He further states that the EU and bioeconomy narratives, as presented in global politics and by influential interest groups, are based on neoclassical models that support a top-down planning strategy of technological solutions, typical of neoliberal ideology (Giampietro, 2019).

Other criticisms allege that an alliance of biotechnology, chemical, food, pharmaceutical and agricultural companies is working on the commercial seizure of all living things (Gottwald & Krätzer, 2014). Gottwald and Krätzer (2014) state that the major areas of the bioeconomy can lead to a mindset that reduces animals and plants to mere biomass, and warn that this trend may eventually extend to humans as well, raising ethical concerns. Moreover, contrary to advocates of the concept, Gottwald and Budde

(2015) have put forth the argument that implementing the bioeconomy could lead to land grabbing and threaten global food security (Birner, 2018).

The second form of critique recognizes the potential of the bioeconomy to promote environmental sustainability in modern economic systems (Birner, 2018). However, it points out that the approaches that have been promoted under the label of bioeconomy may not necessarily contribute to achieving this potential (Birner, 2018; Klauer & Schindler, 2022). Therefore, this criticism aims to prevent the misuse of the term *bio* to portray a fundamentally non-sustainable economic system as beneficial for the environment (Birner, 2018). The focus should be on ensuring that innovations in the life sciences are used to facilitate a transition towards a truly sustainable economic system and not for business-related goals (Birner, 2018). It is assumed that the problem of misusing the term is particularly prevalent in the German-speaking area as it is often interpreted in connection to organic farming (Dallendörfer et al., 2022).

Besides the general criticism of the concept, the underlying foundation and corresponding assumptions, there are also criticisms that relate specifically to the case of Germany. Similar to Birch (2006), Lühmann and Vogelpohl (2023) argue the bioeconomy project in Germany can be regarded as a political initiative with the objective of providing a technological solution to sustain the current neoliberal capitalist system that falls short of its promise to drive social-ecological transformation and fails to attract a more diverse group of stakeholders. Thus, it thereby contributes to maintaining the current unsustainable social order (Lühmann & Vogelpohl, 2023). This type of criticism relates to the first category as described by Birner (2018).

As Eversberg and Fritz (2022, p. 973) pointed out, claims of limitless economic growth driven by biotechnology have been revealed as overstated or unsubstantiated (see e.g., Grunwald, 2020). The bioeconomy, which was often considered a technological solution to solve many of humanity's problems and bring about unlimited economic growth, has now become a smaller piece of a larger puzzle since it is evident that the bioeconomy alone cannot solve the challenges of climate change, biodiversity preservation, and global justice and equality (Eversberg & Fritz, 2022). There has been a growing interest in alternative views on bioeconomic transformations, which prioritize agro-ecology over

biotechnology and sufficiency over economic growth (Bugge et al., 2016; Eversberg & Fritz, 2022; Levidow et al., 2019).

Overall, the bioeconomy is connected to numerous expectations concerning its contribution towards challenges such as resource scarcity, food security, and climate change. Whether the expectations can be met, is unclear (Giampietro, 2019; Klauer & Schindler, 2022). The bioeconomy ultimately relies on finite natural resources such as water and soil, which can be overexploited (Klauer & Schindler, 2022). Bioeconomy transformations can thus cause unintended environmental externalities, which are highly context dependent (Stark et al., 2022). Social inequalities can also occur (Eversberg & Fritz, 2022).

Therefore, the bioeconomy is not inherently sustainable (Gawel et al., 2019; Stark et al., 2022). To ensure that the future of the bioeconomy is sustainable, appropriate, context-dependent governance approaches are needed (Biber-Freudenberger et al., 2020; Dietz et al., 2023; Stark et al., 2022). This, in turn, requires monitoring systems that account for the multifaceted nature of the bioeconomy (Meadowcroft & Steurer, 2018; Robert et al., 2020).

As a result of multifaceted criticism, a broader understanding within the scientific discussion has emerged about the concept of the bioeconomy and its possible consequences. To examine subjective stakeholder perceptions, it is necessary to delineate the bioeconomy from related concepts to ensure analytical clarity.

2.2 Conceptual Delineation

The bioeconomy concept is linked to other concepts used to frame sustainability challenges, some of which overlap (Barañano et al., 2021; D'Amato & Korhonen, 2021; Giampietro, 2019). Therefore, it is necessary to explain and delineate related concepts and their linkages to the bioeconomy. The Green Economy (GE), Blue Economy and CE are frequently used in connection with the concept of the bioeconomy (D'Amato & Korhonen, 2021). The following part will introduce these concepts and assess their relation to the concept of the bioeconomy.

2.2.1 Green Economy

The GE is based on an initiative brought forward by the UN Environment Programme (UNEP). The UNEP defines the GE as "one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities". While the underlying idea can be traced back to earlier UN conferences, the GE concept became increasingly popular after the publication of the UN GE report in 2011. The report sees GE as an essential milestone for sustainable development and poverty reduction (UNEP, 2011). To attain this objective, the environment must be acknowledged as a crucial foundation for growth and development and given greater prominence in national accounts (UNEP, 2011). An essential component of this is the reallocation of public and private assets to enhance natural capital (UNEP, 2011).

Investment in education and research is also considered as crucial to promote the required qualifications and technical skills for the transition in the environmental sector (UNEP, 2011). The GE should also facilitate substituting fossil energy sources with low-carbon and low-emission technologies while simultaneously creating new jobs (UNEP, 2011). As a concept, the GE can be perceived very favorably by governments since it intends to provide potential options to address environmental difficulties as well as unemployment (Borel-Saladin & Turok, 2013; Loiseau et al., 2016, p. 15). Moreover, it is intended to reduce greenhouse gas emissions and dependence on imported raw materials (UNEP, 2011). In this regard, the GE should further contribute to reducing poverty by protecting natural resources such as fish and woodlands, which are the basis of life, especially in developing economies (UNEP, 2011). Thus, it is often perceived as an umbrella concept (Loiseau et al., 2016). It is referred to by multiple international organizations (Borel-Saladin & Turok, 2013; D'Amato & Korhonen, 2021; Ferguson, 2015).

Overall, it can be stated that the GE concept is broader compared to the bioeconomy, and that the sustainable bioeconomy should be considered a component of the overall GE.

2.2.2 Blue Economy

Although various definitions are commonly used in connection with the Blue Economy, it can be stated that oceanic sustainability and the management of marine

resources are central to this concept. The EC, for instance, defines the Blue Economy as “[a]ll economic activities related to oceans, seas and coasts. It covers a wide range of interlinked established and emerging sectors” (EC, 2018a, p. 5). The blue economy can, therefore, also be understood as a sea-related concept under the umbrella of the GE concept.

2.2.3 Circular Economy

The emergence of the concept of the CE is associated with Kenneth Boulding’s idea of a spaceship economy (Boulding, 1966; Giampietro, 2019, p. 153; Reike et al., 2018, p. 247). He introduced the idea of considering planet Earth as a spaceship, a closed system with no possibility of exchanging matter with outer space. Once all the resources on the planet are used up, there will be no opportunity to bring new supplies on board (Boulding, 1966). Likewise, when waste pollutes the planet, it is impossible to dispose of. Boulding assumed that transitioning from the "cowboy economy," where success is measured by the amount of throughput and extraction of raw materials, to a "spaceman economy" was necessary (Ahlheim, 2018, p. 321; Boulding, 1966). Thus, in the spaceman economy, throughput is minimized, and success is measured by the nature, quality, and complexity of the total capital stock rather than production and consumption (Ahlheim, 2018, p. 321; Boulding, 1966). The underlying thought of carefully utilizing scarce resources can be recognized in several concepts related to sustainability, but particularly so in connection with the CE. Boulding describes the vision of a spaceman economy:

In the spaceman economy, what we are primarily concerned with is stock maintenance, and any technological change which results in the maintenance of a given total stock with a lessened throughput (that is, less production and consumption) is clearly a gain. (Boulding, 1966, p. 11)

The concept of the CE has become more prevalent in recent years in research and business settings despite there are concerns from critics that it lacks a clear and consistent definition. The confusion around the concept goes as far as that, according to Kirchherr et al. (2017), it means different things to different people and may eventually collapse or end up in a conceptual standstill due to significantly varying definitions. In this connection, Kirchherr et al. (2017) analyzed 114 definitions and found 95 variations, while the most common definition was only employed eleven times.

Despite the confusion around the various definitions, certain core principles can be identified. Those are commonly summarized in the form of R-frameworks, ranging from four to more than nine Rs (Kirchherr et al., 2017; Reike et al., 2018). A commonly used variant, known as the 4R framework, refers to the terms reduce, reuse, recycle and recover (Kirchherr et al., 2017). Several variations and hierarchies of R-frameworks exist and are used within the academic literature (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Reike et al., 2018). Beyond that, principles of circularity and system thinking are stated as underpinning principles, partly inspired by the work of Boulding (1966) in 1966 (Reike et al., 2018).

However, some definitions of the CE mistakenly equate it with recycling and fail to recognize the broader systemic changes that are necessary for a truly *circular* economy (Kirchherr et al., 2017). Recycling is just one aspect of the CE, and a narrow focus on it can lead to missed opportunities for creating value from waste and reducing resource use.

Another potential problem might arise from whether this concept and closing material and product loops, in fact, prevent primary production (Zink & Geyer, 2017). The increase in overall production due to CE activities can offset their benefits, a phenomenon called “circular economy rebound,” similar to the rebound effect seen in energy efficiency (Zink & Geyer, 2017). This occurs when CE activities lead to increased production levels, reducing their intended environmental advantages (Zink & Geyer, 2017). The limited ability of secondary products to substitute primary products and related price effects contribute to this rebound (Zink & Geyer, 2017).

Further, it appears that scholarly writings on CE largely overlook social considerations and the overall link to sustainable development is weak (Kirchherr et al., 2017, p. 229). However, the overall picture is not clear, as some researchers have identified positive contributions to the achievement of the SDGs (Schroeder et al., 2019). As of today, however, it is still widely used and further developed in combination with other concepts (see e.g., Giampietro, 2019; Leipold et al., 2023).

The concepts of GE and CE are frequently mentioned side by side or linked. However, they are in themselves different concepts. In general, the CE has a different scope than the bioeconomy, although they do overlap. Yet, linking the principles of the CE with the bioeconomy can help ensure the sustainability of the latter. The bioeconomy's focus on

renewable resources and biotechnological innovations can also contribute to implementing CE principles (Birner, 2018, p. 27). Both, bioeconomy and CE, are narrower compared to the GE. Figure 1 illustrates how this work understands the concepts.

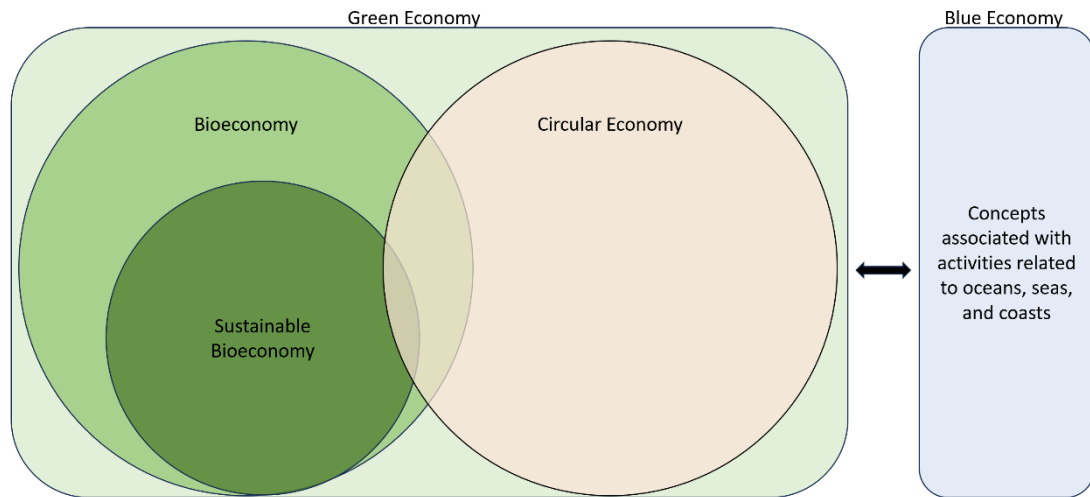


Figure 1. Bioeconomy-Related Concepts. Source: Author, adapted from Kardung et al. (2021), *CC BY 4.0*.

2.3 Bioeconomy Definitions

In addition to conceptual differentiation, clarity concerning the definition of the term bioeconomy is needed. There is a multitude of definitions concerning the bioeconomy. As The underlying understanding, narrative, and usage differ wildly depending on the context, scientific discipline, and other factors (Bauer, 2018; Bugge et al., 2016; Giampietro, 2019; von Braun, 2018; Wesseler & von Braun, 2017).

Internationally, for instance, the OECD understands bioeconomy “as the set of economic activities in which biotechnology contributes centrally to primary production and industry” (OECD, 2018c, p. 14). Thus, it illustrates an emphasis on biotechnology and primary production. Bioeconomy, as defined by the International Advisory Council of the Global Bioeconomy Summit 2018, “is the production, utilization, conservation, and regeneration of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable solutions (information, products, processes and services) within and across all economic sectors and enable a transformation to a sustainable economy” (Global Bioeconomy Summit, 2018, p. 2). This

definition is noticeably broader compared to that of the OECD and integrated a reference towards a sustainable economy.

In 2012, Wesseler and von Braun (2017) noted that the EC emphasized the bioeconomy's contribution to the CE (EC, 2012, p. 2; Wesseler & von Braun, 2017, p. 3). However, as pointed out, the bioeconomy concept encompasses more than the CE as it goes beyond the goal of closing material and product loops to achieve optimal resource flows and resource management. This was subsequently also adopted by the EC.

In the EC's updated bioeconomy strategy from 2018, it is stated that

[t]he bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services. (EC, 2018c, p. 4)

Following the EC's definition, as von Braun (2018) highlights, the bioeconomy goes beyond merely using biomass for energy and encompasses the sustainable management of ecological systems. It acknowledges that land, forests, and soils are scarce resources that provide value through both products and ecosystem services (von Braun, 2018). Biosciences are employed to convert traditional economic sectors, such as chemical industries, agriculture, construction, and pharmaceuticals, into sustainable ones (von Braun, 2018). The bioeconomy is, thus, not limited to resource optimization and management, but rather strives to achieve societal transformation and promote sustainable human development (von Braun, 2018).

An interesting observation is that the present understanding of the bioeconomy in the EU stands in contrast to the initial narrative presented by Baranoff and Georgescu-Roegen, which argued that increasing the use of renewable resources in economic activities would lead to a deceleration in economic growth and establish rigid limitations on the development of the economy (Giampietro, 2019, p. 145).

This work understands the bioeconomy as defined within the German national bioeconomy strategy. According to this strategy, the German Federal Government understands bioeconomy as

the production, exploitation and use of biological resources, processes and systems to provide products, processes and services across all economic sectors within the framework of a future-oriented economy. (BMBF & BMEL, 2020a, p. 4)

The state government of NRW stated in 2013 that it understands the bioeconomy as the development of new products and services using biological resources in a sustainable way - e.g., for the change from a society based on petroleum to one based on renewable raw materials (Landesregierung NRW, 2013, p. 1). However, since the national strategy was published, references are mostly made to the definition of the federal government as laid out in the strategy from 2020.

Generally, definitions of bioeconomy within policy strategies can be distinguished into a narrow and broader understanding (Meyer, 2017). The narrower definitions of the term highlight innovation potential and the application of modern biotechnology, whereas the broader understanding focuses on resource aspects and affected sectors, often including normative aspirations to support the transition to a bio-based economy (Meyer, 2017).

The definitions within the German bioeconomy strategies relate to the broader understanding of bioeconomy and partly use the term bio-based economy synonymously for bioeconomy (BMBF, 2010; BMBF & BMEL, 2020b; BMEL, 2014; Meyer, 2017). However, while the terms bioeconomy and bio-based economy (BBE) are often used interchangeably, it is important to differentiate between them. Bioeconomy encompasses not only the BBE but also the production and utilization of food and feed (Dubois & Juan, 2016, p. 1).

As Figure 1 illustrates, the bioeconomy illustrates a subset within the concept of the GE. Moreover, it is necessary to distinguish between the bioeconomy in general and a sustainable bioeconomy, which is part of the overall bioeconomy. This delineation is important since the bioeconomy in itself is not necessarily sustainable.

The multiplicity of definitions and underlying concepts caused by inconsistent use within and between different scientific disciplines contributes to confusion concerning

the bioeconomy. The fact that policies at different levels emphasize different aspects in the international, European, national and regional contexts further adds to existing challenges. Especially for stakeholders who are not experienced in dealing with such ambiguity it might lead to confusion. One way to address this and structure the existing perceptions is to divide the underlying understandings of bioeconomy into different visions associated with the concept. The purpose of developing these bioeconomy visions is to explore and clarify the various understandings of the concept in order to distinguish between its different perspectives, rationales and implications (Bugge et al., 2016). They are therefore particularly useful when analyzing subjective stakeholder perceptions as intended in this work.

2.4 Bioeconomy Visions

As discussed above, there is no universal definition of the term bioeconomy and the versatile use of related terms and concepts represent a challenge for scientific work in this setting. In addition, there is currently no agreement on clear characteristics a functioning bioeconomy should possess and the kind of society it could help sustain (Hausknost et al., 2017). This is strengthened through varying narratives evolving related to the concept communicating deviating messages (Dallendörfer et al., 2022; Dieken et al., 2021; Dieken & Venghaus, 2020; Hausknost et al., 2017).

A possibility to address this is to examine existing, underlying visions associated within academic literature. In this context, a bibliometric analysis carried out by Bugge et al. (2016) identified the central interpretations of the bioeconomy concept that are presented in scholarly works. From the analysis, it is feasible to differentiate between three distinct visions or ideal types of what a bioeconomy comprises (Bugge et al., 2016).

2.4.1 *Bio-Technology*

The first vision is conceptualized as bio-technology vision. This vision primarily strives to foster job creation and economic growth (Bugge et al., 2016, p. 10). Although it presumes positive effects on climate change and environmental factors, economic growth takes priority over sustainability (Bugge et al., 2016, p. 10). Consequently, unintended outcomes that may arise from bio-technology use are often disregarded

(Bugge et al., 2016, p. 10). In addition, ethical concerns and risks are less pronounced than economic growth (Bugge et al., 2016, p. 10).

In the bio-technology vision, value creation is achieved primarily through the application of biotechnology and the commercialization of research and technology (Bugge et al., 2016, p. 10). This vision is driven by the belief that technological progress will solve resource shortages and waste issues, so these aspects are not vital to be analyzed (Bugge et al., 2016, p. 10). Biotechnologies are also seen as potential solutions for reducing and transforming organic waste into new products (Bugge et al., 2016, p. 10). Research and technology commercialization are crucial for value creation in this vision, requiring close interaction between universities and industry (Bugge et al., 2016, p. 10). Since research is a prominent segment, research councils and funding bodies become key actors, with research governance being a focus of some contributions in the literature (Bugge et al., 2016, p. 10).

Geographically, it is envisioned to bring about a growth concentration in specific regions that accommodate large pharmaceutical companies, small biotech firms, and venture capital, as well as regions with strong public research in biotechnology (Bugge et al., 2016, p. 11). While global competition in the bioeconomy emphasizes the significance of innovation governance, emerging and developing economies could, following this vision, also profit from the bioeconomy and value creation comprises physical and non-physical components (Bugge et al., 2016, p. 11).

2.4.2 *Bio-Resource*

The bio-resource vision aims to achieve economic growth and sustainability by developing new bio-based products (Bugge et al., 2016, p. 11). Unlike the bio-technology vision, which concentrates on capitalizing on biotechnologies, this vision emphasizes using bio-resources to drive economic growth (Bugge et al., 2016, p. 11). While environmental sustainability is also expected to improve, it is not the main focus, and the effects of the transition to a bioeconomy on climate change are rarely assessed (Bugge et al., 2016, p. 11). Despite academic concerns about the sustainability effects of the bioeconomy, policymakers still prioritize economic growth over environmental protection (Bugge et al., 2016, p. 11).

The drivers of innovation include improving land productivity, incorporating degraded land in biofuel production, and promoting research and innovation in multiple fields related to biological materials (Bugge et al., 2016, p. 11). Collaboration across sectors and interaction with customers are emphasized as essential drivers, making the drivers of innovation less linear than in the bio-technology vision. However, implications for changes in land use and the relation between the use of bio-resources and other resources are often not considered (Bugge et al., 2016, p. 11).

The bio-resource vision emphasizes the potential for rural development and the stimulation of employment in rural settings due to the importance of natural resources as crucial location characteristics (Bugge et al., 2016, p. 12). However, in most cases, local competencies related to cultivating and processing biological material must be complemented with external knowledge (Bugge et al., 2016, p. 12).

2.4.3 *Bio-Ecology*

The main goal of the bio-ecology vision is sustainability (Bugge et al., 2016, p. 12). This vision prioritizes sustainability considerations over economic growth and job creation that are the main concerns of the bio-technology and bio-resource visions (Bugge et al., 2016, p. 12). Critical voices in the literature on the bioeconomy that criticize the commercialization of bio-resources and highlight issues such as inequalities in access to bio-resources are taken into consideration (Bugge et al., 2016, p. 12).

The generation of value under the bio-ecology vision is highlighted by the significance of maintaining biodiversity, safeguarding ecosystems, ensuring the provision of ecosystem services, and averting soil degradation (Bugge et al., 2016, p. 12). Moreover, it emphasizes a circular and self-sustained production mode where energy production from bio-waste occurs at the end of the chain after reuse and recycling (Bugge et al., 2016, p. 12).

This vision is predominantly driven by identifying promising organic bio-ecological practices and ecological interactions and using bio-ecological engineering techniques (Bugge et al., 2016, p. 12). Its focus is on efficient land use, waste recycling and reuse, and the conservation of ecosystems (Bugge et al., 2016, p. 12). In contrast to the other two visions, the bio-ecology vision does not prioritize technically-focused research and

innovation activities and rejects certain technologies, such as genetically modified crops (Bugge et al., 2016, p. 12). Instead, research is urged to concentrate on transdisciplinary sustainability topics, global fair trade, and greater participation in discussions and decisions on transition processes (Bugge et al., 2016, p. 12). In addition, the significance of considering the adverse effects of competing bioeconomy visions is stressed (Bugge et al., 2016, p. 12).

It further underlines the potential for rural and peripheral regions, similar to the bio-resource vision, to create value (Bugge et al., 2016, p. 13). The focus is on producing high-quality products with territorial identity (Bugge et al., 2016, p. 13). However, unlike the bio-resource vision, the bio-ecology vision accentuates the significance of developing locally embedded economies as crucial to creating a sustainable bioeconomy (Bugge et al., 2016, p. 13).

Table 1

Key Characteristics of the Bioeconomy Visions.

	The Bio-Technology Vision	The Bio-Resource Vision	The Bio-Ecology Vision
<i>Aims & objectives</i>	Economic growth & job creation	Economic growth & sustainability	Sustainability, biodiversity, conservation of ecosystems, avoiding soil degradation
<i>Value creation</i>	Application of biotechnology, commercialisation of research & technology	Conversion and upgrading of bio-resources (process oriented)	Development of integrated production systems and high-quality products with territorial identity
<i>Drivers & mediators of innovation</i>	R & D, patents, TTOs, Research councils and funders (Science push, linear model)	Interdisciplinary, optimisation of land use, include degraded land in the production of biofuels, use and availability of bio-resources, waste management, engineering, science & market (Interactive & networked production mode)	Identification of favourable organic agro-ecological practices, ethics, risk, transdisciplinary sustainability, ecological interactions, re-use & recycling of waste, land use, (Circular and self-sustained production mode)
<i>Spatial focus</i>	Global clusters/Central regions	Rural/Peripheral regions	Rural/Peripheral regions

Source: Adapted from Bugge et al. (2016), CC BY 4.0.

The key characteristics of the bioeconomy visions are summarized in Table 1. It is worth noting that these visions should not be seen as entirely separate from one another, but rather as model types or prototypes of the bioeconomy (Bugge et al., 2016). Therefore, they can overlap as illustrated in Figure 2. Yet, they provide a useful distinction and allow for further analysis, representing an important aspect of the present work. Therefore, they play an essential role in the following, especially in capturing subjective stakeholder perceptions (Section 6.2).

Schematic illustration of bioeconomy visions

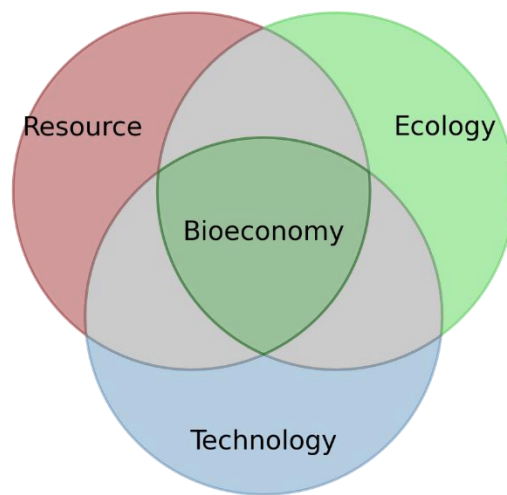


Figure 2. Venn Diagram of Bioeconomy Visions. Source: Author, based on Bugge et al. (2016).

2.5 Bioeconomy Strategies

The interdisciplinary nature of the bioeconomy presents a unique opportunity to tackle intertwined societal challenges holistically (BMBF, 2021). These include ensuring food security, addressing shortages of natural resources, reducing dependence on fossil fuels, and mitigating climate change, all while achieving sustainable development (Dubois & Juan, 2016, p. 2; FAO, 2024a).

In this context, strategies are an important tool for guiding policy in various cross-sectoral policy fields.⁴ For example, the EU and Germany have developed strategies to address complex issues and transformation processes in fields such as sustainability and artificial intelligence (see .g., BMBF & BMEL, 2020b; BReg, 2018; BReg, 2021b). These strategies provide a framework for action and help to coordinate efforts across different stakeholders and policy domains. By setting clear objectives and priorities, strategies can help ensure that policy actions are coherent and effective in achieving desired outcomes. When a country lacks a comprehensive bioeconomy strategy, the related governance approach to the bioeconomy frequently results in the implementing different policies, incentives, and regulations, leading to a lack of coherence and potential inefficiencies (Bracco et al., 2018, p. 10).

Accomplishing sustainable and fair development of the bioeconomy is critical for achieving the SDGs, but it is a complex task. There is no universal approach for determining priorities and addressing sustainability in the development strategies and implementation plans in the context of the bioeconomy (Dietz et al., 2023; Dubois & Juan, 2016, p. 27; Proestou et al., 2024). Until 2016, in a few cases, action plans were created for implementing bioeconomy strategies, which included shortcomings and gaps, particularly in financing, monitoring and evaluation (Dubois & Juan, 2016, p. 27). This includes obstacles to accessing green finance and capital markets and a lack of financial support for small-scale producers and enterprises (Dubois & Juan, 2016, p. 27). Despite these challenges, there are some noteworthy samples of decentralized bioeconomy programs. Several countries recognized the need to develop aligned international sustainability standards and guidelines (Dietz et al., 2023; Dubois & Juan, 2016, p. 27). Although the overall aim towards the SDGs as a normative framework is often stated, it is less obvious how to operationalize these in the context of regional transformation processes. And while current bioeconomy strategies state far-reaching promises, there are still major challenges and conflicts for which is not sufficiently accounted for in societal debates (Meyer, 2017).

⁴ An overview of bioeconomy strategies in relation to sustainability can be found in: FAO. (2024a). Bioeconomy for sustainable food and agriculture: a global opportunity – Position paper. *Food and Agriculture Organization of the United Nations*. <https://doi.org/10.4060/cd1976en>

The following section will thus illustrate the most important developments on the European, national and regional level in relation to the adoption of coherent bioeconomy strategies in Germany and NRW.

2.5.1 European Context

Since the emergence of the concept of the bioeconomy, the European institutions played a central role in promoting related activities. The expectations for future forms of the bioeconomy are high in this regard. The EC, for instance, states that further developing the bioeconomy opens up various possibilities to contribute towards enhanced well-being and progress concerning sustainable development (EC, 2012, 2018c).

Activities within the European institutions contributed notably to the emergence of the bioeconomy concept. The EU bioeconomy strategy was first published in 2012. Initially, it was aimed to expedite the establishment of an eco-friendly European bioeconomy by setting five objectives that a sustainable EU bioeconomy should accomplish (EC, 2012, p. 9). The stated objectives were ensuring food and nutrition security, sustainable management of natural resources, reducing reliance on non-renewable and unsustainable resources from both domestic and foreign sources, addressing climate change through mitigation and adaptation, and enhancing European competitiveness by creating jobs (EC, 2012, pp. 9-11).

In 2017, a review of the EU Bioeconomy Strategy 2012 was conducted and published in 2018. The conclusions drawn were mainly positive. The significance of bioeconomy strategies and the prospects of developing a solid bioeconomy was increasingly acknowledged by EU Member States and regions (EC, 2018b, pp. 5, 6). Moreover, the goals of the 2012 strategy have been incorporated into several national and regional bioeconomy strategies formulated since 2012, both in the EU and worldwide (EC, 2018b, pp. 5, 6).

Yet, several points were identified as requiring improvement. The most relevant ones in connection with this work were that the policy context had evolved significantly since the 2012 EC Bioeconomy Strategy was introduced, with the introduction of policies such as the Paris Agreement (UNFCCC, 2015), and the SDGs (UN, 2015) at global, EU and national levels (EC, 2018b, pp. 5, 6). Moreover, it was underlined that cities' potential

contribution to the bioeconomy still needs to be explored (EC, 2018b, p. 6). Improved monitoring and evaluation frameworks are necessary to evaluate the advancement of bioeconomy development. In this connection, indicators may be established utilizing internationally agreed-upon monitoring and assessment systems being created for the SDGs, potentially in conjunction with further indicators (EC, 2018b, p. 6). This approach will also be further explored in the context of the present work (Section 7.2.2).

Subsequently, the results of the review were then taken up and incorporated into an updated strategy that was published in 2018. Following the review results, the initial five objectives were kept and placed and considered as continuously valid (EC, 2018c, p. 8). To account for the evolving policy priorities, the revised strategy presented three primary action areas to ensure progress towards the five key objectives. The first action area proposed is strengthening and scaling up the bio-based sectors and unlocking investments and markets (EC, 2018c, p. 10). Second, it is proposed to promote the swift implementation of local bioeconomies throughout Europe (EC, 2018c, p. 10). The third aims at developing an understanding of the ecological limits of the bioeconomy (EC, 2018c, p. 14). As pointed out, central aspects of this work include the development of a decision support system and establishment of a monitoring containing related indicators, which are necessary to achieve the goals and implement the proposed actions.

In this context, a “sustainable bioeconomy must value natural resources and diminish environmental pressures and increase the use of sustainable renewable products, restore and enhance ecosystems’ functions and biodiversity” (EC, 2018c, p. 16). Thus, according to the strategy laid out in 2018, a “sustainable bioeconomy is the renewable segment of the circular economy” (EC, 2018c, p. 6). Further, the strategy considers it as crucial to utilize natural resources within an efficient bioeconomy for achieving the SDGs (EC, 2018c, p. 5). However, despite various references to environmental problems and acknowledging the limitations concerning renewable resources, the updated strategy lacks concrete measures mainly aim towards increased growth and technology development (Lühmann, 2020).

Following the publication of the updated bioeconomy strategy, the bioeconomy continues to have a high priority in EU policy. The EC considers the bioeconomy to serve as a driver for fundamental change by addressing the EGD’s economic, social, and

environmental components (EC, 2020). It aims to discover novel ways of producing and utilizing resources while staying within ecological limits and moving away from the traditional linear economy that heavily depends on non-renewable, fossil resources (EC, 2020). The bioeconomy is further expected to be a key factor in driving the EU's recovery from the COVID-19 pandemic by promoting economic alignment with ecological sustainability and enhancing resilience and competitiveness by offering sustainable, long-term solutions that support a fair transformation (EC, 2020). It thus contributes to the core dimensions of the EGD (EC, 2019a, 2020; Ronzon et al., 2020, pp. 9, 10).

It will be crucial for each EU member state to develop a sustainable and circular bioeconomy in order to achieve the objectives as stated in the EGD (Barrett et al., 2021, p. 9). As highlighted by the policy guidelines based on an independent expert report published by the EC in 2021, developing and implementing bioeconomy strategies is thus now imperative for member states in striving towards the SDGs and the objectives laid out in the EGD (Barrett et al., 2021, p. 9). Moreover, as it is stressed within the report, transformations towards a bioeconomy

will also involve the need to choose between alternative visions of the future and how to get there, pointing to the importance of public engagement to foster consultation and reflection. (Barrett et al., 2021, p. 3)

This recognition is of central relevance for the present work.

In 2022, a progress report evaluated the advancement of the 2018 EU Bioeconomy Strategy. The assessment report positions the EU Bioeconomy within the framework of the EGD, emphasizing that the bioeconomy is both the means and outcome of the EGD. The bioeconomy is regarded as a "natural enabler and result" of the EGD transformation (EC, 2022, p. 5). Furthermore, according to the report, bioeconomy policies support policy coherence and vertical coordination at local, national, EU, and global levels (EC, 2022, p. 3). It is further stressed that bioeconomy policies should contribute towards all three sustainability dimensions (EC, 2022, p. 5). This contains implications for regional monitoring approaches and is thus vital for this work. The report also notes that existing bioeconomy policies embrace a holistic approach to enhance coherence in policy-making and recognize and address potential conflicts (EC, 2022, p. 3). These policies, thus, contribute to developing a sustainable bioeconomy that addresses the three dimensions of sustainability (EC, 2022, p. 3). The report additionally concedes that the move towards a

sustainable and circular bioeconomy will not be a uniform process but will occur at varying paces across member states, considering their respective strengths and challenges.

It states that the Bioeconomy Strategy of 2018 provides a systemic and integrated framework that complements sectoral policies and enables countries and regions to develop transition pathways according to their respective opportunities and challenges (EC, 2022, p. 3). This approach is regarded as non-prescriptive and allows for flexibility in designing transition plans (EC, 2022, p. 3). At the same time, the report concedes that the move towards a sustainable and circular bioeconomy will not be a uniform process but will occur at varying paces across member states, considering their respective strengths and challenges. This further highlights the importance of regions within the overall transformation. The EC actively supports the development and implementation of strategies and related guidelines were introduced in 2021 (Barrett et al., 2021).

Overall, the EC thus assesses the developments as successful and states that the “bioeconomy is now more important than ever to contribute to the green and fair transition in Europe” (EC, 2022, p. 4). Respective development in the local and regional context play a special role in this regard (EC, 2022, p. 20; Mubareka et al., 2023). Transitioning to a bioeconomy in the EU requires recognizing the interrelationships between various policy objectives across sectors and avoiding approaches embracing silo-thinking (A. Muscat et al., 2021). An option to accomplish that could evolve by clarifying ambiguous policies and promoting integrated policies that can handle the uncertainty that might arise (A. Muscat et al., 2021). Currently, whether the EU has already entered a transition phase cannot be answered conclusively (Ronzon et al., 2022a).

2.5.2 National Context

In 2010, Germany was one of the first countries in the world to publish a cross-departmental national research strategy related to the bioeconomy setting the intended direction for a transformation towards the year 2030 (BMBF, 2010). In 2014, the federal cabinet adopted the *National Policy Strategy Bioeconomy* as a further milestone for aligning bioeconomy policy in Germany (BMEL, 2014). Moreover, since 2009 the federal government has been advised by the Bioeconomy Council, an advisory body consisting of several scientific experts in bioeconomy-related fields. Although the focus

of the earlier publications was more on technical and economic aspects, the complexity and multilayered nature of the subject were already acknowledged. In this connection, the orientation towards social challenges and holistic perspectives concerning the bioeconomy also characterized the concept by the BMBF published for the first time in 2014, which was updated in 2021 (BMBF, 2014, 2021).

Building upon the *National Research Strategy Bioeconomy 2030* and the *National Policy Strategy Bioeconomy*, the National Bioeconomy Strategy was introduced in 2020 meant to define the guidelines and objectives of national bioeconomy policy and suggesting measures for its implementation. Both the BMBF and the Federal Ministry of Food and Agriculture (BMEL) were involved in developing the strategy (BMBF & BMEL, 2020b). The link to the activities at the EU level is also regularly mentioned throughout the strategy and explicitly desired (see e.g., BMBF & BMEL, 2020b, pp. 4,6, 17, 18, 33, 34).

Overall, the strategy resolves around two guidelines. First, it is planned to use biological knowledge and responsible innovation to achieve sustainable climate-neutral development (BMBF & BMEL, 2020b, pp. 14, 15). Second, biogenic raw materials are supposed to contribute to a sustainable, circular economy (BMBF & BMEL, 2020b, p. 15). Based on these guidelines, six common strategic goals for research funding and policy frameworks serve as a foundation (BMBF & BMEL, 2020b, p. 4).

First, developing bioeconomic solutions is considered essential for achieving sustainability goals (BMBF & BMEL, 2020b, p. 14). Second, it is important to identify and utilize the potential of the bioeconomy while respecting ecological boundaries (BMBF & BMEL, 2020b, pp. 14, 15). Third, expanding and applying biological knowledge can help achieve a sustainable bioeconomy (BMBF & BMEL, 2020b, pp. 17, 24, 26). Fourth, aligning the economy's resource base sustainably is vital for long-term success (BMBF & BMEL, 2020b, pp. 14, 41). Fifth, Germany should strive to become a leading innovator in the field of bioeconomy (BMBF & BMEL, 2020b, pp. 14, 56). Lastly, involving society and intensifying national and international cooperation is important to transition to a sustainable bioeconomy successfully (BMBF & BMEL, 2020b, pp. 14, 33, 52). Implementation is to be achieved through targeted research

funding, the creation of suitable framework conditions and the development of overarching instruments (BMBF & BMEL, 2020b, p. 4).

In particular, the recognition that the involvement of society is of great importance should be emphasized. It is acknowledged and highlighted that further research is required, especially in the fields of social, political, and economic sciences, to comprehend the alterations in society (BMBF & BMEL, 2020b, p. 33). Moreover, it is recognized that expanding our understanding of systemic relationships is central to ensuring that achieving individual goals does not come at the expense of other goals (BMBF & BMEL, 2020b, p. 33). To acquire the necessary knowledge, the importance of interdisciplinary research is underlined (BMBF & BMEL, 2020b, p. 33).

The results of respective research are expected to significantly contribute to evaluating the possibilities of the bioeconomy, developing it in practical terms, determining its impacts on various aspects of sustainability, and identifying the potential courses of action (BMBF & BMEL, 2020b, p. 33). As pointed out, illustrating and contributing to developing potential courses of action while considering existing conflicting objectives of involved actors is also considered a central goal of the present work.

While not explicitly mentioned in the coalition agreement of the Scholz cabinet of the German Federal Government (BReg) from 2021, there are several links and connections to aspects related to the bioeconomy. Moreover, several of the stated goals align with the core characteristics of a sustainable bioeconomy. These include the intention to end the utilization of fossil resources, foster the development of biotechnology as further develop a sustainable agricultural sector in harmony with the natural environment (see e.g., SPD et al., 2021, pp. 2, 5, 14, 20, 30). Thus, the development of a sustainable bioeconomy is a central element of Germany's national policy strategy.

2.5.3 Regional Context

Regional initiatives play an important role within the EU (Barrett et al., 2021; Haarich et al., 2022). This is illustrated in the fact that there are more than three hundred regional bioeconomy strategies in place (Haarich et al., 2022). Rural areas, with the potential for regional bioeconomy pathways varying based on factors such as existing infrastructure, availability of raw materials, and the skills and knowledge of local participants, play a

central role in successfully implementing a sustainable bioeconomy (BMBF & BMEL, 2020b, p. 44). Approaches thus need to account for regional specificities and need to be developed accordingly.

In NRW, a guiding point in the regional bioeconomy policy illustrated the publication of a document in 2013 (Landesregierung NRW, 2013). In this publication, key points for a state bioeconomy strategy were laid out. The goals of the state government were to promote the transformation of the NRW economy into a sustainable economy through the expansion of the bioeconomy, secure the competitive supply of renewable raw materials, and consider the social, economic, ecological, and ethical opportunities and risks of the bioeconomy while observing natural limits of biologization and conservation of resources (Landesregierung NRW, 2013, pp. 2-3). The bioeconomy is, thus, not limited to technological solutions but offers opportunities for societal change and was acknowledged as a transdisciplinary topic (Landesregierung NRW, 2013, pp. 2-3).

Advancing the implementation of a sustainable bioeconomy has remained an objective and was reaffirmed in 2023 (Landesregierung NRW, 2023). In addition, a bioeconomy council comprising 15 experts was set up in 2024 (Landesregierung NRW, 2023). It is intended to develop a comprehensive strategy in collaboration with regional stakeholders within a two-year process (Landesregierung NRW, 2023). An interministerial bioeconomy working group has also been established coordinate respective efforts (Landesregierung NRW, 2023).

In general, the goals for promoting bioeconomy development vary depending on a country or region's available resources and economic expertise (Bracco et al., 2018; Wessler & von Braun, 2017, p. 11). This also applies to the case of NRW. Overall, the RR as a model region represents the focus of activities for bioeconomy in Germany.

The bioeconomy is embedded in a multifactorial setting. Thus, related progress relies on several contributing factors. Those include, for instance, policy frameworks, biotechnology development, consumer behavior, agricultural productivity, as well as the development of energy and resource prices. The creation of bioeconomy strategies can be seen as a contribution to bringing together these interdependent developments to achieve the most progress possible.

2.6 Measuring Bioeconomy

Different countries and regions have divergent priorities and objectives regarding the bioeconomy, requiring other indicators and measurements to assess its development and impact (Bracco et al., 2018; Bracco et al., 2019; Kuosmanen et al., 2020; Lier et al., 2018; von Braun, 2018, p. 82). Additionally, the bioeconomy is a complex and multidimensional concept involving various sectors and industries, making it challenging to measure using a single approach (Kuosmanen et al., 2020). The absence of a consistent definition of bioeconomy makes it difficult to compare the importance of the bioeconomy across different economies (Bracco et al., 2018; Lier et al., 2018).

A commonly used method involves utilizing the national account system to present an overview of the bioeconomy's contribution to the regional or national economy, as well as its share of employment and consumption (Bracco et al., 2018, p. 8; Kuosmanen et al., 2020; von Braun, 2018, p. 82). Yet, this approach offers only a partial understanding of potential prospects (von Braun, 2018, p. 82). In many cases, methodologies for data collection and assessment are not standardized, making it problematic to assess the impact of the bioeconomy (Kuosmanen et al., 2020; Lier et al., 2018). This can result in limited information on effects, data gaps, uncertainties, a lack of comparability of results and possibly the double counting of impacts (Bracco et al., 2018, p. 8). Furthermore, related approaches do not appear to be particularly promising in evaluating and providing possible options for future courses of action. Alternative methods involve analyzing bioeconomy clusters or examining the development of KET, their utilization, and private and public sector financing (von Braun, 2018, p. 82).

Measuring the outcomes of the bioeconomy involves not only technical and economic approaches but also non-price measurement techniques that assess the sustainability of water and soil, improvements in biodiversity, and reductions in carbon emissions (Calicioglu & Bogdanski, 2021; Kardung et al., 2021; Ronzon et al., 2022a; von Braun, 2018). Additionally, effects on well-being, such as improved health related to environmental factors like reduced air pollution and greener cities, should also be considered (von Braun, 2018, p. 82). Those approaches would also entail benefits with respect to economic theory and preferences of citizens (von Braun, 2018, p. 82). Thus,

there is a need for addressing questions of social, ecological and economic sustainability (Kircher, 2022a).

Evaluating the bioeconomy should be viewed in the context of the wider matter of economic advancement that takes into account the matters of spillover effects and sustainability (Bracco et al., 2019; Calicioglu & Bogdanski, 2021; Wesseler & von Braun, 2017, p. 3). There are various reasons a framework across sectors is required to measure the effect of investment in bioeconomy research and innovation (Wesseler & von Braun, 2017). Evaluating the effectiveness of supporting policies and their consequence is challenging without proper measurement (Lier et al., 2018; Ronzon et al., 2022a; Wesseler & von Braun, 2017, p. 3). Moreover, definitions of the bioeconomy vary as potential measurement approaches do, while understanding these differences is crucial for meaningfully interpreting results (Wesseler & von Braun, 2017, p. 3). In addition, measuring the bioeconomy is not only about determining its size but also understanding its contribution to achieving positive economic and well-being outcomes (Wesseler & von Braun, 2017, p. 3). This is also important since tracking the bioeconomy's development and identifying causal relationships with investments, policy changes, and underlying driving forces should provide stakeholders with the required information to base their respective decisions upon (Mesa et al., 2024; von Braun, 2018, p. 82). Therefore, different approaches to measurement can be taken, but it is essential to distinguish what is being measured and how (von Braun, 2018, p. 82; Wesseler & von Braun, 2017).

Bioeconomy aims as stated in official strategies frequently focus on the respective countries competitive advantages and interests while comprehensive ways to measuring and monitoring bioeconomy progress, on the other hand, are typically absent (Bracco et al., 2018, p. 14). Further, many nations predominantly track the bioeconomy's impact on the overall GDP and employment effects in related sectors that could lead to inaccurate understanding of the overall progress and development (Bracco et al., 2018, p. 14). 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 (Bianchi et al., 2024; Bracco et al., 2018, p. 14; Mesa et al., 2024). A bioeconomy strategy that seeks to contribute to sustainable development and meet environmental and social objectives must therefore clearly state these goals in the

strategy's objectives and assure the measurement of those through quantitative, qualitative, or aggregate indicators (Bracco et al., 2018, p. 12).

Connected indicators should incorporate environmental and social aspects of sustainability to avoid underestimating the bioeconomy's inherent strains on ecosystems and the well-being of affected communities (Bracco et al., 2018, p. 14). 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, pp. 12, 14; Abigail Muscat et al., 2021; von Braun, 2014). Thus, Bracco et al. (2018) argue that current initiatives to monitor progress towards a sustainable bioeconomy can be improved to track performance related to the SDGs. The purpose of monitoring and evaluation should not be limited to measuring the progress of the bioeconomy strategy's objectives alone. Instead, the sustainability of the bioeconomy as a whole should illustrate the central point.

2.6.1 Requirements for a Sustainable Bioeconomy

As pointed out, the bioeconomy concept does not necessarily contribute towards sustainability (Section 2.1.6). Therefore, it is crucial to distinguish between the implementation of a bioeconomy and a sustainable bioeconomy.

The academic literature suggests that positive expected outcomes dominate in the context of the bioeconomy and its impact on the SDGs (Biber-Freudenberger et al., 2020, p. 12; Wolff, 2022). However, there is considerable variability in the reliability of evidence and consensus among experts and scientific literature across different sectors of the bioeconomy and dimensions of the SDGs (Biber-Freudenberger et al., 2020, p. 12). While technical and natural scientific studies primarily focus on the direct and desired impacts of bioeconomic growth, social science studies, often using survey-based approaches, are better suited to capture indirect social impacts and often highlight adverse or context-dependent outcomes (Biber-Freudenberger et al., 2020, p. 12). Therefore, it is important to consider both direct and indirect effects and to conduct comprehensive and context-specific assessments to ensure sustainable development of the bioeconomy. Moreover, as Ronzon and Sanjuán (2020) pointed out, there are many positive interactions between the different SDGs related to the bioeconomy concerning European policy coherence, with different goals supporting and reinforcing each other. While some

trade-offs may still exist, it is indicated that they are not as prevalent as the synergies (Ronzon & Sanjuán, 2020).

Measuring sustainable development is a complex task considering multiple economic, social, and environmental factors. The choice of methods and indicators for measuring sustainable development can significantly impact the results and their conclusions (Miola & Schiltz, 2019). Therefore, it is essential to carefully select relevant indicators and methodologies to ensure that the assessment is comprehensive and as accurate as possible. Additionally, the choice of indicators may depend on the specific context and priorities of the region or country being evaluated. The availability of sustainability indicators is a precondition for translating the concept of sustainable development into actionable policy (McCool & Stankey, 2004; Schlör et al., 2013). These indicators serve to define important attributes that are essential for achieving sustainable development. Each indicator focuses on a specific aspect of sustainability in the system being observed (Schlör et al., 2013). Sustainability indicator systems help to capture the complexity and interrelationships within the system, providing new insights that can be communicated to the general public (Lehtonen et al., 2016; Schlör et al., 2013). These indicators, thus, frequently play a crucial role in measuring the gap between the actual state of sustainability and the desired state as normatively defined by sustainability strategies (Schlör et al., 2013).

To effectively implement sustainability strategies, it is necessary to use scoring and evaluation methods that offer a comprehensive understanding of the (socio-)economic and environmental performance of the respective systems (Huguet Ferran et al., 2018). Given the broad scope of bioeconomy strategies, this observation applies and is of particular importance. However, the approaches for achieving this are contested, presenting a major challenge for researchers and policymakers. There is a need for harmonization of sustainability criteria related to the bioeconomy (Calicioglu & Bogdanski, 2021; Kardung et al., 2021; Marvik & Philp, 2020; Mesa et al., 2024).

As diverse circumstances and context-dependent factors notably influence the development of a sustainable bioeconomy and the respective implementation, guidelines can illustrate a valuable contribution towards desirable progress. In 2016, based on an analysis of existing strategies and several interdisciplinary workshops conducted, the FAO identified valuable insights for creating guidelines for developing a sustainable

bioeconomy (Dubois & Juan, 2016, p. 28; FAO, 2021). These guidelines should aim for a balance between providing overall guidance and being flexible enough to adapt to local conditions (Dubois & Juan, 2016, p. 28). A collaborative international partnership led by an international organization should be responsible for implementing these guidelines (Dubois & Juan, 2016, p. 28; FAO, 2021). To enhance their credibility, some elements of the guidelines, such as principles and criteria, should undergo multi-stakeholder approval at an international level (Dubois & Juan, 2016, p. 28). Engaging the general public and generating awareness of the bioeconomy's benefits is vital to ensure public support and participation (Dubois & Juan, 2016, p. 28).

In this context, the FAO established the ISBWG that agreed on a set of P&Cs to pin down what a sustainable bioeconomy should normatively encompass (Table 2). The P&Cs for a sustainable bioeconomy provide a useful framework for guiding the development of a monitoring and evaluation systems for the bioeconomy. Using these P&Cs as a basis, a monitoring framework can be developed that links the overarching principles to context-specific indicators, allowing for a more comprehensive and integrated assessment of the bioeconomy's sustainability (Calicioglu & Bogdanski, 2021, p. 41). This will help to address the current data gaps and uncertainties, ensuring that progress towards a sustainable bioeconomy can be accurately tracked and assessed. Thus, these guidelines illustrate the starting point for the indicator system this work develops in the subsequent sections.

Table 2*Overview of the Aspirational Principles for a Sustainable Bioeconomy*

Nr.	Principle
1	Sustainable bioeconomy development should support food security and nutrition at all levels
2	Sustainable bioeconomy should ensure that natural resources are conserved, protected and enhanced
3	Sustainable bioeconomy should support competitive and inclusive economic growth
4	Sustainable bioeconomy should make communities healthier, more sustainable, and harness social and ecosystem resilience
5	Sustainable bioeconomy should rely on improved efficiency in the use of resources and biomass
6	Responsible and effective governance mechanisms should underpin sustainable bioeconomy
7	Sustainable bioeconomy should make good use of existing relevant knowledge and proven sound technologies and good practices and, where appropriate, promote research and innovations
8	Sustainable bioeconomy should use and promote sustainable trade and market practices
9	Sustainable bioeconomy should address societal needs and encourage sustainable consumption
10	Sustainable bioeconomy should promote cooperation, collaboration, and sharing between interested and concerned stakeholders in all relevant domains and at all relevant levels

Note. Based on FAO (2021), *CC-BY-SA*. For a full overview together with the underlying criteria, see FAO (2021).

Overall, a framework for the bioeconomy in relation to the SDGs needs to be developed that should be tailored to the specific contexts in which it will be applied. The framework should take into account the diverse needs and priorities of different countries and regions and be flexible enough to accommodate the different approaches and strategies that may be needed to achieve sustainable development. This constitutes the core of the development of the regional transformation trajectories in Chapter 7.

2.7 Section Summary

Substituting or reducing the use of fossil resources, for example, by improving technical, chemical, or biological processes, is central to the bioeconomy. Bio-based resources play a key role in this regard. While bio-based resources are renewable and their utilization frequently comes with ecological benefits, they are not infinite since they ultimately rely on natural resources, making a conscious use of available resources vital.

The promotion of the bioeconomy concept was strongly supported by staff members of the EC, facilitating its way as an influential policy concept in Europe and beyond. An important role here was the underlying idea of substituting fossil resources as well as

promising options for future technology development. The efforts on the European level were complemented by various initiatives brought forward by member states and during the last decades the concept became increasingly popular globally.

Following Birner (2018, p. 24), there are two main categories of critique concerning the bioeconomy concept. The first argues that it represents the neoliberalization of nature, shaped by a dominant neoliberal ideology. The second acknowledges its potential for environmental sustainability but suggests that current approaches may not deliver on this promise. The focus should be on using life science innovations to support a genuinely sustainable economy, rather than business interests. In addition, ethical concerns are raised, with the argument that such an understanding could contribute to a mindset that views animals and plants solely as biomass.

Concerning the delineation of the concepts, it can be stated that the GE concept is broader compared to the bioeconomy or CE, and that the sustainable bioeconomy should be considered a component of the overall GE. The CE has a different scope than the bioeconomy, although they do overlap and synergies can be realized.

There is a wide variety of definitions concerning the bioeconomy. Yet, following Meyer (2017), those can generally be distinguished into a narrow and broader understanding. The narrower definitions of the term emphasize the potential for innovation and the application of modern biotechnology, while the broader understanding focuses on resource aspects and affected sectors, often including normative aspirations to support the transition to a bio-based economy. The definitions within the German bioeconomy strategies relate to the broader understanding of bioeconomy and thus constitute the basis for this work.

Given the multitude of bioeconomy definitions and the versatile use of related terms and concepts, three distinct visions or ideal types of what a bioeconomy comprises as introduced by Bugge et al. (2016) illustrate a useful approach for this work. This distinction into bio-technology, bio-resource and bio-ecology can help to grasp the underlying understanding, especially with regard to working with stakeholders, and thus contribute to meeting this challenge for scientific work in this setting.

The bioeconomy operates in a complex environment, and strategies play a key role in shaping policies across multiple sectors. The development of bioeconomy strategies helps

to unify these interrelated efforts, which exist at different levels of government and for different sectors. An important underlying policy objective is frequently striving for sustainability.

It is important to note that the bioeconomy concept in itself does not presume sustainability. Thus, with respect to sustainable development, it is crucial to distinguish between bioeconomy and sustainable bioeconomy. While there is no universal approach concerning bioeconomy strategies on an international, national and regional level, the FAO introduced bioeconomy sustainability guidelines that can support ensuring that bioeconomy developments and respective activities in policy, research and business can strive towards desirable development pathways. Hence, these guidelines can serve as a foundation for respective monitoring systems. Together with the SDGs, these guidelines will illustrate the normative foundation for following measurement approaches in the subsequent chapters.

3 Sustainability Guiding the Transition

The bioeconomy is not necessarily sustainable. However, the question of sustainability is vital to a desirable transformation process. The concept of sustainability is thus of central importance for this dissertation. Vital concepts concerning sustainability for understanding the research approach of this thesis are therefore introduced.

In this connection, addressing such complex transformation processes as pursued in this thesis requires to clarify multiple terms, concepts and definitions. These include properties of complex problems, issues of stakeholder engagement, and transformation pathways. Lastly, the choice of the RR as model region for the approach developed in this thesis is laid out.

3.1 Sustainable Development

The concepts of sustainability and sustainable development are used frequently in policy, research, and society. The term sustainability can serve as a compass to guide the transition to a more sustainable future and thus inform the direction of future policy decisions (Grober, 2014). However, interpretations and associations concerning the term sustainability or sustainable development differ (Rimmel, 2020; Ruggerio, 2021).

For instance, businesses sustainability efforts can be conceptualized and reported using the triple bottom line concept (Elkington, 2004; Milne & Gray, 2013). The approach widens the scope companies should consider beyond traditional business metrics to people, planet and profits and it has been frequently used in business reporting (Elkington, 2004; Hartmann, 2020; Milne & Gray, 2013). With respect to the banking industry and as an approach to guide financial investments, for example, the Environmental-Social-Governance (ESG) concept is frequently referred to (Galletta et al., 2022; Li et al., 2021; Steblianskaia et al., 2023).

Thus, related terms as well as concepts differ and are also widely criticized (Ala-Uddin, 2019; Higgins & Coffey, 2016). Yet, since a bioeconomy is not inherently sustainable, and the planned transformation process is explicitly intended to lead to a sustainable bioeconomy, it is necessary to clarify the underlying understanding of sustainability.

Of central relevance for this thesis are the developments in connection to the UN. The UN's efforts are also subject to widespread criticism. Critical points include power inequalities between countries, too much influence by large cooperations and cooperate interest as well as a dominant focus on techno-economic aspects in formulating the SDGs (Ala-Uddin, 2019; Cummings et al., 2018). While acknowledging that the developments linked to the UN's efforts to define respective terms and concepts, developments concerning sustainability coined by the UN still illustrate the core of the understanding in the context of the present study. The key reason is that the UN's work constitutes a central reference point concerning sustainability in German politics and research and is frequently referred to in connection to the bioeconomy, too (BMBF, 2021; BMBF & BMEL, 2020b; BReg, 2021a).

The concept of *sustainable development* was most prominently defined internationally by the United Nations (UN) World Commission on Environment and Development in 1987 (UN, 1987). This definition was articulated in the landmark document entitled *Our Common Future* and is frequently referred to as *Brundtland Report*. According to this definition, “[s]ustainable development is development which meets the needs of current generations without compromising the ability of future generations to meet their own needs” (UN, 1987, p. 41).

As Ruggerio (2021) points out, there is still no universally accepted definition and related concepts are frequently emerging. Still, in recent decades, the UN and several member states have undertaken considerable efforts to establish sustainability as a common global goal which lay the foundation for the prevailing understanding of sustainability and sustainable development for this work. In particular, four elements are important for the present work. First, the distinction between weak and strong sustainability since it has implication concerning the methodology of the decision-support system. Second, the distinction between the three dimensions of sustainability as they will be used to categorize the resulting indicator system in this work. Third, the SDGs play a crucial role for deriving indicators. And finally, the GSDS as a central element of German sustainability policy. While the distinction between weak and strong sustainability has methodological implications later in this thesis, the other four points are central to the GSDS. Therefore, they are outlined hereafter.

3.1.1 Strong and Weak Sustainability

A critical aspect regarding the conceptualization of sustainability concerns the level or extent of sustainability (Dietz & Neumayer, 2007; Ekins et al., 2003; Simamindra & Rajaonarivo, 2024). Herman Daly's contributions were central in initiating the debate concerning weak and strong sustainability (O'Neill, 2023). Proponents of weak sustainability argue for the interchangeability of different forms of capital, such as natural and built capital, and claim that sustainability is achievable as long as the total capital stock remains constant over time (O'Neill, 2023). Solow and Hartwick, for example, contributed central works in this respect (Hartwick, 1977; Solow, 2000).

Conversely, proponents of strong sustainability argue that substitution is limited and that true sustainability can only be achieved by protecting critical stocks of each form of capital (Neumayer, 2003; O'Neill, 2023). Daly was a strong proponent of this viewpoint, suggesting that different forms of capital complement rather than replace each other (O'Neill, 2023).

As a conceptual approach, the distinction continues to play a role, for example to specify or delimit other concepts (see e.g., Loiseau et al., 2016; Simamindra & Rajaonarivo, 2024). In relation to the CE literature, for instance, weak sustainability practices appear to dominate compared to those of strong sustainability practices (Simamindra & Rajaonarivo, 2024). And the distinction also remains relevant in the context of the bioeconomy (Liobikiene et al., 2019).

For this work, the distinction has methodological implications with respect to the selection of the respective MCDA approach. In particular, it requires addressing the level of compensation between different criteria within the evaluation process. It is also important to understand this perspective in order to be able to categorize different approaches and perspectives on the bioeconomy, as the question of substituting fossil resources with biological resources, for example, plays an eminent role.

3.1.2 Three Dimensions of Sustainability

Sustainable development can be conceptualized as encompassing three interrelated dimensions, namely economic, social and environmental. These dimensions (or pillars) represent the idea that sustainable development should aim to balance economic progress,

social equity and environmental protection to ensure the long-term well-being and prosperity of present and future generations (UN, 1992). Related terms such as dimensions, pillars, aspects and components are used interchangeably (Purvis et al., 2019, p. 681). This work uses the term dimensions with respect to the three areas of action connected to sustainable development as used by the UN (UN, 2012).

The concept has been illustrated for many years either in the form of three intersecting circles, or depicted as literal pillars or as concentric circles, although it is not entirely clear when exactly these representations were introduced and to whom they can be traced back to (Purvis et al., 2019). It can be stated that the 'three-pillar' concept of 'sustainability' or 'sustainable development' is a major interpretation in the literature, although there is semantic ambiguity and the precise conceptual origins are unclear (Purvis et al., 2019). In this context, it can be argued that the dimensions already appear implicitly in the *Brundtland Report* (Purvis et al., 2019). However, they are explicitly mentioned by the UN in *Agenda 21* (Purvis et al., 2019; UN, 1992). It is already recommended in the *Agenda 21* that countries should develop systems to monitor and assess progress towards sustainable development by defining indicators that measure changes in the economic, social and environmental dimensions (UN, 1992 (8.6)). Subsequently, as Purvis et al. (2019) point out, the three pillars were also explicitly considered in the process of formulating the subsequent SDGs (UN, 2012).

The UN emphasizes that it is important to promote a balanced integration of the three dimensions of sustainable development to avoid that progress in one dimension does not result in adverse effects in others (UN, 2012, p. 14). This is an important aspect considering interdependent and potentially conflicting objectives in transformation processes. The categorization based on the three dimensions is therefore also used in the context of the development of transformation paths and the assignment of criteria in this work. The balance between the dimensions is further one of the guiding principles of the GSDS (BReg, 2021a, p. 14).

Schematic illustration of sustainability dimensions

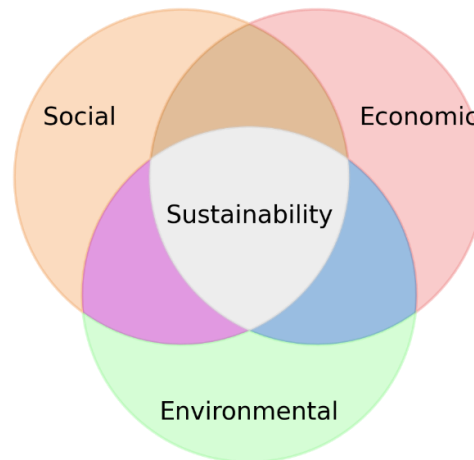


Figure 3. Illustration of Sustainability Dimensions. Source: Author, based on Lozano (2008).

3.1.3 Sustainable Development Goals

Following the UN Millennium Declaration in 2000, from which the Millennium Development Goals were derived, the 2030 Agenda for Sustainable Development was proclaimed (UN, 2000, 2015). It includes 17 SDGs and provides a normative framework for sustainable development (UN, 2015).

The 2030 Agenda for Sustainable Development further provides an internationally agreed framework for quantitative assessment of progress towards sustainability goals, through which countries are intended to report on their progress (UN, 2017a, 2017b). The 169 targets, which provide the quantitative framework for achieving the goals, were published as a resolution and adopted by the General Assembly in 2017 (UN, 2017a). The basis was the work of the Statistical Commission in relation to the 2030 Agenda for Sustainable Development (UN, 2017a). The SDGs are integrated and interdependent aimed at balancing all three dimensions of sustainability (UN, 2015). Yet, using the three dimensions as categories can provide useful insights by allowing for a better overview in order to identify potentially conflicting objectives between the dimensions. Moreover, the concept is easy to communicate to stakeholders and is still utilized in the German strategy (BReg, 2021a).

The internationally recognized SDGs of the UN form the operational basis for the concept of sustainability underlying the present work. In this context, a sustainable bioeconomy must also contribute to achieving these goals in order to ultimately be considered sustainable. The bioeconomy monitoring approach developed in this work is therefore linked to the SDGs.

3.1.4 German Sustainable Development Strategy

Continuing the UN's multilateral efforts, multiple countries have established national sustainability strategies and translated the UN's SDGs into national goals with indicators to assess their progress. The first strategy in Germany was introduced in 2002 and has been continuously adapted and revised since (BReg, 2002). The most recent implementation in Germany is the German Sustainable Development Strategy 2021 (GSDS) (BReg, 2021a).

The strategy emphasizes that the guiding principle of sustainability should be followed (BReg, 2021a, p. 14). In particular, the aspects of the definition based on the Brundtland Report regarding responsibility for future generations, consideration of planetary boundaries, and the goal of a balanced consideration of the three dimensions of sustainability are emphasized (BReg, 2021a, p. 14). Another key principle of the 2030 Agenda is the multi-stakeholder approach, as sustainable development requires the cooperation of all state and non-state actors (BReg, 2021a, p. 20). The priorities for the further development of the current strategy have been directed towards greater involvement of stakeholders and increased efforts to ensure greater policy coherence concerning sustainability (BReg, 2021a, p. 15).

In the sustainability strategy, the BReg also explicitly commits itself to the goals outlined in the bioeconomy strategy: the transformation of the economy and society towards an economy based on sustainable, bio-based and natural cycles (BReg, 2021a, pp. 56, 140, 221, 226, 249, 290, 331). The bioeconomy strategy links the policy areas of industry and energy, agriculture and food, forestry and fisheries, climate and environment, and research and development in order to promote this transformation process (BReg, 2021a, p. 56). The important role of the bioeconomy in achieving the sustainability goals is reflected not least in the fact that the term bioeconomy appears 21 times in the strategy (BReg, 2021a, p. 56).

The broad definition of the Brundtland Report lacks precise and implementable principles and goals, which underlines the need for operationalization. Since sustainability is a normative concept, it is not possible to derive sub-targets, indicators and measurement systems in a logical manner. Instead, sustainability must thus be defined and continuously further developed. The SDGs illustrate a milestone in this regard. Related to the international development linked to the UN, the GSDS can thus be seen as the emergence of an ongoing political negotiation process that defines these sub-goals and measurement systems for Germany. In the case of Germany, hence, many of the criteria and indicators are congruent with those of the UN. However, some are also specific and go beyond the UN framework of indicators.

Overall, the GSDS provides the normative understanding of sustainability for this work and is therefore a central part of the conceptual basis and reference point for the sustainability of the bioeconomy. Achieving progress towards the SDGs, the goals set out in the GSDS, and European as well as national bioeconomy strategies, a comprehensive transformation process is necessary (BMBF & BMEL, 2020b; BReg, 2021b; EC, 2018c; UN, 2015).

3.2 Governance of Transformation Processes

The terms transition and transformation are frequently used in political and scientific discourses (BReg, 2021b; Child & Breyer, 2017; Hölscher et al., 2018; UN, 2015). Both terms are often used interchangeably (Child & Breyer, 2017; Hölscher et al., 2018). For instance, as Wittmayer and Hölscher (2017) point out, the German Advisory Council on Global Change (WGBU) uses the term *Transformation* in the German version of its report while the English version is titled *World in Transition* – even though both terms are common German (WBGU, 2011a, 2011b). This work follows the argument of Child and Breyer (2017) in that it considers it more important to clarify what exactly is meant by the terms instead of delineating potentially different nuances that might distract from the actual change process investigated.⁵ Moreover, as Hölscher et al. (2018) highlight, differences in terminology here are likely to be the result of divergent research

⁵ For an overview of the field of sustainability transitions research, see e.g.: Loorbach, D., Frantzeskaki, N., & Avelino, F. (2017). Sustainability Transitions Research: Transforming Science and Practice for Societal Change. *Annual Review of Environment and Resources*, 42(Volume 42, 2017), 599-626. <https://doi.org/10.1146/annurev-environ-102014-021340>

communities. Both terms and underlying concepts, however, aim to support in describing, interpreting and supporting desirable societal change (Hölscher et al., 2018). They are not mutually exclusive and rather a dualism (Hölscher et al., 2018; Stirling, 2014).

Thus, this work will use both terms interchangeably. For the definition of transformation and transition, it is referred to the understanding as laid out in publications published by the Federal Environment Agency (Umweltbundesamt, 2018; Wolff et al., 2023). Thus, transformations and transitions are understood as

processes of profound change in which developments in different dimensions interlock in a co-evolutionary manner: in markets, technologies and business models, infrastructures, politics, cultural norms and consumer practices, etc. (Wolff et al., 2023, p. 1)

Definitions of governance vary widely (Geels, 2002; Geels & Schot, 2007; Grin et al., 2010; Loorbach et al., 2017; Schot & Steinmueller, 2018). Given the key role technology plays within the future development of the bioeconomy, this work relates its understanding to the governance of transformative innovations (Grin et al., 2010; Schot & Steinmueller, 2018). Thus, governance of transformations is understood as

a political process which should provide room for appraising and negotiating the development of a diverse set of pathways as well as making choices for specific ones. In this negotiation process, visions of various groups do not have to be fully congruent, stakeholders need to recognize sufficient commonly attractive elements they can relate to in order to move forward (Grin et al., 2010, p. 335)

Related research from social sciences should thus contribute to political debates and policymaking by providing different perspectives of potential alternatives along with their respective context (Stirling, 2014). With respect to the energy system transformation, for instance, key questions are frequently not primarily related to the choice of individual technologies but rather how they can be utilized for societal good (Sovacool et al., 2020; Stirling, 2014; Waddell, 2016).⁶ Developing transformation pathways can help here by

⁶ Research on science and technology studies addressing these issues in the context of climate and energy research is a broad field involving multiple disciplines. For an overview, see e.g.: Sovacool, B. K., Hess, D. J., Amir, S., Geels, F. W., Hirsh, R., Rodriguez Medina, L., Miller, C., Alvial Palavicino, C., Phadke, R., Ryghaug, M., Schot, J., Silvast, A., Stephens, J., Stirling, A., Turnheim, B., van der Vleuten, E., van Lente, H., & Yearley, S. (2020). Sociotechnical agendas: Reviewing future directions for energy and climate research. *Energy Research & Social Science*, 70, 101617. <https://doi.org/10.1016/j.erss.2020.101617>

assisting resulting governance efforts (Hof et al., 2020; Wolff et al., 2023). They will thus illustrate a central element of this work. Since the bioeconomy relies strongly on technology development as a key driver (see Sectors, Drivers and Opportunities), related concerns equally apply for a successful transformation process. Issues of development and utilization of bioenergy and biofuels illustrate an example in this regard (Birch & Calvert, 2015).

Approaches related to transition governance are situated within the broader fields of complexity science, governance and sustainability science (Loorbach et al., 2015; Wittmayer & Hölscher, 2017). The underlying perspective is that large-scale societal transitions are inherently complex, uncertain and frequently contested, preventing addressing them through traditional steering approaches successfully and requiring new ones (Loorbach et al., 2017; Loorbach et al., 2015; Wittmayer & Hölscher, 2017). Sustainability transformations, as well as the transformation towards a sustainable bioeconomy, can further be described and interpreted as wicked problems, which implies a need for understanding the perceptions of stakeholders involved (Urmetzer et al., 2020; Vogelpohl & Töller, 2021). Through transformative agency and governance, multiple stakeholders play a vital role in steering desired transitions (Hölscher et al., 2018). Thus, transformation processes are at its core political and related value conflicts and power constellations need to be considered (Patterson et al., 2017). It is therefore crucial to understand respective stakeholder perceptions for the transition for a sustainable bioeconomy, as is stated aim of this work. Yet, it is also crucial to address potential ways forward.

Governing transition processes in the context of sustainability highlights the role of problem-solving and adaptive coordination over direct control (Turnheim et al., 2015; Wise et al., 2014). This requires pluralistic governance approaches that address different dilemmas and support trajectories to desirable, future-oriented outcomes (Turnheim et al., 2015). Some sort of trajectory connecting the past, present and future can help to navigate these challenges (Turnheim et al., 2015). Pathways can illustrate this kind of mean needed to define broad directions for change for strategic goals in an inherently uncertain environment for decision-making (Werners et al., 2021). They are increasingly utilized in connection with implementing goals of the *Agenda 2030*, frequently with SDGs closely related to the bioeconomy, including sustainable food production,

sustainable energy supply, sustainable cities and sustainable consumption and production (Wolff et al., 2023).⁷ To be useful in guiding prospective decision making, they need to be future-oriented and relate to societal objectives (Turnheim et al., 2015; Werners et al., 2021).

Innovation ecosystems, for instance, constitute a key element in a sustainable bioeconomy (Philp & Winickoff, 2019). They can contribute towards addressing societal challenges by, for example, fostering collaboration across stakeholders (Philp & Winickoff, 2019). However, it is frequently unclear how and in which direction since goals and challenges are often only set out at supranational or national levels (Wanzenböck & Frenken, 2020). Thus, there is an increased necessity to contextualize broad goals and potential directions for future bioeconomy development in a regional context. In particular, because regions are especially affected by transformations, such as the phase-out of coal-based energy (Diluiso et al., 2021).

Therefore, the following section addresses four central aspects crucial for supporting decision-making for the future of the bioeconomy, namely the characteristics of wicked problems, the roles of stakeholders, the utility of transformation pathways and the importance of regionalization.

3.2.1 Wicked Problems

Integrative and transformative research approaches that incorporate diverse knowledge and perspectives are promising for a desirable transformation process based on innovation linked to the bioeconomy (Friedrich et al., 2021). However, how this can be achieved is frequently unclear. So far, bioeconomy policy has served more as a conceptual umbrella for a number of existing policies, with little tangible impact (Töller et al., 2021). Especially in group decisions, there is often notable disagreement with respect to the ranking of potential alternatives, even though all involved parties agree that it is better to choose any of the given alternatives instead of remaining with the status quo

⁷ For a literature review analyzing the utilization of transformation pathways for global sustainable development in connection with implementing the goals set out in the *Agenda 2030*, see: Wolff, F., Fischer, C., Gensch, C.-O., Hanke, G., Kenkmann, T., McLennan, A., Ritter, D., & Schreiber, J. (2023). *Transformation pathways to implement the 2030 Agenda: status & possible further developments in selected fields of action*. Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/factsheet_transformation_pathways.pdf

without any change (Sen, 2017a; Sunstein, 1995). This insight can be linked to different kinds of challenges related to climate change and environmental degradation, or to questions such as which transition path should be followed in the RR. To enable aspired innovation ecosystems in a bioeconomy as a sustainable way to produce goods, for instance, it is important to carefully align policies (Philp & Winickoff, 2019). Herein lies a difficulty since societal transformation processes are complex and can be considered wicked problems.

Wicked problems are characterized by certain properties. These include that it is challenging to formulate a specific goal, which constitutes a central element of planning any possible policy solution for a given problem (Rittel & Webber, 1973). Further, there is no optimal solution – or generally a solution in the real sense of the word – for problems of open societal systems, making classical paradigms of science and engineering inapplicable (Rittel & Webber, 1973). Moreover, there is a lack of an undisputable public good or objective definition of equity (Rittel & Webber, 1973). Thus, the required information to comprehend and describe a wicked problem in satisfactory detail depends upon the idea for solving it, implying the need for anticipating all possible solutions at a given time (Rittel & Webber, 1973). As a result, comprehending a problem and resolving it is interdependent and thereby making each problem essentially unique and highly context-dependent (Rittel & Webber, 1973). Wicked problems cannot be adequately approached using classical systems-approaches (Rittel & Webber, 1973). Instead, it is necessary to re-order priorities and re-define the problem at hand to develop innovative goal-oriented actions (Rittel & Webber, 1973). Promising approaches towards wicked problems, however, can be identified in those that comprehend planning as a process of continuous arguing among the participants through which an improved understanding of the problem as well as of possible solutions comes forth as a result of continuous judgment and critical evaluation (Rittel & Webber, 1973).

Latest since the early 1970s, wicked problems have become a component of public policy research (Newman & Head, 2017). The exact delineation and implications for the use for governance and public policy is debated and further, related concepts have been developed over time (Grin et al., 2010; Head & Alford, 2013; Newman & Head, 2017; Schuitmaker, 2012; Wanzenböck et al., 2020). Related concepts to address similarly complex problems are, for instance, what Hisschemöller and Hoppe (1995) described as

ill-structured problems as well as the concept of persistent problems (Schuitmaker, 2012). Wicked problems were addressed in a variety of case studies and across disciplines, including questions related to governance, regional planning, natural resource management (Head & Alford, 2013).

This work follows the argument brought forward by Head and Alford (2013) stating that the “process of democratic political debate provides a robust testing ground for sifting the practical merits of options and for assessing support for policy choices” (Head & Alford, 2013, p. 716). Thus, the characteristics of wicked problems of being open to subsequent adaptation does not constitute a major difficulty but can instead potentially be beneficial (Head & Alford, 2013). This has implications for the present work and can help to arrive at a broader understanding of how to address the transition process for the bioeconomy.

Wicked problems are often characterized by social diversity, as stakeholders have different interests and values, as well as institutional complexity, and scientific uncertainty due to gaps and fragmentation of reliable knowledge (Head & Alford, 2013; Wittmayer & Hölscher, 2017). The complexity of this kind of problem has led the scientific community to collaborate with a wider range of stakeholders (Gerlak et al., 2023). Understanding and perception of such problems can be considered an act of prioritization through which social relevance and potential solutions are shaped (Wittmayer & Hölscher, 2017). Participatory approaches involving stakeholders can contribute in helping to arrive at mutual and common understanding for identifying potential future trajectories (Wittmayer & Hölscher, 2017). Therefore, stakeholders and their role in the context of this work are discussed next.

3.2.2 Stakeholder Engagement

Stakeholder theory is commonly traced back to Freeman, R. Edward’s book *Strategic Management: A Stakeholder Approach* which was intended to be used in relation to strategy courses and business policy (Freeman et al., 2018; Laplume et al., 2008).⁸ While

⁸ Stakeholder theory is a dynamic research field spanning across several fields, including business administration, ethics, and human rights. For an overview and a brief history, see e.g.: Freeman, R. E., Phillips, R., & Sisodia, R. (2018). Tensions in Stakeholder Theory. *Business & Society*, 59(2), 213-231. <https://doi.org/10.1177/0007650318773750>

there has been research on stakeholder theory and the stakeholder concept for several decades, it is still contested and lacking a universal definition (Agle et al., 2008; Kaler, 2002; Miles, 2017; Tullberg, 2013)⁹. Based on the analysis of 885 definitions, Miles (2017) recommends a context dependent meaning instead of striving for a universal one.

Thus, this work understands stakeholders as any individual, group, or organization that has an interest in or is affected by a transformation processes related to the bioeconomy. Stakeholders may include policymakers, businesses, communities, researchers, and other entities. Stakeholder engagement is considered the process of involving stakeholders in decision-making, planning, or implementation. It aims to ensure their perspectives, values, and expertise are accounted for to foster collaboration, improve understanding, and build trust among participants.

Stakeholder engagement has since gain prominence in various contexts beyond the initial setting. Schwab (2017), for instance, argues that stakeholder engagement is crucial to progress with respect to the Fourth Industrial Revolution. As Sachs et al. (2019) stress, the scientific community should develop tools for multi-stakeholder engagement to address trade-offs, ensure feasibility, and highlight the urgency of action to work towards transformations required in striving towards the SDGs. Stakeholder engagement has further evolved into a common component of natural resource management (Han et al., 2024). Managing natural resources as a collective action problem, for instance, requires engaging stakeholders through inclusive, reflective and systemic processes (Han et al., 2024). With regard to environmental decision-making in particular, there is an increased interest in understanding stakeholder dynamics (Gerlak et al., 2023).¹⁰ The importance of integrating science into decision-making to improve governance approaches and resource management is also widely recognized among societal actors (Gerlak et al., 2023; Han et al., 2024). Since the bioeconomy is closely related to issues concerning natural resources this work argues that the inclusion of divergent stakeholders is equally important.

⁹ For an overview of definitions and classification approaches, see: Miles, S. (2017). Stakeholder Theory Classification: A Theoretical and Empirical Evaluation of Definitions. *Journal of Business Ethics*, 142(3), 437-459. <https://doi.org/10.1007/s10551-015-2741-y>

¹⁰ For a comprehensive review addressing the role of stakeholders in environmental decision-making, see e.g.: Gerlak, A. K., Guido, Z., Owen, G., McGoffin, M. S. R., Louder, E., Davies, J., Smith, K. J., Zimmer, A., Murveit, A. M., Meadow, A., Shrestha, P., & Joshi, N. (2023). Stakeholder engagement in the co-production of knowledge for environmental decision-making. *World Development*, 170, 106336. <https://doi.org/10.1016/j.worlddev.2023.106336>

Integrating diverse stakeholders in research initiatives can lead to more relevant policies through better accounting for cultural- and sociopolitical circumstances (Blicharska et al., 2017; Gerlak et al., 2023). The collaborative production (or often *co-production*) of knowledge has become a common approach to addressing problems involving multiple stakeholder groups (Gerlak et al., 2023; Han et al., 2024). It is considered as key idea for governance in the context of global sustainability, including fields such as public administration, science and technology studies, and sustainability science (Miller & Wyborn, 2020).¹¹ Miller and Wyborn (2020) also identify the idea as introduced and key to multiple works Elinor and Vincent Ostrom in the 1970s. It is regarded as particularly useful for engaging diverse stakeholder when conflicts or power inequalities exist (Gerlak et al., 2023; Miller & Wyborn, 2020; Turnhout et al., 2020). In the context of complexity and complex problems, it is expected to enhance understanding of interdependencies and contribute to developing policy solutions (Gerlak et al., 2023; Miller & Wyborn, 2020; Turnhout et al., 2020). That underlines its potential in the context of this work.

However, despite its potential, it is crucial to acknowledge the political dimension of that process and potentially unequal power constellations (Miller & Wyborn, 2020; Turnhout et al., 2020).¹² As Miller and Wyborn (2020) point out, the overall goal of co-production is not just knowledge, actionable knowledge or action as such, but sustainability. Thus, this work follows the suggestion by Turnhout et al. (2020) and understands knowledge co-production as both a knowledge-making as well as a political practice while acknowledging potentially unequal power constellations. Co-production and stakeholder engagement thus constitutes a possibility to contribute to knowledge useful for decision-making in transformations (Gerlak et al., 2023; Han et al., 2024; Mauser et al., 2013; Page et al., 2016; Sterling et al., 2017). It therefore also plays an important role in the context of this thesis.

¹¹ For an overview concerning differences with respect to definition and practices across several disciplinary traditions, including public administration, science and technology studies, and sustainability science, see e.g.: Miller, C. A., & Wyborn, C. (2020). Co-production in global sustainability: Histories and theories. *Environmental Science & Policy*, 113, 88-95. <https://doi.org/10.1016/j.envsci.2018.01.016>

¹² For a literature review on the political and power dimensions of co-production, see e.g.: Turnhout, E., Metze, T., Wyborn, C., Klenk, N., & Louder, E. (2020). The politics of co-production: participation, power, and transformation. *Current Opinion in Environmental Sustainability*, 42, 15-21. <https://doi.org/10.1016/j.cosust.2019.11.009>

From a research perspective that focuses on complex social problems and potential ways to address those, as it is done in this work with respect to the transformation towards a sustainable bioeconomy, relying on insights stemming from only a single discipline is not sufficient (Wittmayer & Hölscher, 2017). As social problems rarely follow disciplinary boundaries, it is necessary to draw on input from different disciplines and various stakeholders to better understand transformation processes and develop possible solutions (Wittmayer & Hölscher, 2017). Moreover, it is important to note that research itself is part of the social system it describes and analyzes, making it an actor with responsibility (Wittmayer & Hölscher, 2017).

Based on the points discussed, the aspect of stakeholder engagement has multiple implications for this work. First, it constitutes a useful tool for co-producing knowledge to better understand the transformation process towards a sustainable bioeconomy, especially with regard to providing orientation for a potential future space of action. Second, it sheds light on the importance of ensuring the integration of multiple, divergent perceptions and perspectives. Third, it is crucial to acknowledge potential power imbalances.

The most common outcome of knowledge co-production processes is dialogue between stakeholders (Gerlak et al., 2023). In the context of the present work, a basis for such dialog is intended to be developed using the decision support system and focused on transformation pathways for a sustainable bioeconomy. Therefore, transformation pathways are examined in more detail in the next section.

3.2.3 Transformation Pathways

As a way to contribute towards decision-oriented approaches to researching and planning for adapting to climate change, transformation pathways gained considerable attention in recent years (Werners et al., 2021).¹³ Pathways have been developed for this purpose in various decision-making contexts (Werners et al., 2021). They are frequently utilized in efforts towards implementing the *Agenda 2030*, especially with respect to

¹³ For a comprehensive review of multiple concepts and applications of adaptation pathways, see e.g.: Werners, S. E., Wise, R. M., Butler, J. R. A., Totin, E., & Vincent, K. (2021). Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, 116, 266-275. <https://doi.org/10.1016/j.envsci.2020.11.003>

action areas relating to sustainable energy supply, food production, cities, consumption and land use (Wolff et al., 2023). Related approaches based on pathways are frequently situated around multiple stakeholders and transformation processes to cope with complexity and uncertainty (Werners et al., 2021). Therefore, they hold great potential for the approach developed in this thesis. As a promising mean to inform decision-making for future directions of transformations, especially under uncertainty, their potential is widely recognized (Bosomworth et al., 2017; Haasnoot et al., 2013; Turnheim et al., 2015; Werners et al., 2021). Pathways are often conceptualized to contribute to addressing adaptation needs and help to enable transformations (Werners et al., 2021). This is equally the case in this work.

The need for novel concepts and a broader understanding of transformation pathways to inform decision makers (DM) has long been recognized in the scientific community (Geels, 2002; Geels & Schot, 2007; Hof et al., 2020; Turnheim et al., 2015; Wise et al., 2014). As Werners et al. (2021) highlight, two different, common understandings of pathways exist in the literature in relation to climate change adaptation and planning. The first understands pathways in a sense of sequence of measures towards a clearly defined objective or adaptation goal (Werners et al., 2021). The second understanding perceives pathways more in broad sense in order to navigate towards varying strategic goals or objectives (Werners et al., 2021). Broader pathways approaches can contribute to inform societal transformations and decision-making (Werners et al., 2021; Wise et al., 2014). This work understands pathways in the broader sense helping to navigate decision making towards a sustainable bioeconomy.

Based on Wolff et al. (2023, p. 1), this work understands transformation pathways as “descriptions of goals or ‘target visions’, of transition processes”, rooted in a future-oriented and explorative sense. Transformation pathways can be underpinned with explorative, normative visions of the future and narratives (Wolff et al., 2023). As Wolff et al. (2023) further point out, this understanding of transformation pathways differs from a historical-empirical conception, which sees transformation pathways as factual, historically observable developments (Turnheim et al., 2015).

For this work, they hold multiple benefits since they can be utilized to support governance in the context of transformation processes (Hof et al., 2020; Wolff et al.,

2023). They can simplify complex concepts and improve communication with stakeholders (Werners et al., 2021; Wolff et al., 2023). This aspect is helpful given the context of the present study since multiple stakeholders are involved and their expertise can differ. Transformation pathways also help to monitor and evaluate policy progress, supporting coordination and implementation efforts (Wolff et al., 2023). This also holds relevance for this work since the monitoring approach developed in this work aims to contribute to these aspects, too. And in the international context pathways can help to make the achievement of goals more accessible to discussions and negotiations in the political sphere (Wolff et al., 2023). Since this work aims to be relevant beyond the specific application, this is also a meaningful aspect.

In the context of the present work, the SSPs are key to the development of corresponding transformation pathways and hold particular relevance (O'Neill et al., 2017; Riahi et al., 2017). The SSPs project global socioeconomic changes up to the year 2100 as defined in the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2021). Similar to the SDGs, however, these initially refer to the global level and must be operationalized accordingly for use in a regional context. The pathways in the SSP framework serve as reference points for researchers to assess the effects of different levels of climate change and policy choices on baseline conditions, and are intentionally designed without accounting for the effects of climate change and climate policies (O'Neill et al., 2014). Because scenarios go beyond the reference SSPs to include a broader range of factors, they are versatile and serve as a foundational step in scenario development (O'Neill et al., 2014).

In this work, the SSPs are a centerpiece of the development of the Regional Transformation Pathways (RTPs). The SSPs constitute a reference for a variety of assessments addressing climate change challenges and broader sustainability issues, and are the successor to the Special Report on Emissions Scenarios (van Vuuren et al., 2014). As an enhancement to the Representative Concentration Pathways (RCPs), the SSPs present socio-economic narratives that consider the challenges of both mitigation and adaptation (van Vuuren et al., 2011; van Vuuren et al., 2014).

As noted by O'Neill et al. (2017), the process of creating the SSP narratives was guided by pre-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), along with other global scenario developments (van Vuuren et al., 2012).

Several papers have outlined potential foundations for SSP narratives, including those by Kriegler et al. (2012), O'Neill et al. (2014), and Schweizer and O'Neill (2014), with van Vuuren and Carter (2014) addressing analogies to SRES scenarios (O'Neill et al., 2017). The role of the concept of adaptation challenges (Rothman et al., 2014) and political economy and governance (Lane & Montgomery, 2014) in shaping narratives is also emphasized by O'Neill et al. (2017). The SSPs and the narratives associated with them are therefore the result of a long-term process of development. SSP pathways are deliberately created disregarding climate change and climate policy impacts (O'Neill et al., 2014). These provide a reference for assessing the impacts of different levels of climate change and policy decisions relative to baseline conditions (O'Neill et al., 2017; O'Neill et al., 2014). As such, the narratives were crafted to take account of socioeconomic and environmental factors (with the exception of climate) that are critical to addressing these challenges (O'Neill et al., 2017). Hence, the SSPs can be utilized to address sustainable development without being focused explicitly on mitigation and adaptation challenges, although these challenges were the initial motivation for their development (O'Neill et al., 2017). In total, five SSPs have been developed that are based on different assumptions regarding mitigation and adaptation (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 are the basis for the development of regional transformation pathways in the context of this work.

The narratives of the SSP provide enough information to sketch out plausible alternative paths of development (O'Neill et al., 2017). However, an extended narrative that is consistent with, but goes beyond, SSPs is needed for analysis at the subnational level and for specific sectors (O'Neill et al., 2020; O'Neill et al., 2017). As opposed to the developed bioeconomy pathways proposed in this work, the period of observation of the SSPs is different and the sectors covered are not primarily focused on matters connected with bioeconomy transformations. Nevertheless, the framework provides a valuable basis for comparability. It aims to help researchers and policymakers understand each other. Aligning pathways with established SSP narratives therefore supports the

translation of global developments into a regional setting for a low-carbon transition. This approach thus contributes towards making respective transformation pathways more tangible in the regional context which is at the core of this work. However, this requires the development of transformation pathways that take into account the context of the bioeconomy on the one hand and regional characteristics on the other. Not least because regions are often at the center of transformation processes, especially with regard to decisions related to the phase-out of coal (Diluiso et al., 2021).

3.2.4 Regionalization - The Rheinische Revier

Realizing potentially positive climate effects set out in international or national targets are crucially dependent appropriate policies in the regional sphere (Diluiso et al., 2021; Wanzenböck & Frenken, 2020). Major challenges for regions historically dependent on coal are linked to structural changes for industry and labor (Diluiso et al., 2021). However, the experiences in Germany with the structural change following the phase-out of hard coal in 2018 amply that effects of structural changes on that scale need to be addressed more broadly and go beyond (Oei et al., 2020).

Based on the definition laid out by Matthes (2017) for the energy transition and the German national bioeconomy strategy, this work understands the structural change process triggered by the transition process towards a sustainable bioeconomy as policy-driven structural change supported by major innovations related to the production, exploitation and use of biological resources, processes and systems to provide products, processes and services across all economic sectors within the framework of a future-oriented economy induced by the policy efforts. Therefore, it differs from other forms of technology-related changes, such as those driven by demand-pull or technology-push, in that it is intentionally implemented and guided by socioeconomic objectives (Hötte, 2023; Matthes, 2017).

Regional transitions and associated shifts are of central importance because of their profound effects on material stocks and flows (van Oorschot et al., 2023). The way resources are produced, distributed, and consumed adjusts as regions undergo transformation. Resource flows and the nature of economic activities are intertwined in these changes in socio-economic systems (Font Vivanco et al., 2019). To develop effective policies that prioritize sustainability and resource efficiency, policymakers must

consider how structural changes will affect future resource flows and consumption patterns. This is of high relevance to bioeconomy transformations.

Multiple regions across Europe aim to further develop their bioeconomy and published dedicated strategies (Haarich et al., 2022). Moreover, various bioeconomy clusters, understood as consortium of organizations aiming to produce biomass and transform it into value-added products, exist throughout Europe (Szarka & Kittler, 2022). This form of networks and clusters on a regional level can also be commonly found in Germany (Kirchgeorg, 2022; Nummert, 2022; Schulze & Beck, 2022; Schurr & Slusarczyk, 2022; Weidtmann et al., 2022). Those exist, for instance, in the state of Saxony-Anhalt (Schulze & Beck, 2022), Baden-Württemberg (Weidtmann et al., 2022), Bavaria (Nummert, 2022) and NRW (Schurr & Slusarczyk, 2022).

For the present study, however, the RR constitutes a particularly promising case study for numerous reasons. It is central to the coal phase-out and political initiatives aiming towards a sustainable bioeconomy in the region (Coal Commission, 2019; Radtke & David, 2024; Zukunftsagentur Rheinisches Revier, 2021). Due to its history, economic and industrial structure and the value added through coal, the energy sector is notably more relevant compared to other coal regions in Germany or the national average generally (Coal Commission, 2019). Moreover, the degree of interconnectedness and interdependence of regional value chains is a special feature of the RR (Coal Commission, 2019). Shifting value chains are expected to fundamentally change material flows in NRW and the RR region (Abdelshafy & Walther, 2022). The effects of implementing a sustainable bioeconomy thus are linked to high risks and high potential. The expected effects on jobs are also likely to lead to major socio-economic changes (Coal Commission, 2019). In addition to coal, there are fertile soils that are suitable for the cultivation of various agricultural goods, contributing to the region's relevance as a model region for a sustainable bioeconomy (BioSC, 2024c; Greiving et al., 2022).

Furthermore, the region is characterized by and embedded in an active research environment within NRW, involving multiple universities and research institutions with the BioSC as an institutionalized network (Schurr & Slusarczyk, 2022). It is a stated aim of the BioSC to bundle competencies across disciplines and in a joint scientific cluster to develop integrated approaches towards a sustainable bioeconomy (BioSC, 2024a; Schurr

& Slusarczyk, 2022). Related research projects include, for instance, projects such as the *PhenoRob* that is conducting world-leading research in robotics and phenotyping for sustainable crop production (PhenoRob, 2024) and *greenRelease* concerning modern biotechnology contributing to the reduction of pesticide use (Kuhn et al., 2022). In addition, questions of how to balance the diverging interests of many societal groups in the transformation are explored as part of the competence platform *Transform2Bio*, in which this work is embedded (BioSC, 2024b; Venghaus, Dieken, et al., 2022).

It is further frequently used as comparative region for case studies in relation to the bioeconomy, for instance concerning environmental awareness and sustainable behavior (Boermans et al., 2024) and transition roadmaps (Cantoni & Claire Brisbois, 2024; Tranoulidis et al., 2024). This contributes to the relevance this study holds beyond the actual case study.

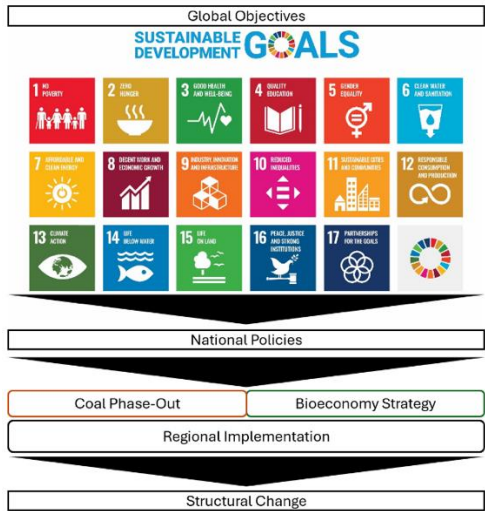


Figure 4. Transformational Trends in the Rheinische Revier. Source: Author, based on UN (2015).

Situated in the area between Aachen, Bonn, Cologne and Düsseldorf, the region is characterized by the presence of both a robust fossil-based economy and a strong bio-based economy (Coal Commission, 2019; Schurr & Slusarczyk, 2022; Zukunftsagentur Rheinisches Revier, 2021). Thus, as illustrated in **Figure 4**, it is strongly affected by two central transforming trends in the region, the phase-out of coal, and the promotion of a sustainable bioeconomy. **Figure 5** further provides an overview of the region and the bordering area.

This is reflected in the high number and variety of stakeholders affected by and engaging with this transformation (Schurr & Slusarczyk, 2022; Zukunftsagentur Rheinisches Revier, 2021). It is an open question how these divergent values of individual members of society for different possible transformation paths can be reconciled into an overall socially beneficial outcome and what implications can be expected for related decision-making processes.

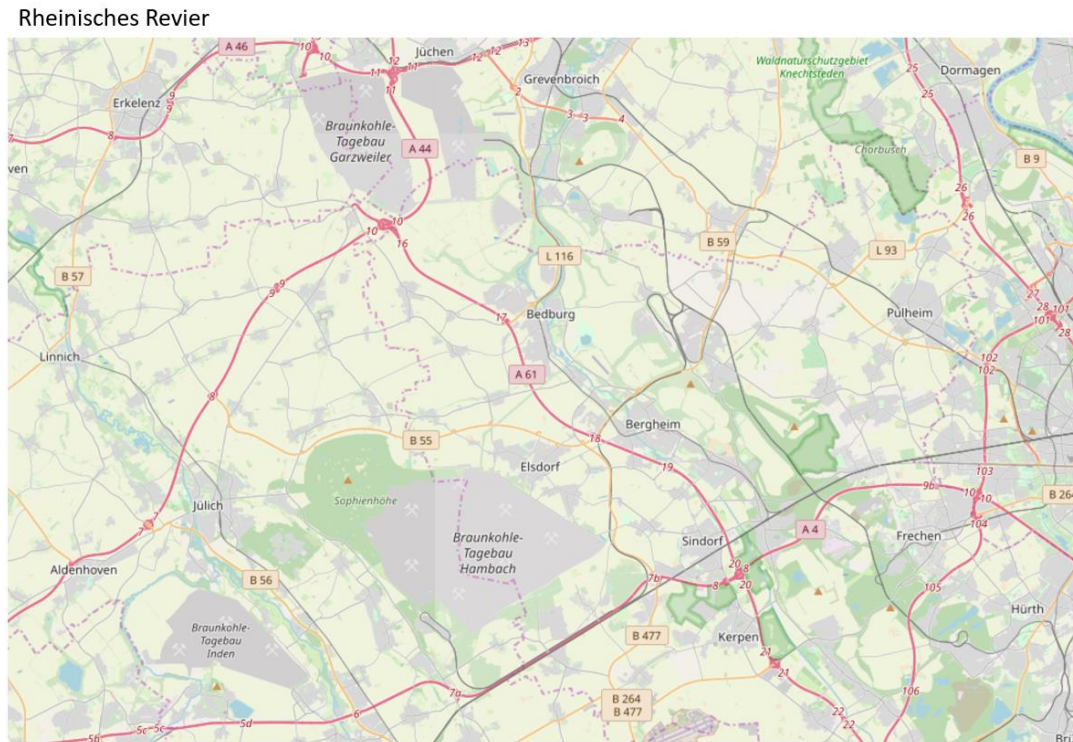


Figure 5. Map of the Rheinisches Revier. Source: © OpenStreetMap contributors, CC-BY-SA.

The ongoing transformation in the RR presents a distinct chance to scrutinize the dynamics among stakeholders and their impact on potential paths toward sustainability in the bioeconomy. The region is an excellent location for transitioning to a sustainable bioeconomy, benefiting from established infrastructures in closely related sectors such as agriculture, chemical and energy industries, and education and research. Therefore, it serves as an ideal case study for this thesis.

3.3 Section Summary

Multiple conceptions of sustainability and sustainable development exist in policy, research and society. This work bases its understanding on the work of the UN,

specifically on the SDGs and its national adaptation in the form of the GSDS. Further relevant with regard to this thesis are the concepts of strong and weak sustainability since the question of indicator substitution has implications for the methodology, as well as the concept concerning the three dimensions of sustainability since it constitutes a useful mean to illustrate conflicting goals and imbalances.

To achieve progress towards the SDGs and goals set out in bioeconomy strategies, a comprehensive transformation process is necessary. Governing transition processes in the context of sustainability demand addressing different dilemmas and efforts to identify trajectories towards desirable future-oriented outcomes. This implies an increased need for contextualizing broad goals and potential directions for future bioeconomy development in a regional context. With this arises a challenge since societal transformation processes are complex and frequently considered wicked problems. Wicked problems are characterized by certain key properties, including uncertainty, complexity, and conflicting stakeholder perceptions.

Approaches that involve stakeholders in research and decision-making processes can contribute to arriving a mutual and common understanding for identifying potential future trajectories. Through stakeholder engagement, knowledge can be co-produced, improving accounting for varying sociopolitical circumstances and contributing towards more relevant policies and informed decision making in transformation processes. Dialogue between stakeholders is the most common outcome of knowledge co-production processes. In this thesis, it is intended to establish a solid foundation for such dialogue by utilizing a decision support system. Thereby, it is contributed to identifying a transformation pathway for a sustainable bioeconomy.

Pathways are frequently developed to help in addressing adaptation needs and enabling transformations. With regard to this work, pathways are understood in a broader sense contributing to navigate towards strategic goals and objectives. Transformation pathways, in particular the SSPs, constitute the basis for regional transformation trajectories developed in this thesis. This allows to make respective pathways more tangible in a regional context since regions are commonly most affected by political decisions to phase-out coal. Central to this work is the region RR because it is strongly affected by the

coal phase-out and the intended transformation towards a sustainable bioeconomy and embedded in a dynamic political, research and economic environment.

Overall, this leads to the question of how these stakeholder dynamics can be brought together with transformation pathways in a decision support system to contribute informing future governance. Thus, in the following chapter, the role of Amartya Sen's work concerning collective choice and its implications for the development of a decision-support system in the context of the present work are introduced and discussed.

4 Collective Choice and Public Reasoning

Reasoning is a robust source of hope and confidence in a world darkened by murky deeds – past and present. (Sen, 2011, p. 46)

A central objective of this work is to enhance understanding concerning stakeholder dynamics and transformation processes in the context of the bioeconomy. To work towards this aim, bringing together stakeholder perceptions and transformation pathways in a decision support system constitute a key element of this work. This demands a solid conceptual foundation to subsequently allow for deriving policy recommendations and supporting governance in respective transformation processes. The basis for the development of this system in this work constitutes the operationalization of Amartya Sen's work on collective decision-making.

Sen explores how social decisions can incorporate multiple values and perspectives. His work builds on, but departs from, classic works in SCT. To allow for a profound understanding of how Sen develops his perspective, this section addresses key terms and concepts on which Sen bases his argumentation. In the context of this thesis, Sen's work provides guidance in multiple ways. It provides a basis for the method selection in the subsequent chapter, contributes to deriving research questions, and contributes to interpreting the results of this work. Bringing together stakeholder perceptions and transformation pathways guided by Sen's remarks on collective choice illustrates a novel approach of addressing transformation trajectories in a societal transformation process.

The core of SCT is the study of methods for aggregating individual preferences, values, or choices to arrive at collective decisions in a fair and consistent way. With regard to SCT, Sen frequently refers to the scholars of the European Enlightenment. Therefore, the origins and historical roots of SCT are traced and their contribution to the development of modern SCT is outlined. The central implications of Arrow's impossibility theorem and the role of informational broadening for Sen's normative social choice approach are then discussed. Next, key terms and concepts related to public reasoning are introduced. Sen's understanding will be distinguished from that of other scholars, especially John Rawls, who has had a profound influence on Sen's work. Finally, the resulting implications for the development of the methodological approach and the prospective interpretation of the results are set out.

4.1 Foundations of Social Choice Theory

4.1.1 Roots of Social Choice Theory

Questions dealing with group decision-making have attracted the interest of researchers and scholars for centuries (Suzumura, 2002). As an approach to reach collective decisions, SCT has been applied in various contexts and across several different disciplines, including political science and economics (Chambers & Echenique, 2016; Dryzek & List, 2003; Feldman & Serrano, 2006; Patty & Penn, 2019). The evaluation of methods for collective decision making and the foundations of welfare economics are central to SCT (Suzumura, 2002).

The roots of SCT date back to the period of the European Enlightenment and build on the work of the French mathematicians Borda and Condorcet (Sen, 2011, pp. 91, 94; Suzumura, 2002). Motivated by the idea of developing a framework for democratic and rational decision-making, taking into account the interests and preferences of a group of people, their approaches to social problems were predominantly mathematical - although Condorcet also discussed several ways in which individual and collective reasoning can influence social decisions (Condorcet, 1994; Lukes & Urbinati, 2012; Sen, 2017a, p. 399). In the course of the research, however, a number of difficulties were encountered.

The fact that procedures aimed at creating a social preference out of individual preferences can often lead to inconsistencies, for instance, has been known for more than two centuries (Suzumura, 2002). This has implications for decision-making and overall societal welfare. And while Condorcet's work on the importance of reasoning and education has been less prominent in the recent development of SCT, Sen recognizes the "belief in the reach of human reasoning" as the connecting element between the earlier writings during the period of Enlightenment and modern SCT (Sen, 2017a, p. 466). The scrutiny through ordinary language is thus necessary and indispensable to the important questions of social choice (Sen, 2017a, p. xxxiii). Mathematical reasoning is at times used to support parts of this inquiry, but it is not a substitute for it (Sen, 2017a, p. xxxiii).

According to Sen, the foundations of SCT and welfare economics are closely linked to ethics and political philosophy, with notable philosophical implications, particularly concerning the theories of justice and his understanding of collective choice (Sen, 2017a,

pp. vii, xiii). Democratic values also play a decisive role (Sen, 2017a, p. 269). Therefore, these must be considered for a comprehensive understanding of the conceptual basis and delimitation. First, however, the central characteristics in the context of modern SCT are discussed with reference to Arrow's work.

4.1.2 General Properties and Arrow's Impossibility Theorem

SCT assumes a relationship between the individual preferences of members of a given society and collective choices (Arrow, 2012). Following that line of thought, the order of individual preferences aggregated could lead to a preference ordering of society overall, on which social choices should depend (Arrow, 2012; Sen, 2017a, p. 4). Preference ordering here is understood as an agent's preference over different options (or alternatives), for instance, A, B, and C.

Regarding the term *preference*, this work follows Sen's generic understanding covering "all these different interpretations of individual concerns which could be invoked, with clear identification, to serve as alternative informational bases of public decisions and of social judgements" (Sen, 2017a, p. 270).

Modern SCT, building on the works of Kenneth Arrow and his General Possibility Theorem (or *impossibility theorem*), illustrated that even considerably mild requirements for a social choice procedure can make it impossible to rank alternatives (Arrow, 1950). In a case where there are at least two agents and at least three alternatives to rank, the conditions unrestricted domain (universality), non-dictatorship, independence of irrelevant alternatives and Pareto efficiency (unanimity) would lead to an impossibility outcome (Arrow, 1950; Sen, 2017a, p. 5).

Non-dictatorship states that a social preference should respect the preferences of various agents so that there is not only one agent determining all other preferences (Arrow, 2012; Sen, 2017a). The condition *unrestricted domain* requires the social preference to be applicable for all individual (complete and transitive) preference orderings (Arrow, 2012; Sen, 2017a). *Independence of irrelevant alternatives* demands that an agent's individual adjustment concerning his preference of alternatives outside of the given subset should not influence the social preference (Arrow, 2012; Sen, 2017a).

Pareto efficiency requires that, if every agent prefers a specific alternative, then so should the social preference ordering (Arrow, 2012; Sen, 2017a).

4.1.3 *Axiomatic Structure and Normativity of Conditions*

The axiomatic conditions for social choice as defined in Arrow's Impossibility Theorem and related theories of social choice can be considered normative and require further reflection (Bordes & Tideman, 1991; Dryzek & List, 2003; Kelsey, 1985; Mackie, 2003). According to Sen, Arrow's Impossibility Theorem, along with the Condorcet paradox, underscore the shortcomings of voting procedures (Sen, 2011, p. 280; 2017a, p. 399).¹⁴ This implies the need for a critical examination of the axiomatic criteria for social choice, making the axiomatic structure itself a vital subject for public reasoning (Sen, 2011, p. 281; 2017a, p. 399).

Certain constellations, for instance, can lead to the incompleteness of the Pareto criterion, which makes it important to evaluate the circumstances in which it is actually used (Sen, 2017a, p. 68).¹⁵ Further, Pareto-optimality can lead to situations where some people live in pure luxury while others live in extreme poverty and it is not possible to improve the latter's situation without taking from the rich – or as Sen summarizes, “a society or an economy can be Pareto-optimal and still be perfectly disgusting” (Sen, 2017a, pp. 68, 69).

It is noteworthy to acknowledge that the agreement on certain value judgments – such as the Pareto principle – does not imply that these should be considered *objective* (Sen, 2017a). In addition, it is conceivable that “there is no aggregate measure for the welfare of a highly diversified society if this measure is claimed to be objective and non-partisan” (Rittel & Webber, 1973).

Social choice problems frequently arise from a lack of unanimity. (Sen, 2017a, p. 71). If one insists on unanimity for a change to take place, it might never occur (Sen, 2017a,

¹⁴ Condorcet's voting paradox demonstrates that majority rule can be self-contradictory in collective decisions among three or more alternatives, showing that group preferences can become cyclical and inconsistent. For an overview of related research, see e.g.: Gehrlein, W. V. (2006). *Condorcet's Paradox*. Springer. <https://doi.org/10.1007/3-540-33799-7>

¹⁵ Named after Vilfredo Pareto, a Pareto optimum is a state in which no improvement can be made in any one aspect without making the other aspect worse. For its relevance concerning, for instance, social welfare, has been subject of debate for decades. See e.g.: Buchanan, J. M. (1962). The relevance of Pareto optimality. *Journal of Conflict Resolution*, 6(4), 341-354. <https://doi.org/10.1177/002200276200600405>

p. 71). As pointed out by Dryzek and List (2003), social choice theorists recurrently model individuals as self-interested utility maximizers, although it is by no means obvious “why the purely logical and normative analysis of aggregation mechanisms should presuppose any specific behavioral assumption” (Dryzek & List, 2003). As Sen points out, the notion that individuals must always vote based solely on self-interest overlooks the broader influence of values and commitments on human behavior (Sen, 2017a, p. 401).

SCT itself is less concerned with empirical observations of how groups make decisions in practice but explores the normative and logical questions of how individual preferences can be aggregated into group decisions (Dryzek & List, 2003). However, ignoring the emergence and development of individual preferences “is a somewhat narrow position to take” and applying assumptions based on economic self-interest pursuit is “not a particularly useful model for understanding problems of social choice” (Sen, 1977, 2017a).

Indeed, axioms of individualism and various forms of rationality underlie most approaches to economic and political theory (Rittel & Webber, 1973; Suzumura, 2016). Yet, humans have only limited capabilities for rational choice and the interaction of thinking and emotion influences the way people make decisions and reason (Simon, 1983).

While the notion of rationality as internal consistency may seem attractive on the surface, it falls short in practice (Sen, 2017a, p. 302). For example, an individual may exhibit consistent nonrational behavior in decision making while maintaining internal coherence (Sen, 2017a, pp. 302, 311). In this connection, Sen questions perspectives that regard self-interest maximization as rational (Sen, 1977; 2017a, p. 303). Behavior can be driven by different motivations, so it is necessary to consider motivations when understanding choices (Sen, 2017a, pp. 310-312). The idea of complete internal consistency in choices is difficult to grasp, and attempting to explain behavior solely on the basis of actions without considering external factors may not be a prudent analytical approach to understanding the world (Sen, 2017a, pp. 310-312).

Thus, it is necessary to distinguish between rational choice theory with its premises and SCT since without a set of normative conditions it is not possible to develop a social

choice procedure (Dryzek & List, 2003).¹⁶ In this context, deliberation can support the process of finding an agreement on a set of conditions (Dryzek & List, 2003). However, even within Arrow's conditions, there are possible escape routes through interpersonal comparisons and cardinal utilities (Dryzek & List, 2003). Sen emphasizes that, while there has been extensive work on formal SCT within the Arrow framework, the constructive part of Arrow's work has not received adequate attention (Dryzek & List, 2003).

SCT and its mathematical foundations, which lies in the formal modeling of decision-making processes based on axiomatic systems to analyze collective preferences, along with related impossibility results, have been intensively studied for several decades by various scholars, among them Kenneth Arrow, Amartya Sen, Eric Maskin, and Kotaro Suzumura (see e.g., Arrow, 2012; Maskin et al., 2014; Sen, 1993; Suzumura, 2016).¹⁷ The impossibility results have implications concerning the feasibility of fair democratic social choice mechanisms and are due to the axiomatic conditions, which cannot all be satisfied at the same time (Arrow et al., 2011). Thus, a wide range of academic literature exists. Its use for societal transformation processes in the context of environmental decision-making along with the role of public reasoning, however, has not been explored yet.

To understand how normative SCT opens up several possibilities for collective decisions in the context of current transformation processes, it is essential to comprehend its roots in democratic thought as well as the role of information and public reasoning. The following sections explore these connections in further detail.

4.1.4 Sen and the Possibility of Social Choice

Among the various roots of modern democratic thought, the period of the European Enlightenment and the French Revolution have been central to the development of contemporary democratic states and decision-making procedures. The idea to create a

¹⁶ Rational choice theory commonly assumes that individual behavior is mainly motivated by self-interest and utility maximization. For an overview concerning its role in political science, see e.g.: Petracca, M. P. (1991). The Rational Choice Approach to Politics: A Challenge to Democratic Theory. *The Review of Politics*, 53(2), 289-319. <https://doi.org/10.1017/S0034670500014637>

¹⁷ For an overview concerning the mathematical foundation, see e.g.: Arrow, K., Sen, A., & Suzumura, K. (2011). *Handbook of Social Choice and Welfare* (1 ed., Vol. 2). Elsevier.

democratic social arrangement drawing on individual preferences of every member of society over a set of different alternatives and using these preferences to base social decisions upon can be regarded as central to modern SCT and can be traced back to this period of democratic thinking (Sen, 2017a). The current understanding of modern SCT is thus deeply embedded in an axiomatic structure based on democratic values (Sen, 2017a, p. 269). Understanding Arrow's impossibility theorem without comprehending the need to include everyone in the process of social decision-making is, therefore, difficult to conceive (Sen, 2017a).

Following Sen's understanding, a distinction can be made between classical social choice, modern social choice and normative social choice (Sen, 2017a). Classical social choice relates to the works of Borda and Condorcet especially regarding voting systems. Modern social choice, on the other hand, builds on Arrow's Impossibility Theorem (Sen, 2017a). Normative social choice, however, highlights the role of reasoning and value judgments in collective decision making, such as justice and fairness, and addressing problems beyond abstract mathematical conditions (Sen, 2017a). Sen recognized great potential in normative social choice in the context of actual societal challenges (Sen, 2017a).

The mathematical approaches related to modern (or sometimes formal) social choice mainly applied axiomatic requirements to strive for an optimal solution. Yet, in the context of social decision-making and societal transformation processes, it is reasonable to reflect on this aspiration and the related axiom system, which is normative in its nature. If this axiom system leads to an authoritarian conclusion, for instance, it implies that it is necessary to re-evaluate the applied axiom system since axiom systems are provisional (Sen, 2017a).

Thus, it can be necessary to assess the axiomatic requirements – individually as well as combined – and reflect on what can be modified, even when the axioms considered individually seem to be reasonable (Sen, 2017a). For instance, the concept of the insular economic man, focused solely on self-interest, while prevalent in traditional economics, is proving inadequate for understanding social choice dilemmas (Sen, 2017a, pp. 50, 51).

Arrow's theorem focuses on individual preferences for a set of alternative social states, but the axioms themselves do not directly imply that it should not be possible to analyze

the characteristics of the alternatives as well (Sen, 2017a). It is the combination of the three axioms Pareto Principle, Unrestricted Domain, and Independence of Irrelevant Alternatives that leads to the ruling out of any information related to the actual nature of the alternatives and a black-boxing of social states – which may be reasonable for a voting system, but not necessarily for assessing and comparing different social states (Sen, 2017a).

It leads to the fact that it does not matter how much violation of human rights or how much inequality prevails in an alternative since all descriptive information with respect to the actual state is ignored in favor of the individual's (or a group's) preferences over them (Sen, 2017a). And even here, how strong or for what reason one state is preferred, is neglected (Sen, 2017a).

Given that social choice formulations of problems, especially of an environmental kind, can be greatly enhanced by detailed descriptions of states of affairs, it appears as not conducive to proceed in that way (Sen, 1995). Addressing environmental challenges requires international and national policy changes to reflect social costs, alongside fostering value formation through public discourse (Sen, 2017a, p. 40). Analyzing social choice problems in this context involves moving beyond individual preferences and choice procedures to consider value formation, departing from assumptions of unresponsive preferences and pure self-interest (Sen, 2017a, p. 40).

Sen critiques the narrow, traditional view of preferences as purely self-interested rankings or revealed preference from observing behavior (Sen, 1973). His understanding is broader than the mathematical approaches based on the neoclassical theory of ordinal utility (Sen, 1973, 2002, 2017a). Instead, preferences can be shaped by an individual's reflections on fairness, justice, and welfare, making them context-dependent and subject to change (Sen, 2017a). Thus, this work bases its understanding on Sen and understands preferences as reflections of broader values that include ethical, social, and moral considerations that shape decision-making in political contexts.

Taking the impossibility theorem as a generalization of Condorcet's voting paradox to all voting rules is therefore not accurate (Sen, 2017a). Arrow's intermediate result, which is central to most works related to the impossibility theorem, first establishes that the

desired social welfare function must apply to voting rules (Sen, 2017a). And only in case that path is pursued Condorcet's paradox becomes pivotal (Sen, 2017a).

The second reason for not taking the impossibility theorem as a generalization of Condorcet's voting paradox can be seen in Arrow's intention to develop a framework to evaluate social welfare in the context of welfare economics based on majority decision – which is questionable even without taking into account matters of intransitivity or inconsistency (Sen, 2017a). While majority-voting procedures are indubitably useful for several kinds of political and decision-making problems, their utility in solving social choice related problems and questions concerning distributional issues is at least doubtful (Sen, 2017a, pp. 276, 277).

Thus, voting-based procedures are appropriate for certain social choice problems, such as elections and referendums, but prove inadequate for many others, such as complex policy decisions that require deliberation (Sen, 2017a, pp. 13, 14). First, voting requires active participation, which leads to underrepresentation of groups that face barriers to voting (Sen, 2017a, pp. 13, 14). Second, even with full participation, voting lacks essential information for welfare evaluation, making it improper to assess social welfare without accounting for societal inequalities (Sen, 2017a, pp. 13, 14). Vote-based solutions for political problems need further scrutiny and their application should be weighed carefully against options involving continuous discussion since voting on unsatisfactorily-described alternatives might contradict prudent social choice (Sen, 2017a).

After all, while there is no doubt that the impossibility theorem is formally valid, the conditions applied are based on value judgments and the overall ethical implications for welfare economics and the design of political design-making processes appear to be less substantial than the formal result might indicate (Bergson, 1976). Arrow's formulation of social welfare had the effect that the informational input is very limited and the axiomatic combination and rules applied for social choice procedures are mainly those referred to in voting applications (Sen, 2011, p. 93; 2017a, pp. 16, 17). To effectively address distributional issues, it is necessary to move beyond the voting rules explored by Borda, Condorcet, and Arrow, and to create space for incorporating more information, thus laying a broader foundation (Sen, 2017a, pp. 16, 17, 21).

Following the scientific consensus at the time, Arrow did not consider interpersonal comparisons of well-being and regarded them as meaningless (Arrow, 2012; Sen, 2017a). Broadening the informational input here by allowing interpersonal comparisons, which is reasonable given the arguments laid out above, opens up several new possibilities for social choice procedures while satisfying Arrow's regulatory requirements (Sen, 2017a). It allows for pursuing different feasible solutions based on ethical concerns and values (Sen, 2017a).

Including and considering values and ethical concerns in decision-making procedures implies the need to discuss and reason what exactly these values are and what people value the most (Sen, 2017a). Values differ between individuals, groups, and societies and the complexity and discrepancies of value systems pose severe challenges for every decision-making process and evaluative task. Yet, SCT has often bypassed the issue of social interactions in value development and their link to decision-making processes, which is crucial to understanding individual behavior (Sen, 2017a, p. 281).

The acceptability of different collective choice systems depends on the societal context, as no single system universally satisfies all conditions (Sen, 2017a, p. 264). While some procedures may work effectively for certain choices and preferences, they may not work for others and need to be evaluated based on specific societal needs and circumstances (Sen, 2017a, p. 264). This recognition underscores the contextual nature of the evaluation of choice procedures (Sen, 2017a, p. 264).

Thus, as Sen points out, "while purity is an uncomplicated virtue for olive oil, sea air and heroines of folk tales, it is not so for systems of collective choice" (Sen, 2017a, p. 265). In SCT, impossible theorems should thus be the beginning of a discussion about how to approach choice problems, rather than the end of any conceivable argument (Sen, 2011, p. 311).

Thus, discussion must be perceived as broader than just the activity shortly before voting takes place (Buchanan, 1954). It must also include the entire period during which majority decisions are reached, overthrown and new compromises arise (Buchanan, 1954). Therefore, it is important that there is discussion preceding democratic decision-making to enable a learning process and respect value pluralism (Peter, 2009). Assuming that individual values are not changing would imply that "discussion becomes

meaningless” (Buchanan, 1954, p. 121). Given that the roots of SCT are deeply anchored in democratic thought and the European Enlightenment that conclusion would be astounded.

The exchange of ideas as part of an open, argumentative process and public reasoning and discourse can be regarded as essential for collective decision-making in complex democratic societies (List, 2006). A fundamental question that arises in this context is how different weightings are chosen, which implies the need for some kind of “reasoned consensus” (including kinds of informal consensus) (Sen, 2017a, p. 360).

Any decision concerning a possible transformation path of the RR will undoubtedly bring along several distributional aspects. Following the arguments above, to regard possible transformation paths in the RR as black-boxes and solely base decisions upon people’s preferences over them would be misleading. Instead, considering informational broadening as the foundation for judgments constitutes a promising option towards decision-making with respect to societal transformation processes.

Normative SCT relies strongly on reasoning, especially public reasoning (Sen, 2017a, p. 462). Understanding how public reasoning relates to social decisions is crucial not only for enhancing democracy, but also for understanding the needs of social choice (Sen, 2017a, p. 462). This constructive starting point is thus used for the conceptual underpinning of this work.

The conceptual underpinning of normative social choice theory as an approach is centrally dependent on reasoning in general, and public reasoning in particular. Indeed, the fundamental connection between public reasoning, on the one hand, and the demands of participatory social decisions, on the other, is central not just to the practical task of making democracy more effective (important as it is), but also for achieving an adequate understanding of the demands of social choice. (Sen, 2017a, p. 462)

4.2 Derivation and Delimitation

Sen's understanding of public reasoning is closely intertwined with his understanding of democracy and justice (Sen, 2011, p. xix; 2017a, p. 401). For this reason, the central aspects concerning the underlying conception of justice and democracy are discussed first, from which the conception of public reasoning is subsequently derived. Sen's understanding of public reasoning is rooted in his approach towards justice and

democracy. Therefore, it is essential to first explore these foundational concepts in order to establish the relevance of public reason to the research approach developed in this thesis.

4.2.1 *Sen and the Theory of Justice*

Sen argues that identifying and addressing injustice is central to the theory of justice (Sen, 2011, p. vii). His approach to justice is broad and differs from contemporary theories in three major ways (Sen, 2011, pp. ix, x). First, it emphasizes practical reasoning to reduce injustice and promote justice, rather than focusing solely on defining perfectly just societies (Sen, 2011, pp. ix, x). Second, it acknowledges that conflicting considerations cannot always be fully resolved in comparative questions of justice, allowing for multiple valid reasons for justice (Sen, 2011, pp. ix, x). Third, it recognizes that redressable injustices may result from behavioral transgressions, not just institutional failures, and emphasizes the importance of considering people's actual lives in assessing justice (Sen, 2011, pp. ix, x).

A comparative perspective that goes beyond the confines of a social contract framework proves valuable in this context (Sen, 2011, pp. xi, xii). Agreed upon changes may reduce injustice, yet, they do not achieve perfect justice, suggesting the need for a more radical departure in justice analysis, driven by both practical and theoretical considerations (Sen, 2011, pp. xi, xii). Justice in his approach is not only defined by institutions but also by people's lives and freedoms (Sen, 2011, p. xii). Institutions still play a crucial role in promoting justice because they contribute directly to people's lives and facilitate public scrutiny of values (Sen, 2011, p. xii).

Sen identifies two divergent approaches to justice, *transcendental institutionalism* and a *realization-focused* perspective (Sen, 2011, pp. 5-8). The former, embraced by thinkers such as Hobbes and Rousseau, prioritizes perfect institutional arrangements without regard to actual societal outcomes (Sen, 2011, pp. 5-8). In contrast, the realization-focused approach emphasizes actual behavior over idealized compliance (Sen, 2011, pp. 5-8). Sen perceives his work as focusing on the advancement or regression of justice rather than on the search for perfect institutions (Sen, 2011, pp. 8, 9).

Sen argues that the transcendental approach faces two challenges, namely the difficulty of reaching reasoned agreement on what constitutes a *just society* and the impracticality of pursuing an unattainable perfect solution (Sen, 2011, pp. 9, 10). It is likely that an impartial agreement may not emerge on any identifiable perfectly just social arrangement (Sen, 2011, p. 15). Thus, his perspective leans more towards a comparative approach (Sen, 2011, pp. 9, 10). Identifying fully just social arrangements is neither necessary nor sufficient for a theory of justice to guide reasoned choice of policies, strategies, or institutions (Sen, 2011, p. 15). Overall, justice cannot be blind to the life experiences of individuals (Sen, 2011, p. 18).

Thus, according to Sen, transcendental theory is concerned with a different question from that of comparative evaluation, one that is intellectually interesting but ultimately of little relevance to the problem of choice (Sen, 2011, p. 17). The identification of a transcendental alternative does not solve the challenge of how to compare two non-transcendental options (Sen, 2011, p. 15). The decisive issue is, thus, to find “an agreement, based on public reasoning, on rankings of alternatives that can be realized” (Sen, 2011, p. 17).

4.2.2 *Delimitation to Rawls*

As Sen points out, his interaction with Rawls greatly influenced his work on the philosophical underpinnings of social choice (Sen, 2017a, p. xxii). He argues that Rawls's emphasis on fairness as the foundation of justice is compelling and relevant not only to Rawls's theory but also to broader analyses of justice, including his own work (Sen, 2011, p. 54). Yet he differs from Rawls on several fundamental matters.

One difference arises from the question about the relevance of liberty. While acknowledging that Rawls has adjusted his position to some extent over time, Sen shares the critique that prioritizing liberty above all else is too extreme because it may overlook pressing concerns like hunger and medical neglect, suggesting that while some priority for liberty is warranted, total priority is likely excessive (Sen, 2011, p. 65).

Another aspect concerns the role of institutions. In the pursuit of justice, institutions should be seen as tools for promoting justice rather than as embodiments of justice itself (Sen, 2011, p. 82). In Sen's view, Rawls' approach simplifies the task of integrating

principles of justice with the realities of human behavior and overlooks the crucial relationship between social institutions and actual individual behavior that is essential for guiding social choice toward justice (Sen, 2011, p. 69).

Thus, Sen emphasizes the need to balance institutional design and behavioral norms in addressing current injustices, adapting strategies to the realities of today's world (Sen, 2011, p. 81). Expecting behavior to exceed these realities can ultimately impede progress toward justice (Sen, 2011, p. 81). Sen further argues that while Rawls emphasizes the role of institutions, focusing only on the institutional definition of justice may lead to overlooking real-world dynamics that contribute to the actual understanding of justice (Sen, 2011, p. 85).

Overall, Sen identifies several problematic exclusions in the Rawlsian approach to justice (Sen, 2011, p. 90). First, it neglects questions of comparative justice, focusing solely on a perfectly just society (Sen, 2011, p. 90). Second, it emphasizes just institutions without considering broader social realities (Sen, 2011, p. 90). Third, it overlooks the adverse effects of a country's actions on people beyond its borders (Sen, 2011, p. 90). Fourth, it lacks a systematic process for addressing the influence of particularistic values (Sen, 2011, p. 90). Fifth, it ignores the possibility of multiple principles of justice emerging from public discourse (Sen, 2011, p. 90). Finally, it lacks consideration of the potential impact of irrational behavior on social arrangements (Sen, 2011, p. 90).

Based on these critiques with respect to Rawls approach, Sen's conception of democracy provides a divergent approach of addressing justice, for instance, through participatory deliberation and public reasoning, which constitute key parts underpinning the research approach developed in this work. Thus, the next part highlights central aspects relevant to understanding these and their role in this work.

4.2.3 *Conceptions of Democracy*

Two main understandings of democracy are distinguished by Sen (Sen, 2017a, pp. 395,396). First, the institutional view focuses on elections and ballots as the defining features (Sen, 2017a, pp. 395,396). The second, broader view emphasizes decisions rooted in public reasoning, involving participatory deliberation and decision-making (Sen, 2017a, pp. 395,396). In this broader perspective, democracy involves fostering

open, informed discussion and ensuring that public decisions are responsive to this interactive process (Sen, 2017a, pp. 395,396). Sen relates this understanding to Rawls and Habermas, as well as public choice theorists such as Buchanan, who emphasize the centrality of deliberation in deliberative democracy (Sen, 2017a, pp. 395,396).

Sen advocates for a broader understanding of democracy where public reasoning can influence voting decisions and sustain the legitimacy of minority rights and personal liberties within democratic structures (Sen, 2017a, p. 401). He agrees with Habermas that public reasoning extends to both moral questions of justice and instrumental questions of power and coercion (Sen, 2017a, p. 401). According to Sen, expanding the scope and impact of public reasoning is crucial to complement the formal understanding of majority rule and the public ballot perspective (Sen, 2017a, p. 408).

Central to his approach, however, is that “democracy is assessed in terms of public reasoning” (Sen, 2011, p. xii). Democracy should be seen not only in terms of political processes but also in its ability to facilitate informed and interactive discussions, thereby enriching reasoned engagement by ensuring access to information and fostering open dialogue (Sen, 2011, p. xiii). This is also the understanding on which the present work is grounded.

Sen’s understanding of democracy is further influenced by early Indian jurisprudence exemplified by the concepts of *niti* and *nyaya* (Sen, 2011, p. xv). *Niti* focuses on organizational propriety and behavioral correctness; *nyaya* is more concerned with actual results and the quality of life people experience (Sen, 2011, p. xv). Following this line of thought, he states that the key insight is that achieving justice, as understood in the sense of *nyaya*, involves evaluating not only institutions and rules but also the societies as a whole (Sen, 2011, p. 20).

Moreover, Sen highlights two Enlightenment ideas that influenced the development of his approach (Sen, 2011, p. xvi). One approach focused on defining perfectly just social arrangements and emphasized just institutions, with thinkers such as Hobbes, Locke, Rousseau, and Kant making major contributions in this direction (Sen, 2011, p. xvi). This contractarian approach, also popularized by Rawls, has come to dominate contemporary political philosophy, according to Sen (Sen, 2011, p. xvi).

In contrast, other Enlightenment philosophers such as Smith, Condorcet, Wollstonecraft, Bentham, Marx, and Mill explored various approaches that compared different ways of life, taking into account factors such as institutions, behavior, and social interactions (Sen, 2011, p. xvi). He places his work in this tradition (Sen, 2011, p. xvi). Although Sen leans towards the comparative rather than the contractarian approach, he identifies commonalities such as a reliance on reasoning and the importance of public discourse as shared principles underlying both traditions (Sen, 2011, p. xvii).

4.2.4 Learning from Rawls - Acknowledged Contributions

The notion of fairness as the foundation of justice had a profound impact on Sen's work (Sen, 2011, p. 54). At its core, fairness involves impartiality, consideration of the interests of others, and the avoidance of bias or personal influence (Sen, 2011, pp. 53, 54). Rawls' conception of fairness, exemplified by the *original position* involves decision-making under a *veil of ignorance*, in which individuals are unaware of their personal identities and interests, leading to a unanimous selection of principles governing social institutions (Rawls, 2005, pp. 22-24; Sen, 2011, p. 54). Rawls' *original position* is a hypothetical setting in which individuals, unaware of their own personal characteristics, choose principles of justice to create a just society for all (Rawls, 2005, pp. 22-28).

Sen explains that Rawls is concerned with how individuals with different *comprehensive doctrines* can cooperate in society through sharing a reasonable political conception of justice (Sen, 2011, p. 56). Rawls defines a *comprehensive doctrine* as a complete religious, philosophical, or moral belief system that encompasses a person's entire worldview (Rawls, 2005, pp. 58-66). These doctrines often provide a framework for individuals to make decisions about how to live their lives and interact with others (Rawls, 2005, pp. 58-66). In contrast to a comprehensive doctrine, a *political conception of justice* focuses on determining publicly acceptable principles for the basic structure of society that can serve as a basis for fair cooperation among citizens with differing comprehensive doctrines (Rawls, 2005, pp. 11-15).

Rawls claims that certain principles of justice, chosen unanimously in the *original position*, form the basis of a well-ordered society and influence individual behavior (Rawls, 2005, pp. 22-24; Sen, 2011, p. 56). In this connection, individuals are encouraged to reach a *reflective equilibrium*, a process of aligning intuitive moral judgments with

overarching principles to achieve a coherent moral framework from a position of impartiality (Rawls, 2005, pp. 89, 90, 96). Yet, Sen expresses skepticism about Rawls's claim regarding the unique choice of principles in the original position and recognizes valuable insights in connection with Smith's account of the impartial spectator (Sen, 2011, pp. 56, 128, 130).

Sen suggests that there are multiple, sometimes conflicting, considerations that influence our conception of justice, suggesting that impartiality can manifest itself in different ways (Sen, 2011, pp. 57, 58). The idea that only one set of principles embodies justice may not be true in all cases (Sen, 2011, pp. 57, 58). Moreover, Sen also sees a tension in Rawls's thinking over time, as he softens his claim of a unique emergence of principles in the *original position* (Sen, 2011, pp. 57, 58). Despite potential flaws in Rawls's theory, Sen acknowledges its major contribution to understanding justice and believes that its insights will continue to shape political philosophy even as aspects of the theory are reexamined (Sen, 2011, pp. 57, 58).

Sen identifies several key contributions of Rawls to the understanding of justice (Sen, 2011, pp. 62-64). First, Rawls emphasizes the centrality of fairness to the theory of justice, despite Sen's reservations about the adequacy of Rawls's approach (Sen, 2011, pp. 62-64). Second, Rawls underlines the need to establish a public framework for reasoned judgment in practical reasoning (Sen, 2011, pp. 62-64). Third, he stresses the importance of individuals' moral power and capacity for justice, challenging theories that reduce human behavior to self-interest (Sen, 2011, pp. 62-64). Fourth, Rawls prioritizes liberty, emphasizing its importance alongside other primary goods (Sen, 2011, pp. 62-64). Fifth, he enriches discussions of inequality by emphasizing procedural fairness (Sen, 2011, pp. 62-64). Sixth, Rawls draws attention to equity in social arrangements, especially for the most disadvantaged. Finally, his focus on primary goods indirectly recognizes the importance of human freedom in providing real opportunities for individuals to pursue their goals (Sen, 2011, pp. 62-64).

4.3 Reasoning and Public Reasoning

Reasoning is essential for understanding the world and goes beyond simple observation (Sen, 2011, p. viii). Sen's understanding of public reasoning diverges from

Rawls' conception as laid out in the work *Political Liberalism*. However, Rawls strongly influenced the emergence and development of Sen's work (Sen, 2011, p. 52; 2017a, pp. viii, xvii, xxii). Sen explicitly states that, while his exploration of justice may differ from that of Rawls, he still finds his basic idea about the connection between justice and fairness to be influential in shaping his own understanding (Sen, 2011, p. 53).

Given the widespread influence of Rawls' explanatory memorandum with respect to legitimacy, stability, public reasoning, and overlapping consensus, the next part will lay out the fundamental aspects of Rawls' related works followed by Sen's understanding and integration into his conception of normative social choice and public reasoning. The focus here is on aspects that help to differentiate and better understand Sen's approach and the conception of reasoning.

4.3.1 *Roots and Idea*

The roots of public reason as a concept are manifold and different researchers locate their justification programs in different spheres. The idea of public reason is frequently presented by proponents as an implication of a specific vision of people as being free and equal and popular origins can be found in the writings of Hobbes, Kant, and Rousseau (Gaus, 2010, pp. 1-49; Rawls, 2005, p. 213; Sen, 2017a, p. 363). Not least because scholars like Rawls, Habermas, and Sen took up and further developed the idea, it still plays an important role in political science and other disciplines today. A core underlying thought is that the moral or political rules that organize our public lives must be defensible or acceptable to everyone over whom the laws are supposed to have jurisdiction (Gaus, 2010, pp. 1-49).

According to Locke and Hobbes, for instance, public reason is the umpire's reasoning that we have agreed to follow (Gaus, 2010, p. 25). In both cases, we curtail our own judgment and give deference to the authority of the state (Gaus, 2010, p. 25). In contrast, Gaus invokes Rousseau's claim that finding a mechanism to impose laws to manage our shared existence is the basic issue for which the social contract is intended to be a solution and that public reason is a notion that stems from certain fundamental aspects of our everyday moral behavior (Gaus, 2010, p. 48).

Other scholars, most notably Habermas, relate public reason as a crucial and integral component of the nature of rational debate concerning moral norms (Habermas, 1990; Habermas, 1995, pp. 124, 127; 1996; Quong, 2022). Sen also makes several references to Habermas' contributions (see e.g., Sen, 2017a, pp. 396, 401, 402, 430). In order to separate Sen's understanding of public reasoning more clearly, Habermas' positions will be included at selected points alongside Rawls'.

Following Habermas, only an idealized intersubjective practice of argumentation can accurately illustrate the validity of political and moral norms (Habermas, 1995, p. 117; Quong, 2022). Therefore, genuinely intersubjectively legitimate norms can only develop through an open, non-coercive discursive process in which all participants are placed equally (Quong, 2022).

In this connection, Habermas suggests a dialogical universalization principle (Habermas, 1995, p. 117). A moral rule is legitimate only if all parties involved can freely agree on the anticipated outcomes and side effects of compliance with it for each person's subjective values and interests (Habermas, 1998, p. 42; Quong, 2022). Thus, implied by the premises of rational moral discourse, having a reasoned political or moral debate with someone else means committing to something akin to the concept of public reason by finding standards that all parties can agree upon without being forced to do so (Quong, 2022).

The foundation of public reason is, hence, found in the realm of reasoned moral argument since if one intends to have a rational conversation with others on political or moral topics, one cannot ignore the concept of public reason (Quong, 2022). This is also shown by the fact that Habermas generally speaks of "public use of reason" and not explicitly of *public reason* (Habermas, 1995). Overall, Habermas work on public reason is considered very influential but has also been criticized, for instance, for embedding public reason within other philosophical concepts such as truth and validity (Quong, 2022).

In contrast, public reason, in particular the interaction between free and equal people in a democratic society, has been portrayed by Rawls as a component of the concept of democracy itself (Quong, 2022; Rawls, 1999, p. 573; Rawls, 2005, p. 213). Following Rawls, public reason is a particularly political concept since it paradigmatically pertains

to our society's laws and other political institutions (Quong, 2022). Its distinctly political aspect might be explained, for example, by relating public reason to the esteem of justice (Quong, 2013, 2022; Rawls, 1999; Sen, 2017a).

According to this perspective, given certain presumptions about the characteristics of functioning liberal democratic societies, public reason is the sole means of achieving justice (Quong, 2022). Society is envisioned as a just system of social interaction between free and equal citizens (Quong, 2022). The only way we can be sure that the rules governing our political institutions are fair and, thus, just is if we can demonstrate to each citizen how these rules can be justified in light of this shared viewpoint, demonstrating that these rules can be the object of public reason (Quong, 2022). The rules of our public life would not be perceived as fair if our political principles were instead relying on certain philosophical, religious, or moral concepts that are reasonably contested (Quong, 2022).

This justification for public reason has a number of benefits, including that it explains why public reason has a distinctly political emphasis (Quong, 2013, 2022). Moreover, the value of justice can also offer a relatively uncontroversial foundation for public reason since it can be embraced by individuals with a variety of moral, religious, and philosophical perspectives (Quong, 2013, 2022).

However, this perspective is also not undisputed. A point that is criticized, for instance, is that in order for political principles to be fair or just, they must be justified to every reasonable citizen, even if conditions of reasonable plurality or disagreement are acknowledged (Quong, 2022). Sen notes that Rawls himself, in his later writings, recognizes the diversity of citizens' conceptions of political justice with respect to the content of public reason (Sen, 2011, pp. 57, 58). Public reason embraces multiple political conceptions, not just justice as fairness, and identifying a single prevailing argument can be arbitrary (Sen, 2011, p. 11).

According to Sen, Rawls emphasizes the importance of deliberative democracy, underscoring the exchange of views and supporting reasons among citizens on public policy issues (Sen, 2011, pp. 324-326). In contrast, Habermas offers a broader treatment of public reasoning, emphasizing procedural democracy and clarifying the dual presence of moral and instrumental questions in political discourse (Sen, 2011, pp. 324-326).

Sen acknowledges the different perspectives on the role of public reasoning in politics and discursive ethics but asserts that these differences do not undermine his main arguments (Sen, 2011, p. 326). Instead, the collective impact of these perspectives underscores the importance of political participation, dialogue, and public interaction in a broader understanding of democracy (Sen, 2011, p. 326). Moreover, the essential role of public reasoning in democracy is closely related to the concept of justice, suggesting an intrinsic connection between the two that is characterized by common discursive characteristics (Sen, 2011, p. 326):

If the demands of justice can be assessed only with the help of public reasoning, and if public reasoning is constitutively related to the idea of democracy, then there is an intimate connection between justice and democracy, with shared discursive features. (Sen, 2011, p. 326)

According to Sen, human reasoning, particularly in public reasoning, involves the exchange of ideas, the formation of values, and the crucial practice of mutual fact-checking and he relates his understanding to conceptions endorsed by Buchanan, Arrow, Mill and Condorcet (Arrow, 2012; Buchanan, 1954; Lukes & Urbinati, 2012; Mill, 1864; Sen, 2017a).

Following Sen's views on reasoning and mutual fact-checking, the next part examines how pluralism shapes the justification of beliefs, which is fundamental to the approach developed in this dissertation, for instance, with regard to stakeholder engagement.

4.3.2 Nature and Properties

Scholars who advocate conceptions of public reason often link their understanding to a form of pluralism or some form of justifiable dissent that occurs from human reasoning under generally fortunate circumstances instead of just being the consequence of irrationality and prejudices (Quong, 2022). This proposition concerning pluralism or disagreement is a crucial component of the rationale for public reason (Quong, 2022). Without it, it is hard to comprehend and illustrate why moral or political beliefs need to be justified or should be acceptable to others instead of solely correct or true (Quong, 2022).

Since Rawls' concept of public reason has a great influence on Sen and Sen's understanding is based on and differentiated from it, the main features of Rawls' concept

will be introduced. Following Rawls, public reason is a defining feature of a democratic society and reflects the reasoning of its citizens (Rawls, 2005, p. 213). It is public in three respects (Rawls, 2005, p. 148). First, it represents the reasoning of citizens collectively and thus embodies the reasoning of the public (Rawls, 2005, p. 148). Second, it is concerned with the welfare of the public and with concerns of fundamental justice (Rawls, 2005, p. 148). Third, its nature and content are public, rooted in the ideals and principles expressed by society's conception of political justice, and carried out openly on that basis (Rawls, 2005, p. 148).

Citizens' understanding of and adherence to public reason is not legally mandated (Rawls, 2005, p. 148). Rather, it serves as an ideal model of citizenship for a constitutional democratic system, illustrating how individuals might behave in accordance with the principles of a just and well-ordered society promoted by the concept (Rawls, 2005, p. 148). Moreover, reasonable citizens do not intend to enforce their beliefs on others (Rawls, 2005, p. 138).

In a liberal society, exercising political power will be legitimate provided it is done in line with the fundamental ideas that base any liberal conception of justice (Rawls, 2005, p. 137). Based on this understanding and connected to the requirement of reciprocity, Rawls lays out his idea of public reason that relates to how citizens illustrate their political decisions among themselves (Rawls, 2005, p. 243). In this connection, a central aspect of public reason is that any justification of their respective political decisions builds upon values and ideals that are open to the public (Rawls, 2005, p. 247).

The values of a political conception of justice are public values that citizens must be able to invoke (Rawls, 2005, p. 223). In contrast, non-public values are those that cannot be reconciled with public values, such as those held by religions restricting women from holding the highest positions (Rawls, 2005, p. 213). Hence, public standards should illustrate the foundation on which citizens should base and explain their political decisions (Rawls, 2005, p. 243). These public standards can be understood as evidence-based guidelines and principles of reasoning that all citizens may presumably agree upon (Rawls, 2005, p. 226).

When the most fundamental political issues, constitutional essentials and matters of basic justice, are at risk, such as which faiths are to be tolerated, who can own property,

and what are potential categories for discrimination in hiring choices, the obligation to uphold public reason applies (Rawls, 2005, pp. 227, 235, 241). In the case of less vital political issues, however, the role of public reason is less pronounced (Rawls, 2005, p. 220).

Only in situations where they engage in certain political activities, typically in connection with a position in public office, citizens do have an obligation to hold their judgments to a standard of public reason (Rawls, 2005, p. 252). Notably, though, citizens should also respect public reason when they vote since, according to the liberal principle of legitimacy, all of these actions must be justified in a way that all citizens may rationally approve because they all involve or promote the exercise of political power (Rawls, 2005, p. 252). Outside of such political activities, however, there is no obligation to adhere to public reason.

4.3.3 *Sen's Perspective*

According to Sen, Rawls' approach uses reasoning consistent with the contractarian school of thought (Sen, 2011, p. 69). Sen, in contrast, highlights the advantages of the Smithian impartial spectator approach over Rawls' contractarian reasoning, emphasizing its capacity for comparative assessment, consideration of social realizations, guidance in addressing injustice, and inclusion of voices beyond the contractarian group to avoid parochialism (Sen, 2011, p. 70).

Sen emphasizes the centrality of reasoning to the understanding of justice (Sen, 2011, p. xix). He stresses that the primary focus should be on discerning what reasoning requires in the pursuit of justice and recognizes the potential existence of different reasonable perspectives (Sen, 2011, p. xix). In this way, he places a different emphasis from that of Rawls concerning the constitutional essentials or reasonable persons and thus refrains from a comparable restriction.

Reasoned scrutiny, in his view, is not about achieving perfection but about striving for objectivity (Sen, 2011, pp. 40, 41). The emphasis on reasoning in ethical judgments stems from the pursuit of objectivity, which requires disciplined reasoning (Sen, 2011, pp. 40, 41). The objectivity of ethical principles is determined by their ability to withstand scrutiny within an open and free framework of public reasoning (Sen, 2011, p. 196).

Objectivity in communication and public reasoning is, thus, intertwined with ethical evaluation's impartiality demands, each playing a distinct yet interconnected role (Sen, 2011, p. 122). Thus, the need for objective reasoning plays a crucial role in dealing with justice and injustice (Sen, 2011, pp. 40, 41).

In contrast to Rawls, Habermas favors procedural approaches, emphasizing the persuasion of individuals through open discourse rather than pre-defined notions of reasonableness (Sen, 2011, pp. 42, 43). While Habermas emphasizes strict requirements for public deliberation, both approaches share similarities in their strategies of argumentation (Sen, 2011, pp. 42, 43). If individuals engage in open dialogue and welcome diverse perspectives, the gap between these approaches may not be substantial (Sen, 2011, pp. 42, 43). Habermas claims that the agreement that emerges from his system differs substantially from Rawls's liberal principles and priorities (Sen, 2011, p. 43). Sen, however, asks whether these differences stem from their procedural approaches or from their beliefs about the dynamics of open democratic deliberation (Sen, 2011, p. 43).

In contrast to Rawls, Sen does not distinguish between reasonable persons and other individuals (Sen, 2011, p. 43). He argues that all individuals essentially possess the capacity to reason by being receptive to diverse information, reflecting on different arguments, and engaging in interactive deliberation (Sen, 2011, p. 43). This perspective is closely related to Rawls's notion of free and equal persons endowed with moral agency (Sen, 2011, pp. 43, 44). In this context, Sen emphasizes the importance of unrestrained public reasoning for democratic politics and the quest for social justice (Sen, 2011, pp. 43, 44).

In Sen's view, public reasoning illustrates an indispensable element of objectivity in political and ethical beliefs (Sen, 2011, pp. 43, 44). He recognizes a fundamental similarity in the approaches to objectivity among Smith, Habermas, and Rawls despite their differing arguments (Sen, 2011, p. 45). They all associate objectivity with the ability to withstand scrutiny from diverse perspectives (Sen, 2011, p. 45). Similarly, in his work, Sen emphasizes the importance of reasoned scrutiny from various viewpoints in maintaining objectivity in ethical and political convictions (Sen, 2011, p. 45). He takes a very inclusive view:

In seeking resolution by public reasoning, there is clearly a strong case for not leaving out the perspectives and reasonings presented by anyone whose assessments are relevant, either because their interests are involved, or because their ways of thinking about these issues throw light on particular judgements – a light that might be missed in the absence of giving those perspectives an opportunity to be aired (Sen, 2011, p. 44)

Thus, Sen stresses that the surviving principles under scrutiny may not constitute a singular set and argues against reducing all opposing positions to fit into a neat box, as advocated in Rawls's theory (Sen, 2011, p. 46). Despite differences in approaches to objectivity, they all emphasize the importance of impartial, reasoned engagement (Sen, 2011, p. 46).

Yet, Sen is not blind to the fact that individuals can become overly convinced by their own arguments, ignoring counterarguments and alternative perspectives (Sen, 2011, p. 48). Still, according to Sen, “[t]he remedy for bad reasoning lies in better reasoning, and it is indeed the job of reasoned scrutiny to move from the former to the latter” (Sen, 2011, p. 49).

Overall, he takes a very broad and inclusive view of reasoning. For example, he also argues for recognizing the importance of emotions and linking them to reason, as there is no inherent conflict between reason and emotions (Sen, 2011, p. xvii). Emotions can be understood within the realm of reason and should be considered for their importance in our decision-making (Sen, 2011, p. 39). Reason and emotion work together to shape human reflection (Sen, 2011, p. 39).

4.3.4 Public Reasoning and Valuation

Reflective evaluation involves thinking about relative the importance, and public reasoning can increase the reach and reliability of respective evaluations (Sen, 2011, p. 241). Public scrutiny and critical evaluation underscore the value of open discussion and public reasoning since relying solely on isolated contemplation can deprive social evaluations of valuable information and compelling arguments (Sen, 2011, p. 242).

Emphasizing the connection between public reasoning and the selection and prioritization of capabilities in social evaluation is critical (Sen, 2011, p. 242). This is not least because there is a strong relationship between economic performance, social

opportunity, political voice, and public reasoning (Sen, 2011, p. 350). Public reasoning, including discussions of promised improvements, institutional choices, and behavioral adjustments, is essential for addressing injustice and promoting justice, questioning the notion that market-based institutional choices alone are sufficient for social progress (Sen, 2011, p. 268).

Given the large gap between capabilities and resources, Sen questions Rawls's focus on primary goods in distributional issues (Sen, 2011, p. 260). A theory of justice, or in a broader sense of normative social choice, must consider both the fairness of processes and the equity and efficiency of opportunities available to people (Sen, 2011, p. 296). A central goal is to make accurate comparative judgments through personal and public reasoning rather than feeling obligated to comment on every possible comparison (Sen, 2011, p. 243).

Sen argues that a comprehensive theory of justice that accommodates multiple considerations need not be seen as incoherent or impractical (Sen, 2011, p. 397). Despite unresolved tensions, meaningful conclusions can still be drawn, allowing for substantial utility in practical applications (Sen, 2011, p. 397). A shared partial ranking, for instance, can serve as the overall outcome of a broad interpretation of a theory of justice, with useful conclusions arising as they emerge, without the need for a guaranteed *best* or *right* choice in every case where justice is invoked (Sen, 2011, p. 398).

It is important to note, however, that seeking consensual acceptance is not the same as, and does not require, complete unanimity in individuals' preference rankings within the domain of the reasoned partial order (Sen, 2011, p. 398). In order to be useful, a social ranking needs to be substantial, but not necessarily complete (Sen, 2011, p. 399). A theory of justice relies on partial orderings that intersect and draw from various reasons of justice, all of which withstand public scrutiny through public reasoning (Sen, 2011, p. 399).

Sen's approach to justice emphasizes both reliance on public reasoning and the way in which questions of justice are framed (Sen, 2011, p. 410). Rather than focusing primarily on the institutional dimension, the emphasis is on assessing social realities and addressing comparative questions of justice improvement and the use of impartiality in open public

reasoning (Sen, 2011, p. 410). Sen thus explicitly distinguishes himself from Rawls's transcendental institutionalism and related approaches (Sen, 2011, p. 410).

4.3.5 Scope and Limitation

A further important concern is the question of scope with respect to the utilization of public reason. An expansive interpretation broadens the application of public reason to encompass everything of social morality (Gaus, 2010, p. 2; Quong, 2022). As Quong (2022) points out, according to this perspective leaned on Gaus, the concept of public reason should be applied anytime we claim to have the authority to instruct others on how they should conduct themselves (Gaus, 2010, p. 228).

Rawls, as pointed out, considers constitutional essentials and matters of basic justice. These matters of basic justice include questions concerning the distribution of resources, such as wealth and income (Rawls, 2005, pp. 214, 227–230). This limitation is disputed since Rawls does not sufficiently provide reasons for the restrictions (Quong, 2022). Moreover, as Quong (2022) further highlights, the majority of actions taken by governments have some form of influence on related aspects, even if that might be indirect. A relevant argument in this regard concerns Rawls claim that public reasoning needs to be complete and should provide at least one definite answer for vital political questions (Quong, 2022). Yet, Sen argues that for some choice problems, for instance, completeness might be desirable but not necessary (Sen, 2017a, pp. 48, 404). Sen emphasizes the necessity of disciplined reasoning in addressing social ethics, evaluating claims about social justice, and tackling other issues of social choice (Sen, 2017a, p. 453). For Sen, the scope is thus notably broader.

Among the most prominent arguments made against the concept of public reason concern its completeness and question whether it is capable of offering answers to all – or nearly all – of the crucial moral and political issues we confront (Quong, 2022; Rawls, 1999, pp. 585-586; Rawls, 2005, pp. 244-246; Sen, 2017a, p. 470). In this connection, Rawls also raises the question of how to determine whether “a question is successfully resolved by public reason” (Rawls, 2005, p. 244).

According to related remarks, public reason can be incomplete in two ways, particularly inconclusive and indeterminate (Quong, 2022; Schwartzman, 2004).

Inconclusive in the sense that while a number of distinct options may appear to be justified by reference to public reason, public reason may not be able to conclusively identify the answer that is accurate or the most reasonable choice among those (Quong, 2022). It is indeterminate when it cannot provide any answer to a particular political or moral question.(Quong, 2022).

Despite these limitations, there are situations where such incompleteness is understandable. Sen, in his interpretation of public reason, suggests that this incompleteness can be acceptable depending on the kind of problem addressed and might only be tentative (Sen, 2017a, pp. 48, 459, 460). In addition, he argues that completeness is not necessary, and incompleteness is a central part in the context of reasoned choices (Sen, 2017a, p. 470). Thus, public reason can be outmost useful and beneficial without the need for providing answers to all crucial questions, especially with regard to aspects concerning distribution elements (Sen, 2017a, p. 470).

Sen emphasizes that while departing from established theories of justice based on national consensus, we must accept that incompleteness is inherent in reasoned choice, especially in a diverse society (Sen, 2017a, p. 470). This should not be viewed negatively, as both tentative and assertive incompleteness are common in decision-making (Sen, 2017a, p. 470). He underscores the value of public discourse in reaching agreed partial orderings, which can significantly aid in resolving issues of decisional justice at various governance levels (Sen, 2017a, p. 470).

Overall, the intended application in the context of societal transformation processes undoubtedly implies dealing with distribution and wealth aspects with respect to a variety of resources. Thus, even the scope suggested by Rawls would fit the utilization within this work.

4.3.6 *Broadening the Constituency*

Another relevant aspect revolves around the issue of who should be considered within the constituency of public reason and the question of who the pertinent principles or rules must be justified for. In this connection, as Quong (2022) highlights, Rawls' conception of reasonable persons has been criticized stating that is too idealized and contains too many normative aspects (Bohman, 2003, pp. 126-129; Habermas, 1995, p. 111).

However, similar arguments can be brought forward concerning related conceptions, too (Quong, 2022).

For instance, both Rawls and Gaus exclude certain individuals from the scope of public reason based on different normative beliefs (Quong, 2014, p. 552). While there is no general objection to exclusionary approaches, it raises questions about the underlying strategies and the emphasis placed on the concept of having a reason rather than considering the reasons themselves within the framework of shared ideals of freedom, equality, and fairness (Quong, 2014, p. 552).

Sen emphasizes the importance of broadening the constituency of public reason to include diverse voices and perspectives (Sen, 2017a, p. 471). He does not present an approach related to a narrow conception of reasonable persons. Instead, he argues for actively including a wide range of individuals, considering various cultural, social, and economic backgrounds (Sen, 2017a, pp. 13, 14, 367, 396, 462). That suggests a rather inclusive and broad understanding related to the constituency of public reason, highlighting the need to ensure that individuals, regardless of their socio-economic status or other characteristics, have the capability and opportunity to participate in public reasoning.

4.3.7 Substance and Content

Rawls considers public reason to include two components (Rawls, 2005, pp. 223, 224). The principles of a political conception of justice constitute the first element and the standards of inquiry make up the second component of public reason and contain crucial civic virtues like reasonableness as well as reasoning based on evidence and norms that specify how principles are intended to be implemented (Quong, 2022; Rawls, 1999; Rawls, 2005, pp. 223, 224). When citizens participate in public reasoning with one another on important political issues, these two elements offer the rules as well as the normative content (Quong, 2022).

Habermas, on the other hand, argues that philosophy offers a collection of guidelines and rules for the performance of public reasoning but cannot discern the normative content of public reason through philosophical analysis (Habermas, 1995, pp. 130, 131; Quong, 2022).

Public reasoning, as conceptualized by Sen, can encompass discussions related to the selection and prioritization of capabilities in social evaluation, including considerations of social opportunity, political voice, institutional choices, and behavioral adaptations (Sen, 2011, p. 268). This broad scope of public reasoning is seen as critical to addressing injustice and promoting equity in society (Sen, 2011, p. 268).

Sen's work and emphasis on democratic deliberation suggest that the content of public reasoning should be directed toward promoting human capabilities, accommodating diversity, and engaging in ethical deliberation within a democratic framework. Sen highlights the importance of taking into account the diversity of human values, perspectives, and cultural contexts in public reasoning (Sen, 2017a, pp. 24, 39, 50, 51, 462, 466-469). Thus, Sen's approach is open to pluralism, and public reasoning should be able to accommodate a range of reasonable perspectives and topics.

4.3.8 *Forms of Consensus*

In the context of public reason, it is necessary to address the question of consensus and related structural aspects (Quong, 2022). In terms of structure, it needs to be clarified whether consensus on underlying principles and rules is required or whether individuals can agree on them for entirely different reasons (Quong, 2022). Following Quong (2022), two different perspectives here can be identified, namely *weak consensus* and *strong consensus*. Strong consensus implies that all must justify a belief on the same grounds, while weak consensus allows acceptance based on shared views despite disagreement about their adequacy (Quong, 2022).

Rawls' concept of an overlapping consensus, which also influenced Sen's work, serves as a central and influential idea for illustrating and distinguishing structural aspects of consensus.

4.3.8.1 Overlapping Consensus. According to Rawls, the basis of public reason and justification can only be a political conception of justice which all citizens may reasonably be expected to support (Rawls, 2005, p. 137). As Rawls points out, three conditions seem to be sufficient for a society to function as a just and stable system of cooperation among free and equal citizens, despite their deep divisions over reasonable comprehensive doctrines (Rawls, 2005, p. 44).

First, the organization of society is guided by a political conception of justice (Rawls, 2005, p. 44). When political power is exercised in conformity with a political conception of justice, it can be considered acceptable from the perspective of political liberalism (Rawls, 2005, p. 137). Second, this political conception is supported by an overlapping consensus of reasonable comprehensive doctrines (Rawls, 2005, p. 44). Third, public discourse, especially on matters of constitutional essentials and fundamental justice, adheres to the principles of the political conception of justice (Rawls, 2005, p. 44).

Following Rawls, an overlapping consensus is a political concept in which citizens with divergent backgrounds and different comprehensive doctrines can still agree on a basic framework of justice (Rawls, 2005, pp. 44, 226). This consensus is formed by individuals who hold different reasonable but conflicting beliefs, but who can agree on principles of justice that accommodate their differences (Rawls, 2005, pp. 44, 226). It is constituted by an agreement reached through public reason, where citizens engage in dialogue and deliberation to find common ground based on shared political values and principles of justice, despite their differing comprehensive doctrines (Rawls, 2005, pp. 44, 226).

Rawls suggests that an overlapping consensus involving reasonable worldviews is likely to persist and attract adherents over time within a just social framework as defined by the political conception (Rawls, 2005, pp. 141-143). An overlapping consensus can thus constitute the basis for stability. An important point is that achieving stability does not mean forcing others to accept a certain point of view or enforcing it with penalties if they disagree (Rawls, 2005, p. 143). Instead, justice and fairness should naturally find support by appealing to everyone's sense of reason and understanding within their own perspective (Rawls, 2005, p. 143).

In other words, citizens support a fundamental set of laws but have different reasons to do so – forming an overlapping consensus. Each citizen endorses a particular idea of publicly acceptable principles for the basic structure of society that can serve as a basis for fair cooperation (political conception of justice) based on reasons that are specific to the respective belief system (comprehensive doctrine). Overlapping consensus can thus be thought of as a space where comprehensive doctrines overlap. Thus, it is not necessary to share the entire comprehensive doctrine.

An overlapping consensus goes beyond simply agreeing to certain authorities or adhering to specific institutional settings based on a confluence of self-interests or group interests (Rawls, 2005, p. 147). Thus, concerning stability, an overlapping consensus is preferable to a mere balance of power involving citizens with divergent worldviews since power constellations can shift and thus weaken or dissolve the stability built on them (Rawls, 2005, p. 148). When an overlapping consensus emerges, individuals sustain a political conception based on their own perspectives, regardless of potential shifts in political power between groups (Rawls, 2005, p. 148). Thus, Rawls argues that an overlapping consensus remains stable because each citizen supports a moral doctrine for intrinsic reasons (Rawls, 2005, p. xlv).

Rawls does not assert that an established overlapping consensus must persist indefinitely, nor is it a universal requirement for every liberal society (Rawls, 2005, p. 168). For instance, there might be too little common ground to agree on a liberal political conception of justice in certain societies (Rawls, 2005, p. 168). Still, Rawls argues that citizens in liberal societies have gradually built trust and bridged their beliefs, suggesting the potential for overlapping consensus despite occasional failures (Rawls, 2005, p. 168).

Rawls' description of an overlapping consensus falls within the scope of a weak consensus since citizens freely assess if an aspect is compatible with their personal viewpoints. In contrast, as Quong (2022) points out, Habermas' perspective seems to support the striving for a strong consensus since he states that an argument-based consensus must be based on identical reasons that are equally persuasive to all involved in exactly the same manner (Habermas, 1996, p. 339).

4.3.8.2 Plural Grounding. Sen emphasizes the need for a reasoned consensus based on multiple perspectives, which he calls plural grounding (Sen, 2011, p. 2). Sen's understanding is clearly different from that of Habermas and closer to Rawls' overlapping consensus, although there are differences here as well, especially regarding the explanatory program.

Plural grounding involves considering different lines of thought without requiring agreement on their relative importance (Sen, 2011, p. 2). It emphasizes that justice allows for a strong sense of injustice from multiple angles, even without consensus on a single overarching reason (Sen, 2011, p. 2). Thus, reducing multiple and potentially conflicting principles to a single one is not necessary to derive useful conclusions about what should be done, neither with respect to the theory of justice nor with respect to other aspects of practical reasoning (Sen, 2011, p. 4). Advancing justice requires public reasoning that considers arguments from multiple perspectives and sources (Sen, 2011, p. 392). In fact, the importance of public reasoning and the acceptance of diverse perspectives in evaluation have generally been central themes in Sen's work (Sen, 2011, p. 394).

Incomplete resolution is an integral part of individual evaluative judgments, and even more so in public reasoning, where accommodating diverse partial rankings and acknowledging their incompleteness is essential for reasonable agreement among individuals (Sen, 2011, p. 396).

Reasoning helps resolve persistent disagreements that arise from prejudices, vested interests, and unexamined biases (Sen, 2011, p. 396). But while many meaningful agreements are possible, it is unrealistic to expect that every social choice dilemma can be resolved in this way (Sen, 2011, p. 396). Like Rawls, Sen recognizes the possibility that consensus may not be reachable. Depending on the context, the presence of a plurality of reasons can either facilitate a clear decision or present a considerable obstacle (Sen, 2011, p. 396).

Drawing on the work of Cass Sunstein, Sen emphasizes the importance of "incompletely theorized agreements" in fostering consensus despite divergent beliefs (Sen, 2017a, pp. 461, 462). He suggests that maximality-based social choice can complement this concept by illustrating the potential for reasoned agreement on action even in the absence of complete convergence on values (Sen, 2017a, pp. 461, 462).

According to Sen, despite conflicting interests on individual issues, there may be unanimity on certain compromises, but this does not imply widespread agreement on individual preferences as a whole (Sen, 2017a, p. 73). Moreover, individuals' willingness to accept compromises depends largely on their assessment of their relative bargaining power, suggesting that community-wide acceptance of a social situation may not necessarily indicate unanimous preference over other alternatives (Sen, 2017a, p. 73). General acceptance of a compromise solution should not be interpreted as a general endorsement (Sen, 2017a, p. 73).

Thus, the form of consensus does not require identical reasons but highlights more the underlying process of reasoned discussion and public debate where different viewpoints are considered. Unanimity, even if it is not initially present, can be achieved through discussion and negotiation (Sen, 2017a, p. 72). Following Sen, despite initial disagreement on social rankings, dedicated public discussions can lead to a consensus on facts and values (Sen, 2017a, p. 419). While not guaranteed, striving for such partial accord is a key objective of public engagement (Sen, 2017a, p. 419). Yet, he stresses that “agreement may only be partial, even after as much public reasoning as we can have” (Sen, 2017a, p. 469).

Sen is under no illusion that it must always lead to success. Yet, while debating and discussing does not always produce the desired results, it can be effective (Sen, 2011, p. 88). Understanding the demands of justice involves more than individual reflection, for it requires engagement with the perspectives and suggestions of others, which may lead us to rethink our own conclusions (Sen, 2011, p. 88). Sen’s consensus based on plural grounding can thus be categorized as a form of weak consensus.

4.4 Implications for Collective Decision Making

The theoretical considerations outlined above have implications for collective decision-making and the utilization of the Social Choice approach as a framework for reasoning as understood in this work. Thus, the next section discusses central features for a broader framework and how Social Choice can serve as a basis for public reasoning. This section further addresses associated issues of incompleteness and maximality, commensurability, and the role of reasoning and public reasoning in this context. Lastly,

it reflects on the related implications for group decisions in the context of sustainable development and derives methodological directions.

4.4.1 Broader Framework for Reasoning

Addressing key issues of justice requires a broad and adaptive approach to identifying and pursuing justice (Sen, 2011, p. 91). In contrast to institutional perspectives, other theories of justice and social choice emphasize the evaluation of actual social conditions to determine fairness. Thus, SCT adopts a broader framework for assessing justice by considering various factors (Sen, 2011, p. 86). The emphasis on a framework for public reasoning, as advocated by Rawls, becomes especially crucial in this broader task, and Sen recognizes SCT to be particularly useful in this context (Sen, 2011, p. 91).

Many political and economic procedures, such as voting and economic assessment, can accommodate only limited information and often require additional discussion for comprehensive understanding (Sen, 2011, p. 91). However, justice, social organization, and effective policymaking require a deeper examination of information (Sen, 2011, p. 91). Formal SCT appears distant from immediate concerns, and its mathematical nature has often hindered its practical applicability, creating a perceived gap between formal methods and public discourse (Sen, 2011, p. 91).

Yet, the underlying perspective can provide valuable insights for decision-making. As an evaluative discipline, SCT focuses on the rational basis for public decisions and judgments, ranking various social alternatives based on “a ‘social point of view’, in the light of the assessments of the people involved” (Sen, 2011, p. 95). This illustrates a notable contrast to the search for a single supreme alternative among all possibilities that theories of justice from Hobbes to Rawls are interested in.

Overall, there is no analytical connection between the existence of a perfect alternative and the necessity or usefulness of referring to it in judging the relative merits of other options (Sen, 2011, p. 102). Sen states that transcendental identification is neither necessary nor sufficient for comparative judgments of justice and, thus, rejects the notion that comparing two alternatives requires prior identification of a superior alternative (Sen, 2011, p. 102).

A theory of justice should also concern itself with the practicality of available choices rather than with idealized and unrealistic hypotheticals (Sen, 2011, p. 106). The aspects related to feasibility, therefore, also play a central role for Sen. Thus, to provide a fruitful and insightful basis for public reasoning, an appropriate framework must go beyond the transcendental perspective. A social choice approach, as a framework for comparing different alternatives that take more information into account, can aid in identifying appropriate decision options.

4.4.2 Social Choice as a Framework for Reasoning

For Sen, the social choice approach is closely linked to justice. He highlights seven links between SCT and the theory of justice he considers particularly crucial (Sen, 2011, pp. 106-111). First, the social choice approach focuses on comparative judgments, emphasizing practical reasoning over idealistic aspirations for a perfectly just society, thus ensuring relevance to real-world choices. This perspective shifts the focus from envisioned perfection to practical decision-making and the actual choices available and is of particular importance for the present work.

Second, recognizing multiple conflicting reasons relevant to social justice underscores the importance of addressing enduring conflicts. Third, SCT's accommodation for ongoing reassessment and scrutiny is noteworthy because it recognizes that initially plausible general principles about social choices may conflict with others, requiring ongoing revision.

Fourth, SCT acknowledges that even a comprehensive theory of justice may produce incomplete rankings in many cases due to assertive incompleteness. Fifth, individual rankings may not always be consistent with individual preferences, as is commonly assumed but may be based on different types of reasoning, contributing to the discipline's goal of deriving collective judgments for social choices by considering different perspectives and priorities. The consideration of various forms of reasoning and divergent perspectives and priorities also underscores the advantages of the approach for this work.

Sixth, SCT can play a key role in clarifying complex human values and social reasoning, balancing the need for explicitness with the recognition of the limitations of

precise axiomatization, thereby contribute towards a meaningful dialogue about important questions.

Lastly, although SCT originated with mathematicians, it has become closely associated with the advocacy of public reason, with mathematical insights serving as valuable inputs to public discourse, in the spirit of individuals such as Condorcet, who emphasized the potential contributions of mathematical results in public discussion.

Overall, the main advantages resulting from using the social choice approach as a framework for reasoning consist in its emphasis on practical reasoning over idealistic aspirations for a perfectly just society, thus ensuring relevance to real-world choices. In addition, the approach takes into account different types of reasoning and helps to derive collective judgments for social choices by considering various perspectives and priorities. Moreover, SCT can clarify complex human values and social reasoning while balancing explicitness with the recognition of limitations in precise axiomatization, thereby fostering meaningful dialogue about important questions. Finally, SCT's link with public reason highlights the valuable potential of mathematical insights in public discourse.

4.4.3 Properties for the Evaluation of Alternatives

For employing the social choice approach as a framework for reasoning, it is necessary to address the issues of incompleteness, maximality and commensurability. These characteristics of decision processes reflect different approaches to evaluating, comparing, and selecting alternatives. They highlight the complexities involved in decision-making and the various considerations that need to be taken into account when assessing alternatives.

4.4.3.1 Incompleteness. Incompleteness refers to situations where there are gaps or uncertainties in the available valuational orderings or decision criteria, potentially leading to ambiguity or indecision (Sen, 2004). Even though completeness is preferable, the question of whether completeness is necessarily needed for the social problem at hand “depends on the nature of the choice” (Sen, 2017a, p. 48).

Thus, completeness is not a fundamental prerequisite to decide. As Sen notes, reasoned practice can accommodate incompleteness or unresolved conflict while agreements

stemming from a "public framework of thought" may be partial yet still beneficial (Sen, 2011, p. 135).

In addition, in cases in which incompleteness is only tentative, it can be necessary to decide at a given point, for instance, to avoid the consequences of not deciding at all (Levi, 1990, 2009; Sen, 2017a, pp. 459, 460). A methodological approach to evaluation, including the evaluation of social justice, need not be totalistic (Sen, 2011, p. 103).

Incompleteness can persist because of information gaps and unresolved judgments involving multiple considerations (Sen, 2011, p. 103). Moreover, recognizing assertive incompleteness does not diminish the importance of ongoing scrutiny and investigation to reduce tentative incompleteness by addressing unresolved conflicts (Sen, 2004).

Incompleteness may persist due to different assessments by individuals, even after accounting for a *veil of ignorance* to mitigate personal bias (Sen, 2011, pp. 104, 105). Conflicting views of social priorities may remain even after vested interests are excluded (Sen, 2011, pp. 104, 105). In addition, if everyone has complete justice orderings, the shared beliefs of different parties result in a partial ranking that differs in clarity (Sen, 2011, pp. 104, 105). But even with persistent incompleteness, useful judgments can be derived (Sen, 2011, p. 103).

Overall, the issue of evaluative incompleteness is central to both SCT and theories of justice (Sen, 2011, p. 105). Despite the claims of theories such as Rawlsian *justice as fairness* that full agreement emerges in the *original position*, this remains an assumption (Sen, 2011, p. 105). Yet, the persistent incompleteness of social justice judgments makes it difficult to identify a perfectly just society and to derive transcendental conclusions, but it does not prevent comparative judgments from being made (Sen, 2011, p. 105).

4.4.3.2 Maximality. Maximality, in this context, refers to identifying an alternative in reasoning that is not judged to be worse than any other available option, even if it may not be considered the best or optimal among all perceivable alternatives (Sen, 2017b). There is a common understanding of the necessity to base reasoning for decision-making on the aspiration to achieve optimality (Sen, 2017a, p. 453).

For decisions related to social choice, however, this aspiration needs to be assessed carefully. In the context of collective decision-making, the difference between optimality

and maximality is essential and can arise from the eventuality of incomplete rankings of the different alternatives (Sen, 1993, 1997, 2017a).

Pursuing maximality through reasoning – and thereby eliminating inferior alternatives – can already be regarded as an achievement in itself (Sen, 2017a, p. 454). A failure of reasoned decision-making, on the other hand, would constitute the rejection of a superior alternative (Sen, 2017a). But that difficulty does not arise in situations in which there is no optimal alternative and, thus, making a maximal choice is justified (Sen, 2017a). Distinguishing between maximality and optimality is, hence, central to reasoning and social decisions (Sen, 2017a, p. 454).

In contrast to Rawls, Sen suggests that people may prioritize decisions in different directions for good reasons so that there is no guarantee of an optimal solution (Sen, 2017a, p. 455). Rather than expecting a single unambiguous answer, Sen argues that multiple answers can coexist without necessarily reaching what Rawls calls a reflective equilibrium (Sen, 2017a, p. 455).

The difference between the maximal and the optimal is relevant not only in theoretical contexts but also in practical decision-making and moral philosophy (Sen, 2017a, p. 459). Understanding this distinction is crucial for evaluating different theories of justice (Sen, 2017a, p. 459). While maximizing choices may seem straightforward, incompleteness in rankings can arise due to unresolved judgments or information gaps, especially in decisions with future consequences (Sen, 2017a, p. 459). Therefore, maximality provides a sufficient path for reasoned decision-making and can be a viable basis for social choice, especially in situations where there is substantial disagreement among alternatives (Sen, 2017a, p. 461). This scenario often occurs in group decision-making, where different options are ranked differently but share the common goal of avoiding a worse outcome (Sen, 2017a, p. 461). This finding also has key implications for the present work. Assuming that a sequence of pairwise comparisons inevitably leads to the best alternative is fallacious since only a well-ordered ranking over a finite set would ensure that the set of pairwise comparisons leads to the best alternative (Sen, 2011, pp. 102, 103).

In sum, the thoughtful use of incomplete rankings offers promising opportunities in welfare economics and normative evaluation (Sen, 2017a, p. 462). SCT greatly enriches the analysis of social justice, especially when decisions rely on partial ordering and

maximality as guiding principles of reasoned choice (Sen, 2017a, p. 462). Thus, Sen advocates for a more nuanced understanding of social choice that considers individual rights, freedoms, and the distributional impact of decisions (Sen, 2017a, pp. 469-471) and emphasizes the importance of acknowledging “that not all issues of decisional justice can be fully resolved by agreed reasoning on values” so that some form of agreed partial ordering can already be considered as tremendously helpful (Sen, 2017a, p. 470).

4.4.3.3 Commensurability. Another central aspect concerning decisions in social contexts is the non-commensurability of different alternatives. Commensurability refers to the ability to compare or measure different things using a common standard or scale (Sen, 2004, pp. 43-45). Frequently, making decisions is easier when alternatives can be compared on a common scale (Sen, 2004, pp. 43-45).

While commensurability can make it easier to choose between given alternatives, it is not fundamentally necessary since people often make reasoned choices when confronted with non-commensurable alternatives without difficulty (Sen, 2017a, p. 456). Non-commensurable results make choices complex, but they do not necessarily make them impossible or overly difficult (Sen, 2011, p. 241).

Non-commensurability is often misperceived as a problem, but the real difficulty is the inability to rank alternatives despite thorough reasoning efforts (Sen, 2017a, pp. 456-458). When evaluating alternatives, ranking them against each other is inevitable, highlighting the close relationship between measurability and ranking (Sen, 2017a, pp. 365-367). Even informal evaluations involve some form of partial ranking (Sen, 2017a, pp. 365-367). Thus, grasping the various forms of measurability is vital for ensuring analytical clarity in reasoning (Sen, 2017a, pp. 365-367).

Even after exhaustive reasoning, some pairs may remain incompletely ranked, indicating the limitations of the evaluation (Sen, 2017a, pp. 456-458). However, this does not imply a lack of effort or justification for not attempting to rank unranked pairs (Sen, 2017a, pp. 456-458). The existence of unranked pairs highlights the complexity of evaluation in general, and is a common outcome in ethical and policy evaluation (Sen, 2017a, pp. 456-458). It is plausible to reach a point where certain alternatives cannot be ranked due to ethical concerns or divergent value systems.

Yet, alternatives, unranked based on values, can still exist next to reasoned rankings (Sen, 2017a, pp. 456-458). Thus, it is necessary to acknowledge the fact that it is not uncommon to deal with unranked pairs as an outcome “of reasoned analysis of ethical and political evaluation” (Sen, 2017a, p. 458). Neglecting this would imply that there is no possible way of normative evaluation that includes the handling of incomplete rankings (Sen, 2017a, p. 458).

The inclusion of partial rankings in SCT greatly expands its applicability and facilitates the achievement of practical solutions despite remaining disagreements since partial rankings of agreement allow for various useful actions in such contexts (Sen, 2017a, pp. xxix, xxx). Overall, using reason-based maximality and incomplete rankings “can serve as an acceptable basis for making social choice” (Sen, 2017a, p. 461).

4.4.4 Decisions and Reasoning

The meaning of reasoning in such a framework also needs to be clarified. According to Sen, the role of human reasoning, including public reasoning, remains central to what he calls the social choice approach, even outside Arrow's framework (Sen, 2017a, pp. 466, 467). The fundamental link between public reasoning and participatory social decisions is central to strengthening democracy and shaping a robust notion of social justice based on fairness and social choice (Sen, 2011, pp. 112, 113). Thus, public reasoning plays a vital role in the pursuit of justice generally (Sen, 2011, p. 122).

According to Sen, “[r]eason cannot but be central to social choice”, and especially public reasoning is conceptually underpinning normative SCT (Sen, 2017a, p. 462). This process may entail personal contemplation, as described by John Rawls as reflective equilibrium, as well as engaging in public reasoning with others (Sen, 2017a, p. 462). Endorsing this point, he recognizes a “fundamental connection between public reasoning” and “the demands of participatory social decisions” (Sen, 2017a, p. 462). This assumes that people are willing to listen to one another's arguments (Appiah, 2009; Sen, 2017a, p. 462).

In contrast to rational choice theory, Sen argues that the narrow view of reason and rationality overlooks the fact that individuals often have reasons to consider goals beyond self-interest, such as broader values or normative rules (Sen, 2011, p. 179). Whether an

individual personally benefits from altruistic acts depends on the nature of the reason behind them (Sen, 2011, p. 179). There are various approaches to rational behavior, not all of which rely on the advantage-based rationale of mutually beneficial cooperation (Sen, 2011, p. 206).

Sen emphasizes the key importance of the kind of reasoning that people engage in, suggesting that while individuals may not always adhere strictly to reason in every situation, they do respond to it both in their everyday actions and in considering broader issues such as justice and societal ideals (Sen, 2011, p. 178). Thus, people's capacity for reasoning and self-reflection suggests that there is no unbridgeable gap between their understanding and evaluation of their own decisions and those of others (Sen, 2011, p. 178).

Reasoning, thus, should be understood as “a process rather than an instantaneous occurrence” (Sen, 2017a, p. 460). In this context, it is surprising that the connection between how values are formed and how they influence decision-making processes, as well as the role of social interactions, has not been central to SCT (Arrow, 2012; Sen, 2017a, pp. 40, 467). This question is also of interest for the present work.

Overall, human reasoning, and in particular public reasoning, the exchange of ideas and formation of values, as well as the importance of mutual fact-checking can, thus, be regarded as a core element of democratic decision-making endorsed by – among others – Condorcet, Arrow, Mill and Buchanan (Arrow, 2012; Buchanan, 1954; Lukes & Urbinati, 2012; Mill, 1864; Sen, 2017a). The process of public reasoning, hence, plays a central role in social decisions, but also beyond that, such as for concepts like human rights and capabilities (Sen, 2005).

4.4.4.1 Group decisions. There are further implications for the use of such a framework in the context of group decisions and sustainable development. SCT, historically centered on the reasoned choice of groups, holds relevance for broader contexts of group decision-making (Sen, 2017a, p. 467). This insight underscores the versatility and applicability of the theory beyond its original scope (Sen, 2017a, p. 467).

Thus, SCT can “be seen as the pursuit of critical reasoning in dealing with group decisions, including aggregative assessment of the lives of people who constitute a group”

(Sen, 2017a, p. 453). In this connection, groups can range from small entities to entire nations (Sen, 2017a, p. 467).

Sen further emphasizes that several concepts discussed, such as the legitimacy of incomplete rankings, using maximality as bases for decisions, and the importance of public reasoning, imply the potential applicability of the social choice framework to global issues. These include considerations like human rights, interpersonal comparisons of well-being, and the role of human freedom and capabilities (Sen, 2017a, pp. 467, 468).

Sen stresses that the arguments developed can "be immediately interpreted and used in the context of group decisions in general" (Sen, 2017a, p. 467). They, therefore, form the basis for the present work.

4.4.4.2 Sustainable Development. Sen's conception of sustainable development does not offer a readily applicable theory but rather serves as a philosophical foundation (Martins, 2022; Thrasher & Vallier, 2015). He does not provide an applicable framework for his theoretical arguments right away. Yet, he stresses the importance of considering constructive human intervention empowered by development in addressing contemporary environmental challenges (Sen, 2011, pp. 248, 249).

It is, thus, necessary to operationalize Sen's arguments in a way so that they can be used for the desired purpose of evaluating options for the strategic implementation of transformation paths in the RR. This raises the question of what lessons learned from normative SCT mean for transforming RR. Since evaluation in the context of social decisions is context-dependent, normative evaluation criteria need to be identified. Sustainability, as defined by the SDGs, is set to be the core requirement of future transformation processes.

Consequently, this should be regarded as a fundamental requirement for any sustainable bioeconomy transformation pathway within the RR. Achieving a successful transition towards a sustainable bioeconomy in the RR necessitates the integration of various forms of knowledge, including transformative, normative and system knowledge (Urmetzer et al., 2020). To acquire the information needed for social decisions, participatory elements are important (Urmetzer et al., 2020). In the framework of normative social choice, this knowledge can feed into the decision-making process and broaden the information base. Participatory elements can further ensure that diverse

values and preferences are brought into the process and ensure that a framework for public reasoning is in place.

4.4.5 Methodological Implications

The interpretation of Sen's arguments has far-reaching implications for the selection of an appropriate method for contributing to the provision of valuable information. Information is a prerequisite for making intelligent social choices. While decisions of individuals can easily be biased, collective decisions – provided that there has been an open discussion and public reasoning before the decision was taken – can reduce the influence of individual biases and improve the overall decision-making as well as its legitimacy (Landemore, 2013).

Any decision with respect to technological progress and the future of societal transformation process involves considerable uncertainty. That applies to the aspired transformation in the RR, too. Hence, it should not be unexpected to acknowledge that it is often not possible to bridge the lack of judgmental and informational knowledge to achieve a complete ordering of alternatives.

For the fact that the problem dealt with is a wicked problem, it is reasonable and necessary to dispense with completeness. It is impossible to anticipate all the information needed at the point of decision-making. The decision alternatives are not fully commensurable, given that any transformation path will have unforeseeable spillover effects, which will reach far beyond the region itself. However, the development of regional transformation paths offers an opportunity here. Yet, it implies that there is no optimal solution, and it is advisable to strive for maximality instead of optimality.

Following the reasoning above, it is necessary to identify a method that incorporates the requirements and can support the process to overcome these limitations, balance related conflicts of objectives, and identify desirable, feasible, and acceptable transformation paths. In this context, methods of MCDA represent suitable tools to find common ground across stakeholders. Thus, it is not surprising that social choice has inspired research in MCDA and that Arrow himself contributed noteworthy to the development of MCDA approaches (Arrow & Raynaud, 1986; Köksalan et al., 2013).

Although MCDA approaches have been used in a variety of decision-making processes related to sustainable development, they often lack the involvement of affected stakeholders, especially local communities (Kandakoglu et al., 2019). Moreover, they often neglect the importance of the social dimension in the context of sustainability (Kandakoglu et al., 2019). Stakeholder involvement plays a particularly important role in this process. Therefore, it needs to be evaluated which methods are used to identify and structure related stakeholders and what degree of involvement is appropriate.

Moreover, the role of discourse, in particular in the context of environmental policy, can be considered as a central element for decision-making (Hajer & Versteeg, 2005; Leipold et al., 2019; van Mill, 1996). In the framework of normative social choice, discourse can fill the information gap that is necessary for societal decisions. Thus, MCDA could represent a form of bridging deliberative elements and SCT through informational broadening and public reasoning.

With respect to the capability approach, Sen highlights the importance of linking public reasoning and the choice of weighting, stating that weights should be subject to ongoing scrutiny and public debate (Sen, 2017a, p. 369). While agreement on weights may not be comprehensive, the use of ranges of weights allows for partial rankings and limited agreement, facilitating welfare-economic evaluations without the need for exhaustive assessments (Sen, 2017a, p. 369). This insight can also be interpreted in the context of an SCT framework for public reasoning in the context of the weighting of divergent objectives.

Depending on the particular MCDA approach chosen, it aligns adequately with normative SCT. A related method should, thus, not require transitive preferences and strive to find maximality instead of an optimal solution. Thereby, it helps to find an alternative matching the declared goals of the group based on their understanding of the problem. A normative social choice approach linked with MCDA – that allows informational broadening and acknowledges the importance of public reasoning while ensuring participatory elements – is therefore beneficial for applying in the context of collective decision-making dealing with a wicked problem.

Overall, Normative social choice as a framework for public reasoning, as laid out by Amartya Sen, thus serves as the basis for interpreting the results of this work.

4.5 Chapter Summary

In this chapter, the historical roots, interdisciplinary nature, and philosophical implications of SCT are explored, highlighting its role in addressing group decision-making processes and its connections to ethics, political philosophy, and democratic values.

SCT examines the relationship between individual preferences and collective choices, highlighting the limitations exposed by Kenneth Arrow's General Possibility Theorem. This requires a critical evaluation of the axiomatic structure of social choice, particularly in light of democratic values and the shortcomings of purely rational models. The historical roots of modern democratic thought, which can be traced back to the Enlightenment era, underscore the importance of including all members of society in decision-making processes, challenging the narrow focus on voting procedures and advocating for a broader foundation that incorporates diverse perspectives and values.

According to Sen, normative SCT relies heavily on reasoning, especially public reasoning, which is crucial for participatory social decisions and a deeper understanding of social choice demands. While impossible theorems in SCT may seem conclusive, they should instead initiate discussions on how to address choice problems, emphasizing the ongoing nature of the debate and the need for more informational input, rather than providing definitive answers.

Sen's understanding of public reason is closely linked to his views on democracy and justice, with a focus on the promotion of justice rather than the search for perfect institutions. Influenced by his interaction with Rawls, he distinguishes between two approaches to justice, both of which emphasize fairness but differ in fundamental ways. Sen identifies exclusions in the Rawlsian approach to justice and emphasizes the need for broader analyses.

Moreover, Sen distinguishes between two main understandings of democracy: the institutional view, which focuses on elections, and a broader perspective, which emphasizes public reasoning and participatory deliberation. He argues for a democracy based on public reasoning that complements formal political processes with informed, interactive discussion. Influenced by early Indian jurisprudence and Enlightenment ideas,

Sen's approach prioritizes the assessment of social justice and the comparison of different ways of life, emphasizing the importance of reasoning and public discourse in a democratic framework.

Sen acknowledges different perspectives on the role of public reasoning in politics and ethics, such as those of Rawls' and Habermas' but asserts that these differences do not undermine his main arguments. Instead, he highlights the collective impact of these perspectives, emphasizing the importance of political participation, dialogue, and public interaction for a holistic understanding of democracy, and closely linking the essential role of public reason in democracy to the concept of justice, suggesting an intrinsic connection between the two, characterized by common discursive features.

Sen contrasts the Smithian impartial spectator approach with Rawls' contractarian reasoning, citing its strengths in comparative assessment, consideration of social realizations, guidance in addressing injustice, and inclusion of diverse voices to avoid parochialism. He argues for the importance of incorporating perspectives and arguments of all relevant parties in public reasoning to ensure a comprehensive understanding of issues and to prevent overlooking valuable insights. All in all, Sen adopts a broad and inclusive approach to reasoning, rejecting a narrow conception of reasonable persons and advocating for the active inclusion of individuals from diverse cultural, social, and economic backgrounds.

Sen's concept of plural grounding, inspired by Rawls' overlapping consensus, prioritizes reasoned consensus from multiple perspectives over agreement on relative importance and emphasizes the role of public reasoning in considering diverse arguments. This approach values the process of reasoned discussion and public debate, which fosters acceptance of diverse viewpoints without requiring identical reasons for consensus. Plural grounding can thus be categorized as a form of weak consensus.

The theoretical aspects as laid out by Amartya Sen provide the foundation for a Social Choice approach as a framework for public reasoning and thus serve as basis for interpreting the results of this work. This has implications for collective decision making and related issues of incompleteness and maximality, commensurability.

Completeness is desirable, but in most real-world decision situations it is neither possible nor necessary. Incompleteness and information gaps may persist due to different

assessments by individuals or groups. The persistent incompleteness of social justice judgments makes it difficult to identify a perfectly just society or to derive transcendental conclusions, but it does not prevent comparative judgments from being made.

Maximality provides a viable approach to decision-making, especially when there is no optimal choice. It offers a sound basis for social choice, particularly in group settings where options vary but share the goal of avoiding worse outcomes. Pursuing maximality through reasoning, thus eliminating inferior alternatives, demonstrates a substantial contribution to decision-making.

Commensurability is preferable, but people often make reasoned choices without difficulty when they are faced with non-commensurable alternatives. Thus, the inability to rank alternatives despite thorough reasoning efforts is the actual challenge. Ultimately, the existence of unranked pairs is a common outcome in ethical and policy evaluation, highlighting the complexity of evaluation in general, but not an unsolvable problem because unranked alternatives can still coexist alongside reasoned rankings.

As suggested by Sen, these findings are interpreted and applied in the context of group decisions and sustainable development. Methodological aspects are therefore addressed in the next section.

5 Methodology – Multiple Criteria Decision Aid

As discussed in the previous chapter, Amartya Sen advocates that societal decisions should be based on a diversity of values and perceptions and emphasizes the importance of pluralism and multidimensional perspectives in decision-making. Accounting for the diversity of human interests and values in collective decision-making can therefore be considered as particularly important with respect to ethical and practical questions of policy making.

The present work interprets and utilizes these remarks, as suggested by Sen, in the context of group decision making and sustainability. In particular, they serve as the foundation for the development of a decision support system in the context of the transformation process towards a sustainable bioeconomy. To pursue this objective, a methodology that allows for the incorporation of multiple perspectives into the decision-making process is required.

The use of MCDA is beneficial for this purpose. Related methods allow for a structured, transparent and comprehensible approach, particularly in situations confronted with complex decision problems, as is the case concerning bioeconomy transformations. Through MCDA, it is possible to account for various conflicting objectives and integrate aspects that go beyond a singular belief and value system. This is in line with Sen's arguments with respect to plural grounding.

Therefore, this chapter proceeds by laying out the reasoning for selecting MCDA as method, followed by introducing its role within the framework and implications derived from Sen's remarks on normative social choice. Subsequently, the decision-theoretical foundations of MCDA are outlined and the question of how MCDA contributes to the decision-making process is explored. This is followed by the definition and delineation of the relevant approaches and the elaboration of the key components required to develop the analytical framework. Contextual requirements resulting from the intended application in the regional transformation process towards a sustainable bioeconomy in the RR as well as implications arising from the context of sustainable development are also discussed in the next section.

This is followed by an overview of the process of conducting an MCDA in general with an explanation of the various steps involved, as well as by discussing vital aspects given the context of utilization under consideration of social and environmental aspects. In the next sections, vital elements determining the selection of the appropriate methodology for the context of the transition process are discussed and, based on the desired properties derived from the link to normative social choice and the link to sustainability, identified. The main strengths of the identified methods and the reasons for their selection are then elaborated. Thereafter, the methods are introduced and the steps required for their application are presented.

The chapter concludes with an overview of the developed framework and remarks about the implementation using Python libraries, followed by the section summary.

5.1 Determining the Research Methodology

Multiple methodological approaches to analyze or support decision making, policymaking and governance in the context of the bioeconomy exist, each characterized by individual features. System Dynamics, for instance, offers great potential to understand systems and changes in systems, also with respect to the bioeconomy (Blumberga et al., 2018; Forrester, 1961; Pyka et al., 2022). However, in relation to the objective pursued in this work, including the integration of multiple stakeholders with varying degrees of expertise, simulating complex system behavior appears less suitable with regard to traceability of the decision-making process and transparency with respect to the subsequent results. Approaches for future-oriented research, such as Delphi for example, potentially appear promising for addressing the future of the bioeconomy, especially with respect to individual sectors (Elgabry et al., 2022; Hurmekoski et al., 2019). However, the focus on experts stands contrary to the intended approach of this work concerning the integration of perspectives of multiple stakeholders (Winkler & Moser, 2016). Another promising approach, for instance, can be found in social network analysis, which can provide valuable insights in how relationships and structures between entities work (Giurca & Metz, 2018; Harrahill et al., 2023). Yet, the emphasis here is centered around the relationship between the actors and less focused on a quantitative evaluation of decision criteria and transformation pathways.

For the requirements in the context of this work, MCDA provides multiple advantages. While all of the approaches mentioned, as well as further research approaches, provide useful insights with respect to the bioeconomy, they are less suitable for the specific research objectives of this thesis in bringing together subjective stakeholder perceptions and transformation pathways.

MCDA does not usually refer to an individual method (Dean, 2022). Instead, it is frequently used as an umbrella term for different approaches in which decision problems including multiple criteria and objectives can be addressed (Dean, 2022). It has been used across multiple fields in relation to this work, for instance, in the context of sustainability with respect to sustainability assessment, environmental planning, and energy system transformations (Cinelli et al., 2014; Cinelli et al., 2020; Etxano & Villalba-Eguiluz, 2021; Ferla et al., 2024; Huang et al., 2011; Kandakoglu et al., 2019; Mesa Estrada et al., 2022).

As Ferla et al. (2024) point out with regard to sustainability assessment, three characteristics contribute notably to the potential of multi-criteria approaches in addressing multidimensional questions concerning sustainability. First, related approaches enable the integration of divergent and conflicting objectives (Dean, 2022; Ferla et al., 2024; Greco & Munda, 2017; Kandakoglu et al., 2019). Second, depending on the decision context, various forms of stakeholder participation, if intended, and weighting approaches are feasible (Ferla et al., 2024; Liu et al., 2020; Paradowski et al., 2021; Poulsen, 2022; Wang et al., 2009). And third, it provides a solid foundation for transparent stakeholder engagement and communication (Etxano & Villalba-Eguiluz, 2021; Ferla et al., 2024; Talukder & W. Hipel, 2018).

Multiple authors relate the increased popularity of MCDA methods to a realization that contemporary policy problems are complex and need to account for numerous perceptions (Dean, 2022; Giampietro, 2003; Greco & Munda, 2017; Munda, 1995; Munda, 2008). Given the complex, wicked problem of the transformation process towards a sustainable bioeconomy addressed in this work (Section 3.2.1) and the need to account for imprecise stakeholder perceptions (Section 3.2.2), these benefits equally prove to be useful. This further includes the flexibility to integrate additional approaches within an

MCDA, such as a focus group workshop and surveys, as is the case in this work. Thus, the role of MCDA within the developed approach is introduced subsequently.

5.1.1 Role of MCDA for the Framework

The role MCDA within the developed framework needs to be clarified. Following Roy (1996a), decision aiding is intended to support in forming, establishing, and justifying beliefs (Roy, 1996a, p. 11). Both the foundation and the methods used to formulate the decision should be subject to critical deliberation (Roy, 1996a, p. 11). Especially in connection with issues concerning decisions in a social context, where ethical aspects, such as justice, are of concern (Sen, 2017b). Thus, every decision involves elements of discovery, reasoning, occasional irrationality, and organizational impacts (Roy, 1996a, p. XVIII). The main purpose of MCDA, according to Roy (1996a, p. 11), is not to find an optimal solution, but instead develop something that is thought to be useful in assisting an actor in a choice process, for instance by debate or support in identifying an option that is in line with the actors aims (Roy, 1996a, p. 11).

The understanding of MCDA as presented by Roy underlies this work. On this basis, MCDA can be part of the public reasoning framework.

5.1.2 Implications Derived from Normative Social Choice

For the use of MCDA in the context of this thesis, methodological implications can be derived from the operationalization of Sen's arguments from the previous chapter. These should therefore be considered when selecting the specific method.

- a) **Completeness:** While completeness is desirable, it is frequently not possible or necessary. Thus, the method identified needs to be able to provide useful information and assist decision-making in a situation dealing with information gaps and incompleteness.
- b) **Maximality:** The chosen method should strive for a decision based on maximality and not just try to find an optimal decision that cannot be identified in the context of a wicked problem.
- c) **Commensurability:** Commensurability is preferred.

- d) Partial and complete rankings: Given that the existence of unranked pairs is a common outcome in ethical and policy evaluation, the chosen method should be able to illustrate unranked pairs as well as partial or complete rankings.
- e) Plural grounding: The identified method should enable the pursuit of a consensus that accommodates the consideration of diverse perspectives, each expressed from its subjective viewpoint.

The specific selection of methods is therefore guided by these derived aspects.

5.2 Decision-Theoretical Basis, Assumptions and Challenges

Most decisions require accounting for more than one single criterion. Generally, it can be stated that considering multiple criteria in a decision process constitutes the rule rather than an exception. When buying a product, for instance, consumers often consider various aspects, such as price, quality and environmental impact (see e.g., Macht, Klink-Lehmann, & Venghaus, 2023).

Yet, utilizing a single-criterion model can prove beneficial in certain instances as it offers a well-defined mathematical approach (Brans & De Smet, 2016, p. 189). Examples include technical settings or production processes, where predefined criteria need to be met precisely. However, it frequently fails to adequately account for the complex socio-economic conditions of practical situations. Multi-criteria models provide a closer approximation of real-world situations, but they do not inherently possess a deeper mathematical meaning in the sense that it is not always possible to arrive at mathematically perfect solution (Brans & De Smet, 2016, p. 189).

From a decision theoretical angle, decisions can be regarded from different perspectives. Following Keeney (1992), decision-making approaches can be distinguished into normative, descriptive and prescriptive. Normative approaches to decision-making revolve around rational processes and the necessity for logical consistency in decision-making (Keeney, 1992). Descriptive decision-making focuses on understanding how individuals make decisions and predicting their choices (Keeney, 1992). Prescriptive decision-making aims to assist in making well-informed and, ideally, better decisions (Keeney, 1992). This work thus relates to descriptive and prescriptive

decision-making, aiming to support informed decision-making. Better decisions would be those leading to progress towards the goals set out in the SDGs.

5.2.1 Contributions of Decision Analysis

Decisions based on MCDA approaches are not meant to deduct an optimal solution in the context of policymaking and wicked problems. After all, it needs to be stressed that an actual decision should only be made by democratically legitimized DMs. Decision analysis (DA) can support DMs and stakeholders by providing a scientific basis under consideration of the applied working hypothesis and assumptions made during the structuring of the decision problem at hand (Roy, 2016, p. 21). Taking that into account, Roy identifies five aspects to which DA can generally contribute in a meaningful way (Roy, 2016, p. 21):

- 1) Investigating the context in which a decision problem is embedded, by identifying possible actions and related consequences as well as the actors involved
- 2) Structuring the decision-making process and thereby enhance the consistency with respect to underlying values, goals and objectives
- 3) Foster mutual understanding and possibly cooperation between involved actors by offering a framework for a constructive discourse
- 4) Develop recommendations based on computational approaches within the framework of applied assumptions and models
- 5) Support in legitimizing the final decision through participation in the overall process

Thus, DA does not offer a complete representation of the overall decision problem. However, it can contribute substantially to the aspects pointed out, especially in the context of complex problems with several actors involved. Furthermore, the majority of decisions are not based on a single objective, but rather on a combination of factors that may vary in importance.

The importance of considering more than a single criterion increases even more in cases where several actors are involved. Only focusing on a single aspect (monocriterion) could, depending on the decision-making context in which a given decision takes place, result in neglecting crucial aspects and illustrating features of only a specific belief and

value system as the overall goal (Roy, 2016, p. 22). The use of a multi-criteria approach can help prevent such problems by encouraging debate about the importance of any one criterion and by including multiple perspectives (Roy, 1993; 2016, pp. 21,22).

5.2.2 *Objectivity*

In many cases, those who claim to shed light objectively on a decision in fact take a stand—consciously or unconsciously—for an a priori position or for a prevailing hypothesis which they then seek to justify. (Roy, 2016, p. 22)

While MCDA approaches aim to provide a scientific basis for decision-making, they also face limitations regarding the objectivity of the results obtained. The absence of an optimal solution to a wicked problem underlines that the application of an MCDA approach can only support the search for a *good* solution rather than a *bad* solution. But even in a different context, striving for objectivity by using an MCDA approach is limited, and not just because of epistemological considerations (Roy, 1993, 2016).

Further reasons include that the difference between what is feasible and what is not is recurrently fuzzy in a real-world decision and the modeling of preferences is associated with a varying degree of ambiguity (Roy, 2016, p. 22). Moreover, data sets considered in MCDA can be imprecise or reflect a specific belief system (Roy, 2016, p. 23). The problem of biased data is not limited to MCDA approaches but constitutes a common problem in data analysis. Recent examples here include discriminatory tendencies in machine learning models.

As pointed out, MCDA is frequently utilized in cases in which an optimal decision is not identifiable. This raises the question of what constitutes a good decision. Certain properties can characterize a good decision, including transparency, which ensures that the decision-making process is open and understandable. Additionally, the decision should also be traceable, allowing for a clear audit trail of how it was arrived at.

A good decision often involves participation from various stakeholders, reflecting their diverse interests and values (Munda, 2016, p. 1255). It considers numerous objectives, recognizing that decisions often involve multiple criteria. When applicable, it incorporates scientific information, grounding the decision-making process in empirical data or expert knowledge (Roy, 2016, pp. 21-23). These properties collectively contribute to what can be deemed a good decision in the context of MCDA.

Moreover, it is not uncommon that situations arise where it is impossible to identify the best possible option. In this context, Sen also stressed the elimination of inferior alternatives can already be considered beneficial (Sen, 2017a, p. 454).

5.3 Definition and Delimitation

MCDA draws from insights across various fields, such as political science, economics, psychology, mathematics, and computer science (Köksalan et al., 2016). Methods have been developed to address multi-criteria problems in a wide variety of contexts (Kandakoglu et al., 2019). This diversity is reflected in the wide range of fields in which MCDA methods have been applied, including health care, urban planning, energy, finance, and environmental management, as well as in the diverse use of related terms (Dean, 2022).

Concerning related terminology, Multiple Criteria Decision Making (MCDM), Multiple Criteria Decision Analysis (MCDA) and Multiple Criteria Decision Aid (MCDA) are often used interchangeably.

This work understands MCDA as decision *aid*, as defined by Roy (1996a, p. 10):

Decision aiding is the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps obtain elements of responses to the questions posed by a stakeholder of a decision process. These elements work towards clarifying the decision and usually towards recommending, or simply favoring, a behavior that will increase the consistency between the evolution of the process and this stakeholder's objectives and value system. (Roy, 1996a, p. 10)

Roy's definition aligns with Sen's remarks concerning the importance of accounting for diverse perspectives and value system within decision-making processes as well as highlighting the relevance of the evolutionary character of the process itself for developing recommendations and taking decisions (Sen, 2017a).

Further delimitation concerns cost-benefit analysis (CBA). Implementing policies often requires comparing various options and assessing their social desirability through valuation and evaluation (Greco & Munda, 2017; Munda, 2017). Historically, approaches related to welfare economics have been frequently employed for this purpose, such as cost-benefit analysis (Munda, 2017). Concerning public policy problems, CBA and

Multi-Criteria Evaluation (MCE)¹⁸ can be seen as competitive methods only under specific conditions: when all policy decision consequences can be accurately converted into monetary values, and efficiency is the sole relevant policy objective (Munda, 2017, p. 3).

Alternatively, CBA can be incorporated as a criterion within an MCE framework in all other situations (Munda, 2017, p. 3). In general, CBA and MCE are thus complementary approaches (Munda, 2017, p. 3). Otherwise, MCE appears suitable as a public policy framework for integrating various scientific perspectives, especially when considering societal concerns and future generations alongside policy objectives and market conditions (Munda, 2017, p. 3).

5.3.1 Types of Decision Problems

MCDA is usually applied in contexts pertaining to decision-making problems. While not exhaustive, respective decision problems can be categorized into four main categories, namely choice problem, sorting problem, description problem and ranking problem (Roy, 2016, p. 27).

Confronted with a *choice problem*, the objective is to identify the best single alternative or narrow down the group of alternatives to a subset of options that are equally good or incomparable (Roy, 2016, p. 27). For instance, this can be analogized to a manager choosing the most suitable person for a project.

A sorting problem, on the other hand, occurs when alternatives are assigned to predefined categories with the aim of regrouping them based on similar characteristics (Roy, 2016, p. 27). For instance, in the context of student performance evaluation, this problem involves categorizing students as outperforming, average, or weak-performing during an initial screening.

¹⁸ While the terms and respective abbreviations MCE and MCDA are frequently used interchangeably, MCDA, as understood in this work, places a stronger emphasis on the decision-making process, while MCE appears to be more commonly used in settings specifically focused on the aspect of evaluation and assessment.

A description problem involves the objective of detailing alternatives and their corresponding outcomes (Roy, 2016, p. 27). This step is often utilized as an initial approach to better understand the issue at hand.

Lastly, a ranking problem entails sorting alternatives from best to worst based on pairwise comparison scores (Roy, 2016, p. 27). The outcome can be a complete or partial ranking, depending on the context (Roy, 2016, p. 27). University rankings, for example, often consider criteria such as teaching quality and research expertise, which fall within this category.

Since all these decision problems usually involve several criteria, it implies an increase in complexity. Further decision problems include those that can be categorized as design problems or group decision problems (Roy, 2016, p. 27).

Moreover, overlaps exist in the sense that decision problems fall into two categories, as is the case for the decision problem dealt with in this work, which illustrates a ranking problem as well as a group decision problem.

5.3.2 Main Branches of MCDA

As illustrated in Figure 6, MCDA can be categorized into two main branches: Multiple Attribute Decision-Making (MADM) and Multiple Objective Decision-Making (MODM) (Geldermann & Lerche, 2014, pp. 11-13). In MADM, the decision process centers around a finite set of possible alternatives, each defined by a set of attributes or criteria, with the goal of selecting a single alternative from this group (Geldermann & Lerche, 2014, pp. 11-13).

On the other hand, MODM focuses on solving optimization problems by defining an objective function that represents the desired state of the system. It involves a solution space that is not explicitly defined but constrained by feasible solutions. This space is continuous and allows for an infinite number of potential elements (Geldermann & Lerche, 2014, pp. 11-13). The goal of MODM is to calculate a single alternative that optimally satisfies these objectives (Geldermann & Lerche, 2014, pp. 11-13). This often involves the use of vector optimization models (Geldermann & Lerche, 2014, pp. 11-13). MODM is a frequently utilized methodology in design processes, with the objective of identifying the optimal solution for a particular design, such as the ideal bicycle.

To illustrate, in the context of MADM, the objective might be to select the best bicycle from a list of alternatives. In MODM, the emphasis would shift towards designing the bicycle that best meets the predefined objectives and constraints. The present work deals with the field of MADM.

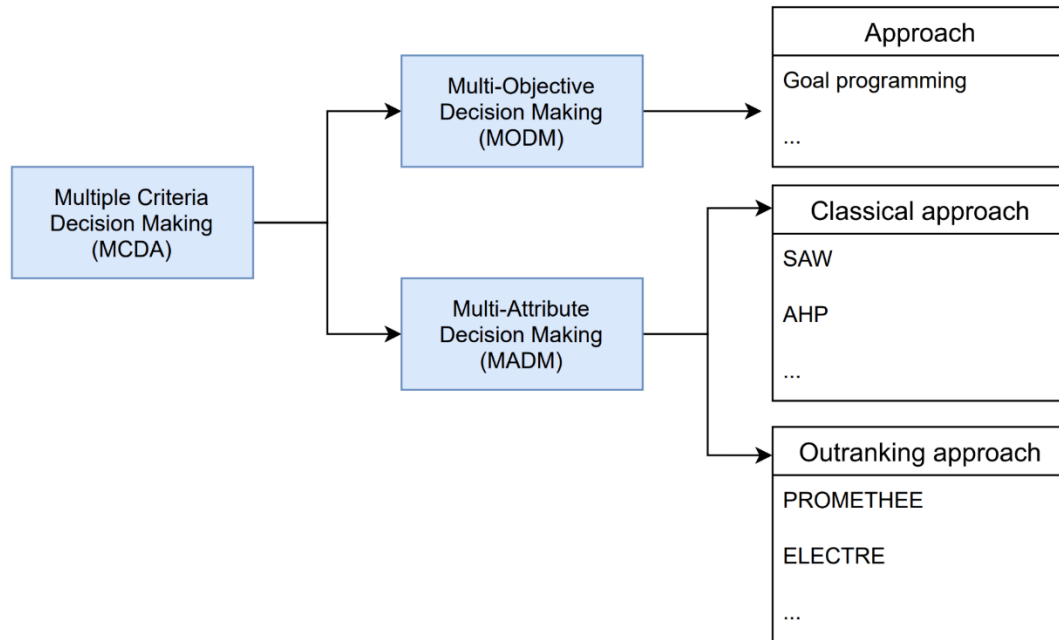


Figure 6. Overview and Classification of MCDA Approaches. Source: Author, based on Geldermann and Lerche (2014, p. 11).

5.3.3 *Classical Approaches*

Within MADM, approaches can be categorized into two main branches with distinct differences (Geldermann & Lerche, 2014, pp. 11-13).

The first is called Classical Approaches or value-based theories (Geldermann & Lerche, 2014, pp. 11-13). Classical methods like Simple Additive Weighting (SAW) operate under the assumption that the DM is capable of expressing its preferences through a utility function (Dean, 2022; Geldermann & Lerche, 2014, pp. 11-13). This utility function quantifies the DM's preferences for each alternative based on the set of criteria, allowing for a numerical representation of their choices. The alternative with the highest utility value is selected.

However, this assumption may not always hold in practical scenarios, as it can be challenging for the DM to precisely articulate their preferences in the form of a utility function. These approaches aim to model the compensatory behavior of the DM

(Geldermann & Lerche, 2014, pp. 11-13). Another frequently used method from the group of classical approaches is the multi-attribute utility theory (MAUT) (Dean, 2022; Geldermann & Lerche, 2014, pp. 11-13).

5.3.4 *Outranking Approaches*

Contrarily, as a critique of these traditional approaches and their underlying assumptions, the outranking methods, often associated with the European or French school of thought, were developed (Dean, 2022; Geldermann & Lerche, 2014, pp. 12,53). Outranking methods operate on the premise that decision-makers may not have a precise awareness of their own preferences and, as a result, may struggle to represent them accurately (Geldermann & Lerche, 2014, pp. 11-13, 53). In light of this, outranking methods accommodate contradictory information, recognizing that decision-makers can have imprecise preferences (Dean, 2022; Geldermann & Lerche, 2014, pp. 11-13).

Their primary objective is not only to reach a decision but also to enrich the decision-making process with valuable insights (Geldermann & Lerche, 2014, pp. 12,13). These methods aim to enhance transparency in the decision-making process, fostering the decision-maker's awareness of the problem and its pertinent factors (Geldermann & Lerche, 2014, pp. 2,17,18). This heightened understanding empowers the decision-maker to make more informed and well-considered choices. Outranking approaches compare the preference relations of alternatives to each other (Geldermann & Lerche, 2014, p. 61). These methods are particularly useful when mostly qualitative evaluations of alternatives exist or when less precise preferences must be included in the model (Geldermann & Lerche, 2014, p. 13). Examples of the most representative outranking methods are Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE) and ELECTRE (Greco & Munda, 2017, p. 316).

Outranking methods are based on the concept of partial comparability (Dean, 2022; Greco & Munda, 2017, p. 316). Partial comparability in MCDA refers to circumstances where not all criteria used to evaluate alternatives can be directly compared or aggregated (Dean, 2022). This can arise when criteria are expressed in various units, have varying measurement scales, or illustrate fundamentally different aspects of a decision problem.

In this context, partial comparability acknowledges that some criteria may not be commensurable, meaning they cannot be compared on the same scale (Dean, 2022). Related MCDA methods aim to address this issue by providing mechanisms to handle partial comparability, allowing DMs to make informed choices despite the differences in criteria.

This allows for depicting real-world decisions more accurately. For instance, in a setting where all economic factors favor a particular policy option, that option can still be rejected if one environmental factor strongly opposes it (Greco & Munda, 2017, p. 316). The specific definition of strongly opposing, such as the threshold for a veto, plays a crucial role in this determination (Greco & Munda, 2017, p. 316).

Outranking methods are further characterized as partially non-compensatory (Dean, 2022; Greco & Munda, 2017, p. 317). This means they do not strictly adhere to a compensatory approach where the advantageous performance on one criterion can fully compensate for a poor performance on another. In contrast, non-compensatory approaches are more stringent, where poor performance on any single criterion can disqualify an alternative, irrespective of its performance on other criteria (Dean, 2022).

There is a focus on determining which alternatives have relative advantages over others based on pairwise comparisons (Dean, 2022; Geldermann & Lerche, 2014, p. 53; Greco & Munda, 2017, p. 317). Weights are typically used to indicate the importance or significance of each criterion in the decision-making process (Greco & Munda, 2017, p. 317). Consequently, the weak sustainability philosophy is usually avoided (Greco & Munda, 2017, p. 317). Thus, some criteria, especially those related to critical environmental or ethical considerations, cannot be offset by outstanding performance in other areas. Therefore, these methods are more aligned with a precautionary principle, emphasizing the importance of avoiding solutions that may have detrimental consequences in certain respects, even if they offer advantages in others.

Two challenges are associated with outranking methods and other pairwise comparison-based approaches (Greco & Munda, 2017, p. 317). Firstly, they do not adhere to the axiom of independence of irrelevant alternatives, leading to the phenomenon of rank reversal where the preference between options a and b can change based on the consideration of a third option, c (Greco & Munda, 2017, p. 317). Secondly, the

Condorcet paradox may occur, wherein alternative a is ranked higher than b, b higher than c, and c higher than a (Brans & De Smet, 2016; Greco & Munda, 2017, p. 317; Tsakalerou et al., 2022). Moreover, depending on the method, it can be necessary to set several parameters, for instance, indifference and preference thresholds, as well as assigning weights to criteria (Greco & Munda, 2017, p. 317). Managing these numerous parameters can result in reduced transparency and model consistency (Greco & Munda, 2017, p. 317).

Overall, however, the advantages of this branch of methods outweigh those of classical approaches. Therefore, the focus of this work is on outranking approaches.

5.4 Key Components

MCDA encompasses several essential elements. These include a defined goal that is sought to be achieved, a range of alternatives that offer potential solutions to the decision problem, and criteria or attributes used to assess whether the objective is met. Further elements include the stakeholders' preferences, which encapsulate their individual insights and viewpoints related to the issue at hand and are integrated into the process to model perspectives. Additionally, the inclusion of weights allows for a subjective evaluation by the stakeholders, assigning varying levels of importance to different criteria. The following part will introduce these elements in further detail.

5.4.1 Goal

An essential prerequisite for successful decision support is the clarification of the objectives pursued (Dean, 2022). In this connection, a goal, as understood in this work, is the description of a future state that differs from the status quo and is desired. The stated goals should be measurable, realistic, and formulated as clearly as possible to achieve a common understanding among all parties involved in the decision-making process.

5.4.2 Alternatives

The individual alternatives are mutually exclusive, so precisely one alternative must be selected (Geldermann & Lerche, 2014, p. 5). However, in real-world decision contexts, this is not necessarily always the case (Roy, 2016). In the context of decision support,

therefore, the comparison is between two or more alternatives (Geldermann & Lerche, 2014, p. 5). Depending on the context, it is often the case that all alternatives are known from the start (Geldermann & Lerche, 2014, p. 5). However, new information may be gathered during the process. Alternatives may be adjusted, or new alternatives may be developed (Geldermann & Lerche, 2014, p. 5).

To compare the alternatives using MCDA methods, they must first be described with their characteristic and decision-relevant features. An advantage of MCDA methods is that, depending on the method, quantitative and qualitative criteria can be included. For a direct comparison to take place, it is necessary that all characteristics used to describe the alternatives can also be defined for all alternatives (Geldermann & Lerche, 2014, p. 5). If this is not possible, the alternatives should be reconsidered, or different parameters should be used for the description (Geldermann & Lerche, 2014, p. 5).

5.4.3 Criteria

Criteria are essential for evaluating the degree to which a goal is attained. While identifying the criteria pertinent to the decision, it is essential to establish a link to the corresponding objectives (Dean, 2022). In this connection, the development of a criteria hierarchy can be a useful approach (Geldermann & Lerche, 2014, p. 6).

A criterion serves as a means designed to assess and compare potential actions based on a distinct perspective (Roy, 2016, p. 24). This evaluation must consider all relevant effects or attributes associated with the given viewpoint for each action, denoted and referred to as the performance of an action according to the respective criterion (Roy, 2016, p. 24).

As part of the subsequent assessment process, information between the criteria as well as within each criterion is required (Behzadian et al., 2010; Cinelli et al., 2014). Information between criteria is expressed as weights which are independent of the measurement scales (Behzadian et al., 2010; Cinelli et al., 2014).

These criteria are then defined using attributes, which involves assigning a unit of measurement and determining whether the objective is to maximize or minimize the attribute (Geldermann & Lerche, 2014). Additionally, various measurement scales can be employed to assess the attributes. The individual criteria should be as independent of one

another as possible (Geldermann & Lerche, 2014). Ideally, underperforming in one criterion should not result in a lower evaluation in another (Geldermann & Lerche, 2014). Yet, it can be challenging to maintain complete independence between criteria in practice (Geldermann & Lerche, 2014). However, recognizing these interdependencies can offer valuable insights and contribute to a more comprehensive understanding of the decision problem.

5.4.4 *Weights*

The use of MCDA methods provides the flexibility to incorporate subjective assessments of how critical each criterion is in the context of the overall problem. This evaluation is represented by a weighting factor for each criterion, indicating its overall importance (Dean, 2022). Weighting factors are typically non-negative numbers measured at a cardinal scale level (Geldermann & Lerche, 2014, p. 8).

Various methods exist for determining the criteria weighting (Wang et al., 2009). A simple approach, for instance, is to assign equal weight to all criteria, referred to as equal weighting. Alternatively, stakeholders can be tasked with providing their own weightings.

Determining the precise weighting factors can be challenging because it relies on subjective judgments. There might be instances where stakeholders can only express their weightings vaguely or encounter difficulties in assessing the relative importance of criteria.

5.4.5 *Preferences*

Preferences reflect the stakeholders' positive or negative disposition toward the consequences associated with each criterion (Geldermann & Lerche, 2014, p. 7). The classification into indifference, weak preference, or strict preference depends on the magnitude of the differences in preferences (Geldermann & Lerche, 2014, p. 7). These preferences serve as a pivotal foundation for evaluation, forming the basis for establishing the resulting ranking. Through this ranking, actionable recommendations can be generated concerning the individual alternatives (Geldermann & Lerche, 2014, p. 7).

5.5 Decision Support for Sustainable Development

To illustrate the differences between individual MCDA methods and related implications for utilizing MCDA in a sustainability context, further aspects need to be addressed.

With respect to aggregation approaches within MCDA methods, compensation is an important aspect to consider. Compensation involves offsetting the value of one attribute with the value of another. In connection with sustainability, complete compensability is to be avoided (Munda, 2016, p. 1245). In particular with regard to the distinction between strong and weak sustainability (see Strong and Weak Sustainability) this aspect is crucial (Liobikiene et al., 2019).

Further, incommensurability is vital as one fundamental concept in multi-criteria evaluation (MCE) is establishing a basis for comparing inherently incommensurable values (Greco & Munda, 2017, p. 311; O'Neill, 2017). Incommensurability occurs when there is no common unit of measurement for the attributes (Martinez-Alier et al., 1998; O'Neill, 2017). Moreover, incomparability needs to be addressed (Greco & Munda, 2017; Martinez-Alier et al., 1998; Munda, 2016). Two alternatives are incomparable when conflicts exist regarding different attribute values (Brans & De Smet, 2016). In this case, one alternative may perform better in some attributes while the other excels in different attributes.

MCDA methods address aspects of compensation, incommensurability and incomparability differently. Thus, these characteristics are relevant for the content-dependent selection of the respective methods within the decision-making process.

5.5.1 General Implications

Utilizing MCDA approaches in the context of sustainable development requires clarifying underlying questions regarding the perspective taken. Munda contributes notably to the linkage of MCDA and its application in the connection to sustainable development (Munda, 2005a, 2005b, 2006, 2008; Munda & Saisana, 2011).

Multi-criteria evaluation can serve as a robust framework for operationalizing the principle of incommensurability (Munda, 2016, p. 1262). It achieves this by being

interdisciplinary and participatory, involving various research disciplines and engaging the local community (Munda, 2016, p. 1262). The transparency of the approach is highlighted, as it presents all criteria in their original form without converting them into common measurement units (Munda, 2016, p. 1262). As a result, multi-criteria evaluation emerges as a fitting assessment framework for both micro and macro sustainability policies (Munda, 2016, p. 1262). However, this does not apply equally to all MCDA methods and application scenarios, so care should be taken to take these aspects into account.

Following Munda (2016, p. 1240), two points need to be considered. First, a thorough assessment of sustainability options requires the consideration of a diverse array of legitimate values and interests present within society (Munda, 2016, p. 1240). From a societal standpoint, relying solely on economic optimization as the evaluation criterion is insufficient (Munda, 2016, p. 1240). This limitation arises because not all goods possess a market price, and in instances where they do, the price may be too low, and market failures can occur (Munda, 2016, p. 1240). Therefore, it becomes essential to incorporate environmental and distributional outcomes into the evaluation process, encompassing intra/inter-generational aspects and consequences on non-human entities (Munda, 2016, p. 1240). In light of these considerations, adopting a multi-criteria evaluation approach proves to be favorably coherent (Munda, 2016, p. 1240).

Secondly, if sustainability is viewed through the lens of society having an indefinite lifespan, an extended time horizon becomes crucial, surpassing conventional market-oriented timelines (Munda, 2016, p. 1240). However, this introduces a contradiction, as political leaders typically operate within short timeframes, often constrained by electoral cycles (Munda, 2016, p. 1240). Consequently, sustainability is frequently deprioritized in political agendas (Munda, 2016, p. 1240). To address this challenge, the evaluation of public projects should extend beyond the limited perspective of short-term policymakers (Munda, 2016, p. 1240). Instead, it should embrace the comprehensive viewpoints of "civil society," considering ethical concerns related to future generations (Munda, 2016, p. 1240).

It follows that the involvement of social actors in the decision-making process should be taken into account. In the context of policymaking, the role of science implies a

responsibility on the part of scientists toward the entire society rather than solely catering to an abstract decision-maker (Munda, 2016, p. 1254). In this connection, the matter of public involvement has gained prominence in MCE (Greco & Munda, 2017, p. 313). Specifically, Social Multi-Criteria Evaluation (SMCE) acknowledges the necessity of integrating the social actor's perspective (Greco & Munda, 2017, p. 313). As a result, an effective SMCE process should involve participation and should emphasize transparency (Greco & Munda, 2017, p. 313). SMCE's strength lies in its ability to directly translate diverse evaluation criteria into a representation of the multitude of values employed in the evaluation process (Greco & Munda, 2017, p. 313).

Yet, while participation is a necessary condition, it is not sufficient on its own, as the scientific team cannot unquestionably accept the inputs of a participatory process (Munda, 2016, p. 1255). This is the primary reason why the concept of SMCE is suggested instead of participatory MCE or other stakeholder approaches (Greco & Munda, 2017, p. 313). Public participation and scientific studies should not be exploited for political convenience, and decision-makers must prioritize the legitimacy of their decisions (Munda, 2016, p. 1255). Upholding deontological principles is vital for maintaining the quality of the evaluation process. Social participation does not absolve scientists and decision-makers of their responsibility for the advocated policy actions and decisions, as their actions can have far-reaching implications (Munda, 2016, p. 1255).

Therefore, the handling of later results also plays a decisive role. The interpretation of multi-criteria results hinges on several key factors. Firstly, the quality of available information plays a pivotal role (Munda, 2016, p. 1253). Additionally, the indicators chosen, representing a specific perspective on reality and considering whose interests are taken into account, significantly influence the outcomes (Munda, 2016, p. 1253). The direction of each indicator, indicating whether larger values are advantageous or not, adds another layer of complexity, subject to cultural and contextual considerations (Munda, 2016, p. 1253). The relative importance of these indicators, expressed through weighting factors, further shapes the results (Munda, 2016, p. 1253). Finally, the method employed for ranking introduces another dimension to the interpretation process (Munda, 2016, p. 1253). In essence, the multifaceted nature of these factors underscores the need for a comprehensive understanding of the context in which multicriteria evaluation unfolds (Munda, 2016, p. 1253).

Thus, overall, the quality of a multi-criteria study hinges greatly on how the mathematical model is integrated into the social, political, and technical structuring process (Munda, 2016, p. 1253). It is also essential to consider the diverse values and interests within society, to recognize the longer time horizons of societies, to promote participation and transparency, and to be cautious in interpreting results. Thus, the emphasis is placed on the importance of the decision process rather than solely on the resulting solution (Munda, 2016; Roy, 1996b).

5.5.2 Implications for Interpreting Weightings

Munda (2016, p. 1256) argues that assigning weights to different criteria entails assigning importance to distinct societal groups. Based on that, Munda derives four main implications.

First, in social decision processes, deriving weights from participatory techniques is undesirable due to technical challenges, pragmatic reasons since potential conflicts among involved parties can occur, and ethical unacceptability (Munda, 2016, p. 1256). Second, ethical judgments are inherent elements of the evaluation process, greatly influencing the outcomes (Munda, 2016, p. 1256). This is also frequently highlighted by Sen (Sen, 2017a, 2017b). Consequently, ensuring transparency regarding the underlying assumptions becomes crucial (Munda, 2016, p. 1256). Thirdly, weights should be regarded as coefficients of importance rather than as trade-offs, given the divergence in ethical perspectives on criterion importance (Munda, 2016, p. 1256). This implies the use of non-compensatory mathematical algorithms for aggregation conventions. Non-compensability ensures that perspectives represented by criteria with less weight can still exert considerable influence (Munda, 2016, p. 1256). Fourthly, sensitivity and robustness analysis in SMCE takes on a distinct meaning compared to single-person and technical decisions (Munda, 2016, p. 1256). This implies that sensitivity or robustness analyses need to assess the impact on the final ranking of only these positions, not all possible combinations of weights (Munda, 2016, p. 1256). Therefore, sensitivity and robustness analyses serve as a means to enhance transparency (Munda, 2016, p. 1256).

These arguments merit further discussion, particularly the first and fourth, which appear less convincing in the context of this work. Concerning the first argument above, three aspects need to be taken into consideration. First, the issue is mitigated through the

group decision-making approach taken in this work which allows to assign weights within each respective stakeholder group individually. Thus, weights are only assigned within each group and the groups will be considered equally within the overall evaluation. Second, while the difficulties concerning related participatory techniques are acknowledged, they are useful within the decision context of this work and help to inform the overall decision process. Third, identifying existing problems among the involved parties is explicitly desired to foster mutual understanding and enable constructive discussions among the involved groups. With respect to the fourth point, it is acknowledged that sensitivity and robustness analysis have a different meaning. However, the aspect that they can, if at all, only serve as an option to increase transparency does not appear fitting for the present analysis since it would increase complexity and reduce transparency.

5.5.3 *Desirable Properties*

Decisions in a social and environmental context differ from those in a purely technical setting. In a finite world with limited resources, not every aspect of the natural environment can be substituted. Acknowledging these limitations influences how sustainability is perceived and has implications for related policies. Regarding the use of MCDA, that raises the question of how to handle compensability. Compensability relates to the presence of trade-offs and the ability to compensate for a loss on criteria with a suitably big advantage on other criteria, although lesser advantages would not be sufficient (Munda, 2016, p. 1259). Therefore, a preference relation is compensatory when trade-offs take place and non-compensatory if trade-offs are prevented (Munda, 2016, p. 1259). Thus, for an MCDA framework addressing sustainability issues, complete compensability is not preferred (Munda, 2016, p. 1261).

Another important assumption is that weights within an MCDA framework linked to sustainability decisions are not trade-offs but should be understood as importance coefficients since they represent divergent ethical considerations that result in varied perspectives on the significance of criteria (Munda, 2016, p. 1256). That further strengthens the argument in favor of non-compensatory approaches since lesser-weighted criteria, potentially illustrating perspectives of minorities or less influential stakeholder

groups, can maintain a considerable impact on the obtained results (Munda, 2016, p. 1256).

Decision-making processes based on scientific approaches frequently benefit through the inclusion of a wide range of people and respective viewpoints to arrive at a more comprehensive understanding of the decision problem (Gerlak et al., 2023; Mauser et al., 2013; Miller & Wyborn, 2020; Munda, 2016, p. 1261). Moreover, it indicates that not all dimensions considered can be reduced to a single unit of measurement in a meaningful manner (Munda, 2016, p. 1261). To be regarded as fair, accounting for value diversity is a crucial aspect of public policies (Greco & Munda, 2017, p. 318; Sen, 2017a).

5.5.4 Implications for MCDA Method Selection

Following Munda (2016, p. 1261), a set of desirable properties for selecting an appropriate method for addressing sustainability decision problems can be summarized.

Concerning descriptive domain assumptions, handling mixed information on criterion scores (SD-a) should involve ordinal, crisp, stochastic, and fuzzy criterion scores (Munda, 2016, p. 1261). This allows for more flexibility with regard to the decision problem and, potentially, a more comprehensive way since different types of data and uncertainty can be dealt with (Munda, 2016).

With respect to normative domain assumptions, simplicity is preferred (SD-b), aiming to minimize the use of ad hoc parameters (Munda, 2016, p. 1261). In relation to stakeholder engagement, this point is convincing since it facilitates communication in comprehensible terms, which is frequently necessary to address, for instance, inequalities in power relations (Gerlak et al., 2023).

Moreover, the most valuable outcome for policy-making involves a complete ranking of alternatives (SD-c), and weights are meaningful solely as importance coefficients, not as trade-offs (Munda, 2016, p. 1261). Sen also argues that complete rankings are preferable while highlighting that partial rankings still can prove useful (Sen, 2017a). Overall, this point is reasonable, too, since complete rankings provide a clear starting point for discussion and the respective ranking order can easily be understood without familiarity with partial ranking approaches.

In addition, complete compensability (SD-d) is not deemed desirable (Munda, 2016, p. 1261). In connection with the discussion of strong and weak sustainability, this leans towards a strong sustainability perception in avoiding complete compensation of, for instance, natural resources (Section 3.1.1).

In terms of heuristic descriptive assumptions, useful exogenous parameters include indifference and preference thresholds (SD-e) when not all intensities of preference are meaningful (Munda, 2016, p. 1261). Depending on the decision context, they can help to depict whether certain differences in intensity (e.g., expressed as weights in the context of this work) are actually meaningful for the overall decision process.

Additionally, dominated alternatives (SD-f) must be taken into consideration (Munda, 2016, p. 1261). This is also relevant in the decision context of this work. It can increase transparency in that all available alternatives have actually been addressed. Moreover, it is not always clear whether the dominating alternatives can actually be realized. Thus, taken those into consideration provides an important opportunity for discussion as well as for potential learnings, which are also relevant in the context of transformation processes and pathways (Werners et al., 2021).

Moreover, only methods that meet a number of conditions, namely the formal domain assumptions (SD-g) of unanimity, monotonicity and neutrality, are eligible for these selection attributes (Munda, 2016, p. 1261). In decision theory, monotonicity states that in case two alternatives are equal except for the fact that one has a beneficial outcome in at least one attribute, that alternative should be preferred (Birnbbaum, 1997). Unanimity means that supposing everyone in a group prefers option X over option Y, the collective choice should also prefer X over Y. Thus, a decision that is universally preferred by all should be the overall choice. Neutrality here implies that the method should be impartial. Lastly, the anonymity property (equal treatment of all individual indicators) is lost due to the trade-off between decisiveness and anonymity (Munda, 2016, pp. 1248, 1261). In certain instances, such as the intended application in this work, the loss of anonymity in favor of decisiveness is regarded as a beneficial outcome (Munda, 2016, p. 1248).

Collectively, these assumptions aim to provide fairness, consistency, and rationality in the decision-making process (Munda, 2016, p. 1261). They set criteria that a method should fulfill to be considered desirable in terms of reflecting the preferences of

individuals in a group setting. Violations of these assumptions can lead to paradoxes or situations where the outcome seems counterintuitive or unfair.

5.6 Framework for Structured Decision-Making

5.6.1 General Remarks

The overall objective of pursuing MCDA in this work is to structure the decision process and enhance the informational basis needed to make an informed decision. It is explicitly not intended to automate the decision-making process or to take the decision away from the responsible, legitimized person or entity. Instead, it is intended to contribute by providing vital information based on knowledge co-production to reflect diverse perspectives and support well-informed decision-making.

The process of an MCDA consists of several steps. Those include identifying and formulating the decision problem, constructing the evaluation model, and developing a recommendation (Dean, 2022; Geldermann & Lerche, 2014).

Identifying the problem entails a thorough understanding of the decision context (Geldermann & Lerche, 2014, pp. 17,18). This can include determining the involved stakeholders and recognizing the power dynamics and constellations within the context (Talukder & W. Hipel, 2018). Moreover, it is crucial to identify the existing objectives, considering the varied perspectives and goals of the stakeholders (Geldermann & Lerche, 2014, pp. 17,18).

Formulating the problem involves further details. It requires the identification of alternatives and related criteria that are essential for evaluating these alternatives (Dean, 2022; Geldermann & Lerche, 2014, pp. 20,21). Additionally, it is helpful to specify the type of decision problem, whether it is a choice among alternatives, sorting alternatives into categories, or addressing a ranking issue (Roy, 2016, p. 27).

Following the problem formulation, the next step in the MCDA process is to construct the evaluation model (Geldermann & Lerche, 2014). This involves making vital decisions, such as choosing a suitable mathematical model and setting the appropriate parameters to effectively represent the features of potentially diverse perspectives.

Moreover, selecting a method to address the problem is pivotal, as it lays the foundation for generating a recommendation subsequently (Dean, 2022).

Once the recommendation can be developed, the results must be able to be presented in an understandable manner tailored to the specific audience (Gerlak et al., 2023). Therefore, it is important to clearly convey the process to the stakeholders and ensure they comprehend the underlying assumptions.

In addition to the points mentioned above, the planned application in the context of this work requires further aspects to be taken into account. In particular, the works of Munda and the SMCE framework provide valuable insights that form the basis for the development of the framework in this thesis.

5.6.2 Insights Derived from SMCE

Using MCDA in connection with policy poses different challenges than those traditionally encountered in the context of MCDA processes. For instance, when implementing public policies, the need to assess and compare various options arises, each entailing conflicts stemming from competing values, interests, and diverse community perspectives they represent (Greco & Munda, 2017, p. 318).

5.6.2.1 Conceptual Aspects. As Etxano and Villalba-Eguiluz (2021) point out, the foundation of SMCE is based on the work of Munda and has been refined over several years (Munda, 1995; Munda, 2004; Munda et al., 1995). SMCE builds upon three main concepts derived from the theory and philosophy of complex systems, namely reflexive complexity, post-normal science, and incommensurability (Etxano & Villalba-Eguiluz, 2021, p. 3; Munda, 2004, 2008).

In terms of reflexive complexity, it is crucial to recognize that the real world is a complex system in which a single perspective fails to capture all relevant aspects of a problem (Etxano & Villalba-Eguiluz, 2021, p. 3). This is consistent with Sen's reasoning addressing the need to take different considerations and perspectives into account (Sen, 2017a).

Second, it is assumed that post-normal science differs from traditional sciences in that its guiding principle is not *truth* but *quality* (Etxano & Villalba-Eguiluz, 2021, p. 4).¹⁹ Thus, to effectively inform public policies, science must integrate two key elements, specifically the inherent uncertainty in scientific work and the presence of conflicting values (Etxano & Villalba-Eguiluz, 2021, p. 4). This also fits in with Sen's argument that people are fundamentally capable of making good decisions even in the context of uncertainty and information gaps, and can instead decide based on maximality, for example (Sen, 2017a).

And third, it refers to the concept of incommensurability, which involves the rejection of reductionism and, in the connection to MCDA, means that the values in conflict cannot be reduced to a single metric when determining the common comparative term for ranking alternatives (Etxano & Villalba-Eguiluz, 2021, p. 4; O'Neill, 2017). This too is compatible with Sen's conception of plural grounding (Sen, 2017a). Overall, these assumptions are therefore also helpful for understanding the approach pursued in this work.

Ensuring fairness in public policies requires honoring value pluralism, where a diverse array of values and dimensions is respected (Greco & Munda, 2017, p. 318; Sen, 2017a). SMCE achieves this by directly reflecting the multitude of values and dimensions employed within the evaluation process (Greco & Munda, 2017, p. 318). Following Greco and Munda (2017), SMCE further attains the objectives of being multi- and interdisciplinary concerning the research team and participatory concerning the local community. Additionally, it maintains transparency by presenting all criteria in their original form without any transformations into different units of measurement (Greco & Munda, 2017, p. 318). SMCE has proven to be applicable to problems in diverse geographical and cultural contexts (Etxano & Villalba-Eguiluz, 2021; Greco & Munda, 2017, p. 316).

In the context of SMCE, outranking approaches appear beneficial (Greco & Munda, 2017, p. 316). However, to ensure consistency with the social process underpinning problem structuring, it is recommended to maintain simplicity in the mathematical aggregation rules (Greco & Munda, 2017, p. 316; Munda, 2008). Thus, less intuitive

¹⁹ For an overview of the philosophical origin of the concept, see e.g.: Strand, R. (2017). Post-Normal Science. In C. L. Spash (Ed.), *Routledge Handbook of Ecological Economics: Nature and Society* (pp. 11). Routledge. <https://doi.org/10.4324/9781315679747>

outranking approaches such as EElimination and ChoiceExpressingREality (ELECTREE) seem less fitting in the context of the present work (Govindan & Jepsen, 2016).

SMCE is dedicated to decision-making under uncertainty, a situation commonly encountered when evaluating sustainability through MCDA (Etxano & Villalba-Eguiluz, 2021, p. 2; Kandakoglu et al., 2019). In this connection, the inherent uncertainty in sustainability decision-making can be incorporated into the multi-criteria model, for example, by employing fuzzy set theory in the aggregation procedure (Etxano & Villalba-Eguiluz, 2021, p. 5). In the pursuit of compromise solutions, the process itself may bring attention to issues that are crucial to consider in favor of sustainability (Etxano & Villalba-Eguiluz, 2021, p. 6). Seeking compromise solutions among social actors may contribute to more promising sustainability outcomes, as this approach could lead to longer-lasting developments compared to scenarios without compromise among social actors (Etxano & Villalba-Eguiluz, 2021, p. 6). Yet, as Etxano and Villalba-Eguiluz (2021, p. 6) point out, it is important to note that compromise solutions may not inherently support sustainable choices, as the selected alternative could be deemed unsustainable (Etxano & Villalba-Eguiluz, 2021, p. 6).

5.6.2.2 Process and Application. From an operational perspective, Munda (2008, p. 45) initially suggested seven steps as the ideal SMCE process. Yet, those are explicitly not rigid (Munda, 2008, p. 45). As with the steps regarding MCDA generally, the process can differ depending on the respective method and is sometimes described in more detailed steps or broader frames (Dean, 2022; Roy, 1996b). While several of these steps frequently form part of the process, it is often necessary to diverge from them and tailor the approach to the specific context of the decision problem at hand (Greco & Munda, 2017, p. 318). Thus, as Greco and Munda (2017, p. 314) emphasize, “flexibility and adaptability to actual situations are among the main advantages of SMCE” (Greco & Munda, 2017, p. 314).

Garmendia et al. (2010, p. 390) subsequently grouped similar steps based on Munda into three main categories. The first category, *approaching*, consists of the identification of the relevant social actors and the problem definition. The second category, *representing*, involves the creation of alternatives and the definition of evaluation criteria.

The third category, *evaluating*, includes the selection of the multi-criteria method, the application of the selected method and the discussion of the results.

Based on the works of Munda (2008, p. 45) and Garmendia et al. (2010, p. 390), Etxano and Villalba-Eguiluz (2021, p. 4) later summarized the respective steps into four major steps linked to their underlying objective and potentially suitable methods.

The first step, *problem definition*, aims to identify the relevant social actors and define the conflict. Related methods include institutional analysis, historical analysis and workshops. The second step is to *structure the problem* with the objective to selecting the evaluation criteria and the creation of alternatives. The third step is *evaluation* intended to complete the multi-criteria impact matrix using multi- und interdisciplinary methods. Lastly, the fourth step is *analysis* in which the alternatives are ranked based on the aggregation method.

In terms of basic categorization, these steps are not very different from the general steps performed in an MCDA. However, the division into the four main steps is also suitable for the present analysis.

5.6.3 Main Steps of the Developed Framework

The framework that is developed in this work is therefore based on the steps outlined by Munda (2008, p. 45) and Garmendia et al. (2010, p. 390) and uses the division of Etxano and Villalba-Eguiluz (2021, p. 4) into four main steps as starting point. The individual steps are presented in connection with the related derivation based on Sen's remarks on normative SCT, resulting research questions (*RQ*), underlying objective and the associated methodological approach.

5.6.3.1 Defining. Sen emphasizes the importance of including multiple, potentially divergent perspectives and value systems into decision-making processes (Section 4.3.8.2). Moreover, he argues in favor of broadening the informational input concerning aspects related to collective decisions (Section 4.1.4). With regard to the transformation process in the RR, it is thus crucial to arrive at a comprehensive understanding of the actual decision problem as well as where and between whom potential lines of conflict exist. In relation to *Step I* of the analysis, this leads to the following *RQs*:

- 1) From a stakeholder perspective, what are the key issues that need to be addressed in relation to the transformation process to a sustainable bioeconomy?
- 2) The bioeconomy perceptions of which stakeholder groups are frequently explored?
- 3) What are existing value conflicts between the stakeholders involved?
- 4) How is the concept of the bioeconomy perceived by the German population?

Objective:

The objective is to arrive at a clearer understanding of the decision problem, the context it is embedded in and to identify lines of conflict as well as lines of opportunities. Furthermore, it is aimed to identify the relevant social actors to be included within the analysis. This constitutes a vital step for the overall objective of bringing together subjective stakeholder perceptions and transformation pathways in a decision support system to identify sustainable transformation trajectories for the bioeconomy. This provides valuable insights into the governance of transformation processes.

Method:

First, a focus group workshop was used to gain initial insights into the lines of conflict in the region. Second, a systematic literature review of stakeholder perceptions of the bioeconomy was conducted to identify the current state of research and potential directions for further investigation. Subsequently, a representative survey of the German population was used to investigate the general public's understanding of the term bioeconomy, citizens' knowledge, fears, expectations and factors explaining their attitudes towards the bioeconomy.

5.6.3.2 Structuring. Sen argues to broaden the informational input in the context of collective decision making (Section 4.1.4). In relation to the bioeconomy transformation, this implies the need for a holistic approach to monitor related developments. In addition, to contribute towards a foundation for public reasoning in the context of a regional transformation process, the aspect of commensurability is central to increase people's ability to compare potential decision alternatives. These aspects are at the core of *Step II*. Therefore, the following *RQs* are addressed:

- 5) How can a holistic monitoring system of the bioeconomy related to sustainability be conceptualized?
- 6) How can regional transformation trajectories be developed?

Objective:

The evaluation criteria are identified and the alternatives are developed.

Method:

A systematic process of deriving an indicator system connected to the SDGs and the requirements of a sustainable bioeconomy is developed.

Moreover, a novel approach to developing RTPs for implementing a sustainable bioeconomy will be created. Based on the SSPs, pathways can be developed that are consistent with the established narratives within the scientific community, while at the same time being tailored to the needs of decision-makers in a regional context and making them more tangible.

5.6.3.3 Evaluating. *Step III* sets the frame for integrating the divergent viewpoints of stakeholders. Through this step and the weights assigned to different decision criteria, stakeholders can express the relative importance of elements from their own perspective. This aligns with Sen's remarks on the importance of deliberation under inclusion of diverse perspectives with respect to decision-making (Section 4.3). This leads to the following *RQ*:

- 7) How do different stakeholders weigh criteria?

Objective:

The aim is to complete the multi-criteria impact matrix by integrating subjective stakeholder perceptions.

Method:

Subjective stakeholder perceptions are integrated using criteria weights within the MCDA. This is done by identifying an appropriate method that fits the use case and considers the individual contextual requirements.

5.6.3.4 Analyzing. *Step IV* relates to Sen's concept of plural grounding (Section 4.3.8.2). According to Sen, a potential consensus does not require identical reasons but should involve a reasoned debate from various angles. Despite disagreements on rankings, a subsequent discussion could contribute to finding a way forward – even if that is not always feasible. This leads to the following *RQ*:

- 8) Which decision alternative could illustrate a potential compromise solution?

Objective:

Stated objective is to arrive at a ranking of feasible transformation pathways.

Method:

Based on insights derived from the operationalization of Sen's arguments and the application in relation to sustainability, a method is selected to rank the developed alternatives. Moreover, the gathered information is presented in a way suitable for communicating with stakeholders.

This defines the basic procedure for the analysis. The next step is to identify the methods that will be used in steps three and four.

5.7 Method Selection

In some cases, method selection can be straightforward. For example, if the utility function for each criterion is known, MAUT might be appropriate. However, often, stakeholders do not precisely know how to represent their preferences. Therefore, selecting an appropriate method for MCDA is frequently a challenging task. Explaining the choice of a method can be intricate due to the absence of a universally applicable approach, as no method is flawless. Thus, it is vital to consider and address the limitations, underlying assumptions, goals, and characteristics of the specific decision problem. A

generalized framework, case studies, and the existing literature can serve as valuable starting points for method selection.²⁰

5.7.1 Data and Scale

It is further relevant to consider the level of measurement in question. MCDA has the capacity to integrate both qualitative and quantitative data, depending on the methodology employed (Roy, 2016). The data needed to conduct an MCDA can be provided at different scales of measurement. The level of measurement states what kind of mathematical operations and transformations can be performed on related variables without altering the inherent information (Geldermann & Lerche, 2014; Roy, 2016). Further, it indicates how the information can be understood and interpreted (Roy, 2016). Data measured on an ordinal scale allows the creation of a ranking (Roy, 2016). Information concerning the distances between those ranks, however, is not provided (Roy, 2016). In MCDA, ordinal scales are frequently used to measure qualitative data in relation to social indicators (Dean, 2022; Geldermann & Lerche, 2014; Roy, 2016). Cardinal scales (e.g., interval and ratio) provide a higher degree of information and allow for more mathematical operations (depending on the exact scale used) (Dean, 2022; Moretti et al., 2016; Roy, 2016).

5.7.2 Approaches for Method Selection

One possible approach is to select a method based on the required input information, such as the availability of data and parameters (measuring scale). The modeling effort that results from each method should also be assessed, as well as a comparison of the expected output in terms of form and level of detail, all of which are highly dependent on the problem and its context.

Wątróbski et al. (2019) created a generalized MCDA method selection framework for decision problems based on the formal representation of decision rules for MCDA method selection (Wątróbski et al., 2019). However, as the authors acknowledge, the framework in its current form has certain limitations. At present, it does not always lead to recommending a particular MCDA method (Wątróbski et al., 2019). Instead, it is

²⁰ An overview of existing MCDA methods and their respective underlying main assumptions is provided by Greco, S., Ehrgott, M., & Figueira, J. R. (2016). *Multiple Criteria Decision Analysis: State of the Art Surveys*. Springer. <https://doi.org/10.1007/978-1-4939-3094-4>.

designed to offer a selection of potential methods that may be considered for the decision-making process (Wątróbski et al., 2019). In addition, the application context related to sustainable development results in special requirements, such as dealing with compensatory aspects of a method, so the application of the framework developed by the authors is not promising (Wątróbski et al., 2019, p. 109).

Cinelli et al. (2020) developed a taxonomy to support selecting suitable MCDA methods. Subsequently, the developed taxonomy was extended and implemented as a tool (Cinelli et al., 2022). The developed Multiple Criteria Decision Analysis Methods Selection Software (MCDA-MSS) is structured in four major parts (Cinelli et al., 2022). The key components encompass the problem typology, which defines the category and structure of the decision-making problem. Next, the preference model that designates the model type preferred for the application needs to be addressed. Furthermore, the nature, method, and frequency of elicitation of preferences needs to be considered. Lastly, the utilization of the preference relation generated by the preference model delineates the strategy employed to extract and enhance the decision recommendation.

While this taxonomy can support narrowing down potential methods, not least by excluding unsuitable ones considering aspects of developed methodologies, it is ultimately just an orientation and a reduction. Overall, determining an appropriate method to employ necessitates an examination of its feasibility in practical applications. This involves the method's conceptual and operational validation when addressing real-world issues. Researchers face the task of justifying their choice of method, ensuring that it is not only theoretically sound but also practically viable for solving real problems.

In the course of the research process, based on an intensive study of related literature, the group of PROMETHEE methods was identified as advantageous for the intended application. In the following section, the respective reasoning as well as characteristics of the methods with regard to the desired properties are laid out and discussed. Subsequently, the main strengths of the identified methods, along with the reasoning for their selection, are elaborated. Thereafter, the PROMETHEE methods are introduced, and the required steps for the application are presented.

5.7.3 *Selection and Discussion*

5.7.3.1 General Remarks. Methods based on MCDA illustrated their potential in coping with problems connected to sustainable development from a micro and macro perspective (Kandakoglu et al., 2019; Munda, 2016). Depending on the specific method applied, they are not exclusively meant to deduct an optimal solution in the context of energy planning but can help to rank alternatives ranging from best to worst. In this connection, MADM methods have proven to be useful in supporting decision-makers faced with complex problems in the context of sustainability transformations in real-world group decision-making settings (Kandakoglu et al., 2019).

PROMETHEE outranking approaches allow for considering subjective stakeholder assessments expressed as weighted decision criteria while avoiding complete compensation. It is only partial compensatory, which is closer to the actual decision problem. These properties are of particular importance in the context of the transformation towards a sustainable bioeconomy. Qualitative and quantitative indicators can be integrated, which further strengthens the flexible integration of subjective stakeholder perspectives.

Further, it can be extended to the PROMETHEE Group Decision Support System (GDSS) and thereby support the search for a compromise solution (Macharis et al., 1998; Macharis et al., 2015). The majority of multi-criteria group decision methods were intended for utilization within a business setting (Macharis et al., 2012, p. 611). A major difference between those methods is the way in which information concerning value trees is addressed, either as one value tree for all stakeholders or different ones for each stakeholder individually (De Brucker & Macharis, 2010; Macharis et al., 2015, p. 131; Macharis et al., 2012, p. 611). In situations where it is vital to distinguish between divergent perspectives, using multiple value trees and subsequent aggregation is most suitable (Macharis et al., 2015, p. 131). Multi-actor Multi-Criteria Analysis (MAMCA) thus differs from SMCA in how different value trees are handled (Macharis et al., 2015, p. 131).

In the context of the identification of a sustainable bioeconomy pathway, the stakeholder groups will be diverse, and the points of view will differ. Thus, approaching related decisions will need to account for these differences. In contrast to decisions taking

place in an organizational setting, a shared value tree is often not viable (Macharis et al., 2015, p. 131). Hence, a method able to integrate divergent value trees into one comprehensive model is necessary (Macharis et al., 2015, pp. 131,132). The PROMETHEE GDSS constitutes these properties (Macharis et al., 2015, p. 131). Therefore, it is eligible for an application in this connection.

5.7.3.2 Normative Social Choice Implications. Referring to SCT implications, PROMETHEE can cope with incompleteness and information gaps. It strives to identify the best possible decision rather than an optimal decision, which does not exist in the context of a wicked problem. Commensurability is provided, and using PROMETHEE I and II, it is possible to produce both complete and partial rankings. Sen's concept of plural grounding is respected as different perspectives can be integrated.

Building on the implications derived from the SCT chapter, utilizing PROMETHEE enables to integrate input from various sources and it is possible to use it in situations where completeness is not achievable (a). Moreover, it is used to identify the best possible option, so that a decision is based on maximality instead of trying to find a non-existent optimal solution in the context of a wicked problem (b). Commensurability (c) is provided since all criteria can be integrated with their respective form, as each attribute is compared on a pairwise basis. It is further possible to generate partial- as well as complete rankings using the method (d). Finally, the GDSS allows for the search for a compromise solution, taking into account different subjective perspectives, in accordance with the idea of plural grounding (e).

5.7.3.3 Sustainable Development Implications. Regarding Munda's remarks on the use of MCDA in the context of sustainable development, PROMETHEE fulfills the characteristics described as desirable for a fair and transparent decision-making process. For instance, Munda highlights the importance with respect to the mathematical approach to be able to handle information expressed on mixed criterion scores to contribute towards the transparency of the overall framework (Munda, 2016, p. 1260). PROMETHEE satisfies that as it can integrate various criteria without requiring transformations.

Moreover, the mathematical aggregation approach applied in relation to sustainability decisions should be selected in such a way that as few parameters from external sources are needed as possible (Munda, 2016, p. 1260). Even though those are helpful in various

decision-making contexts, they could stand in the intended transparency and simplicity when utilized connected to sustainability decisions (Munda, 2016, p. 1260). Therefore, Munda (2016, p. 1261) argues to refrain from using further parameters derived externally besides weights if they are not considered absolutely crucial. In this connection, the PROMETHEE approach offers the flexibility to use preference functions that do not require further input from the stakeholders. If desired in a certain context, however, it can incorporate further information obtained and integrate other parameters such as preference thresholds. In addition, PROMETHEE does not prescribe a specific means to obtain weights, so that the composition of stakeholders and the respective policy context can be considered as needed.

Moreover, as Munda (2016, p. 1261) points out, having a ranking of the potential alternatives in a policy context is preferable to just identifying a single option since a compromise might be easier to achieve in cases where the second (or third) best option faces notably less opposition of the involved parties compared to the highest ranked alternative. This further implies that dominated alternatives should not be left out from the beginning of the analysis as they potentially support the overall decision-making process (Munda, 2016, p. 1261). Here, using PROMETHEE I and II is suitable since it allows ranking all alternatives and illustrates potential incomparabilities that can contribute to identifying a compromise solution.

Concerning Munda's remarks, PROMETHEE is capable of handling mixed information on criterion scores (SD-a) and is relatively simple (SD-b) compared to other outranking approaches, which helps to communicate how the method is applied and how the results are derived. It provides a complete ranking (SD-c) and complete compensability can be avoided (SD-d). If desired, preference thresholds (SD-e) can be adjusted as needed and dominated alternatives are included in the evaluation (SD-f). Lastly, the formal domain assumptions (SD-g) of unanimity, monotonicity and neutrality are met.

5.7.3.4 Overview. The PROMETHEE group of methods is chosen for the current analysis for several reasons. Firstly, it offers a clear method for assessing stakeholders' priorities and managing degrees of compensation among criteria by providing the possibility to set thresholds for indifference and varying preference degrees. Secondly, stakeholders understand it more easily than comparable outranking approaches like ELECTREE. Thirdly, it enables the inclusion of criteria that are often challenging to integrate, especially those involving qualitative judgments. Fourthly, it can handle uncertain and fuzzy information. Additionally, it can be extended using the GDSS for application within a group decision-making context. Lastly, it aligns with the properties deemed desirable in the context of utilizing MCDA in a sustainability framework as described by Munda (2016, p. 1261) and aligns with the implications derived from the operationalization of Sen's arguments. Overall, insights from SMCA, MAMCA and the conceptual insights related to SD and the implications of Sen's work can be combined for the framework developed in this thesis.

The PROMETHEE methods were repeatedly applied in connection with questions concerning environmental management and dealing with sustainable development (Behzadian et al., 2010; Kandakoglu et al., 2019). The following section will thus introduce the method in detail.

5.8 PROMETHEE Methods

The PROMETHEE outranking methods, initially introduced in the early 1980s as a partial-ranking method (PROMETHEE I), underwent subsequent development to enable the complete ranking of finite alternative sets (PROMETHEE II) (Brans & De Smet, 2016; Brans et al., 1984; Brans et al., 1986). Various versions of the PROMETHEE methods have been developed and tailored to address complex decision-making situations (Brans & De Smet, 2016). Intuitively, the complete order according to PROMETHEE II can be more inclusive for stakeholders not familiar with related approaches (Brans et al., 1986). However, the partial preorder developed through PROMETHEE I offers potentially valuable information, especially concerning existing incomparabilities, that can address the decision problem more realistically (Brans et al., 1986). To provide respective stakeholders with as much information as possible and support the decision-making process comprehensively, both approaches can be utilized.

5.8.1 PROMETHEE I and II

A distinguishing feature of PROMETHEE I is its ability to illustrate incomparabilities. These occur in cases where an alternative excels in some attributes but performs worse in others. PROMETHEE I aims to establish a partial order of preference, distinguishing between preferences, indifference, and incomparabilities. This distinctive feature of PROMETHEE I allows for representing situations where alternatives cannot be definitively compared (Brans & De Smet, 2016).

Incomparabilities arise when comparing the output and input flows concurrently. In a direct comparison, an alternative is preferred only if it has a larger output flow and a smaller input flow (Brans & De Smet, 2016). In cases where the output flow is higher but the input flow is also higher (or vice versa), the result is incomparability (Brans & De Smet, 2016).

In contrast to PROMETHEE I, PROMETHEE II aims to establish a complete order. PROMETHEE is used to address the following problem with an absent optimal solution (Brans & De Smet, 2016):

$$\max [g_1(a); g_2(a), \dots (g_j(a), \dots g_k(a) \mid a \in A] \quad (1)$$

where A stands for a finite set of potential alternatives $[a_1, a_2, \dots a_i, \dots, a_n]$ while $[g_1(\cdot), g_2(\cdot), \dots, g_j(\cdot), \dots g_k(\cdot)]$ illustrates a set of evaluation criteria (Brans & De Smet, 2016). To approach this, a generalized preference function for each criterion is selected. Brans and De Smet (2016) specify six types of preference functions sufficient for most use cases (Brans & De Smet, 2016). The applied preference function can be chosen based on the individual evaluation criteria. Additionally, PROMETHEE necessitates a set of criterion weights.

Subsequently, the PROMETHEE method computes the outranking relation π for all alternatives (Brans & De Smet, 2016):

$$\pi(a, b) = \sum_{i=1}^k w_i \cdot P(a, b) \quad (2)$$

The preference index $\pi(a, b)$ is a measuring unit for the preference strength for an alternative a over an alternative b while considering all criteria.

As a next step, the leaving flow, which serves as a measure of the strength of all alternatives, is determined as follows (Brans & De Smet, 2016):

$$\Phi^+(a_j) = \frac{1}{n-1} \cdot \sum_{j=1}^n \pi(a_j, a_j) \quad (3)$$

Subsequently, the entering flow, which measures the weaknesses of all alternatives, is defined as follows (Brans & De Smet, 2016):

$$\Phi^-(a_j) = \frac{1}{n-1} \cdot \sum_{j=1}^n \pi(a_j, a_j) \quad (4)$$

By using this strength and weakness index, the net flows of all alternatives $a_1, \dots, a_n$ can be calculated (Brans & De Smet, 2016):

$$\Phi(a_j) = \Phi^+(a_j) - \Phi^-(a_j) \quad (5)$$

By utilizing the resulting net flow, PROMETHEE II can be employed to rank the alternatives, enabling the identification of the preferred alternative for a stakeholder. Yet, due to the loss of information during aggregation to the net flow, it is advisable to employ both PROMETHEE I and PROMETHEE II. Using both methods allows for a more comprehensive analysis, capturing different aspects of the decision-making process and providing a more nuanced understanding of the alternatives.

5.8.2 Rankings

The calculation steps of I and II are initially the same. The differences arise from the different approaches to ranking.

5.8.2.1 PROMETHEE I. To derive the PROMETHEE I partial ranking (P^I, I^I, R^I) both the positive and negative outranking flows are used (Brans & De Smet, 2016, p. 198). These flows typically result in different rankings. PROMETHEE I represents the intersection of these two flows (Brans & De Smet, 2016, p. 198).

P^I stands for preference. In the case of $a P^I b$, a greater strength of a corresponds to a lesser weakness of a compared to b . The information from both outranking flows is consistent and can therefore be regarded as reliable (Brans & De Smet, 2016, p. 198).

A preference ($a P^I b$) for one alternative thus exists in case the following applies (Brans & De Smet, 2016, p. 198):

$$a P^I b \Leftrightarrow (\phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b)) \text{ or}$$

$$\begin{aligned}
& (\phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b)) \text{ or} \\
& (\phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b)); \\
a I^I b & \Leftrightarrow \phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b);
\end{aligned} \tag{6}$$

I^I stands for indifference. In this context, indifference means that a and b have the same level of positive and negative outranking flows, showing no preference for one over the other. This implies that neither a is preferred over b , nor b over a , since they are equivalent in terms of their comparative strengths and weaknesses. Thus, in case of *indifference* ($a I^I b$), both positive and negative flows are equal (Brans & De Smet, 2016, p. 198):

$$a I^I b \Leftrightarrow \phi^+(a) = \phi^+(b) \text{ and } \phi^-(a) = \phi^-(b) \tag{7}$$

In the case of R^I , a higher strength of one alternative is paired with a lower weakness of the other. This typically occurs when a performs well on certain criteria where b is weak, and conversely, b performs well on other criteria where a is weak (Brans & De Smet, 2016, p. 198). In such situations, the information from both outranking flows is inconsistent (Brans & De Smet, 2016, p. 198). Therefore, the two alternatives are considered incomparable ($a R^I b$):

$$\begin{aligned}
a R^I b & \Leftrightarrow (\phi^+(a) > \phi^+(b) \text{ and } \phi^-(a) > \phi^-(b)) \text{ or} \\
& (\phi^+(a) < \phi^+(b) \text{ and } \phi^-(a) < \phi^-(b));
\end{aligned} \tag{8}$$

In such situations, the PROMETHEE I ranking does not rank the alternatives and the question of which action is best remains within the responsibility of those involved in the decision-making process (Brans & De Smet, 2016, p. 198).

5.8.2.2 PROMETHEE II. PROMETHEE II features a complete ranking. In this case, the net outranking flow can be used to rank the alternatives (Brans & De Smet, 2016, p. 199).

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{9}$$

It represents the balance of positive and negative outranking flows. A higher net flow indicates a better alternative (Brans & De Smet, 2016, p. 199).

$$a P^{II} b \Leftrightarrow \phi(a) > \phi(b)$$

$$a I^H b \Leftrightarrow \Phi(a) = \Phi(b) \quad (10)$$

According to the PROMETHEE II complete ranking, a outranks b (aPb) if $\Phi(a) > \Phi(b)$ and a is indifferent to b (aIb) if $\Phi(a) = \Phi(b)$.

Using PROMETHEE II, all alternatives are considered comparable, so there are no incomparabilities (Brans & De Smet, 2016, p. 199). However, the resulting information may be more debatable because more details are lost by only focusing on the difference (Brans & De Smet, 2016, p. 199). Thus, it is recommended to use both, PROMETHEE I and II (Brans & De Smet, 2016, p. 199).

5.8.3 Determine Preference Functions

The PROMETHEE method allows for selecting various preference functions for each criterion. While not exhaustive, there are six common types of criteria used in the application of PROMETHEE in the literature that have been proven to be useful in real-world applications (Brans & De Smet, 2016). Those are illustrated in **Figure 7**:

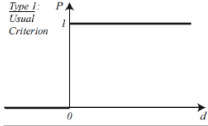
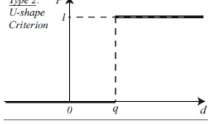
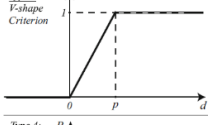
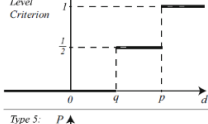
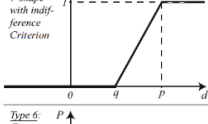
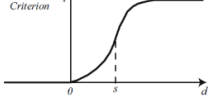
Generalized criterion	Definition	Parameters to fix
 Type 1: Usual Criterion	$P(d) = \begin{cases} 0 & d \leq 0 \\ 1 & d > 0 \end{cases}$	—
 Type 2: U-shape Criterion	$P(d) = \begin{cases} 0 & d \leq q \\ 1 & d > q \end{cases}$	q
 Type 3: V-shape Criterion	$P(d) = \begin{cases} 0 & d \leq 0 \\ \frac{d}{p} & 0 \leq d \leq p \\ 1 & d > p \end{cases}$	p
 Type 4: Level Criterion	$P(d) = \begin{cases} 0 & d \leq q \\ \frac{1}{2} & q < d \leq p \\ 1 & d > p \end{cases}$	p, q
 Type 5: V-shape with Indif- ference Criterion	$P(d) = \begin{cases} 0 & d \leq q \\ \frac{d-q}{p-q} & q < d \leq p \\ 1 & d > p \end{cases}$	p, q
 Type 6: Gaussian Criterion	$P(d) = \begin{cases} 0 & d \leq 0 \\ 1 - e^{-\frac{d^2}{2s^2}} & d > 0 \end{cases}$	s

Figure 7. Types of Generalized Criteria. Source: Brans and De Smet (2016) p. 195. *Reproduced with permission from Springer Nature.*

Preference functions can be chosen based on the nature of the respective criteria (Abdullah et al., 2019). Linear preference functions, for instance, are generally more suitable for quantitative criteria than using a usual criterion. On the other hand, for qualitative criteria, applying a level function can be more reasonable and closer to the decision problem. For binary criteria, applying the usual criterion might yield the most promising results. In practice, however, the choice of the respective preference function depends on the context of the decision problem.

In the context of applying the PROMETHEE methods, employing a single preference function proves advantageous as it helps reduce the number of parameters that need to be fixed. Thus, preference function type 1 (usual criterion) is used for the decision problem in the context of this work. This approach contributes to keeping the overall complexity manageable, ensuring that the model remains straightforward and easier to communicate. Furthermore, as stakeholders become more familiar with the method, there is potential for future extensions. These considerations align with implications for MCDA in the realm of sustainability as laid out by Munda (2016), emphasizing the importance of simplicity, manageability, and stakeholder familiarity in decision-making processes.

5.8.4 *PROMETHEE Group Decision Support System*

Introduced by Macharis et al. (1998) in 1998, the PROMETHEE GDSS constitutes an extension of the PROMETHEE methods to be applied in a group decision framework. The approach can be employed in a multi-actor setting since it permits distinct value trees of multiple stakeholders to be used within one comprehensive model (Macharis et al., 2015). MAMCA is therefore a useful tool in support of sustainable decision-making (Macharis et al., 2012).

It has been successfully applied in diverse settings (Macharis et al., 2015). Early contributions include the assessment of renewable energy projects and transportation scenarios integrating actors from, for instance, local authorities, public pressure groups, potential investors and civil servants within the decision-making process (Macharis et al., 2015; Martin et al., 1999; Polatidis & Haralambopoulos, 2007). In their study, Gonçalves and Neyra Belderrain (2012) used the PROMETHEE GDSS to evaluate the performance of satellite subsystems while integrating affected managers and project members. Tavana et al. (2013) presented an evaluation of different pipeline routes in the Caspian Sea basin

using the GDSS. Behzadian et al. (2013) applied the PROMETHEE GDSS in the context of technical requirements in a house of quality process addressing customer demands. Hashemian et al. (2014) introduced a hybrid group decision-making approach to evaluate suppliers. In this connection, they linked Fuzzy Analytical Hierarchy Process (FAHP) to determine the weighting vectors and applied a fuzzy PROMETHEE GDSS for an overall ranking of all evaluated suppliers (Hashemian et al., 2014). Seddiki et al. (2016) used a combination of the swing method to acquire weights within a Delphi approach dealing with thermal renovations and used the PROMETHEE GDSS to create a global ranking. Recent applications include Ortiz et al. (2018) who used the PROMETHEE GDSS linked to an environmental and social impact assessment. Moreover, Fontana and Morais (2017) presented a model based on PROMETHEE GDSS to support decision-making related to water network segmentation.

Overall, applications of the PROMETHEE GDSS differ notably with respect to the respective field of application as well as the way and degree to which stakeholders are included within the process. It is worth noting that, depending on the respective use case, the PROMETHEE GDSS technique may be employed under actual stakeholder involvement or to model potential stakeholder behavior (Macharis et al., 2015).

Similar to other PROMETHEE methods, it can be used in conjunction with further MCDA methods. In this connection, the combination of the Analytical Hierarchy Process (AHP) for weight determination and PROMETHEE to rank the alternatives is considered as beneficial in the context of the GDSS (Macharis et al., 2015; Turcksin et al., 2011). The enhancement of using the FAHP approach (as suggested in this study) can further support to capture of potentially prevailing vagueness ambiguity in stakeholder expressions.

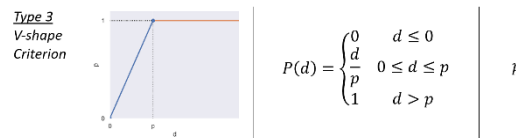


Figure 8. Generalized Criterion Type 3. Source: Author, adapted from Brans and De Smet (2016) p.195.

It is applied following the individual evaluations of each DM and can support in identifying a consensus solution for the decision problem while illustrating potential conflicts between the DMs. Using the net flows of each DM a global evaluation matrix

($n \times R$) is created in which each criterion represents the subjective perspective of an individual DM (Macharis et al., 1998). Depending on the context of the decision problem, each criterion is assigned a weight that states the influence each DM is intended to have on the final outcome (Macharis et al., 1998). For the proposed use case, equal weighting is suggested to underline that each stakeholder perception is considered in a similar fashion. Further, a generalized criterion of Type 3 ($p = 2$), as illustrated in **Figure 8**, is assigned to the criteria to account for the deviations proportionally (Brans & De Smet, 2016). Subsequently, a global PROMETHEE II ranking is calculated. **Figure 9** provides an overview of the approach.

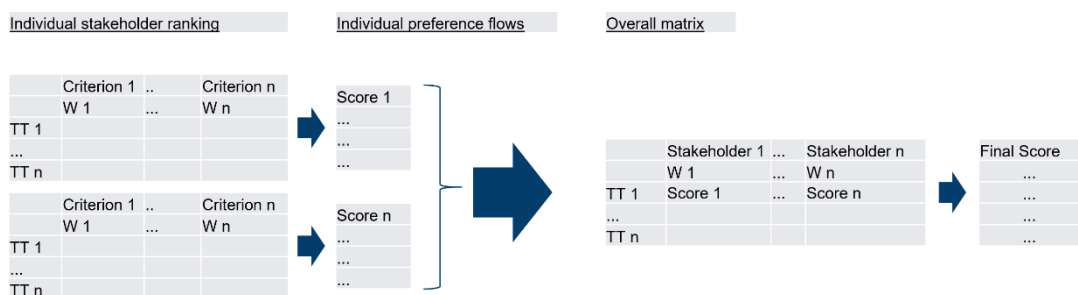


Figure 9. PROMETHEE GDSS Structure. Source: Author, based on Brans and De Smet (2016).

Macharis et al. (2015) recommend appropriate communication tools as an important aspect of a successful application in a multi-actor setting. Thus, the results will be visualized.

5.8.5 Rank Reversal Phenomena

The rank reversal phenomena are a known issue in the context of pair-wise comparison methods in MCDA. And while there is no universal definition, it is generally conceived as a problem through which the position of two alternatives can be affected by a copy of an alternative, a dominated alternative and, besides others, the presence of a non-discriminating criterion (Brans & De Smet, 2016).

As an outranking method, PROMETHEE does not satisfy the assumption of independence to third alternatives. This implies that the ranking of two possible alternatives can potentially be influenced by a third option. The occurrence of these phenomena has been known since researchers started to work on SCT and were extensively illustrated as part of Arrow's impossibility theorem concerning the condition

of irrelevant alternatives (Arrow, 1950; Brans & De Smet, 2016, pp. 200, 201). Thus, when applying pair-wise comparison MCDA methods, the rank reversal phenomena can constitute a problem and the PROMETHEE method is no exception (Mareschal et al., 2008; Roland et al., 2012; Verly & De Smet, 2013).

The occurrences of rank reversal problems have been studied by several authors and for different methods, including AHP, ELECTRE and PROMETHEE (see e.g. (Barzilai & Golany, 1994; Mareschal et al., 2008; Roland et al., 2012; Verly & De Smet, 2013; Wang & Triantaphyllou, 2008; Wang & Elhag, 2006)). In relation to PROMETHEE I and II, it has been shown that rank reversals only appear if flow score differences are relatively small (Verly & De Smet, 2013). That implies that the deletion of one alternative will only lead to a swap in the overall ranking in cases where the flow scores are very close together (Verly & De Smet, 2013). Thus, flow score comparisons should be carefully interpreted with respect to ordinal information (Verly & De Smet, 2013). As the rankings in this work are primarily intended to inform the decision-making process and the results should be interpreted carefully, these phenomena are not a major obstacle.

5.9 Weighting Methods

While not all MCDA methods demand the allocation of weights, those potentially relevant for the present analysis require a different weighting of the various criteria and underlying goals. The PROMETHEE method does not prescribe any specific method regarding the gathering of weights but assumes that the DMs are able to allocate weights appropriately as long as there are not too many criteria overall (Brans & De Smet, 2016; Macharis et al., 2004, p. 308). Therefore, the choice of procedure needs to be comprehensible and traceable.

Setting weights for indicators within MCDA approaches allows for integrating different priorities and assigning relative importance to criteria. Thus, choosing an appropriate weighting method and respective weights can be considered a key step within the decision-making process. While various approaches exist, they differ notably with respect to the fundamental assumptions and required input (in case stakeholders are involved during the process) and have a substantial influence on the result obtained by analysis.

With respect to decision-making in sustainable energy research, two main categories have been widely applied, namely equal-weights and rank-order weights (Jia et al., 1998; Wang et al., 2009). As the name suggests, equal-weights distribute the weights equally among the respective number of criteria. Using this approach, no external input is required. While this approach has been widely applied and its utilization is simple, it has repeatedly been criticized since it ignores the relative importance of criteria (Wang et al., 2009). It is expressed as:

$$w_i = \frac{1}{n}, i = 1, 2, \dots, n \quad (11)$$

In contrast, rank-order weights allow for addressing these differences of relative importance among criteria. Generally, rank-order weighting methods for MCDA can be distinguished into *objective* and *subjective* methods, as well as *integrated* (sometimes referred to as *hybrid*) approaches. The following part illustrates commonly used approaches of these subcategories and depicts their main differences.

5.9.1 Objective Weighting Methods

Objective approaches do not require the DM to actively assign weights to the different criteria. Instead, weights are assigned based on the information provided by the criteria themselves. Depending on the specific method, the information is obtained through computational procedures based on the initial data or the decision-matrix (Keshavarz-Ghorabae et al., 2021). Thereby, the amount of information within a criterion illustrates the relative importance. However, applying an objective weighting method still entails subjective considerations since the results gathered might differ notably depending on which of these methods is applied.

5.9.1.1 CRiteria Importance Through Intercriteria Correlation. A commonly used method includes CRiteria Importance Through Intercriteria Correlation (CRITIC) (Anand et al., 2022a; Diakoulaki et al., 1995; Paradowski et al., 2021). This method assesses objective importance using contrast intensity and conflict measurement (Diakoulaki et al., 1995).

High contrast intensity, determined by the standard deviation across different topologies, indicates higher importance (Diakoulaki et al., 1995; Paradowski et al., 2021). Conflict measurement is based on the correlation coefficient between objectives, with a

lower correlation indicating higher conflict (Diakoulaki et al., 1995; Paradowski et al., 2021). Contrast intensity and conflict measurement are combined to calculate the final attribute weight (Diakoulaki et al., 1995; Paradowski et al., 2021).

5.9.1.2 Entropy. Another frequently used method is based on entropy (Anand et al., 2022b; Paradowski et al., 2021; Potomkin et al., 2020). Entropy measures information uncertainty using probability theory and assesses the disorder in a system (Anand et al., 2022b). When entropy is low for an indicator, it indicates that the indicator provides more useful information and should be given a higher weight (Anand et al., 2022b). Conversely, high entropy means less information and a lower weight (Anand et al., 2022b).

5.9.1.3 General Remarks. Moreover, other statistical approaches, such as approaches based on standard deviation or variance, are used (Odu, 2019; Paradowski et al., 2021; Zardari et al., 2015).

Beneficial aspects of objective weighting methods include that they require little to no stakeholder input. Hence, they can be considered as specifically useful in situations where stakeholders either have no knowledge of the particularities concerning the intended analysis or obtaining that knowledge is not feasible. Examples of situations where obtaining stakeholder input is not feasible can manifest if stakeholders can expect negative repercussions should they express their views openly or if the effort to accumulate this knowledge exceeds the hoped-for benefits.

In addition, time and budget constraints can further limit possibilities to incorporate stakeholder input appropriately. Since it is a stated goal of the present analysis to include subjective stakeholder perceptions in the analysis, objective weighting methods are unsuitable to achieve this to a sufficient degree.

5.9.2 Subjective Weighting Methods

Subjective weighting methods rely on stakeholder input. Depending on the method, the degree of stakeholder involvement and the complexity of implementing the method vary notably. Thus, the decision of which method is considered the most useful is strongly determined by the decision problem. In practice, budget and time constraints must also be considered. Several methods have been developed to systematically involve

stakeholders in the weighting process. A selection of commonly used methods is presented below.

5.9.2.1 Direct Weighting. To obtain weights according to direct weighting, the DM is asked to directly assign weights to the respective criteria so that the overall sum adds up to 1. While this approach can work sufficiently in cases where involved DMs are familiar with the methodology and the total number of criteria is low, it might yield questionable results for a high number of criteria and could potentially be overwhelming for DMs.

5.9.2.2 Point Allocation. Point allocation requires the DM to allocate numerical values to describe the criteria weights directly (Zardari et al., 2015, p. 27). A common approach consists of allocating a total of 100 points among the criteria. Alternatively, it is also possible to restrain from setting a value of total points and let the DM divide the points freely (Zardari et al., 2015, p. 27).

To account for the necessity that the overall sum of criterion weights must be 100, normalization procedures can be utilized (Zardari et al., 2015, p. 27). While an advantage consists in the simplicity of the approach, the gathered weights are not necessarily precise and a high number of criteria can further be an obstacle to a successful application of the method (Zardari et al., 2015, p. 27).

5.9.2.3 Direct Rating. Following the direct rating approach, the DM is asked to provide the evaluation along a scale (Alfares & Duffuaa, 2015; Van Ittersum et al., 2007; Zardari et al., 2015, p. 26)]. In this connection, Likert-scale schemes ranging from 1-5, 1-7 and 1-10 are commonly used (Zardari et al., 2015, p. 26).

Hence, it is possible for the DM to adjust the weights individually on those scales without directly affecting weights assigned to other criteria (Zardari et al., 2015, p. 26). This can be considered a beneficial property for stakeholder involvement since it can lower the obstacles and the required effort for the DM. Further, it can be easily included in surveys and questionnaires.

5.9.2.4 Ratio Weighting Method. Based on Edwards (1977), this method asks the DM to rank the respective criteria by their importance as a first step. Next, the criteria considered least important are assigned a weighting factor of 10, while the remaining criteria are evaluated as multiples of 10 (Zardari et al., 2015, p. 29). Lastly, the resulting weights are normalized to achieve a sum of 1 (Odu, 2019, p. 1454; Zardari et al., 2015, p. 29).

5.9.2.5 Swing Weighting Method. The swing weighting method has been described by von Winterfeldt and Edwards (1986) in 1986. The starting point to determine the weights is an alternative with the weakest properties across all given criteria. From here, the DM is asked to adjust the criterion from worst to best (swing) that can constitute the most notable benefit overall. The identified criterion is considered the most important one and will be assigned 100 points (Odu, 2019, p. 1454; Zardari et al., 2015, p. 29).

Next, this step is repeated for the following criteria expected to offer notable benefits and the following swings are expressed as percentages in relation to the first, most important swing (Odu, 2019, p. 1454; Zardari et al., 2015, p. 29). The resulting percentages then need to be normalized (Odu, 2019, p. 1454; Zardari et al., 2015, p. 29). A direct comparison of the criteria conducted by the DM does not take place (Zardari et al., 2015, p. 29).

5.9.2.6 Simple Multi Attribute Rating Technique. Another common approach to determining weights by stakeholder involvement is the Simple Multi Attribute Rating Technique (SMART), originally introduced by Edwards (1977) [Edwards 1977]. The first step consists of instructing the DM to rank potential changes in criteria levels from worst to best (Wang et al., 2009, p. 2271).

Following this, the DM is asked to assign 10 points to the least important criterion and a higher amount of points to the remaining criteria to reflect the importance relative to the least important one (Wang et al., 2009, p. 2271). To improve and address the shortcomings of the original variant, Edwards and Barron (1994) presented two additional, related methods, namely SMARTS and SMARTER (Edwards & Barron, 1994; Wang et al., 2009, p. 2271).

5.9.2.7 Analytic Hierarchy Process. The AHP developed by Thomas Saaty (1980) is an established method within MCDA to deal with complex decision problems and has been applied in various academic disciplines and real-world case studies (Ishizaka & Labib, 2011; Wang et al., 2009). Initially, it was introduced as a stand-alone method (Saaty, 1980, 1990). However, it has proven to be useful as an approach to obtain weights indirectly, which is especially useful in cases where it is not practical to ask the DM to assign weights directly. Further, it can be combined with other MCDA methods. It is based on pair-wise comparison in order to identify weights for each individual criterion (Saaty, 1990). In conjunction with PROMETHEE, AHP can complement PROMETHEE and allow for synergies (Macharis et al., 2004).

Here, the DM is asked to compare all criteria against each other (Saaty, 1990). Based on these comparisons, an evaluation matrix is developed. Based on the resulting matrix, several approaches can be used to calculate the weights, either similar to eigenvalue approaches or the geometric mean (Ishizaka & Labib, 2011). Overall, approaches based on the geometric mean received the widest support within the AHP community, although Saaty argued in favor of the eigenvalue approach (Ishizaka & Labib, 2011, p. 14339).

Using a pairwise comparison approach and linguistic variables can potentially lower the cognitive burden for involved stakeholders and help to account for ambiguity in expressing subjective perspectives.

5.9.2.8 Fuzzy Analytic Hierarchy Process. FAHP is based on Saaty's AHP, which has been extensively studied and applied, not least because of its ease of application. However, AHP is commonly applied to crisp data, which does not sufficiently account for the fuzziness in real-world applications. In brief, FAHP can be considered an enhancement of the conventional AHP method, linking it to fuzzy set theory.

5.9.3 Selection of Weighting Method

All the different approaches have advantages and disadvantages. Thus, there is no optimal procedure to obtain weights within MCDA. Therefore, the respective method must be selected according to the decision problem and is highly context-dependent.

For this analysis, the FAHP approach entails several benefits. First, human decision-making is prone to be influenced by a variety of biases. People often experience

difficulties in expressing their perspectives precisely, especially in situations where they are faced with complex decisions. This is further amplified by the vagueness and fuzziness that people are confronted with in real-world settings. To address that, FAHP illustrates an approach to capture impreciseness and integrate that into the decision-making process. Second, it can be used in conjunction with questionnaires as well as in a workshop setting. This allows for a wide range of potential applications and use cases. And third, FAHP has proven to be useful in numerous application areas and has frequently been combined with other methods, including PROMETHEE, highlighting the flexibility of the technique (Kubler et al., 2016).²¹ It has been used for evaluation, decision-making, product and process development, resource allocation and determining criteria weights (Kubler et al., 2016).

For instance, Bottero et al. (2018) developed a participatory, PROMETHEE-based evaluation model to assist the decision-making process in the context of an urban regeneration program and related renewal strategies in northern Italy. Zihare et al. (2021) introduced a methodology to assess linkages and influencing factors concerning the bioeconomy using AHP as well as PROMETHEE. Methodologically, PROMETHEE and FAHP have been integrated to select power substations and machine tool selection (Kabir & Sumi, 2014; Kubler et al., 2016; Roghanian & Alipour, 2014; Taha & Rostam, 2012). As far as available information indicates, a participatory method integrating FAHP for weight determination, in conjunction with PROMETHEE GDSS for decision support, has not been previously devised for the purpose of identifying sustainable transformation pathways in the bioeconomy.

FAHP is therefore applied in this work. The following section will introduce the method and illustrate the main properties regarding the subsequent analysis.

5.10 Fuzzy Analytic Hierarchy Process

FAHP is theoretically embedded in fuzzy set theory which was developed to address partial truth values within the scope of absolutely true and absolutely false (Emrouznejad

²¹ For an overview of various combinations concerning the application of FAHP, see e.g.: Kubler, S., Robert, J., Derigent, W., Voisin, A., & Le Traon, Y. (2016). A state-of the-art survey & testbed of fuzzy AHP (FAHP) applications. *Expert Systems with Applications*, 65, 398-422. <https://doi.org/10.1016/j.eswa.2016.08.064>

& Ho, 2017). Zadeh (Zadeh, 1975) argued that using common quantification methods leads to difficulties in capturing expressions in a reasonable manner when confronted with complex environments (Emrouznejad & Ho, 2017; Zadeh, 1971). Thus, utilizing linguistic variables such as words or sentences in natural (or artificial) language can be beneficial (Emrouznejad & Ho, 2017; Zadeh, 1975). The use of linguistic variables further provides several opportunities to integrate fuzziness into questionnaires and surveys while maintaining comprehensibility and allowing for various participatory approaches. The mathematical foundation, fuzzy set algebra, was introduced by Zadeh in 1965 (Zadeh, 1965). The possibility to deal with problems that previously appeared unsuitable, lead to an adoption of fuzzy set theory within MADM, but also beyond that in fields such as artificial intelligence (Emrouznejad & Ho, 2017).

The abilities to account for impreciseness and fuzziness in real-world applications and to deal with subjective perspectives and judgments illustrate distinguishing features of FAHP. Given the complex, wicked decision problem in the RR and the intended integration of subjective stakeholder perspectives, FAHP offers several benefits compared to the conventional application of AHP for the proposed use case.

5.10.1 Fuzzy Sets

In FAHP, linguistic terms can be used to describe the relative importance of a criterion. Such a linguistic term is depicted by a fuzzy set that includes two main parts, namely a set of elements of x along with a respective membership function $u(x)$ (Kubler et al., 2016; Liu et al., 2020). Several fuzzy sets with varying membership degrees indicating to what extent a certain element is contained within the set have been developed, including Trapezoidal Fuzzy Numbers, Intuitionistic fuzzy sets and Triangular Fuzzy Numbers (TFN) (Atanassov, 1986; Buckley, 1985; Liu et al., 2020; van Laarhoven & Pedrycz, 1983).

Overall, TFNs (Figure 10) are most frequently used and are less complex compared to other existing fuzzy sets (Liu et al., 2020). Further, TFNs are most applicable when opinions involve answers that are partly yes and partly no and describe the imprecision of a crisp number with a precise membership function (Liu et al., 2020). Thus, they are more comprehensible for involved stakeholders and therefore more suitable for use in an interactive environment such as workshops, for instance. At the same time, they allow for

sufficiently capturing the aspired subjective perceptions. Hence, for the proposed case, TFNs are used to represent the pairwise comparisons and can be used to indicate the relative importance of the weights.

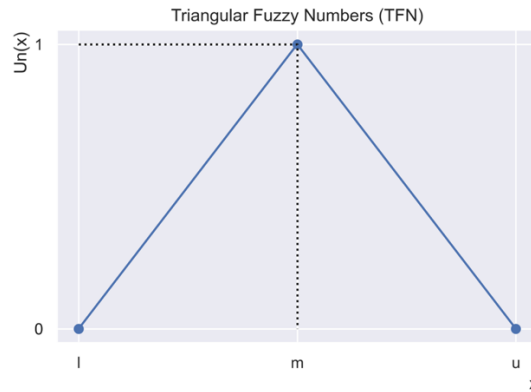


Figure 10. Triangular Fuzzy Numbers. Source: Author, based on Liu et al. (2020, p. 12).

5.10.2 Fuzzy Scales

As previously stated, a linguistic term can be described by a fuzzy set. With the help of a fuzzy scale, a sequence of fuzzy sets illustrates the importance of each term and links it to the numerical expression on which it is based (Liu et al., 2020). Although there are no particular guidelines for selecting which sort of fuzzy set to employ, 5-level and 9-level fuzzy scales are most widely used (Liu et al., 2020). Further, when applying identical scales, miscellaneous linguistic phrases are used (Liu et al., 2020). This study adopts a 5-level fuzzy scale to define TFNs. For the intended application in the RR, the linguistic terms will be translated into German to empower targeted stakeholders to express their subjective perceptions in their native language.

5.10.3 Consistency

Pairwise comparisons of subjective expert and stakeholder perspectives can be prone to contradictions. Depending on the respective stakeholder group, those can be more or less pronounced. While a certain degree of inconsistency is considered acceptable, Saaty (2008) proposed a consistency ratio (CR) expressed in a random index (RI) for the common AHP approach. This approach can be used for assessing the consistency within FAHP when applied to crisp numbers (Liu et al., 2020).

Yet, incorporating fuzzy set theory into the AHP introduces a level of uncertainty and vagueness in the decision-makers' judgments (Liu et al., 2017). With this vagueness, it becomes unreasonable and impractical to demand strict equality between two judgments, one obtained through direct comparisons and the other through indirect comparisons (Liu et al., 2017). This strict consistency requirement contradicts the fundamental concept of fuzzy set theory, which aims to model and accommodate the inherent vagueness in pairwise comparisons (Liu et al., 2017).

Depending on the intended application, it can make sense to check consistency for each obtained pairwise comparison matrix and exclude extreme cases prior to the group aggregation. In the context of the present analysis, however, that is not the case.

First, potentially inconsistent evaluations might provide useful information on existing lines of conflict. To exclude or question these would run counter to the aim of striving for a consensus based on Sen's plural grounding. Particularly since Sen recognizes that people regularly make inconsistent decisions and act inconsistently.

Second, they could potentially contribute to foster insightful discussions and allow for subsequent reflection of underlying reasons. Immediately labeling these perspectives as inconsistent or contradictory would likely contribute to stakeholders refraining from contributing contentious opinions.

Third, the threshold values for the corresponding indices regarding the acceptable degree of inconsistency are ultimately chosen arbitrarily. While this approach may be reasonable in a business context, it is less convincing when it comes to structuring the subjective perspectives of stakeholders and in political decision-making. Thus, the present analysis will not apply consistency indices.

5.10.4 Step-by-Step

Following the introduction of the AHP approach (Saaty, 1980) and early extensions related to fuzzy set theory (van Laarhoven & Pedrycz, 1983), several approaches to conducting the FAHP have been developed and applied. Based on recommendations derived from Liu et al. (2020), Fu et al. (2020), as well as the considerations laid out above, the following procedure is used to determine weights using the FAHP.

5.10.4.1 Step 1: Structure for Weight Determination. The problem is structured in a hierarchy that includes the goal (sustainable bioeconomy), dimensions (technology, resources, ecology), and criteria (lowest level) and is illustrated in **Figure 11**.

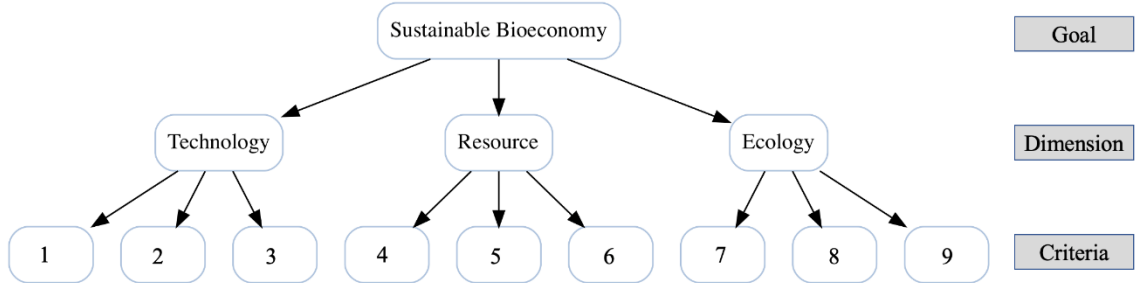


Figure 11. Goal Hierarchy for the Determination of Weighting Factors. Source: Author.

Building on the investigations in the following chapters, the indicator system to be developed will therefore be used to query weightings in the form of pairwise comparisons between the criteria and dimensions.

5.10.4.2 Step 2: Pairwise Comparison. Subsequently, the pairwise comparisons matrix is determined. The matrix is constructed based on the stakeholders' preferences for alternative i over alternative j , using the pairwise comparisons. The mathematical representation of the pairwise comparison matrix according to Saaty (1980) is:

$$A = a_{ij} = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad (12)$$

Preferences for only the top triangle of the matrix are collected using a pairwise comparison questionnaire. The lower triangle of the matrix is then filled with the inverse of the DMs judgment according to the following equation (Saaty, 1980):

$$a_{ij} = \frac{1}{a_{ji}}, (for i, j = 1, 2, \dots, n) \quad (13)$$

Here, a_{ij} is determined based on the importance scale.

Next, crisp values are replaced by fuzzy sets, in this case TFNs, along a fuzzy scale, in this case a 5-level fuzzy scale. This replacement of crisp values using fuzzy sets illustrates the fundamental difference between FAHP and AHP (Liu et al., 2020, p. 6).

5.10.4.3 Step 3: Synthesize the Subjective Judgements. When multiple stakeholders are involved, there may be differences in the assessment of the weighting of the criteria as expressed in the pairwise comparison matrices, not only between the different groups but also within each stakeholder group. These perspectives must be taken into account for the calculation of fuzzy weights and are thus aggregated.

In this connection, several approaches have been developed to aggregate the weights of criteria obtained from multiple fuzzy pairwise comparison matrices. Those include mean methods (e.g., arithmetic mean, geometric mean), max-min methods and intuitionistic fuzzy weighted averaging (Liu et al., 2020).

A suitable method for the intended application is particularly the geometric mean. Introduced by Buckley (1985), it constitutes a popular approach within the mean methods, highlighting the average across stated assessments (Liu et al., 2020). The geometric mean approach is most applicable in combination with TFNs and has been widely used to calculate fuzzy weights (Kubler et al., 2016; Liu et al., 2020). It has proven useful to integrate the weights of experts and stakeholders and is less affected by extreme values (Liu et al., 2020). In addition, it is unaffected by difficulties that may arise from rank reversal (Barzilai, 1997; Liu et al., 2020). Moreover, opting for a more complex procedure might cause imbalances between different groups concerning comprehensibility as the level of methodological expertise and familiarity with related approaches might differ notably. Thus, it illustrates a suitable approach to handling subjective evaluations for the intended use case.

Using the geometric mean, the potentially divergent opinions within stakeholder groups can be aggregated to subsequently calculate the fuzzy weights for each criterion. This allows handling individual assessments of members of each stakeholder group. The aggregation can be done using the following formula (Fu et al., 2020):

$$\tilde{a}_{ij} = (\tilde{a}_{ij}^1 \otimes \tilde{a}_{ij}^2 \otimes \dots \otimes \tilde{a}_{ij}^N)^{\frac{1}{n}} \quad (14)$$

where

$\tilde{a}_{ij}$ illustrates the TFN by N stakeholders;

$\tilde{a}_{ij}^k$ is the i -th to the j -th factor pair comparison.

5.10.4.4 Step 4: Calculate Fuzzy Criteria Weights. Subsequently, fuzzy geometric mean ($\tilde{r}_i$) matrices as suggested by Buckley (1985) can be determined using this formula:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{\frac{1}{n}} \quad (15)$$

where

$\tilde{a}_{in}$ is the fuzzy comparison value of criterion i against criterion n ;

$\tilde{r}_i$ is the geometric mean of the fuzzy comparison value of criterion i with respect to each criterion.

To obtain the fuzzy weights ($\tilde{w}_i$) of the criteria, the calculation can be performed using this formula (Buckley, 1985):

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \otimes \tilde{r}_2 \otimes \dots \otimes \tilde{r}_n)^{-1} \quad (16)$$

where

$\tilde{w}_i$ is the fuzzy weight of the i -th criterion and can be represented by a TFN.

5.10.4.5 Step 5: Defuzzify Weights. For the subsequent evaluation within PROMETHEE and the PROMETHEE GDSS, the resulting fuzzy weights must be converted into crisp numbers. The most common methods to perform this step are the extent analysis method (EAM) proposed by Chang (1996) and the centroid method (also referred to as *center of area* and *center of gravity*) (Liu et al., 2020).

Despite its widespread use, the EAM has several shortcomings that can lead to criteria being overlooked and incorrect weights being applied (Liu et al., 2020; Wang et al., 2008; Zhu et al., 1999). Therefore, the centroid method can be considered the most suitable option (Liu et al., 2020). Thus, the centroid method is applied to defuzzify and obtain crisp values. It is stated as follows (Liu et al., 2020, p. 33):

$$x^* = \frac{l+m+h}{3} \quad (17)$$

The resulting crisp weights for each stakeholder group are then normalized by sum and can subsequently be integrated into the PROMETHEE II methods to obtain the respective ranking and total net flows. These can then be used for the PROMETHEE GDSS.

5.11 Overview of Developed Framework

As pointed out, the developed approach is building upon insights gathered from SMCA and MAMCA (Etxano & Villalba-Eguiluz, 2021; Garmendia et al., 2010; Macharis et al., 2012; Munda, 2004, 2008). Given the decision problem and the respective context, the developed approach adapts the framework to the problem at hand and connects it to the insights derived from the operationalization of arguments by Sen. With the methodological aspects of steps three and four clarified, the framework is complete. Thus, the research questions can now be addressed. These guide the subsequent analysis and are summarized in Table 3.

Table 3

Research Questions

Steps	Related Research Question	Related Chapter
I: Defining	RQ 1 - From a stakeholder perspective, what are the key issues that need to be addressed in relation to the transformation process to a sustainable bioeconomy?	6
	RQ 2 - The bioeconomy perceptions of which stakeholder groups are frequently explored?	
	RQ 3 - What are existing value conflicts between the stakeholders involved?	
	RQ 4 - How is the concept of the bioeconomy perceived by the German population?	
II: Structuring	RQ 5 - How can a holistic monitoring system of the bioeconomy related to sustainability be conceptualized?	7
	RQ 6 - How can regional transformation trajectories be developed?	
III: Evaluating	RQ 7 - How do different stakeholders weigh criteria?	8
IV: Analyzing	RQ 8 - Which decision alternative could illustrate a potential compromise solution?	9

Note. See Table 4 for an overview of the steps conducted.

The developed framework along with the respective methodological approaches to address the research questions is summarized in Table 4.

Table 4*Steps for Identifying Sustainable Transformation Trajectories*

Steps	Goal	Methodological Approaches
I: Defining	Define overall decision problem	Focus-group workshop
	Identify relevant social actors	Systematic literature review
II: Structuring	Determine decision criteria	Representative survey
	Development of alternatives	Systematic Multi-Layer Filtering Approach
III: Evaluating	Integrate stakeholder perspectives	Regional Transformation Pathways
	Complete decision matrix	Applying FAHP to determine weights
IV: Analyzing	Rank alternatives	Merging information
	Process information	Aggregation using PROMETHEE II and PROMETHEE GDSS
		Illustrating as stakeholder profiles

Note. See Table 3 for the related research questions.

Following this procedure, the guiding research questions will constitute the basis for the discussion section and the development of policy recommendations.

To conclude this chapter, the subsequent section discusses software options to conduct the respective calculations and implement the approach.

5.11.1 Software for Multiple Criteria Decision Aid

5.11.1.1 Existing Software Options. Several methods and approaches have been introduced in the literature to tackle MCDA-related problems, with numerous accompanying software options designed to implement or facilitate the use of these approaches. Decision analysis software can potentially aid DMs at multiple stages of the decision-making process, encompassing problem formulation, identification of decision alternatives, calculation of rankings, as well visualization.

Commercial software packages often cost high prices, which can be an obstacle for researchers. These products commonly have websites and may include training courses and technical support Weistroffer and Li (2016, p. 1302). Conversely, nonprofit software

developed by academics often lacks support and may offer limited (or no) documentation Weistroffer and Li (2016, p. 1302).

Moreover, there are limitations with respect to customization with respect to the specific decision-making process and the number of methods available for each software package. Therefore, one would have to get acquainted with a larger number of individual software packages, which are often not compatible with each other. Alternatively, one would have to accept that only the methods provided by a specific software come into question. Both cases are not desirable, particularly because it can lead to a dependence on a single software, and an absence of maintenance can cause further problems.

5.11.1.2 Python Libraries and Packages. Given the difficulties regarding existing software options, researchers frequently decide to pursue alternative paths to support the utilization of MCDA methods. Two common ways include using Microsoft Excel Spreadsheets and performing calculations manually and implementations using Python. In this connection, Papathanasiou and Ploskas (2018) contributed a book containing the implementation of six methods along with the theoretical background, numerical examples and the respective programming code. This makes it a good introduction to the subject. However, in the respective Python implementation, intermediate results are often not displayed comprehensibly, and possibilities for visualization are limited.

Other notable libraries include *pyrepo-mcda* and *pymcdm* (Kizielewicz et al., 2023; Wątróbski et al., 2022). However, both do not include FAHP, which is a vital part of this work. Moreover, given that they have only been introduced recently, it is unclear whether they will be maintained and functional in the future. Thus, similar problems as those described with existing software options might arise.

Thus, the programming parts needed for this thesis have been developed independently. This allows for cooperation in all desired aspects in terms of functionality and to match the model precisely to the problem at hand.

5.11.1.3 Developed Implementation. The MCDA conducted in this thesis was performed using the programming language Python, version 3. Python is a general-purpose programming language and offers the possibility to use existing code libraries on which individual applications can be set up. The availability of a wide range of open-source code enables researchers to adjust existing code and develop research approaches for a variety of research questions.

Another advantage of Python is the opportunity to further refine a developed model throughout the research process without being limited to existing functions of commercially available software packages. This flexibility is particularly helpful in cases where the requirements change in the course of the research process or new, special requirements appear that have not been identified at the beginning of the project. In such a case, a model written in Python should allow for an appropriate adaption.

The model developed in this thesis builds upon the following libraries:

NumPy is a Python library that extends the capabilities of the Python programming language, enabling support for large, multi-dimensional arrays and matrices (Harris et al., 2020). It also provides a comprehensive collection of high-level mathematical functions for performing operations on these arrays (Harris et al., 2020).

Matplotlib is a Python library primarily used for creating visualizations and plots, commonly in conjunction with NumPy, which is a numerical mathematics extension for the Python programming language (Hunter, 2007).

Pandas is a software library designed for the Python programming language, specializing in data manipulation and analysis (The pandas development team, 2023). It provides comprehensive data structures and functions for efficiently handling numerical tables and time series data (The pandas development team, 2023).

These libraries have been maintained for several years and are used in a variety of applications. Given their popularity and wide range of applications, it can be expected that they will remain functional for the foreseeable future.

5.12 Section Summary

The development of the methodological framework for the following analysis is the focus of this chapter. MCDA plays a central role in this regard. MCDA is understood as a decision aid, as outlined by Roy, intended to shape, develop, and justify convictions. Its primary function is thus not to find an absent optimal solution, but to assist an actor in the choice process, for example, by facilitating debate or supporting the identification of options that are consistent with the actor's goals. Building on this understanding, MCDA can be part of the public reasoning framework.

From a decision theoretical angle, this work relates to prescriptive decision-making, aiming to assist in making well-informed decisions. MCDA approaches aim to provide a scientific basis for decision-making but have limitations in terms of objectivity of results. Thus, in the absence of an optimal solution to wicked problems, MCDA can only help find better solutions and avoid bad ones.

The decision problem dealt with in this work can be categorized as a ranking problem and a group decision problem (Section 5.3.1). MADM methods, especially outranking methods, are well suited for this purpose due to their characteristics of non-compensating and representation of real-world decision problems (Section 5.3.4). While these methods may not be perfect, they do have a number of key advantages. Outranking methods acknowledge that stakeholders may have unclear preferences and can accommodate contradictory information to reflect this ambiguity. For the decision problem addressed in this work, this is crucial since it is stated aim to include a broad variety of perspectives and value systems. Their core purpose is to enhance the decision-making process by providing valuable insights, increasing transparency, and raising the stakeholders' awareness of the problem and its relevant factors. They are also particularly useful when there are mostly qualitative evaluations of alternatives, or when less precise preferences need to be included in the model. Outranking methods are partially non-compensatory, thus typically avoiding the weak sustainability philosophy and ensuring that criteria related to critical environmental or ethical considerations cannot be outweighed by superior performance in other aspects.

In general, MCDA includes key elements such as a clear objective, a set of alternative solutions, and criteria for evaluating the achievement of the objective. It also considers

stakeholder preferences, integrating their insights and viewpoints, and uses weights to assign different levels of importance to each criterion, allowing for subjective evaluation.

The MCDA process involves identifying and formulating the decision problem, constructing the evaluation model, and developing recommendations. It is explicitly not meant to automate decision-making, but to extend the information base for making an informed decision. The use of MCDA in the policy context presents different challenges than those traditionally encountered in MCDA processes. These include recognizing that the real world is a complex system in which no single perspective captures all relevant aspects of a problem. For example, when implementing public policy, there is a need to evaluate and compare different options, each of which has conflicts arising from competing values, interests, and the different community perspectives they represent.

Based on these conceptual considerations, the basic procedure for the analysis is divided into four main steps, namely defining the problem, structuring the problem, evaluating the problem and analyzing the problem. For the evaluation and analysis of the decision problem, the selection of the methodological approach is vital. There are two aspects that play a key role in the choice of methods. These derive on the one hand from the operationalization of Sen's arguments from the previous chapter, as well as from the application context in connection with sustainable development.

Concerning the operationalization of Sen's arguments, the selected method must be capable of dealing with incompleteness and providing useful information based on maximality in case there is no optimal solution, which is generally the case when dealing with wicked problems. Further, Commensurability is preferred, and the methodological approach should be able to provide partial- as well as complete rankings. Lastly, referring to plural grounding, the identified method should allow for the pursuit of consensus that allows for the consideration of different perspectives, each expressed from its subjective point of view.

The most important considerations with regard to the application to sustainability decision problems, as stated by Munda (2016), include the need for the method to be as concise as possible while also integrating information about the criteria in various forms.

In addition, a complete ranking is desirable, but complete compensation should be avoided. Moreover, dominated alternatives should also be considered and formal assumptions such as unanimity, monotonicity and neutrality should be taken into account.

The group of PROMETHEE methods is identified as suitable because they fulfill the requirements posed by the decision problem. This includes the ability to create complete and partial rankings, the avoidance of complete compensability, as well as the option to utilize it as a group decision system striving to find a compromise solution.

FAHP is used as the subjective weighting method. Given the complex, wicked decision problem in RR and the intended integration of subjective stakeholder perspectives, FAHP offers several advantages over the conventional application of AHP for the proposed use case. These include the ability to account for imprecision and fuzziness in real-world applications and to deal with subjective perspectives and judgments, which are distinguishing features of FAHP.

Since existing software options are not convincing for the intended implementation of PROMETHEE and FAHP, a custom model in Python is developed and used. Overall, with the clarification of the methodological aspects, the framework is complete. The next chapter is therefore centered on the first step of the analytical framework, specifically the definition of the decision problem and the identification of the relevant social actors.

6 Decision Context and Stakeholders

This chapter focuses on the first step of the analytical framework, which consists of defining the decision problem and identifying the relevant social actors.

The first part of the process was a focus group workshop to gather preliminary insights into existing lines of conflict and opportunities and to arrive at an overview of stakeholder groups involved. The insights gathered during the focus group workshop further served as valuable foundation for informing the coding scheme used in the systematic literature review that was subsequently conducted. The systematic literature review of stakeholder perceptions of the bioeconomy was used to assess the current state of research and define the stakeholder groups to be explored in the subsequent analysis. Additionally, a representative survey of the German population was utilized to examine the public's understanding of the bioeconomy, including their knowledge, concerns, and expectations.

From the empirically derived insights, a comprehensive understanding of the decision problem, its context, and the existing lines of conflict was obtained, along with the identification of the key social actors to be included in the analysis. The chapter concludes with a summary section.

6.1 Focus Group Workshop

Focus groups have a long record of accomplishment as a method to acquire insights across various scientific disciplines. They have been utilized in fields ranging from political science, economics, and psychology to sociology. This method is widely recognized as a prominent exploratory and qualitative approach to studying diverse subjects (Robson et al., 2001). Moreover, they are frequently used as a participatory method in relation to energy research (see e.g., Hoolohan et al. (2018); Vaidya and Mayer (2016)).

Focus groups can provide valuable insights into the opinions and underlying rationales held by various groups of individuals. Moderation plays a pivotal role as a fundamental necessity in guiding discussions when conducting a focus group workshop. It serves to maintain focus, ensuring that conversations stay on topic and preventing any one participant from dominating the discussion, thus allowing all participants the opportunity

to express their opinions. Thereby, as Schmidt-Scheele et al. (2022) point out, the group discussion aligns with the ideals of Habermas, aiming to incorporate as many diverse opinions as participants are willing to offer and share. These characteristics make focus groups more time-efficient than individual interviews and underscore this method's intrinsic social nature (Schmidt-Scheele et al., 2022). Participants' statements are made in the presence of and with awareness of the group, altering the entire communication process (Schmidt-Scheele et al., 2022). Statements are promptly assessed, agreed upon, or challenged by other participants, thereby enhancing the depth of insight into the subject (Schmidt-Scheele et al., 2022).

The workshop conducted in connection with this analysis aimed to encompass a diverse range of stakeholders. The participants were selected following a snowball sampling approach in collaboration with the active stakeholder network the *Transform2Bio* project was embedded in (Parker et al., 2019). Held in November 2019 in Jülich, Germany, the workshop facilitated a group discussion with open-ended questions to provide an inclusive and comprehensive exploration of viewpoints.²² The moderation responsibilities were undertaken by the *Transform2Bio* project team, ensuring that discussions remained focused and allowed all participants to contribute. The workshop spanned approximately two hours. The diverse backgrounds of the workshop participants (n=8) represent a wide range of stakeholder groups (Table 5), including farmers, environmental organizations, industry representatives, and a priest. The inclusion of the priest as a representative of one of the local churches was noteworthy, given their active involvement in discourses within the affected regions. This diverse representation ensured a comprehensive exploration of perspectives and viewpoints during the workshop discussions.

²² The focus group workshop was conducted as part of the project *Transform2Bio*. It was organized in collaboration with Sophia Dieken, Mirko Dallendörfer and Sandra Venghaus. It took place in November 2019.

Table 5*List of Participants Transform2Bio Stakeholder Workshop*

Number	Stakeholder Group
3	Farmers
1	Industry & commerce
1	Church
2	Social and environmental initiatives & NGOs
1	Government & political actors

Note. Two of the participating farmers were connected to the same farm.

During the workshop addressing the transformation towards a sustainable bioeconomy, questions were strategically employed to uncover vital insights. They served as a catalyst for delving into the key issues that concerned stakeholders most, highlighting their core concerns and perspectives. Additionally, these inquiries were intended to identify potential conflicts and areas where compromises might be necessary, thus offering a view of the challenges and opportunities within the bioeconomy transformation. In addition, the workshop was structured around a pre-developed discussion guide specifically designed to explore related concerns. Through these questions and structure, promising discussions began to emerge, paving the way for a more informed and collaborative exploration of aspects relevant for sustainable bioeconomic pathways.

6.1.1 Results

The workshop was transcribed and the results analyzed based on qualitative text analysis. It became evident that the stakeholders placed the highest importance on three aspects. First, regional added value was considered very important. Stakeholders were notably concerned about the economic benefits and contributions generated within the RR, emphasizing the importance of regional added value in bioeconomic initiatives.

Second, environmental sustainability emerged as a paramount concern. This reflects the stakeholders' deep interest in ensuring that bioeconomic activities align with ecological objectives and contribute positively to environmental sustainability.

And third, a fair share of financial burdens was a central concern. The equitable sharing of financial responsibilities was a crucial issue for all stakeholders, underlining their

commitment to achieving fairness and shared financial accountability within the context of the transformation process.

6.2 Systematic Literature Review²³

The role of society in a bioeconomy has become a widespread policy concern, given the profound changes envisioned in the management of natural resources. It necessitates a clear understanding of the positions held by involved stakeholders and society as a whole. The various stakeholders are recognized as crucial drivers of the bioeconomy and its potential to contribute meaningfully to sustainable development. Related research emphasizes that the transformation towards a bioeconomy is a process of societal change wherein various stakeholders play a vital role in shaping its development and governance (Hausknot et al., 2017; Johansson & Henriksson, 2020; Lynch et al., 2020; Mukhtarov et al., 2017; Peltomaa, 2018; Priefer & Meyer, 2019). Specifically, challenges such as deficient social acceptance, emerging societal conflicts, and the potential for disillusionment illustrate substantial obstacles for the bioeconomy (Meyer, 2017).

However, research in this field is broad. It includes an increasing collection of works, ranging from conceptual articles and policy reviews to surveys and expert interviews targeting specific stakeholder groups or bioeconomy sectors. Furthermore, the bioeconomy concept intersects with several interconnected and extensively researched topics, such as the relationship between nature and humans, attitudes towards agriculture and technology, responsible consumption behavior, the sustainability paradigm, and the circular economy concept.

Consequently, research on bioeconomy perceptions is pursued in various disciplines and research communities, with many of them only recently starting to connect their work to the bioeconomy concept. As a result, research works greatly vary in their goals, concepts, and methodologies, making it difficult to conduct an overarching comparison or draw generalized conclusions regarding stakeholder perceptions of the bioeconomy. Instead, observations tend to be case-specific and context-dependent. This represents a

²³ The following is based on a co-authored paper: Dieken, S., Dallendörfer, M., Henseleit, M., Siekmann, F., & Venghaus, S. (2021). The multitudes of bioeconomies: A systematic review of stakeholders' bioeconomy perceptions. *Sustainable Production and Consumption*, 27, 1703-1717. <https://doi.org/10.1016/j.spc.2021.04.006>

deficiency in both research and policy, particularly considering that studies indicate connections between individual bioeconomy issues and understandings, which are closely tied to distinct actor groups participating in the policy discourse to varying extents (Dieken & Venghaus, 2020; Mukhtarov et al., 2017; Vainio et al., 2019).

The primary objective of the following section is thus to offer a comprehensive overview of the scientific literature concerning stakeholder perceptions of the bioeconomy. This overview serves two purposes: firstly, to assess the current state of research in this area, and secondly, to guide subsequent research efforts. In the context of this work, that specially refers to the respective stakeholder groups to be included within the consecutive steps of the analysis.

To achieve this, a conceptual framework was devised to describe the key characteristics of stakeholders' bioeconomy perceptions, encompassing a diverse range of research studies. This framework was then applied in a content-based review of empirical research. Through systematic comparisons of results related to different stakeholder groups and their perceptions of the bioeconomy, the section provides valuable insights into the necessity for more in-depth research, as well as the practical applicability of the bioeconomy concept.

The subsequent section introduces the framework for the systematic literature review which is followed by a section presenting the findings of the extensive review of empirical research articles on bioeconomy perceptions. The consecutive section then discusses these results. The last part concludes the analysis of research on bioeconomy perceptions to propose directions for future research.

6.2.1 Methodology and Framework

6.2.1.1 Data. Given the intricate and ambiguous nature of the bioeconomy concept, the primary research challenge in analyzing perceptions is to establish a clear definition and delineation of the concept. Consequently, an essential condition for the literature review dataset selection was determined. Due to the extensive amount of relevant literature on the bioeconomy, the focus was exclusively placed on research that explicitly addressed *the bioeconomy* and sought to explore perceptions related to this concept. To accomplish this, the data for the literature review was compiled through a search query for the term in a research database.

The decision to utilize a specific research database was influenced by the objective of reviewing empirical research on bioeconomy perceptions. Given the focus on empirical research, journal articles were deemed the primary format for original scientific investigations, necessitating a search specification for this type of publication. Furthermore, due to the widespread popularity of the term "bioeconomy" as a buzzword, it was crucial to adjust the search query to exclude literature that merely referenced the term in citations or affiliations without directly investigating the bioeconomy as a subject of research.

To meet these criteria, the *Web of Science* database was selected, as it allowed for refining the search to include journal articles that contained relevant search terms in titles, abstracts, or keywords. The database also provided the most extensive results compared to alternatives such as Scopus. Additionally, the database allowed for the pre-selection of citation indices in the social sciences and humanities, further aligning the search parameters with the research intent.

The search query was developed by combining terms related to the bioeconomy and perceptions. Specifically, variations like *bio-economy* and *bio-based economy* were included for the bioeconomy term, focusing solely on the bioeconomy concept itself. To find synonyms for perceptions, a step-by-step approach was used, testing terms found in the literature in previous search runs. Beginning with the term *perception*, additional terms used in titles, abstracts, or keywords were considered to represent synonyms or related concepts concerning stakeholder perceptions. An overview can be found in Table

6. This process was repeated until no new search results were obtained. Conducting the database search on July 2nd, 2020, retrieved 311 results, excluding duplicates.

Table 6

Key Search Terms

Search terms for bioeconomy	Search terms for perceptions
"bioeconomy"	"attitude"
"bio-economy"	"definition"
"bio-based economy"	"frame"
"definition"	"imaginary"
	"narrative"
	"perception"
	"preference"
	"understanding"
	"vision"

Source: Dieken et al. (2021).

The initial results underwent several manual narrowing-down steps. Firstly, the results were restricted to English-language journal articles. Secondly, a thorough examination was conducted on all remaining articles to verify that they primarily focused on bioeconomy perceptions. It was essential to distinguish between the bioeconomy as a policy vision and the understanding used in the context of medical research. Thirdly, conceptual articles and policy reviews were excluded from the analysis to concentrate exclusively on empirical research concerning stakeholder perceptions. Following these selection steps, a dataset of 108 publications formed the basis for the analysis.²⁴

6.2.1.2 Analytical Framework. The developed approach involved creating and assigning codes to texts (Gibbs, 2014; Maxwell & Chmiel, 2014). By employing this method, key characteristics and findings from the research works were identified and compared using a combination of qualitative and quantitative means.

The research questions guiding the review were first developed and then translated into the coding system and procedure. For the content analysis, research questions were

²⁴ A comprehensive list of all articles can be found in Table A1, Dieken, S., Dallendörfer, M., Henseleit, M., Siekmann, F., & Venghaus, S. (2021). The multitudes of bioeconomies: A systematic review of stakeholders' bioeconomy perceptions. *Sustainable Production and Consumption*, 27, 1703-1717. <https://doi.org/10.1016/j.spc.2021.04.006>.

formulated to investigate how stakeholders' perceptions of the bioeconomy are studied and what specific perceptions are discovered. These questions were informed by the concerns raised in the conceptual and policy review literature. Specifically, the issues addressed included the ambiguity and various design options of the bioeconomy concept, its context dependence and scope, as well as the lack of participation by certain stakeholders.

Table 7

Groups of Research Questions Guiding the Literature Review

Category	Research questions
1 - Research approach	▪ What is the geographical scope of the article? ▪ What methodological approach is applied?
2 - Stakeholder group	▪ What groups of stakeholders are observed? ▪ What level of expertise is ascribed to them?
3 - Bioeconomy perceptions	▪ Is the bioeconomy conceptualized holistically or as a specific element or sector? ▪ What bioeconomy vision prevails?

Source: Adapted from Figure 1, Dieken et al. (2021).

The guiding analytical questions can be categorized into three groups, focusing on the research approach, the observed stakeholder groups, and the identified bioeconomy understanding (as depicted in Table 7). Within the context of this literature review, the identification of the articles' methodological approach and geographical scope is of interest. Additionally, the analysis examines the observed stakeholder groups. Given the prevalent presence of experts in the bioeconomy discourse, it is also of interest to explore the stakeholders' level of knowledge and previous engagement in the bioeconomy (Dieken & Venghaus, 2020).

Moreover, the literature underscores the challenge of defining and outlining the bioeconomy. Therefore, an effort is made to comprehend the insights offered by the studies concerning stakeholders' perceptions. This involves initially exploring the interpretation of objectives and strategies. Given the dataset's heterogeneous composition, this query is further supplemented by considering assumptions about the bioeconomy's design and, particularly, the anticipated level of changes and the aspect of the bioeconomy under discussion.

To facilitate the content analysis and operationalize these questions, they were transformed into coding categories. Each category was accompanied by inductively derived individual codes based on the dataset, enabling the delineation of variations while maintaining the possibility of aggregation. As a result, the codes were relatively comprehensive and general (Table 8).

The overview of conceptual and review articles was instrumental in aiding the identification and differentiation of text characteristics. However, for the category of bioeconomy understandings, it was necessary to deviate from the inductive approach and rely on the bioeconomy visions (Section 2.4) proposed by Bugge et al. (2016). Given the significant research challenge posed by the ambiguity of the concept, the codes for bioeconomy understanding had to strike a balance: they needed to be comprehensive and meaningful while also encompassing a wide range of diverse research approaches and findings.

The conceptualization of three bioeconomy visions was adapted because it offered a broad enough scope to summarize the extensive literature while allowing for differentiation along the major lines of thought concerning the bioeconomy's objectives and design. Further, this conceptualization is widely cited in the literature and serves as an essential reference frame for research on bioeconomy perceptions (D'Amato et al., 2017; Hausknost et al., 2017; Priefer et al., 2017). Consequently, a coding system was developed based on the visions introduced by Bugge et al. (2016).

Table 8*Coding Scheme*

<i>Part 1: Research approach</i>	6. Level of expertise
1. Methods	6.1. High
1.1. Quantitative	6.2. Low
1.2. Qualitative	6.3. Mixed / unspecific
1.3. Mixed methods	
1.4. Unspecific / divers	<i>Part 3: Bioeconomy perceptions</i>
2. Sample size	7. Bioeconomy focus
2.1. [Number]	7.1. Holistic concept
2.2. Not applicable	7.2. Underlying management principle
3. Scope	7.3. Specific product / process / sector
3.1. International	8. Bioeconomy elements
3.2. National	8.1. Governance & regulation
3.3. Regional	8.2. Biomass production
3.4. Local	8.3. Utilization & biotech
3.5. Generic	8.4. Consumption
4. Location	8.5. Ecological system
4.1. [Name]	8.6. General overview
<i>Part 2: Stakeholder Group</i>	9. Bioeconomy understandings
5. Type of stakeholder group	9.1. Bio-technology
5.1. Citizens & consumers	9.2. Bio-resource
5.2. Farmers & forest owners	9.3. Bio-ecology
5.3. Government & political actors	9.4. Multiple / diverse
5.4. Industry & commerce	
5.5. Media	
5.6. Research	
5.7. Social and environmental initiatives & NGOs	

Source: Dieken et al. (2021).

For the analysis of the articles' research approaches, codes were devised to encompass methods, sample size, scope, and location. To facilitate comparison, the sample size was established as the minimum number of individual observations. Regarding the scope, a distinction was made based on whether the bioeconomy was discussed in the context of local, regional, national, and international development or as a non-specific, generic phenomenon. Additionally, when texts identified a particular country or place being investigated, this information was coded as the location.

Concerning the type of stakeholder group, the codes predominantly align with the categories most frequently employed in the articles. The most prominent stakeholder groups associated with the bioeconomy are research, Non-Governmental Organizations (NGOs), industry, and public administration (e.g., Hausknost et al. (2017)). Building on these categorizations, seven stakeholder groups were established, each distinguished by their specific roles in the process of bioeconomy transformation.

Research involves stakeholders engaged in knowledge generation and technology development. Farmers and forest owners contribute biomass, while industry and commerce utilize both knowledge and biomass to create bio-based products. Citizens and consumers reflect the societal demand for bioeconomy products and participate in bioeconomy governance. Government and political actors play a role in defining the political framework of the bioeconomy, whereas social and environmental initiatives and NGOs shape the societal and ecological framework. Additionally, a dedicated code for media as an expression of public opinion was designated to account for the aspect that studies of citizens represent a subset of society.

Given the ambiguity and nuances of group affiliation and expertise levels in reality, categorizations adhered to the individual studies' own characterizations whenever feasible. Concerning the level of expertise, a distinction was made between stakeholders who possessed extensive knowledge of and involvement in the bioeconomy (e.g., scientists in life sciences) and those with limited knowledge or no prior contact with the bioeconomy before the respective study (e.g., consumers). A third code was also created to represent studies that included a mixed group of experts and laypeople.

Subsequently, codes were formulated to analyze bioeconomy perceptions concerning three distinct aspects: the chosen focus (ranging from individual products to grand policy concepts), the included sectors (e.g., biomass production), and the identified bioeconomy understanding. When the results in the articles aligned with one of the core characteristics defined by Bugge et al. (2016) for the three bioeconomy visions, the corresponding codes for those visions were assigned.

Only the most predominant vision was assigned a code in cases where diverse stakeholder perceptions were identified. In situations where the results in articles were mixed or did not align with the bioeconomy visions, they were coded as

"Multiple/diverse." Concerning the emphasis on the bioeconomy, a distinction was made between three levels of detail presented in the articles: 1) a comprehensive, broad outlook encompassing the bioeconomy as a whole, 2) the bioeconomy as portrayed within a specific sector, process, or technology, and 3) an intermediate-level view pertaining to managerial paradigms, such as circularity.

With respect to bioeconomy elements, it was observed that articles frequently spotlighted particular sectors or policy areas when discussing the bioeconomy, such as stages of biomass production or industrial utilization. Consequently, differentiation was established for five bioeconomy elements, ranging from the ecological system to the governance and regulation of the bioeconomy. Furthermore, articles that did not emphasize a specific element were categorized as providing a general overview.

Analyzing the research articles' dataset involved combining qualitative and quantitative methods. The articles were categorized using the developed coding scheme, and the qualitative observations were further complemented with a (semi-) quantitative summary of the coding results (for more on the approach, see Venghaus and Hake (2018)). Consistent with the inductive code development, code assignment was based on the characterization and wording provided by the articles themselves, whenever possible. Articles were coded as mixed or unspecified when the information provided was insufficient. One code was assigned for each category and article, except for category 5, where up to five separate codes were allowed per article to identify each stakeholder group included.

The findings presented are primarily derived from articles that address multiple groups of stakeholders. However, it is explicitly mentioned when the results are exclusively based on articles focused solely on one stakeholder group. Further, intercoder reliability needs to be addressed (Mayring, 2004). To ensure and account for intercoder reliability, the coding scheme was collaboratively developed and refined in regular meetings among the authors throughout the coding process.

6.2.2 Results

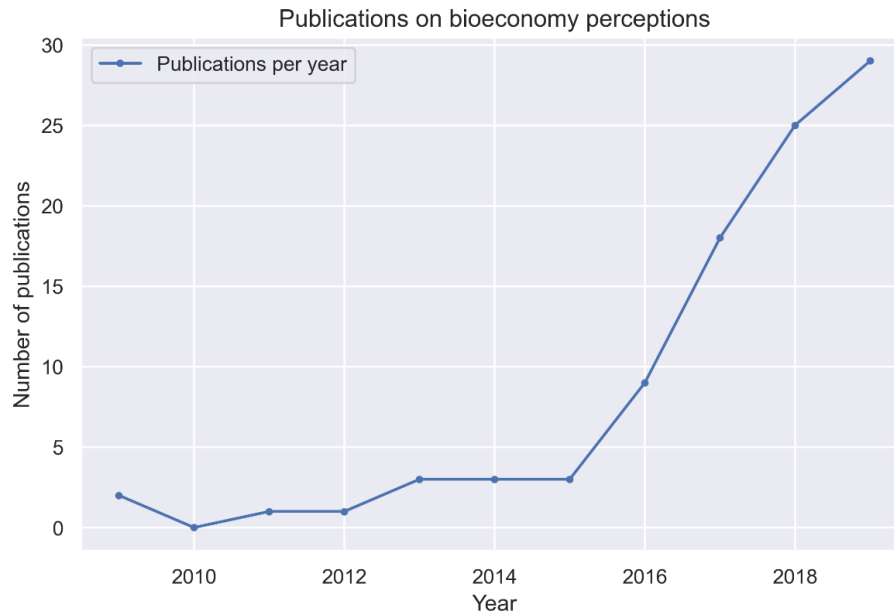


Figure 12. Journal Article Publications on Bioeconomy Perceptions. Source: Dieken et al. (2021).

The policy concerns regarding the acceptance, legitimacy and potential developmental trajectories of the bioeconomy are evident in the substantial surge in research dedicated to bioeconomy perceptions (as depicted in Figure 12). The coverage of this subject in articles extends back to 2009. While the number of journal publications remained relatively consistent, averaging around three articles per year until 2015, there has been a pronounced increase since then, with a total of 29 articles in 2019. However, it appears that the pace of this upward trend has moderated more recently. For the year 2020, a total of 14 articles had already been published in the first six months. Analyzing bioeconomy perceptions thus constitutes a substantial and expanding segment of bioeconomy research.

Overall, the research articles on bioeconomy perceptions primarily center around a national bioeconomy within Europe, employing qualitative or mixed methods approaches to investigate the industry, government, and research stakeholders. These studies address general and regulatory inquiries about specific products and sectors. The geographical emphasis is particularly enunciated, with 76 out of 108 articles focusing on European cases, while only two Asian and three African cases were included.

Research on stakeholder perceptions of the bioeconomy concentrates on a distinct and narrow set of actors and their stances on rather general aspects of the bioeconomy. However, the findings in the category "bioeconomy perceptions" demonstrate that articles cover a diverse range of sectors and challenges, and perspectives are relatively evenly distributed. Thus, detailed data analysis is necessary to identify differences in perceptions across stakeholder groups and methodological approaches.

6.2.2.1 Stakeholder Perceptions. As Figure 13 illustrates, the research articles included diverse stakeholders. The groups of government & political actors, industry & commerce, and research were studied nearly double as often as citizens & consumers, farmers & forest owners, or stakeholders from social and environmental initiatives & NGOs. Additionally, just two articles were solely dedicated to the analysis of the media, conducted by Peltomaa (2018) and Ranacher et al. (2019). Therefore, the results for the media will not explicitly be compared with other stakeholder groups. Still, these data points are integrated into the figures for illustrative intent. This finding aligns with the observation that the bioeconomy is primarily discussed by the government, universities, and industry (Mukhtarov et al., 2017).

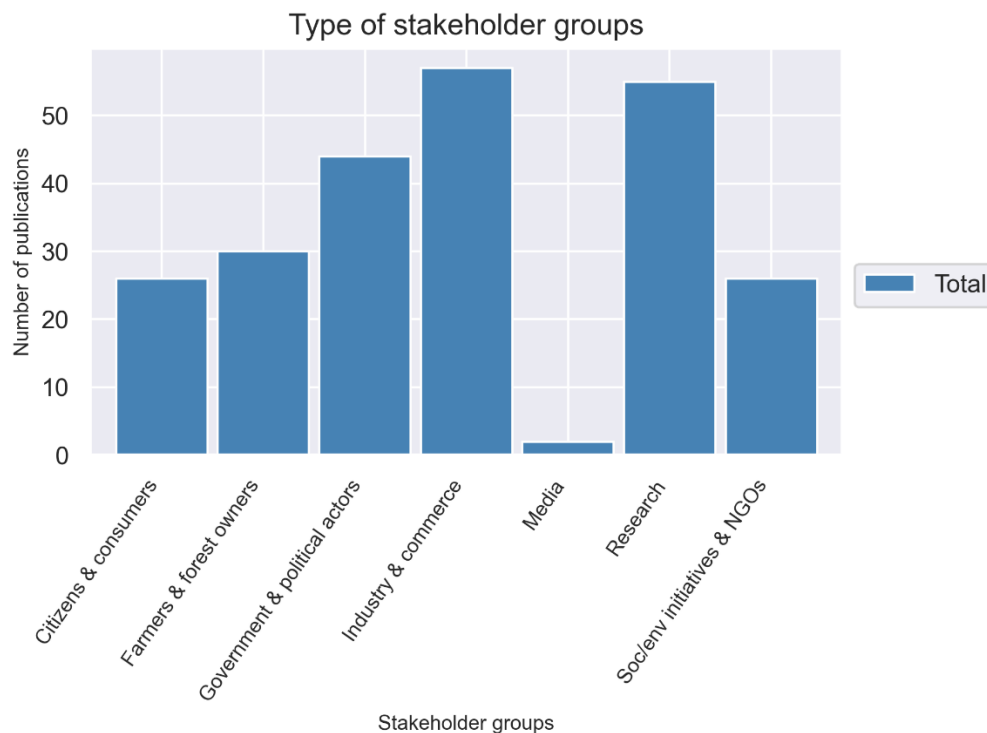


Figure 13. Type of Stakeholder Groups Investigated. Source: Dieken et al. (2021).

There is a notable imbalance in the analysis of stakeholder groups, with general, non-expert society being less frequently studied. This discrepancy is evident from the prevalence of expert stakeholders (61.1%) compared to laypersons (10.1%), which largely corresponds to the category of *citizens & consumers*. Consequently, the majority of research on stakeholder perceptions primarily focuses on well-established expert groups.

The relatively low number of research works on farmers & forest owners is unexpected, considering their substantial role as the spine of the bioeconomy, particularly in Scandinavian countries, as demonstrated in articles by Albrecht (2019) and Fischer et al. (2020). Likewise, the participation of the general public has been emphasized as crucial, yet the number of articles dedicated to *citizens & consumers* is even lower. This is particularly noteworthy since this category also includes articles exclusively focusing on society understood as a market.

The lower prevalence of these stakeholder groups is also linked to methodological differences in the articles. Out of 65 articles (60.2%), the majority examines more than one group of stakeholders, often combining empirical observations into a unified result. However, *citizens & consumers* and *farmers & forest owners* are more frequently analyzed exclusively and quantitatively. At the same time, further groups are more commonly examined together and qualitatively, leading to a higher representation of the latter in the overall share. As a result, a closer examination is reasonable for the 43 studies that exclusively investigate one group of stakeholders (Table 9).

Table 9*Type of Stakeholder Groups Investigated*

Observed Group	Freq.	Percent	Cum.
Citizens & consumers	15	32.61	32.61
Farmers & forest owners	10	21.74	54.35
Government & political actors	3	6.52	60.87
Industry & commerce	7	15.22	76.09
Media	2	4.35	80.43
Research	9	19.57	100.00
Total	46	100.00	

Note: Number of Articles with Sole Focus on the Respective Group. *Source:* adapted from Dieken et al. (2021).

The roles of the first two stakeholder groups are swapped, with *citizens & consumers* (34.9%) and *farmers & forest owners* (23.3%) becoming the two highest-scoring codes, resulting in almost the exact opposite distribution. This comparison reveals that when less-informed stakeholders from broader society are analyzed, it is often done separately from the analyses of the dominant, expert stakeholder groups.

One potential explanation for this separation is the disparity between official policy and stakeholder visions (Hausknost et al., 2017; Vainio et al., 2019). Researchers often focus on analyzing the (assumably) consistent position of a specific group or group constellation, either the predominant or an alternative view. This division is also evident in the conceptual literature, which generally differentiates between two differing understandings of the bioeconomy, namely a socio-ecological approach and a technology-based (Priefer et al., 2017; Stern et al., 2018). Assessing the extent of these differences becomes challenging when investigated separately. Consequently, discrepancies in results between studies focusing on one or multiple stakeholder groups are henceforth emphasized where relevant.

In this context, a comparison was made of the perceptions of the bioeconomy identified in research articles across different stakeholder groups. In particular, the research focused on differences in the selected sector and focus, as well as the underlying understandings and key challenges and opportunities.

Regarding the focus on the bioeconomy, the majority of articles either deal with it as a holistic concept (33.3%) or as a specific product, process, or sector (51.9%), with only a few addressing it as an underlying management principle (14.8%). Comparing the results per stakeholder group (Figure 14), this trend is generally consistent. However, some differences roughly align with the identified split between two clusters of stakeholder groups, as noted earlier.

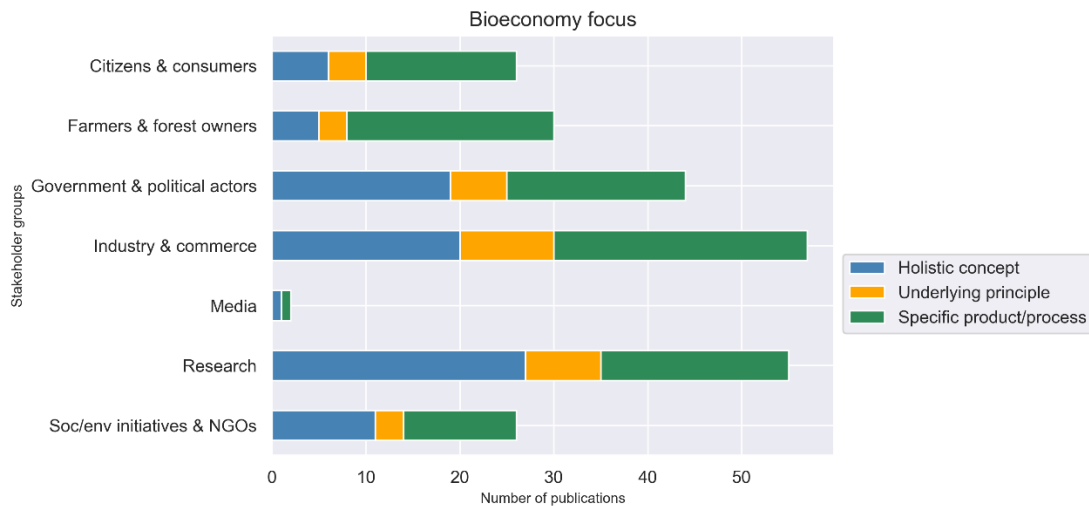


Figure 14. Bioeconomy Focus – by Stakeholder Group. Source: Dieken et al. (2021).

For *citizens & consumers*, *farmers & forest owners*, and *industry & commerce* stakeholders, articles primarily focus on specific products. On the other hand, stakeholders from research and government & political actors emphasize the holistic concept more. Social and environmental initiatives & NGOs exhibit a more evenly distributed focus, likely due to their relatively heterogeneous disposition.

The finding that articles on *industry & commerce* stakeholders have a product-oriented focus is expected, but it is surprising that *farmers & forest owners* and *citizens & consumers* are rarely asked about the broader concept of the bioeconomy. Instead, research on their perceptions seems to be confined to the acceptance and adoption of specific products and processes.

Similarly, it is surprising that researchers' perceptions are predominantly investigated in terms of the bioeconomy as a holistic concept, despite the articles indicating that this group of stakeholders is primarily involved in the research and development of specific

biotechnologies. Therefore, the results regarding the bioeconomy focus underscore the dominance of particular expert groups in bioeconomy research and policy.

The analysis reveals differences in stakeholder perspectives, prompting an investigation into whether stakeholder perceptions also vary in content. Comparing the elements of the bioeconomy addressed in the literature, the research shows a relatively even distribution across different aspects. The most prevalent elements include governance & regulation (25.9%), biomass production (17.6%), and utilization & biotechnology (15.7%). Conversely, there are fewer works on consumption (10.1%) and the ecological system (4.6%). Additionally, a significant portion of the research provides a general overview (25.9%). These findings support the earlier observations, indicating that articles predominantly focus on perceptions of the bioeconomy as a whole or on specific products related to the stages of biomass production or utilization in the bioeconomy.

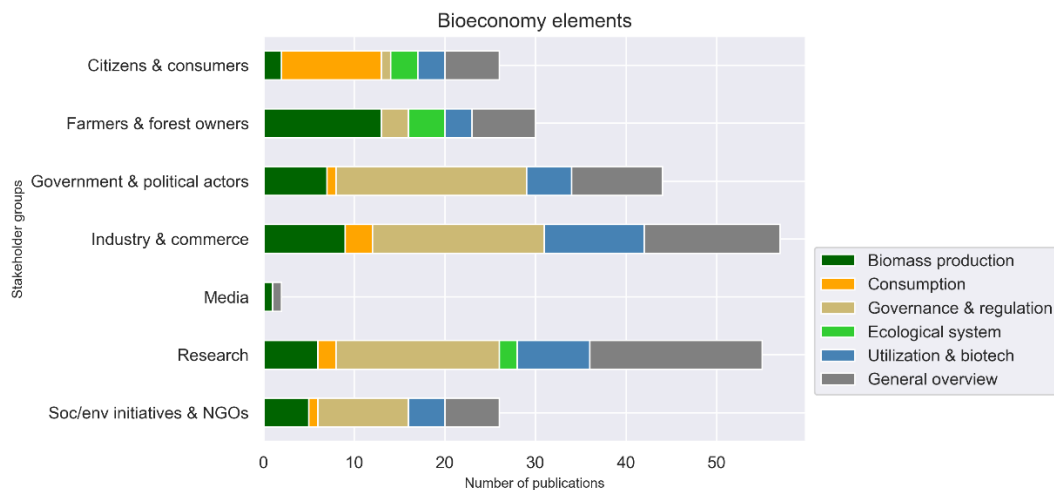


Figure 15. Bioeconomy Elements Focused on – by Stakeholder Group. Source: Dieken et al. (2021).

A comparison of results among stakeholder groups (as shown in Figure 15) reveals that many of the observed differences were in line with expectations. Notably, farmers & forest owners are predominantly addressed in relation to biomass production. Similarly, government & political actors and social and environmental initiatives & NGOs tend to be analyzed in terms of governance aspects. Citizens & consumers, on the other hand, are frequently examined regarding consumption patterns. This finding aligns with the earlier discussed notion that the general public is often surveyed about their consumption preferences rather than broader inquiries about the bioeconomy or its governance.

However, some outcomes are less anticipated. Particularly noteworthy is the exclusive focus on perceptions related to the ecological system, observed in studies concerning *citizens & consumers, farmers & forest owners*, and *research* actors. Intriguingly, this specific perspective is not at all addressed in studies involving *social and environmental initiatives & NGOs*. This might be attributed to the fact that the latter group is not the central focus in most articles and was only studied in conjunction with at least two other stakeholder groups, indicating that these articles concentrate on different aspects. Furthermore, this analysis reinforces the earlier finding that broader perceptions of the bioeconomy are predominantly explored within the stakeholder groups of *research, industry & commerce*, and *government & political actors*.

Comparing stakeholder groups in terms of their understanding of the bioeconomy, the differences become more evident. Overall, 40.7% of all articles did not distinctly align with any specific bioeconomy vision as defined by Bugge et al. (2016). This lack of alignment can be attributed to various reasons. Additionally, over half of the articles focus on specific products or processes, making it challenging to determine a clear overarching bioeconomy understanding in these cases. Consequently, a substantial portion of articles exhibited multiple or diverse understandings of the bioeconomy.

The analysis of bioeconomy visions revealed a nearly equal distribution between the bio-technology vision (26.9%) and the bio-resource vision (28.7%). In contrast, only four articles were identified as reflecting the bio-ecology vision. This demonstrates a considerable dominance of the technology- and resource-based perspective in bioeconomy perceptions. The notable focus on technology and resources may also be linked to the dominant stakeholder groups, as shown in Figure 16.

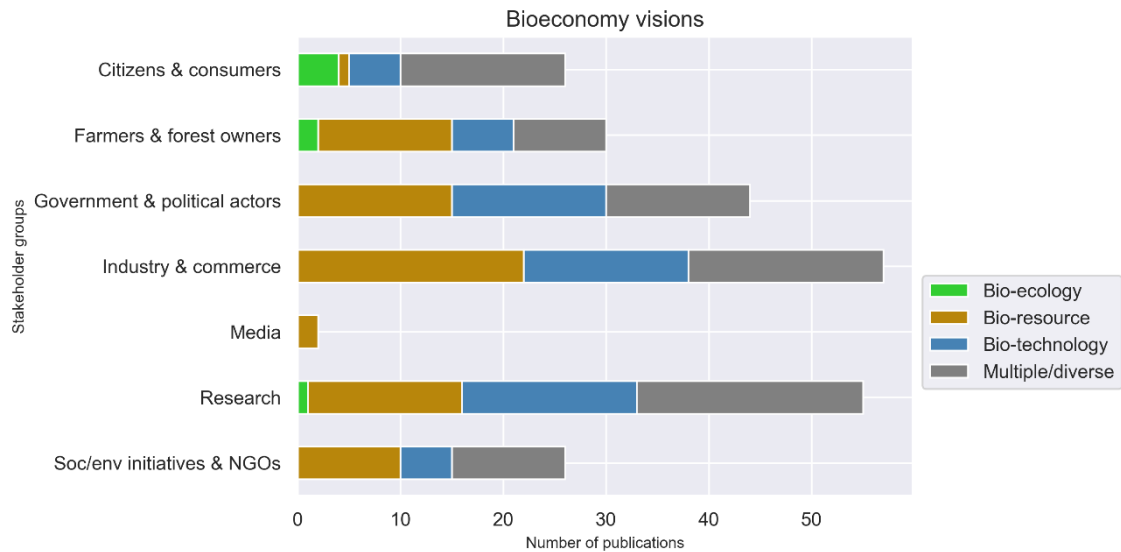


Figure 16. Bioeconomy Visions Identified – by Stakeholder Group. Source: Dieken et al. (2021).

The analysis revealed that *citizens & consumers* showed the highest diversity of visions, with 61.5% of the results containing multiple visions. For other stakeholder groups, 30-42% of the results were categorized as having multiple visions. Additionally, *citizens & consumers* were the only group notably associated with the bio-ecology vision. This vision was also found to a lesser extent in the groups of *research* and *farmers & forest owners*.

Moreover, the bio-resource vision was most prevalent among *farmers & forest owners*, *industry & commerce* actors, and social and environmental initiatives & NGOs, which is consistent with their thematic focus on biomass production. The presence of forest-related industries may explain the relatively noteworthy tendency towards the bio-resource vision among *industry & commerce* stakeholders. On the other hand, the bio-technology vision was mostly encountered among *citizens & consumers* (19.2%) and *research* (30.9%). Government & political actors were evenly divided between both visions (34.1% respectively).

These findings challenge, to a degree, the assumption of an overly dominant technology-based understanding of the bioeconomy. Instead, stakeholders' perceptions appear to be more evenly split between the bio-technology and bio-resource visions. Additionally, the bio-technology vision, often associated with elitist actors, was found to have strong support among other societal actors, including *citizens & consumers*, who also represented the marginal bio-ecology vision and held diverse understandings.

The majority of articles investigated multiple stakeholder groups, making it difficult to discern differences among individual groups, particularly those that were frequently analyzed together, such as *industry & commerce* and *government & political actors*. To address this issue, a separate comparison of bioeconomy visions was conducted within the subset of 43 articles that focused exclusively on one stakeholder group *Figure 17*.

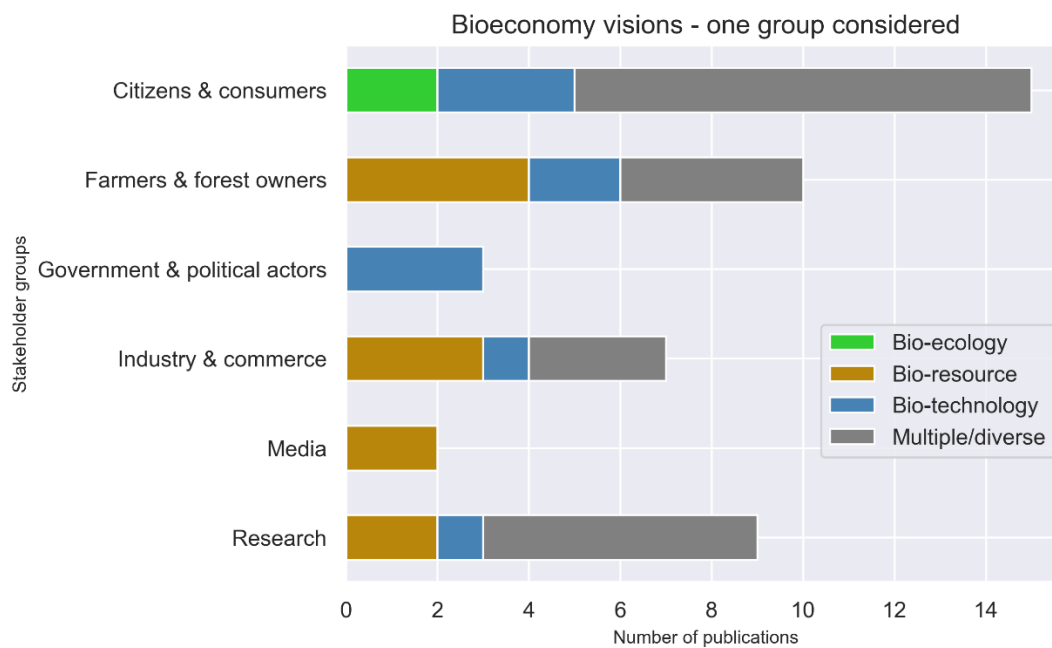


Figure 17. Bioeconomy Visions Identified in Articles Covering Only One Group. Source: Dieken et al. (2021).

When comparing articles covering only one stakeholder group to those that analyze multiple groups, some differences emerge in the bioeconomy visions. For *industry & commerce* and *research*, the focus on the bio-resource vision becomes more prominent in articles that exclusively investigate these stakeholder groups. Conversely, *government & political actors* are mainly analyzed in the context of a bio-technology vision, and this is evident in the limited number of articles that focus on this group.

Overall, the pattern remains consistent with the previous findings: a substantial portion of articles do not identify a prevailing vision (classified as multiple/diverse), while the remaining articles are divided between the bio-resource and bio-technology visions, with a slight inclination towards the bio-resource vision. The sole exception is the group of *citizens & consumers*, where articles show a split between the bio-ecology and bio-technology visions, with few articles focused on the bio-resource vision. Therefore, the comparison between articles analyzing single vs. multiple stakeholder groups leads to

similar conclusions: a considerable diversity of visions and a clear dominance of technology- and resource-based perspectives.

6.2.2.2 Methodological Approaches. The comparison of stakeholder-specific bioeconomy perceptions raises questions about the methodologies used in the literature. This is particularly interesting given the diverse and fragmented nature of research on bioeconomy perceptions. Analyzing the methodologies employed allows for understanding how the topic has been studied, identifying gaps, and discussing the implications of the findings.

The analysis reveals that research articles predominantly utilize qualitative (56.5%) or mixed methods (23.1%) approaches, while a minority (20.4%) employed a quantitative approach. The median sample size for qualitative studies was 23, while for quantitative studies, it was 218.5. Generally, the research focused primarily on explorative and in-depth analyses of specific stakeholder perceptions in a limited number of cases instead of conducting representative surveys of a broader population.

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This finding sheds light on the current state of research on bioeconomy perceptions. Despite the bioeconomy concept being present in political documents for up to two decades, research in the social sciences, especially regarding bioeconomy perceptions, is still in its early stages. Exploratory and qualitative works are more prevalent, allowing for the examination of views on the bioeconomy from individuals who may not be well-versed in the concept. However, this qualitative approach comes with limitations, such as a lack of comparability and explanatory strength in understanding broader patterns and trends across stakeholder groups.

Beyond the sample size, the methodology dissimilarity is also connected to the amount and kind of stakeholders examined. Quantitative studies predominantly focus on a single stakeholder group (68.2%), while this is less common for qualitative (36.1%) and mixed

methods (36.0%) studies. Particular stakeholder groups are also often analyzed in combination. For instance, government & political actors, industry & commerce, research, and social and environmental initiatives & NGOs are oftentimes examined together. This selection of stakeholder groups might reinforce the assumption of a coherent coalition between government and industry (and research) with common perceptions while civil society is separately investigated. Analyzing specific groups only in certain combinations or with specific approaches may blur potential differences or commonalities of perceptions across or within stakeholder groups. Even by employing a relatively general approach that relates sparse existing findings to each other, the assumption of the group of citizens as an outsider to the dominant bioeconomy discourse can already be questioned. This highlights the vital influence of methodology in determining bioeconomy perceptions and understanding the connections between different stakeholder groups.

6.2.3 Discussion

The literature review revealed that research articles covered various aspects and stakeholders related to the bioeconomy. There was considerable attention given to political, research, and industry actors, and these groups were often analyzed together. This supports concerns about the unequal participation of stakeholders in the bioeconomy debate, with a shortage of research on civil society actors and biomass producers being particularly notable.

The most prevailing stakeholder groups showed equal support for both the bio-technology and bio-resource understandings, which aligns with the assumption of those being the prevailing bioeconomy visions. Yet, the framework used in the analysis revealed noteworthy deviations. When examining individual stakeholder groups, it became evident that the bio-technology vision is mainly associated with political actors, while the bio-resource vision is more prevalent among industry actors. This highlights the necessity for a more nuanced analysis of government, industry, and research, as jointly analyzing them might oversimplify their perceptions and potential differences.

Additionally, the literature showed substantial support for a technology-based bioeconomy understanding among citizens and consumers. This suggests the potential for different coalitions than the prevailing assumption of a techno-centric group of specific

stakeholders and a marginalized civil society. Furthermore, citizens and consumers demonstrated notable support for the bio-ecology vision, which was only marginally present in findings on other stakeholders. The diversity of perceptions among citizens and consumers raises questions about where this large group stands regarding the bioeconomy.

Altogether, the joint analysis of stakeholder groups and the different methodological approaches for various groups indicate potential differences and commonalities that might be blurred. More research and further analysis are necessary to understand bioeconomy perceptions among various stakeholders comprehensively.

The lack of ecological and social concerns, as well as the underrepresentation of stakeholder groups associated with such concerns, is particularly noteworthy. This gap is exacerbated by the lack of research on developing and emerging countries. Not only does this neglect the global trade dimension of biomass and biotechnology, but it also overlooks issues of global justice related to the potential negative ecological and social implications of biomass production and consumption, which may be outsourced to developing countries.

For instance, out of 108 articles, only one focused on India, two on China, and none on Brazil, despite their significant involvement in bioeconomy-related activities. Additionally, there were only three studies concerning African case studies, specifically in the countries of Kenya, Madagascar, and Uganda. This lack of research on developing countries restricts the understanding of how bioeconomy activities impact these regions and their local communities. However, this observation might also be due to the usage of different terms.

The findings of this literature review challenge the bioeconomy concept's claim to contribute to sustainable development. The disconnect between the conceptualization of the bioeconomy as a pathway towards sustainability and stakeholders' perceptions, which primarily focus on national economic growth through biotechnology and biomass utilization, raises concerns. To ensure that the bioeconomy truly aligns with sustainability goals, it is crucial to closely monitor its impacts.

One central challenge is the delineation and differentiation of bioeconomy understandings among stakeholders. While the approach based on Bugge et al. (2016)

framework provided a comprehensive way to compare literature on bioeconomy perceptions, it has limitations in capturing differences identified in the field. Still, it proved its usefulness for the application in the referred case.

The prevalence of unspecified bioeconomy visions in the studies on bioeconomy perceptions suggests that stakeholders' understanding and reasoning about the bioeconomy may not neatly align with the conceptual frameworks developed by policy and research communities. This observation supports the notion that experts and researchers strongly influence the bioeconomy discourse. To address these conceptual and methodological challenges, there is a need for more research that takes an exploratory and inductive approach to analyzing visions. Such research can delve deeper into the differences between and within specific stakeholder groups, going beyond the generalized themes captured by existing concepts.

For instance, narrative analysis could be a valuable framework for identifying stakeholders' distinct arguments concerning the bioeconomy. This approach allows for a more detailed examination of stakeholders' perspectives and their unique reasoning, going beyond the broad categorizations used in this review.

The identification of stakeholder groups also presents challenges. Stakeholders frequently play multiple roles, and their positions can change depending on the context and the questions asked. For instance, a person may be both a farmer and a political actor, depending on the specific context in which they are involved. Moreover, some stakeholders may fall into multiple categories, such as ministerial researchers or farmers engaged in bio-refineries. This complexity can make it difficult to categorize stakeholders unambiguously. Even within seemingly clear stakeholder categories, there can be considerable variations. Farmers in different countries or regions may have different perspectives and interests related to the bioeconomy. To capture these complexities, this review chose to assign relatively broad stakeholder categories, allowing for identifying trends while avoiding an overly complex classification system.

Given the challenges in defining bioeconomy understandings and stakeholder groups, the methodological choices in studies of stakeholder perceptions become crucial. The choice of small-scale qualitative research highlights the difficulties in analyzing an elusive concept like the bioeconomy. However, qualitative approaches often address the

leading players in the bioeconomy debate, likely due to their prominence and influence. This suggests a need for more large-scale representative research, such as public surveys on national bioeconomy strategies, to identify key issues that are unknown to the public or on which perceptions may conflict.

The minor role of citizens and societal actors in research on bioeconomy perceptions can be partly attributed to their absence from bioeconomy governance processes, which makes their identification by researchers challenging. In light of these observations, the review reveals a concerning lack of engagement with the public in bioeconomy research. While there is a large and growing body of research on bioeconomy perceptions, it also highlights numerous open questions. Despite the diversity of research approaches and the complexity of the bioeconomy concept, the coding of three distinct visions allowed for categorizing individualized and context-specific perceptions into major lines of argumentation, providing a broad overview of the current state of research findings.

6.2.4 *Section Conclusion*

The review reveals a notable tendency towards case-specific and in-depth research focusing on a narrow set of stakeholders, particularly industry, political, and research actors, who predominantly hold a technology-based and resource-based understanding of the bioeconomy. Moreover, there is a considerable gap in considering the ecological dimension in stakeholder perceptions, and an absence of public involvement, raising questions about the bioeconomy's contribution to sustainable development.

To address these gaps, future research should prioritize the integration of diverse stakeholder groups beyond specific consumption topics, promoting a more inclusive approach. Additionally, further investigation is required to understand why the ecological dimension is less explored, specifically among stakeholders shaping the transformation process.

Given the fragmented and explorative nature of the existing literature, more in-depth and representative studies are necessary to examine potential differences between stakeholder perceptions while carefully accounting for methodological choices. This will enable a comprehensive understanding of stakeholder perspectives on the bioeconomy. Addressing these research gaps will contribute to a more robust assessment of the

bioeconomy's potential to foster sustainable development and promote greater inclusivity in its implementation.

The limited attention to ecological and social aspects and the underrepresentation of developing countries in the literature raise concerns about the comprehensiveness and global applicability of bioeconomy perceptions. Addressing these gaps is crucial to develop a more inclusive and sustainable approach to the bioeconomy that considers the perspectives and challenges faced by diverse stakeholder groups and regions worldwide.

As the review reveals ambiguity concerning the bioeconomy perceptions of citizens and consumers, the following section delves into the public's understanding of the bioeconomy, based on a representative survey of the German population.

6.3 Representative Survey²⁵

Issues concerning the bioeconomy are not free from conflicting objectives. A famous example in this connection illustrates the conflict between food production and fuel generation, necessitating addressing related aspects through dialogue with the society that integrates experts and citizens within the political processes (Fleischer et al., 2018). Related aspects have already played a central role with regard to the energy transition in Germany (Fischer et al., 2016; Schumann et al., 2016; Schürmann et al., 2019).

Hence, facilitating a successful transformation towards a sustainable bioeconomy demands understanding how the general public perceives the proposed modifications. This encompasses a thorough grasp of favorable associations, anticipations, and apprehensions and reservations. These aspects are particularly crucial, given that unrealized hopes and expectations have the potential to trigger an adverse reaction and obstruct desired changes. Evaluating and ensuring the effectiveness of connected communication strategies necessitates a more profound comprehension of citizens' viewpoints regarding the bioeconomy, particularly in Germany.

Previous research on stakeholder perspectives related to the bioeconomy primarily concentrates on specific groups, such as industry and research, with limited attention given to the viewpoints of the broader population. Thus, a survey at the national level is carried out to assess citizens' understanding, anticipations, worries, and viewpoints regarding diverse technological facets and trajectories of transformation. The objective of this is to provide decision-makers and researchers with valuable understandings concerning possible societal obstacles pertinent to communicating about and shaping the bioeconomy's advancement in Germany.

6.3.1 Background

Regarding Germany, there exists a shortage of empirical investigations into citizens' perceptions of the bioeconomy. A notable exception can be identified in the work of Hempel et al. (2019). They employed the Q methodology to empirically evaluate

²⁵ The following is based on a co-authored paper: Dallendörfer, M., Dieken, S., Henseleit, M., Siekmann, F., & Venghaus, S. (2022). Investigating citizens' perceptions of the bioeconomy in Germany – High support but little understanding. *Sustainable Production and Consumption*, 30, 16-30. <https://doi.org/10.1016/j.spc.2021.11.009>

perspectives regarding the bioeconomy in Germany. The researchers formulated 56 statements encompassing various aspects, such as sufficiency, biotechnology, and smart farming. Subsequently, 45 participants ranked these statements based on their level of agreement. The outcome revealed three distinct bioeconomy perspectives: *sufficiency and close connection to nature*, *technological advancement* and *not at any price*. Each of these perspectives underscores distinct goals and methods, consequently being linked to different procedures and technologies.

Approaches such as precision farming, genetic engineering, and circular economy find support from the *technological progress* perspective. Conversely, the *sufficiency and close affinity to nature* perspective advocates for strategies like organic farming and sufficiency principles. The third standpoint, *not at any price*, prioritizes considerations of cost-benefit ratios and price stability. As a result, the diverse processes and technologies encompassed within the bioeconomy notion are likely to resonate with distinct segments of the population. Notably, these three viewpoints bear resemblance to the three bioeconomy visions put forth by Bugge et al. (2016), known as the bio-technology, bio-resource, and bio-ecology vision.

The importance of acquiring additional data concerning citizens' perceptions was also acknowledged by the German Academy for Technical Sciences (AcaTech) and the Koerber Foundation (Koerber Stiftung & Deutsche Akademie der Technikwissenschaften, 2020). Through a representative survey that employed a stratified random sampling approach, 2006 participants were engaged in computer-assisted telephone interviews. The focus was on their technological interests and viewpoints regarding various bioeconomy facets. The findings demonstrate a widespread appreciation for the fundamental principle of substituting fossil resources with renewable alternatives. Moreover, there exists a perceived urgency to reevaluate consumption patterns for the sake of enhanced environmental protection. Bioplastics and biofuels garner substantial support, whereas genetic engineering in agriculture encounters resistance in favor of conventional breeding techniques. The acceptance of in vitro meat is relatively cautious, and gene therapies are primarily endorsed for adult applications.

Currently, there are only a limited number of studies that delve into the perspectives of German citizens on the bioeconomy, and these are primarily characterized by

descriptive approaches. Thus far, an elucidation of the varying degrees of support for a bioeconomy still needs to be included. Notably, pertinent insights from existing literature have the prevalence of ecological themes in the conception of the concept and the high hopes pinned on environmental benefits originating from the bioeconomy. Should citizens' perceptions of the bioeconomy be grounded in anticipation of addressing pressing environmental issues, a robust emphasis on environmental concerns would be imperative to ensure widespread acceptance and successful implementation. This is particularly vital as prevailing literature indicates that the dominant political interpretations of the bioeconomy accentuate technological innovation and the utilization of natural resources (Dieken et al., 2021; Dieken & Venghaus, 2020; Hausknost et al., 2017; Levidow et al., 2012, 2013; Priefer et al., 2017). Such divergent perspectives suggest a potential risk of disillusionment and opposition from segments of society.

6.3.2 *Methods and Procedure*

The variation in emphasis on the desired aspects of the bioeconomy transformation can significantly differ among different stakeholders, thereby influencing their anticipated benefits. Consequently, the objective is to examine citizens' comprehensive understanding of the bioeconomy. This involves analyzing their existing knowledge and expected outcomes. Subsequently, the investigation delves into the factors shaping their attitude towards the bioeconomy.

Since a considerable number of citizens may not yet be well-acquainted with the concept and are in the process of forming their attitudes towards it, factors such as information and prior familiarity are expected to have an impact. When framing the bioeconomy as a sustainability concept, the hypothesis is that support for it can be largely explained by individuals' expectations concerning both environmental and economic advantages stemming from the transformation. Within this framework, the study takes into account broader pro-environmental beliefs that indicate environmental consciousness, as well as beliefs related to growth and the open market, as explanatory variables. These variables are examined alongside more immediate expectations associated with the concept itself.

To address the existing gap in both descriptive and explanatory research concerning citizens' perspectives on the transformation of the bioeconomy, a survey was conducted

among the German population. The survey commenced by inquiring about respondents' associations with the term "bioeconomy." Subsequently, participants were presented with a definition of the bioeconomy as the utilization of renewable resources instead of fossil ones in production processes, underpinned by novel technologies and sustainability principles. This definition was formulated as an extension of the EU's definition (EC, 2018c), retaining the emphasis on renewable resources while encompassing issues related to technology and sustainability. Following this, respondents were queried about their perspectives on implementing such a bioeconomy concept.

Following pre-testing with around 30 participants and subsequent revisions, the survey was carried out in December 2019 by a professional market and opinion research agency. This survey was incorporated into an omnibus survey, conducted in tandem with a more extensive monitoring survey that centered on knowledge and attitudes regarding the German energy transition (*Energiewende*). Additionally, the survey encompassed a set of inquiries pertaining to general environmental and economic beliefs.

Conducted as computer-assisted telephone interviews, each interview had an approximate duration of 30 to 40 minutes. The total count of completed interviews was 1002. The sampling process was executed using proportionally stratified random sampling for German households. Stratification was based on federal states and districts or district-free cities. Randomization incorporated both landline and mobile numbers, with the exclusion of commercial numbers when known and the inclusion of non-registered numbers. Within households, the "birthday method" was employed to select the member with the most recent birthday and an age of at least 18 years. The sample composition effectively mirrors the German population in terms of age, gender, and education. Consequently, it seems plausible to extrapolate values and attitudes to a considerable extent for the broader German population.

The analysis and presentation of the results are structured in two stages: firstly, examining the initial understanding of the bioeconomy concept, and secondly, providing a descriptive overview of the bioeconomy perceptions among the German population.

To examine the interpretations that citizens associate with the bioeconomy, the method begins by categorizing and presenting their responses to the open-ended question.

Additionally, descriptive statistics are utilized to illustrate citizens' anticipated outcomes and inclinations concerning the bioeconomy transition.

6.3.3 Results

6.3.3.1 Understanding of the Bioeconomy. An examination of responses from the open-ended question reveals a diverse range of understandings concerning the bioeconomy, as presented in Table 10.

Table 10

Associations with the Term Bioeconomy

	Percent
Don't know / no idea	49.5%
Ecological economy	11.7%
Biomass / agriculture and energy	9.1%
Something with energy	6.5%
Something with renewable instead of fossil resources	5.9%
Something with nature or ecology	4.5%
Environmentally friendly production	3.9%
Something with agriculture	2.3%
Other	6.7%
Sum	100%

Source: Dallendörfer et al. (2022).

Around half of the respondents were unaware of the term *bioeconomy* and its meaning. Among the remaining participants, numerous associated it with agriculture or energy in some way. Those who viewed the bioeconomy as an ecologically-oriented economic system were somewhat closer to common definitions, yet their understanding of the concept remained vague.

Responses within this category, as well as those relating to environmentally conscious production or broader ecological and natural contexts, could also reflect a literal interpretation. This might be attributed to the association of the term *bio* with organic agriculture in the German context. Respondents who linked the bioeconomy to biomass, agriculture or just associated it with energy might have done so due to the context of the survey, which included questions about the German energy transition. Consequently, previous inquiries could have influenced these responses.

Only a small fraction (5.9%) of the population understood the term in relation to replacing fossil resources with bio-based resources. Given that this notion is central to the definitions of the bioeconomy in EU and German strategies, higher awareness of this facet was anticipated. Additional notions were centered around nature, ecology, environmentally-friendly production, or agriculture. Based on these findings, the understanding of the term "bioeconomy" remains rather diffuse at present.

6.3.3.2 Perspectives Towards a Sustainable Bioeconomy. Even though the open-ended question revealed limited familiarity with the bioeconomy concept, the notion of transitioning from a 'fossil' economy to a sustainable bioeconomy enjoys widespread support within the population. This endorsement becomes evident when the bioeconomy is defined as an economic framework based on renewable resource-utilizing technologies, as described at a later stage within the survey.

Most respondents supported such a transformation, while a small number held a negative perspective. However, a substantial portion considered the matter ambivalent. Considering the limited previous understanding of the bioeconomy, the concept, as commonly defined, seems to elicit a rather positive perception. Nonetheless, the substantial number of responses around the midpoint also suggests a need for more clarity about the practical implications of the bioeconomy.

When considering its implementation, people hold varying estimations of characteristic bioeconomy technologies. Based on the findings, the use of renewable materials in the building and construction sector, as well as in everyday products like packaging, is widely appreciated. Yet, the perception of biofuels and biogas is less favorable. On a seven-point scale, about 35% (biogas) and 37% (biofuels) of respondents chose scores of 4 or lower, indicating that just about over 60% hold a preference for these technologies.

In contrast, the acceptance of bioplastics and organic construction materials is more pronounced, with only approximately a quarter of respondents opting for the mid-point score of 4 or lower. The expansion of organic farming receives strong approval, as more than three-quarters of respondents assign scores higher than 4, and 36% express the highest preference with a score of 7.

As expected, genetic engineering in agriculture is met with strong rejection, with only 25% showing a willingness to (rather) endorse it and 52% (rather) oppose it. In a medical context, the acceptance is more mixed, with 35% favoring it and 39% rejecting it. Similarly, genetic engineering in an industrial context is viewed unfavorably, with 46% selecting scores between 1 and 3 and only 29% choosing scores of 5 or higher.

Considerable opposition in the agricultural context is expected. Yet, the reluctance toward genetic engineering in the industrial sector is noteworthy, considering that industrial genetic engineering typically does not encompass products intended for human food consumption or the introduction of genetically modified organisms into the environment, which are the primary concerns frequently associated with rejecting GMOs in agriculture (Bonny, 2003).

Furthermore, there is a strong endorsement of circular processes and recycling, with 80% of respondents choosing scores between 5 and 7. A similar trend is observed for improving information and education about the bioeconomy. Moreover, at least 70% of respondents indicate a preference (scores 5 to 7) for enhancing the participation of individuals and companies in the transformation process towards a bioeconomy. This underscores the apparent necessity for improved communication strategies concerning the bioeconomy.

In the subsequent segment of the questionnaire, participants were requested to express their anticipations regarding a sustainable bioeconomy as a solution for various environmental challenges. The responses demonstrate that the notion of a sustainable bioeconomy is widely acknowledged as a potential resolution for numerous environmental issues, particularly those concerning non-living components of the environment.

Slightly more skepticism emerged in the case of reducing species extinction and the loss of unspoiled nature, which also echo concerns frequently articulated by scholars and experts in this domain. These items revolve around the potential consequence that the heightened demand for renewable materials might result in an expansion of cultivated landscapes, thereby diminishing their status as habitats for species and as elements of unspoiled nature. Notably, many respondents anticipate that the transition to a

bioeconomy will mitigate problems associated with plastic waste in the environment and oceans.

This inclination could stem from the fact that bioplastics constitute one of the most tangible and experiential categories of bio-based products that consumers may have encountered. In this context, the prospect of bio-degradability might indeed offer substantial advantages. However, it is crucial to acknowledge that bioplastics are not universally biodegradable, a distinction often confused in public discourse. Consequently, these findings likely embody rather exaggerated expectations.

A comparable question was asked with regard to the bioeconomy's potential to address economic challenges. Participants were prompted to express whether they leaned towards agreement or disagreement regarding the bioeconomy's contribution to specific economic issues, or they could opt not to respond. The outcomes reveal that economic benefits are primarily anticipated in terms of generating new employment opportunities and advancing novel domains of research and education. These advantageous expectations align harmoniously with the emphasis on research, education, and the objectives of the bioeconomy as pursued by the predominant bio-resource and bio-technology visions. To all stated challenges, a minimum of half of the respondents hold an optimistic view that the bioeconomy could lead to improvements. Still, the proportion of participants choosing not to answer is higher compared to the previous question addressing environmental challenges. This could potentially be attributed to factors such as reduced familiarity with these economic matters, a higher level of abstraction, or the absence of a neutral response option.

Subsequently, participants were asked to denote their level of acquaintance with several subjects associated with the bioeconomy transformation process. Respondents were given the option to specify whether they were completely unaware of a particular topic, possessed some knowledge of it but lacked substantial information, or considered themselves rather well-versed in it. As per their self-assessment, the majority of respondents only felt relatively well-informed about the subject of *coal phase-out*, a perception consistent with the extensive media coverage surrounding this topic during the interview period. Around half of the participants indicated having some degree of familiarity with regional structural change, as well as with the SDGs and digitization in

agriculture. Conversely, the topics related to genetic engineering received the least recognition, with the cultivation of energy crops following closely in terms of familiarity.

6.3.4 Discussion

Based on survey findings, familiarity with the bioeconomy as an economic concept is limited during this study. About half of the participants lacked associations with bioeconomy, while others linked it to eco-friendly production or nature-related aspects. Particularly in the German context, this could be due to how the term is understood, possibly influenced by a direct translation. In German, *bio* also means organic, making it more familiar to respondents in the context of organic food labels rather than biological resources. This viewpoint aligns with the results presented by Stern et al. (2018), where they similarly observed numerous connections with organic agriculture in an open-ended query in Austria.

In contrast, just a small number of participants connect the bioeconomy with replacing fossil fuels with renewable sources, as emphasized in various official strategies. Nonetheless, those who make this connection tend to exhibit more favorable attitudes toward the bioeconomy, likely due to their prior familiarity or engagement with the concept. The limited awareness is unsurprising given that the bioeconomy was still relatively novel and had yet to garner substantial attention in German public discourse as of 2019, when the survey took place. Yet, there has been an uptick in media exposure and greater engagement with the subject since the survey, notably with the release of the German bioeconomy strategy and the advent of the scientific year of the bioeconomy. Thus, it is possible that awareness has since grown.

If presented with a broad vision of a transition toward a sustainable bioeconomy, most of the populace expresses approval, viewing it as a viable approach to address significant environmental and economic challenges. This result is promising, although caution is necessary. Due to a lack of comprehensive knowledge on the subject, many respondents conceivably expressed support based on spontaneous, optimistic associations. Public sentiment could quickly shift if the high positive expectations associated with the bioeconomy are not realized in practice.

Moreover, not all aspects of bioeconomy-related technologies are equally popular. Particularly, the utilization of genetic engineering technologies in agriculture and industry tends to be met with skepticism, with more individuals opposing its integration into the bioeconomy than supporting it. Views regarding the application of genetic engineering in medicine are divided. These outcomes align with results from further surveys (Hempel et al., 2019; Koerber Stiftung & Deutsche Akademie der Technikwissenschaften, 2020).

This divergence in opinions may arise from the perception of the bioeconomy as a sustainability-driven transformation, as described in the provided definition within the survey. Genetic engineering, especially in the context of GMOs in agriculture, is not commonly linked with positive sustainability outcomes in public discussions. In contrast, within the medical realm, genetically engineered bacteria have been widely employed for many years, offering clear benefits such as the production of insulin (as demonstrated in Leader et al., 2008), without sparking substantial recent public debates. Another noteworthy distinction lies in concerns about GMOs in agriculture, often centering on their release into the natural environment. This matter is not typically associated with established medical procedures utilizing GMOs to produce various biological substances.

Comprehensive and reliable information regarding the advantages and drawbacks of these technologies could have a powerful impact on the transformation process towards a sustainable bioeconomy. In this regard, it would be promising to assess whether attitudes towards genetic engineering in medicine have shifted in the aftermath of the Covid-19 pandemic. This is pertinent because techniques akin to genetic engineering (such as the application of recombinant DNA to develop vector-virus vaccines) played a crucial role in developing effective vaccines (see e.g. van Riel and de Wit (2020)).

Broader and easier-to-understand information dissemination might foster a generally more favorable outlook on the subject, particularly in non-agricultural contexts. However, emphasizing genetic engineering within the framework of the bioeconomy transformation carries the potential risk of generating opposition from environmentally-conscious individuals who presently endorse the concept. Consideration of these issues informs prospective governance approaches in the context of the bioeconomy and related policymaking.

Altogether, the findings suggest that the bioeconomy concept garners significant positive reception, primarily due to the high expectations linked with it. This broad support bodes well for effective development and implementation. However, these heightened expectations could pose challenges in light of the fact that respondents generally possess limited prior knowledge of the concept and demonstrate relatively low familiarity with associated issues, except for the coal phase-out. The bioeconomy concept is frequently advocated in political strategies as a comprehensive approach to advancing sustainability across various domains. Nevertheless, as technologies and projects are put into action, trade-offs may become more visible, making it difficult to meet unrealistically optimistic expectations regarding the transition to a sustainable bioeconomy.

Hence, the assertion here is that to sustain a high level of support, it is crucial to convey information about the bioeconomy, not solely as an abstract concept but also by highlighting concrete projects along with their particular advantages, constraints, and trade-offs. In light of the greater trust placed in information about the bioeconomy originating from civil society organizations, implementing participatory governance involving social and environmental NGOs becomes vital since these organizations engage with environmentally-conscious citizens who presently endorse the shift toward a sustainable bioeconomy.

Given the high expectations regarding economic and environmental advantages, it is essential to establish a robust monitoring framework for the bioeconomy (see e.g. Jander and Grundmann (2019); Jander et al. (2020); Kardung et al. (2021)). This framework should ensure that the technologies and projects implemented as part of the transformation do indeed yield positive impacts on environmental, economic, and social aspects. This monitoring is vital not only for substantiating the contribution to sustainability but also for sustaining public support and enabling transparent and plausible communication. Developing such a framework will therefore play a central role in the next step of the analysis.

Should the actual outcomes fail to align with respective expectations concerning economic and environmental benefits, there exists a noteworthy risk of diminishing support for the bioeconomy, potentially leading to opposition from certain segments of society. Consequently, placing a strong emphasis on and fortifying sustainability

measures within the national bioeconomy strategy and the execution of associated projects can play a pivotal role in upholding the generally positive perception of the bioeconomy and securing public support for and involvement in political decisions within this realm.

In this regard, the results highlight that the German populace places greater trust in civil organizations and scientists compared to the government when it comes to information about the intended transformation. Consequently, adopting decision-making processes that involve multiple stakeholders could promote mutual comprehension and facilitate the exchange of knowledge and ideas in an open and inclusive discourse.

6.3.5 *Section Conclusion*

This section lays out and analyzes the current perception of the German population regarding the bioeconomy, based on a representative survey conducted in December 2019. The findings reveal that the understanding of the term "bioeconomy" is presently ambiguous and does not align with the fundamental concept of substituting fossil resources with renewable, bio-based resources, as outlined in common definitions found in policy documents and strategies. This highlights the necessity for improved communication strategies to prevent misunderstandings and unrealistic expectations among the general population.

When examining support for a transformation characterized by replacing fossil resources with renewable alternatives, it becomes evident that the core concept and its underlying aspirations receive broad support within the population. This suggests that effective communication of this fundamental aspect of the bioeconomy has the potential to amplify widespread support for the planned transformation process.

Altogether, this work contributes to the literature investigating stakeholders' perspectives on the bioeconomy. It accomplishes this by offering insights into the level of support among German citizens for the bioeconomy, their expectations regarding the envisioned transformation, and their level of knowledge on this subject.

6.4 Chapter Summary

Based on findings from a focus group workshop, a systematic literature review, and a representative survey of the German population, this chapter defines the decision problem in more detail and identifies key social actors. These elements are foundational to understanding stakeholder perspectives and public perceptions of the bioeconomy, enabling a comprehensive analysis of the decision-making context.

The focus group workshop provided initial insights into stakeholders' priorities and concerns. Three main themes emerged: the importance of regional value added, environmental sustainability, and the just distribution of financial burdens. Participating stakeholders emphasized the need for initiatives related to the bioeconomy to generate economic benefits within the RR, to be consistent with environmental goals, and to ensure fairness in the distribution of financial liabilities. These findings underscore stakeholders' desire to balance the economic, environmental and social dimensions of the bioeconomy. Moreover, they provided valuable input for the subsequent coding scheme developed for the systematic literature review.

The systematic literature review highlighted the prevailing focus on actors from political, research, and industry groups in bioeconomy-related research, with these groups often analyzed collectively. Respective groups frequently support a technology-based understanding of the bioeconomy and there is a notable lack of emphasis on ecological and social concerns. The review also identified a notable gap in studies that address the perspectives of developing and emerging economies, overlooking global trade and equity issues related to biomass production. In addition, the literature suggests that while citizens and consumers support a bioecological vision, their role in the discourse remains marginal, reflecting their underrepresentation in bioeconomy governance and research. This disconnect between the conceptualization of the bioeconomy and stakeholder perceptions, which tend to focus on national economic growth through biotechnology, raises concerns about the alignment of the bioeconomy with sustainability goals.

The representative survey provided further insights into public perceptions of the bioeconomy. The results revealed limited familiarity with the bioeconomy among the German population, with many participants associating it with environmentally friendly production rather than the substitution of fossil resources with bio-based alternatives.

Despite this ambiguity, the concept of the bioeconomy was generally well received, with high expectations for its economic and environmental benefits. However, the survey also highlighted the challenges posed by these expectations, given the public's limited knowledge of the bioeconomy. The potential trade-offs that may emerge as technologies and projects are implemented could complicate the transition to a sustainable bioeconomy, making clear communication and robust monitoring essential.

Overall, this chapter contributes to a comprehensive understanding of the decision problem, its context, and existing lines of conflict, as well as the identification of key societal actors (*RQ 1-4*). The next section focuses on the development of a monitoring framework and the specification of decision alternatives (*RQ 5-6*).

7 Regional Transformation Pathways²⁶

Following the analytical framework, this chapter proceeds with *Step II*, consisting of structuring the decision problem by defining the evaluation criteria and defining the decision alternatives. Thus, this chapter outlines a novel approach to translating global SSPs into RTPs specifically tailored for the bioeconomy transformation.

It begins by providing the necessary background. The chapter then details the methodological approach, starting with the development of narratives for the RTPs, followed by a systematic method for identifying indicators for the monitoring system, and finalizing with the quantification of the respective RTPs. Subsequently, five distinct RTPs are presented and the results are discussed.

At the end of the chapter, the evaluation criteria are defined and the decision alternatives in the form of regional transformation pathways are developed. A summary section concludes the chapter.

7.1 Background

Leipold et al. (2023) underscore the relevance of three pivotal research domains crucial to the expanding realm of CE knowledge. These areas aim to enhance communication with policymakers and decision-makers. The first involves exploring diverse narratives related to the CE, the second entails integrating technical, managerial, socio-economic, environmental, and political viewpoints, and the third necessitates a critical evaluation of the opportunities and constraints arising from the interplay between CE science and policy. Considering the common features of research on the bioeconomy, it is argued that these suggestions are equally applicable.

Based on narratives derived from SSPs, this work presents a novel approach to developing RTPs for implementing a sustainable bioeconomy.²⁷ Using SSPs as a starting point, pathways can be developed that are consistent with the established narratives within the scientific community, while at the same time being tailored to the needs of

²⁶ The following is based on a co-authored paper: Siekmann, F., & Venghaus, S. (2024). Regional transformation pathways for the bioeconomy: A novel monitoring approach for complex transitions. *Journal of Industrial Ecology*, 28(3), 603-616. <https://doi.org/10.1111/jiec.13484> CC BY 4.0.

²⁷ For an in-depth discussion of transformation pathways, the SSPs and their role for policy, see section 3.2.3.

decision-makers in a regional context and making them more tangible. In this manner, efforts are directed towards addressing challenges arising from the interaction between science and policy in the development of future bioeconomy policies. Within the developed framework, consideration is given to managerial, socio-economic, environmental and political factors. The comprehensive approach assures that the analysis and associated recommendations take into account the intricacies of transitioning to a sustainable and inclusive bioeconomy.

To demonstrate the practicality of the approach, it has been applied within the regional transformation process to establish a sustainable bioeconomy in the RR. The conceptual framework outlined in this work provides a valuable foundation for researchers and policymakers to navigate the transition to a low-carbon economy.

The remainder of this section is structured as follows: First, the key features of the SSP narratives are summarized, serving as basis for the development of the RTP narratives is presented, along with the systematic process used to derive the indicator system, which served to the creation of the set of transformation trajectories. The results of the methodology are presented in the next section. This is followed by an elaboration of the features of the set of RTPs, focusing on the potential of the approach to inform decision-making processes. Finally, the discussion concludes by examining the implications of the findings, identifying key limitations, and presenting suggestions for future research directions.

7.1.1 Shared Socioeconomic Pathways Narratives

Key aspects of the existing SSP narratives were extracted and summarized (see Figure 18) to develop the RTP narratives. Particular attention was given to those aspects that are at the core of the respective transformation path and to those elements that are of interest for regional development and imply interdependencies. Table 11 outlines the core elements of each SSP narrative, derived from O'Neill et al. (2017).

Table 11*Overview of SSPs 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 towards 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 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 & human capital - Exploitation of fossil resources - Energy intensive lifestyles - Rapid economic growth - Local environmental problems addressed (e.g., air pollution)
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Source: Siekmann and Venghaus (2024), CC BY 4.0.

7.2 Methodological Approach

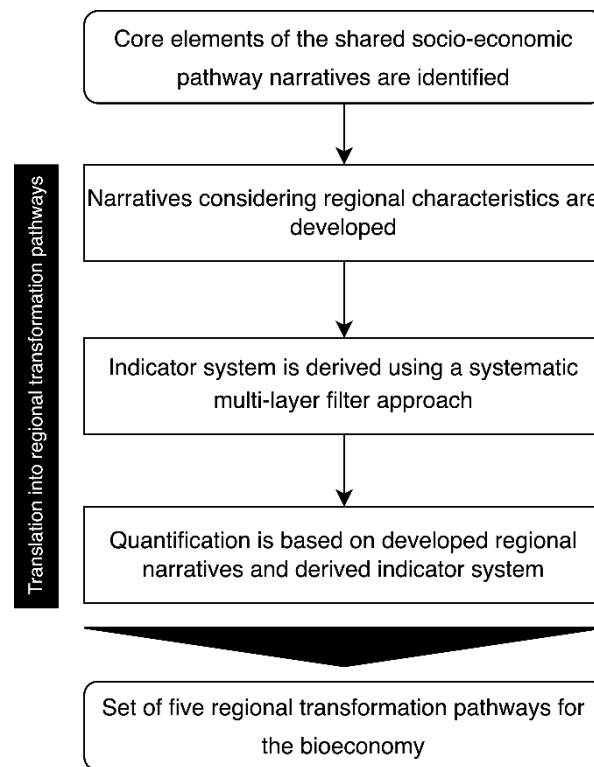


Figure 18. Developing the Regional Transformation Pathways – Overview of Steps. Source: Siekmann and Venghaus (2024), CC BY 4.0.

The overall steps of the developed approach are shown in Figure 19 and are now explained in further detail.

7.2.1 Developing Narratives for Regional Transformation Pathways

The development of the SSP narratives provided guidance for the RTP narrative creation process (O'Neill et al., 2017). Altogether, three considerations were central.

First, the RTP narratives, while grounded in the SSPs, address challenges important to bioeconomy transitions. Second, they incorporate core features related to the context of RR and the perceptions of stakeholders engaged in the transition. Third, they must be consistent with the core elements of the SSP narratives, while taking into account regional characteristics. These considerations involved an iterative process between the stated goal of creating RTP stories consistent with the SSPs and the identification of contextual narrative elements and assumptions. This approach provides a solid foundation for the quantification that follows, increasing transparency and allowing researchers to relate to the underlying key assumptions.

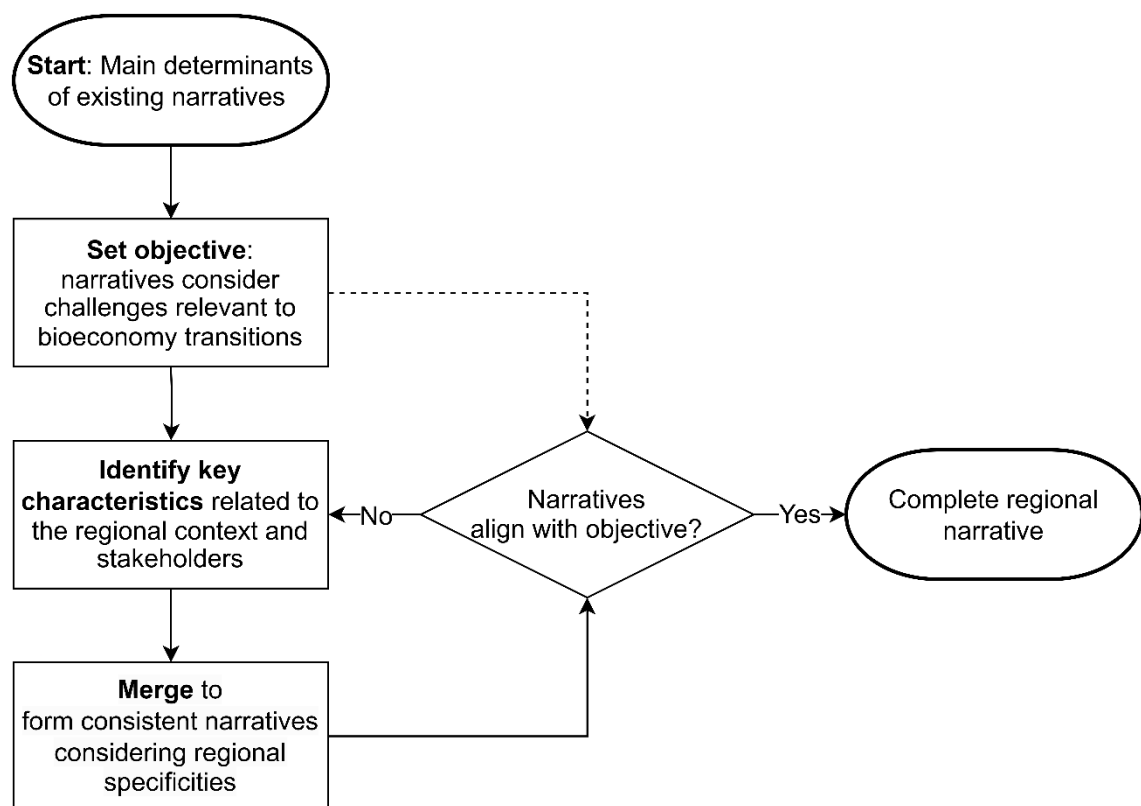


Figure 19. Narrative Development for Regional Transformation Pathways Illustrated as flowchart, guided by O'Neill et al. (2017). Source: Siekmann and Venghaus (2024), CC BY 4.0.

The content of the RTP narratives was developed based on an in-depth familiarization with the decision context in three steps, building upon *Step I* of the overall analytical framework (Section 5.11). This included a focus group workshop, systematic literature analysis on stakeholders' perceptions of the bioeconomy as well as a representative survey of the German population (Dallendörfer et al., 2022; Dieken et al., 2021). The outcome of *Step I* was thus incorporated into the narratives and the associated transformation paths.

7.2.2 *Deriving the Indicator Framework*

The indicator framework developed in this work emphasizes a holistic approach and is designed to encompass not only the bioeconomy itself, but also its contribution to sustainability as defined by the SDGs. This is achieved by linking indicators from the GSDS on the basis of their relevancy to the concept of the bioeconomy. This makes it possible to use a robust set of data that includes information on the current state and the corresponding target values for each indicator. On the basis of the work of Calicioglu and Bogdanski (2021) and the principles and criteria for a sustainable bioeconomy (FAO, 2021), a systematic multilevel filter approach (SMLFA) is developed to identify a comprehensive set of indicators aimed at capturing relevant aspects of the transition process. To be included in the resulting framework, each indicator must meet four requirements:

First, it must be part of the global SDGs. The SDGs provide a broad and well-established basis, often supported by widely available data sources, to guide research and policy activities. In addition, the possibility of transferring the developed approach to other regions is enhanced by using the SDGs.

Second, the indicator must cover elements of relevance to a sustainable bioeconomy. This is based on the principles and criteria of a sustainable bioeconomy as set out by the ISBWG (FAO, 2021) and the analysis of Calicioglu and Bogdanski (2021).

Third, an indicator needs to be embedded in national sustainability strategies. The rationale is that this enables national priorities to be taken into account and strengthens the legitimacy of the aspect being measured. For the RR, the relevant policy document is the GSDS (BReg, 2021b).

The fourth criterion is the evaluation of indicators in terms of their relevance to the decision problem under consideration. For instance, SDG 14 indicators covering issues linked to sustainable fishing practices in the oceans may not be of interest for a transformation process in a landlocked region, or in cases where the target has already been achieved at the time of data collection.

Figure 20 illustrates the conceptual approach and the corresponding filter layers.

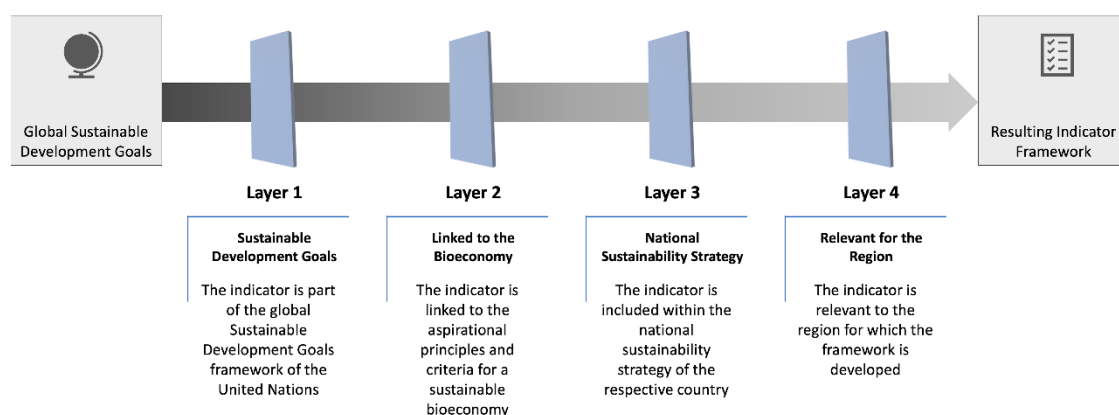


Figure 20. Conceptual Illustration of Systematic Multi-layer Filter Approach. Source: Siekmann and Venghaus (2024), CC BY 4.0.

In order to ensure that the obtained set of indicators provides a balanced representation of the social, economic and environmental dimensions of sustainability, the indicators are categorized and mapped according to their characteristics. Furthermore, the identified indicators can be categorized according to the three central dimensions of the bioeconomy, biotechnology, bio-resources and bioecology, as laid out by Bugge et al. (2016). The mapping of indicators along these bioeconomy visions helps to provide an overview of potential unintentional biases in certain perceptions, to increase transparency, and to highlight unbalanced aspects for targeted improvements where needed.

7.2.3 *Building Regional Transformation Pathways*

In order to finalize the RTPs, the previous steps need to be brought together. The subsequent quantification is based on the developed narratives (see Table 12) and the derived indicator system (see Table 13). Reports from the German Federal Statistical Office, which provide information on the monitoring of the GSDS indicators, form the basis for the indicator data on which the RTPs are formulated. It is derived from the publicly available data sources used for the GSDS.²⁸

²⁸ Further information on each indicator can be found in the Supplementary Information (SI) section: Siekmann, F., & Venghaus, S. (2024). Regional transformation pathways for the bioeconomy: A novel

RTP 1 is designed as *SDG Pathway*. Thus, the target data in the GSDS are the basis for the corresponding values. The target values for the indicators at federal and state level in NRW were adopted by default as defined in the GSDS and the NRW SD strategy. In cases without a value for NRW, the national target value was used. In cases without an explicit target value, the target value was derived from the indicator description in the GSDS.

RTP 2 *Incremental Progression* is portrayed as a pathway that achieves half of the SDG target because, as the name suggests, it makes incremental progress but does not completely achieve the objectives of the GSDS.

The narratives accompanying the remaining RTPs form the foundation for assessing the trend of each indicator. If the narrative assumes an optimistic development, a positive trend is also assumed for the respective indicator, whereas if the narrative assumes a negative one, this is correspondingly reflected in the trend of the respective indicator.

The remaining RTPs are built using a four-scale scheme. It includes much improved (++), improved (+), worse (-), and much worse (--). Historical data was used to calculate target values for individual indicators:

- Much improved (++): The compound annual growth rate (CAGR) for each year was calculated using historical data. Subsequently, to account for years with exceptionally high CAGRs, the 75th percentile (third quartile) of the resulting CAGRs was used.
- Improved (+): The incremental progress achieved was assumed to be half of the SDG target. Thus, the same value as in RTP 2 is derived for the corresponding value.
- Worse (-): In line with the GSDS, which advocates urgent and profound change, the assumption in these cases mirrors the perspective that the current status quo is unsustainable (BReg, 2021b). Within the overall context of the climate crisis and biodiversity loss, continuation of the status quo is seen as a disadvantageous starting point for the future, with potentially limited options to mitigate undesired developments. In this way, worse can be perceived as similar to business as usual

monitoring approach for complex transitions. *Journal of Industrial Ecology*, 28(3), 603-616. <https://doi.org/10.1111/jiec.13484>.

and worse in comparison to the targets set by the SDGs. The most recent available CAGR is used to calculate the value.

- Much worse (--): As with ‘much better’, each year's CAGR was calculated using historical data. The target was then determined using the 25th percentile (first quartile).

The future value formula below is used for the calculations,

$$FV = PV * (1 + r)^t, \quad (18)$$

where PV is the present value, r is the interest rate (CAGR in this case), and t is the number of years. The formula constitutes a useful tool because it enables the projection and evaluation of the long-term effects of several factors relevant to sustainability, in order to support evidence-based decision making and planning. It is often used to identify trends and evaluate indicators that lack quantified targets (eurostat, 2023). The formula is consistently applied to all indicators, regardless of their unit, including application to indicators originally reported as percentages.

7.3 Results

Five narratives were developed based on the SSPs and familiarity with regional conditions and stakeholder expectations in the region. The full set of RTP narratives developed is presented in Table 12.

Table 12*Overview of Regional Transformation Pathway Narratives*

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 towards more sustainability, but the willingness to pay for regional products and the acceptance of novel, biobased products is 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, 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.

Note: Based on the Shared Socioeconomic Pathways. *Source:* adapted from Siekmann and Venghaus (2024), CC BY 4.0.

Deriving the indicator system was the next step. The 231 indicators in the global SDG framework and the 72 in the GSDS framework were reduced to 18 using the SMLFA. The obtained indicator framework as well as the mapping along the sustainability dimensions and the bioeconomy vision are presented in Table 13.

Table 13

Derived Indicator System and Categorization

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 gov. in attaining approp. nutr. 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 renew. energies in gross final energy consumption	Environmental	Technology
8.1	8.4.2	Raw material input productivity	Economic	Resource
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	Technology
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

Note. Categorization according to sustainability dimensions and bioeconomy visions. GSDS: German Sustainable Development Strategy 2021, SDG indicator: Global SDG reference indicators. Source: adapted from Siekmann and Venghaus (2024), *CC BY 4.0*, bioeconomy visions of indicators 8.1 and 10.2 adjusted.

The application of the SMLFA results in a balanced set of eighteen indicators: six related to the economic dimension, six to the environmental dimension, and six to the social dimension. These indicators are further categorized into six related to the technology perspective, six related to the ecology perspective, and six related to the resource perspective, in line with the bioeconomy visions introduced by Bugge et al. (2016). In addition, it includes indicators that are linked to twelve goals from the national GSDS and eleven goals from the global SDG framework.²⁹

²⁹ The discrepancy is due to indicator 5.1.a, which is associated with SDG eight in the global framework but falls under SDG five in the national GSDS.

Following the methodology introduced, the construction of the remaining RTPs required the consolidation of previous work steps and the use of narratives associated with each indicator. Each of these narratives, reflecting either optimistic or pessimistic assumptions, formed the basis for assessing the trend of each indicator. RTPs were quantified using a four-point scale: much improved (++), improved (+), worse (-), and much worse (--). The results are listed in Table 14.

Table 14

Narrative-based Trend Evaluation

GSDS	SDG	Description	RTP 1	RTP 2	RTP 3	RTP 4	RTP 5
1.1.a	1.2.2	Material deprivation	SDG	½ SDG	-	--	++
1.1.b	1.2.2	Severe material deprivation	SDG	½ SDG	-	--	++
2.1.b	2.4.1	Organic farming	SDG	½ SDG	+	-	-
2.2	2.a.2	Support for good gov. in attaining approp. nutr. worldwide	SDG	½ SDG	--	--	-
5.1.a	8.5.1	Gender pay gap	SDG	½ SDG	-	-	++
6.1.a	6.3.2	Phosphorus in flowing waters	SDG	½ SDG	--	+	++
6.1.b	6.3.2	Nitrate in groundwater	SDG	½ SDG	--	+	++
7.1.a	7.3.1	Final energy productivity	SDG	½ SDG	-	+	+
7.1.b	7.3.1	Primary energy consumption	SDG	½ SDG	--	+	--
7.2.a	7.2.1	Share of renew. energies in gross final energy consumption	SDG	½ SDG	-	+	-
8.1	8.4.2	Raw material input productivity	SDG	½ SDG	+	+	++
8.4	8.1.1	Gross domestic product per capita	SDG	½ SDG	+	+	++
9.1.a	9.5.1	Private and public expenditure on research and development	SDG	½ SDG	--	+	++
10.2	10.2.1	Gini coefficient of income after social transfers	SDG	½ SDG	-	--	++
11.2.c	11.2.1	Accessibility of med.-sized and large cities by pub. transport	SDG	½ SDG	-	-	-
12.2	12.6.1	EMAS eco-management	SDG	½ SDG	+	-	--
15.1	15.5.1	Biodiversity and landscape quality	SDG	½ SDG	+	-	--
17.3	17.11.1	Imports from least developed countries	SDG	½ SDG	--	-	++

Note. GSDS: German Sustainable Development Strategy 2021, SDG indicator: Global SDG reference indicators. *Source:* adapted from Siekmann and Venghaus (2024), CC BY 4.0.

RTP 1 is formulated on the basis of the GSDS target values and is aligned with the corresponding sustainability goals. RTP 2 takes a more middle-of-the-road approach, achieving half of the GSDS targets, and is therefore less ambitious in terms of progress towards sustainability.

For RTP 3, the results show indicators with mixed degrees of improvement and deterioration. In particular, indicators reflecting significantly worse performance (occurrences of (--): 6) highlight areas of concern, while indicators with a negative rating (occurrences of (-): 7) indicate potential challenges. At the same time, several indicators show improvement

(occurrences of (+): 5), indicating progress in certain areas. There were, however, no indicators that were rated as much improved (occurrences of (++): 0) within this pathway.

With respect to RTP 4, the findings show indicators that reflect a much worse performance (occurrence of (--): 4) in several areas that necessitate attention. In addition, indicators that receive an unsatisfactory rating (occurrences of (-): 6) indicate potential challenges that need to be addressed. Positively, several indicators show improvement (occurrences of (+): 8), indicating progress in certain areas. Yet, as with RTP 3, no indicator in this pathway was rated as much improved (occurrences of (++): 0).

The results for RTP 5 show indicators with a range of degrees of improvement. In particular, indicators reflecting a noticeably worse performance (occurrences of (--): 4) are less prevalent. One indicator shows improvement (occurrences of (+): 1), indicating positive developments, and RTP 5 stands out with a sizeable number of indicators rated as much improved (occurrences of (++): 10), indicating its potential for having a profound positive impact.

Lastly, following the procedure described in 3.3, the quantified values for the RTPs are calculated. The full set of five RTPs developed, with the corresponding indicators and their categorization, is presented in Table 15.

Table 15*Complete Overview of Regional Transformation Pathways*

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. GSDS: German Sustainable Development Strategy 2021, SDG indicator: Global SDG reference indicators. SQ (status quo) refers to last value available in the data set. Calculations based on Federal Statistical Office (Destatis), 2023. *Source:* adapted from Siekmann and Venghaus (2024), *CC BY 4.0*, bioeconomy visions of indicators 8.1 and 10.2 adjusted.

7.4 Discussion

The integration of a range of aspects, including managerial knowledge, political perspectives, socio-economic concerns, and environmental perspectives, is essential to make a meaningful contribution to related research (Leipold et al., 2023). The developed pathways contribute to action-oriented knowledge for sustainability by acknowledging the cross-sectoral and interconnected impacts included in the indicator system, by integrating transparent core assumptions, and by recognizing the relevance of socio-economic impacts for policy design. This helps to avoid compartmentalization and silo thinking.

The developed RTPs constitute a useful tool for supporting governance in regional transformation processes. They contribute to simplifying complex concepts and providing a basis for fostering communication among and across stakeholders, in particular in situations where expertise differs. Moreover, they provide a framework for monitoring and evaluating policy progress across various dimensions. In addition, these regional pathways strengthen coordination efforts by making global goals more accessible in a regional context and thus establishing a solid foundation for further discussion. The future-oriented, explorative approach also supports efforts for steering the transformation process into desired directions laid out by the SDGs. In the context of the present work, they further constitute the foundation for the subsequent evaluation within the MCDA approach.

Based on key features designed to provide pathways that help address current research challenges, the systematic approach further provides multiple benefits. By using a well-defined methodology, it contributes to transparent decision-making processes. In terms of transferability, the narrative development based on the key aspects of the SSPs is flexible and applicable to different regional settings. Likewise, the SMLFA, used to build a balanced indicator system, is adjustable to varying contexts. Quantifying transformation pathway values with SDG data ensures a transferable framework that can be deployed beyond the initial case.

Using SSPs allows for a profound examination and reflection on the underlying narratives and facilitates robust RTPs that take into account regional specificities. This

makes the pathways more accessible to stakeholders and researchers and improves comparability across regions and settings. By integrating insights from stakeholder analysis, covering social, environmental and technological factors, the approach recognizes different value systems and provides a balanced representation. It enhances transparency by mapping sustainability dimensions and bioeconomy visions. It also identifies over- and under-representation of stakeholder interests. Its adaptability is demonstrated by its application in a region undergoing dynamic change. The RTPs show a range of possible future pathways, represented in a coherent way with both narrative and data, making possible directions easy to understand. The indicator framework rests on a sound normative footing, which is in line with the global SDG framework through the SMLFA. Linking to the principles of a sustainable bioeconomy ensures that indicators for monitoring developments are both relevant and suitable. Moreover, their inclusion in the GSDS strengthens their contextual relevance. Data access, traceability, and transparency can be achieved by using the SDGs and national sustainability strategies while also incorporating different sustainability dimensions. Familiarity of DMs with the SDG framework facilitates communication. Yet transferability may be limited by the extent to which not all national sustainability strategies are constructed in such a way as to permit straightforward derivation.

With respect to the SMLFA, there are limitations. On the one hand, while there are advantages to deriving the indicator system from the SDGs and national sustainability strategies, there are also potential limitations related to the pre-selection of indicators. On the other hand, the link between indicators and aspects relevant to a sustainable bioeconomy can be interpreted in different ways, potentially causing the inclusion or exclusion of some indicators. The application of the SMLFA may therefore lead to different results compared to other approaches (see e.g., Bringezu et al., 2021; Egenolf & Bringezu, 2019; Jander & Grundmann, 2019; Jander et al., 2020; Sturm & Banse, 2021). To overcome this, the inclusion of contextual indicators identified through participatory or expert-led approaches can offer feasible options.

With regard to the narratives and RTPs, it should be noted that the RTPs are not to be understood as a prediction of the future, but rather as solution spaces for potential developments. Future is seen as a sphere of possibilities which can be the subject of

shaping and influence. Thus, before deriving relevant measures, it is essential to formulate a basic concept of the desired outcome.

The purpose of this framework, which is intended for use by decision-makers, is to provide guidance for decisions on the basis of stakeholder interests, including societal concerns, and to provide direction for future policy-making. It does this by integrating the insights from *Step I* which served as basis for the narrative development and guided the quantification. Specifically, it is aimed at informing key stakeholders in policy, industry and research who play a central role in shaping transformation processes (Dieken et al., 2021). Frequently, there is a predominant technical understanding of the bioeconomy and a shortfall of environmental and societal concerns in these areas, that might not be in line with the expectations of the general public (Dallendörfer et al., 2022; Dieken & Venghaus, 2020).

Contemporary sustainability science seeks to provide actionable knowledge to help societies transition to more sustainable development pathways, but there are limited quantitative methods available to assess these pathways (Topf et al., 2023). In three key ways, the developed approach contributes to strategic processes for the transformation of bioeconomy regions. The first is to support the establishment of monitoring and evaluation capabilities to track the regional progress of the bioeconomy transformation. It involves the derivation of indicator frameworks to assess the success of implemented strategies. Secondly, the methodology can be used to inform policy development at different levels (local, regional, national) in order to design supportive frameworks that foster sustainable practices. And third, in the formulation of communication activities intended to raise awareness, engage communities through the provision of information, involve them in decision-making, and ensure the equitable distribution of benefits, taking into account local perspectives.

7.5 Chapter Summary

In this chapter, an alternative approach to the development of transformation pathways at the regional level is proposed. Building upon *Step I* of the analysis, the content of the RTP narratives was developed based on an in-depth familiarization with the decision context wherein three considerations played a major role.

First, the RTP narratives, while grounded in the SSPs, address challenges that are important for bioeconomy transitions. Second, they incorporate key properties related to the context of RR and the perceptions of stakeholders involved in the transition. Third, they need to be aligned with the central elements of the SSP narratives while reflecting regional specificities.

Second, the indicator framework developed in this work highlights a holistic approach and is intended to encompass not just the bioeconomy itself, but also its contribution to sustainability as outlined in the SDGs. Thus, each indicator must meet four requirements to be included in the resulting framework: it must be part of the global SDGs; it must cover elements of relevance to a sustainable bioeconomy; needs to be embedded in national sustainability strategies; and relevant to the RR. Mapping indicators along bioeconomy visions serves to provide an overview of potential unintentional biases in certain perceptions, increase transparency, and reveal unbalanced aspects for targeted improvements where appropriate.

And third, the previous steps need to be brought together to finalize the RTPs. The subsequent quantification is thus based on the developed narratives and the derived indicator system. Each RTP's narrative provides a basis to assess each indicator's trend. Where the narrative assumes an optimistic trajectory, a positive trend is assumed for the indicator; where the narrative assumes a negative trajectory, this is reflected in the trend for the indicator. Using the approach ultimately results in five RTPs.

With the development of the indicator framework and the quantification of the developed RTPs, the evaluation criteria and decision alternatives for structuring the decision problem according to *Step II* of the analytical framework are completed (*RQ 5-6*). The next step is to use the identified criteria and developed pathways within the multi-stakeholder decision making context. In the subsequent section, the integration of subjective stakeholder perceptions into the analytical framework is addressed.

8 Stakeholder Perceptions

In this chapter, *Step III* of the analytical framework is pursued. The objective is to incorporate the subjective perceptions of stakeholders into the MCDA by weighting different decision criteria according to their respective importance to the stakeholders.

The basis for this is the FAHP method. To facilitate the application of the FAHP, the decision problem must first be structured based on a goal hierarchy and made applicable to the characteristics of the RR and the overall decision context. Subsequently, a questionnaire that builds on the goal hierarchy is developed and used to gather responses in the form of pairwise comparisons, which allow integration into the FAHP method. The calculations are then carried out accordingly, followed by a presentation and discussion of the results.

At the end of the chapter, the criteria weights are determined to integrate the subjective stakeholder perceptions. This provides the necessary information for the next and final step of the framework. The chapter concludes with a summary.

8.1 Integrating Subjective Perceptions

Following the step-by-step procedure described in (Section 5.10.4), the following section illustrates how the subjective stakeholder perceptions are integrated into the overall framework of the analysis.

8.1.1 *Step 1: Structure for Weight Determination*

The first step is to structure the decision problem for determining criteria weights. As previously highlighted, the distinction into three bioeconomy visions introduced by Bugge et al. (2016) can support categorizing existing perceptions and associating indicators towards the underlying areas of focus. To operationalize the developed indicator framework within the research design, it is necessary to consolidate it while maintaining a close link to the decision problem. Accordingly, to construct the goal hierarchy for the integration of subjective stakeholder perceptions, nine key indicators were extracted across the three bioeconomy visions.

Building upon prior research investigating stakeholder perceptions concerning the bioeconomy (Dallendörfer et al., 2022; Dieken et al., 2021; Dieken & Venghaus, 2020) as well as experiences from the stakeholder workshop conducted with affected parties from the RR, nine key indicators were identified. To ensure a balanced representation of the overall framework, three indicators are associated with each of the three bioeconomy visions. This procedure ensured the feasibility of the intended pairwise comparison and resulted in a total of twelve comparisons. The respective three indicators per bioeconomy vision represent the sub-weights. An overview of the respective allocation of visions and evaluation criteria is presented in the hierarchical graph illustrated in Figure 21 and summarized in Table 16.

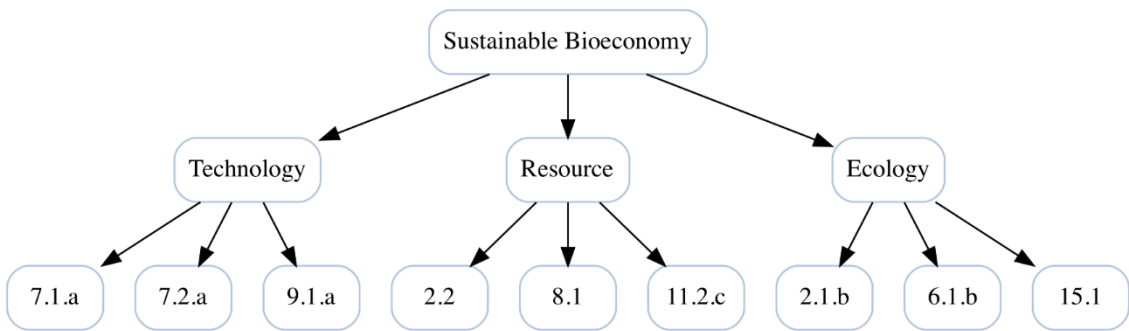


Figure 21. Hierarchical Structure and Associated Criteria. Source: Author.

Deriving key indicators was necessary for three reasons. First, it was crucial to maintain effective communication with stakeholders without overwhelming them with an excessive number of indicators, which could strain the interaction process.

Second, certain indicators were developed to address related impact categories, allowing for a more nuanced and comprehensive assessment. While this approach is advantageous in the context of a monitoring system, the added value of an individual evaluation by stakeholders appears rather limited. Consequently, the benefits of consolidating such indicators outweigh the potential insights gathered through stakeholder interaction. For instance, consider the GSDS indicators 6.1.a (Phosphorus in flowing waters) and 6.1.b (Nitrate in groundwater). Both indicators aim to mitigate water pollution caused by harmful substances, and a detailed evaluation does make sense in various circumstances. However, it was expected that stakeholders' perceptions of these indicators would not notably differ, given their common objective of enhancing water quality.

Third, keeping the number of indicators manageable was essential, considering the need for pairwise comparisons. An excessive number of indicators would have complicated the comparison process, making it less transparent. Therefore, the indicator selection process aimed to balance comprehensiveness and manageability to ensure effective and meaningful pairwise comparisons.

The procedure to derive key indicators involved multiple steps. The initial step focused on identifying overlapping impact categories with the goal of consolidating into a single, representative indicator. This approach ensured that the assessment captured the essential aspects of these interconnected impact categories, streamlining the subsequent evaluation process.

Second, the selection process considered indicators frequently utilized within stakeholder integration related to the bioeconomy. These indicators are used in various contexts, such as progress reports, strategies, and academic papers. This ensures their relevance and importance and facilitates a smoother integration of the assessment into existing frameworks and dialogues within the bioeconomy community. Further, familiar indicators are more likely to resonate with stakeholders, making the assessment more accessible and impactful.

Third, the procedure prioritized indicators that were specifically pertinent to Germany and, more specifically, to the RR region. This selection process was guided by prior research, which included a focus group workshop, a survey, and an extensive literature analysis (see *Step 1*). The deliberate selection of indicators, aligned with the unique characteristics and challenges of the RR region, ensured that the assessment's outcome would provide valuable insights and recommendations specific to the context, thereby enhancing its practical utility.

Fourth, the intention throughout this process was to allow for a balanced representation of the three existing bioeconomy visions as introduced by Bugge et al. (2016). This balanced representation ensured that the chosen indicators reflect the diverse perspectives and goals associated with these visions, contributing to a more comprehensive and inclusive assessment.

Lastly, data availability was taken into account. In cases where data for NRW was available, the corresponding indicator was prioritized over those relying solely on

national-level data. This consideration was helpful as it allows for a more localized and region-specific assessment, further enhancing the relevance and accuracy of the selected indicators for the RR region. Table 16 presents the resulting list of key indicators, along with their associated dimensions and visions.

Table 16

Indicator System for Weighting by Participating Stakeholder Groups

GSDS	SDG	Description	Vision
2.1.b	2.4.1	Organic farming	Ecology
6.1.b	6.3.2	Nitrate in groundwater	Ecology
15.1	15.5.1	Biodiversity and landscape quality	Ecology
2.2	2.a.2	Support for good governance in attaining appropriate nutrition worldwide	Resource
8.1	8.4.2	Raw material input productivity	Resource
11.2.c	11.2.1	Accessibility of medium-sized and large cities by public transport	Resource
7.1.a	7.3.1	Final energy productivity	Technology
7.2.a	7.2.1	Share of renewable energies in gross final energy consumption	Technology
9.1.a	9.5.1	Private and public expenditure on research and development	Technology

Note. GSDS: German Sustainable Development Strategy 2021, SDG indicator: Global SDG reference indicators.

8.1.2 Step 2: Pairwise Comparison

The FAHP allows to account for impreciseness and fuzziness in real-world applications and to deal with subjective perspectives and judgments. Moreover, linguistic terms can be used to describe the relative importance of a criterion in a pairwise comparison. Thus, an exploratory questionnaire was developed and conducted to collect responses for the integration of subjective perceptions into the developed framework.

8.1.2.1 Linguistic Variables and Scale. Once the key indicators were delineated along the bioeconomy visions, linguistic variables were used to reflect stakeholder perceptions of importance. The fuzzy scale and related linguistic terms are summarized in Table 17.

Table 17

Overview of Linguistic Variables and Fuzzy Scales

Positive Ling. Var.	Abbr.	Fuzzy Scale	Negative Ling. Var.	Abbr.	Fuzzy Scale
Equally important	EI	$\tilde{1}$	Equally important	EI	$\tilde{1}^{-1}$
Moderately important	MI	$\tilde{3}$	Not moderately important	NMI	$\tilde{3}^{-1}$
Important	I	$\tilde{5}$	Not important	NI	5^{-1}
Very important	VI	$\tilde{7}$	Not very important	NVI	$\tilde{7}^{-1}$
Absolutely important	AI	$\tilde{9}$	Not absolutely important	NAI	$\tilde{9}^{-1}$

Note. Adapted from Fu et al. (2020), CC BY 4.0.

Subsequently, a questionnaire was developed based on these indicators (Appendix). As described in Section 5.10, there are methodological requirements for the creation of the questionnaire to allow for integration into the FAHP approach. The methodology involved employing a pairwise comparison approach, where stakeholders were asked to assess the importance of specific aspects of the transformation process from their own perspective. Following the hierarchical structure outlined in Figure 21, pairwise comparisons were pursued using the questionnaire to explore the relative importance of the bioeconomy visions and criteria.

For example, stakeholders were prompted to consider which was more important: an increase in public and private spending on R&D or a higher share of renewable energy sources in the electricity mix. Alternatively, they could express that both aspects held equal importance. Stakeholders used linguistic terms to compare criteria within each vision and across the three dimensions outlined by the bioeconomy visions.

8.1.2.2 Questionnaire Design. Concerning questionnaire design, the linguistic scale was complemented by a graphical representation, as illustrated in Figure 22. In this context, a horizontal format was chosen due to its capacity to reduce primacy effects (Menold & Bogner, 2016). The horizontal arrangement ensures that no single option or item gains undue prominence merely because of its position.

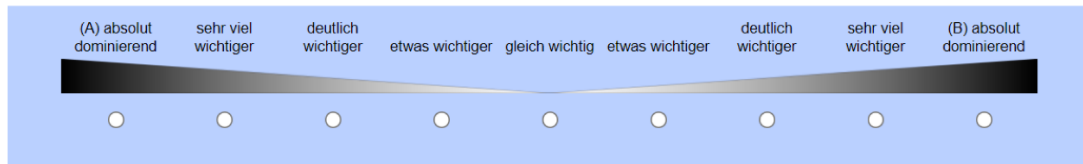


Figure 22. Linguistic Scale and Graphical Representation as used in the questionnaire. Source: Author, created with SoSci Software.

This approach was designed to prevent any particular choice from being favored over others, which can support collecting unbiased responses. This decision aimed to mitigate any undesired effects that could influence respondents when they answer questions. The goal was to eliminate potential confusion and misunderstanding by providing explicit verbal labels alongside graphical scales. Proceeding in this way was further intended to ensure that participants clearly and consistently understood the presented response options, promoting more accurate and meaningful replies. Thus, the questionnaire design strategy incorporated a horizontal format for graphical representation and verbally labeled graphics.

8.1.2.3 Gathering Subjective Stakeholder Responses. FAHP can be applied to the responses from both small groups and large groups, and data can be collected personally, via mail, through an online survey system, or through a combination of these methods. For the intended purpose, this can be done personally, via mail or through an online survey system (or through combinations of those). With respect to the present study, a hybrid approach was chosen. It was pre-tested (n=6) and subsequently applied. In line with the research objectives, the aim was to obtain responses from stakeholders engaging with the transformation process towards a sustainable bioeconomy in Germany and the RR.

Following the procedure laid out in Section 5.10.4.2, the next steps consist of:

- 1) Determine pairwise comparison matrices

Using the questionnaire results on the importance of the bioeconomy visions and criteria, pairwise comparison matrices are obtained as positive reciprocal matrices. Pairwise comparison matrices are filled with the linguistic scaling abbreviation (Table 17) in the upper triangle. The inverse of the stakeholders' evaluation is then entered into the lower triangle of the matrix.

2) Conversion of fuzzy scales to triangular fuzzy numbers

The present study used a 5-point scale to weigh the importance of each vision and criterion, as shown in Figure 21. Each scale of fuzzy numbers is defined by three parameters of the TFN as shown in Table 18 (Fu et al., 2020). Recognizing that individuals often struggle to articulate their preferences precisely, the linguistic terms (Table 17) and associated fuzzy scales were transformed into TFNs (Table 18). The fuzzy scale, along with the associated TFNs, are presented in Table 18.

Table 18

Overview of Fuzzy Scales and Triangular Fuzzy Numbers

Fuzzy Scale (Positiv Variable)	TFN	Fuzzy Scale (Negative Variable)	TFN
$\tilde{1}$	(1, 1, 3)	$\tilde{1}^{-1}$	$\left(\frac{1}{3} \frac{1}{1} \frac{1}{1}\right)$
$\tilde{3}$	(1, 3, 5)	$\tilde{3}^{-1}$	$\left(\frac{1}{5} \frac{1}{3} \frac{1}{1}\right)$
$\tilde{5}$	(3, 5, 7)	$\tilde{5}^{-1}$	$\left(\frac{1}{7} \frac{1}{5} \frac{1}{3}\right)$
$\tilde{7}$	(5, 7, 9)	$\tilde{7}^{-1}$	$\left(\frac{1}{9} \frac{1}{7} \frac{1}{5}\right)$
$\tilde{9}$	(7, 9, 9)	$\tilde{9}^{-1}$	$\left(\frac{1}{9} \frac{1}{9} \frac{1}{7}\right)$

Note. Adapted from Fu et al. (2020), CC BY 4.0.

Using the TFNs instead of the crisp numbers constitutes the fundamental difference between FAHP and AHP (Liu et al., 2020, p. 6).

8.1.3 Step 3: Synthesize the Subjective Judgments

The individual assessments within the stakeholder groups frequently differed. Therefore, they must be aggregated in order to proceed with the group evaluation (Liu et al., 2020, p. 19). Thus, adopting the approach used by Fu et al. (2020, p. 8), step 3 (Section 5.10.4.3) is used to synthesize individual assessments of members of each stakeholder group.

8.1.4 Step 4: Calculate Fuzzy Criteria Weights

Subsequently, as discussed in Section 5.10.4.3, the geometric mean approach introduced by Buckley (1985) is widely used to compute fuzzy weights and is most applicable in combination with TFNs (Kubler et al., 2016; Liu et al., 2020). Thus, the procedure laid out in Section 5.10.4.4 is used to calculate the fuzzy geometric mean matrices and to obtain the fuzzy weights of the criteria.

8.1.5 Step 5: Defuzzify Weights

Lastly, the centroid method (Section 5.10.4.5) is used to defuzzify the weights and obtain crisp values. Those can then be utilized within the subsequent evaluation within the PROMETHEE methods.

8.2 Results

Using the questionnaire as developed in Step 2, a total of 37 responses were obtained. Respective responses originated from a printed form (n=14) and through an online survey system (n=23) using *SoSci* software.

Looking at the responses by stakeholder group, the picture is rather unbalanced. As illustrated in Figure 23, it is apparent that stakeholders from the groups *Research, Industry & commerce* and *Government & political actors* are notably more present than the other groups. The least number of responses were collected from groups *Media* as well as *Social or environmental initiatives & NGOs*, followed by *Farmers & forest owners* and *Citizens and consumers*.

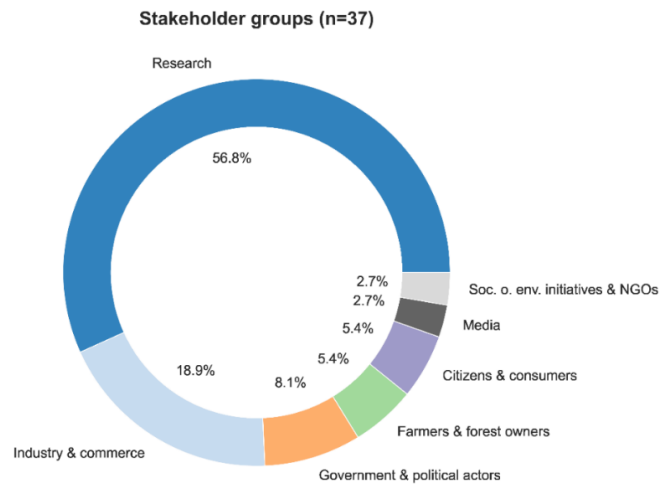


Figure 23. Number of Responses According to Stakeholder Groups. Source: Author.

The resulting weights are summarized in Table 19 and visualized in Figure 24. Within the groups *Research* and *Industry & commerce*, evaluations appear rather balanced, resulting in a relatively even distribution of indicator weights across all visions and key indicators. Yet, concerning the other groups, the findings reveal variations in stakeholder perspectives and priorities, both with regard to the importance of the respective bioeconomy visions as well as with respect to individual indicators.

Table 19*Weights by Participating Stakeholder Groups*

GSDS / Vision	Gov. & pol.	Media	Farm. & f.	Research	Ind. & c.	Citi. & c.	Soc. / NGOs
Ecology	0,25	0,12	0,27	0,35	0,33	0,44	0,07
Technology	0,39	0,14	0,31	0,32	0,33	0,15	0,19
Resource	0,36	0,74	0,42	0,33	0,33	0,41	0,75
2.1.b / Ecology	0,10	0,01	0,04	0,11	0,11	0,06	0,02
6.1.b / Ecology	0,09	0,07	0,11	0,12	0,12	0,19	0,04
15.1 / Ecology	0,07	0,03	0,11	0,12	0,10	0,19	0,01
7.1.a / Technology	0,16	0,04	0,10	0,10	0,12	0,04	0,04
7.2.a / Technology	0,09	0,06	0,11	0,11	0,10	0,05	0,03
9.1.a / Technology	0,13	0,04	0,10	0,11	0,11	0,07	0,12
2.2 / Resource	0,14	0,14	0,10	0,11	0,12	0,22	0,40
8.1 / Resource	0,11	0,07	0,09	0,11	0,10	0,09	0,09
11.2.c / Resource	0,11	0,53	0,23	0,11	0,12	0,10	0,26

Note. GSDS: German Sustainable Development Strategy 2021 reference indicators.

For instance, as illustrated in Figure 24, a different setting compared to the balanced evaluations emerges in the *Social or environmental initiatives & NGOs* stakeholder group, where the *Resource* vision is perceived as significantly more important. Additionally, certain indicators are deemed considerably more critical within this category than others (Table 19). Especially indicator 2.2 (support for good governance concerning nutrition worldwide) stands out as notably prioritized. The *Ecology* vision, on the other hand, is valued much less and indicator 15.1 (Biodiversity and landscape quality) is perceived to be the least important.

Dimension weights per stakeholder group

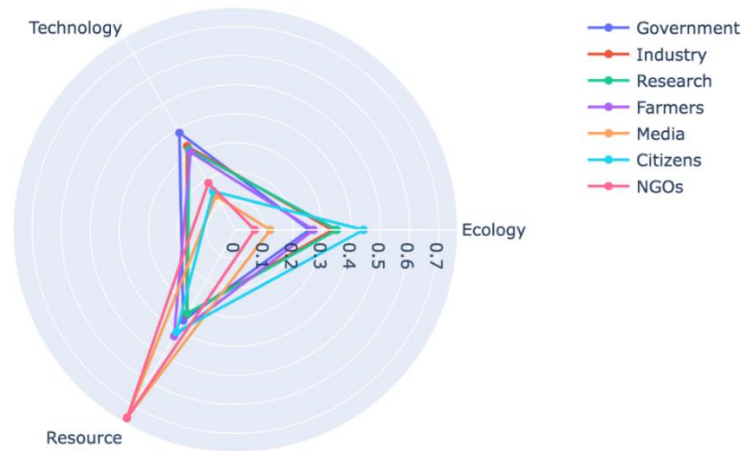


Figure 24. Bioeconomy Vision Weight According to Stakeholder Groups. Source: Author.

Similarly, as shown in Figure 24, stakeholder group *Media*, also places notable weight on the *Resource* vision. In particular, indicator 11.2.c (Accessibility of medium-sized and large cities by public transport) receives noteworthy attention with respect to the overall evaluation. In contrast, the *Ecology* vision receives considerably less attention and the indicator 2.1.b (Organic farming) is perceived as the least important.

Another notable observation in the sample is the contrasting priorities among *Citizens & consumers* and *Government & political actors* stakeholder groups. *Citizens & consumers* place the highest importance on the *Ecology* vision, while stakeholders in the *Government & political actors* category tend to emphasize technological aspects. In contrast, aspects related to the *Technology* vision play only a subordinate role for the *Citizens & consumers* stakeholder group and are rated as notably less important than aspects related to *Ecology* or *Resource* vision.

Responses obtained associated with the stakeholder group *Farmers & forest owners* place emphasis on the *Resource* vision, followed by the *Technology* vision. Interestingly, the *Ecology* vision is considered the least important and indicator 2.1.b (Organic farming) receives the lowest importance in the overall evaluation of the group.

8.3 Discussion

Overall, the observed differences underscore the importance of considering diverse stakeholder viewpoints and related implications for decision-making and resource

allocation in the context of the bioeconomy. The unbalanced representation of responses from stakeholder groups appears to reflect the insights from the analysis in *Step I*, especially with respect to the systematic literature review (Dieken et al., 2021). Hence, a larger number of participants from the groups *Research, Industry & commerce* and *Government & political actors* is expected, as well as an underrepresentation of groups from civil society, such as *Social or environmental initiatives & NGOs* and *Citizens and consumers*. Due to the central role that this group plays in the transformation process towards a sustainable bioeconomy, however, a stronger representation of group *Farmers & forest owners* might have been expected. The results further seem to reinforce the impression that, with stakeholder groups *Research, Industry & commerce* and *Government & political actors*, similar actors often intervene more actively in the transformation process. However, it cannot be ruled out that the willingness to participate in surveys may be higher within these particular groups.

Concerning the resulting weights, the balanced weightings of groups *Research* and *Industry & commerce* are unexpected, as these groups are frequently associated with a stronger weighting of resource and technology visions in the literature (Dieken et al., 2021). Moreover, it is noteworthy that the aspect of organic farming is considered the least important by the *Farmers & forest owners* group. This is surprising insofar as this aspect represents a not insignificant association with regard to the populations' understanding of the bioeconomy in general (Dallendörfer et al., 2022).

The results indicating a higher degree of importance of ecological aspects associated with *Citizens and consumers* are consistent with the focus group workshop, systematic literature review, and the results obtained from the representative survey among the German population. Similarly, the prioritization of technological aspects associated with actors summarized in the stakeholder group *Government & political actors* further coincides with respective observations in prior steps of the analysis (Dieken et al., 2021).

The strong focus on elements linked to the *Resource* vision connected to the groups *Social or environmental initiatives & NGOs* and *Media* also appears to reflect the prevailing perceptions brought to light in the course of the literature review. However, it must be noted here, particularly with regard to stakeholder group *Media*, that the group as a whole is only rarely investigated regarding their perception of the bioeconomy,

beyond few studies addressing bioeconomy discourses within German media (see e.g., Dieken and Venghaus (2020)), and the feedback in the course of the questionnaire was also among the lowest.

Overall, based on this study, the performance of the developed approach in real-world conditions appears to confirm related research approaches and indicates its usefulness in capturing existing, subjective stakeholder perceptions among stakeholder groups. Both the fact that the participating stakeholder groups are expectedly unbalanced and that the different bioeconomy visions are considered to be of varying importance indicate this. In addition to the possibilities envisaged in the context of the present work, this also opens up further possibilities of use, both complementary and, depending on the context, as an alternative to other approaches that deal with questions of subjective stakeholder perceptions.

Yet even though the developed approach contributes towards a more holistic understanding of the decision problem, it is important to address related limitations. This includes the development of the goal hierarchy along the bioeconomy visions and key indicators. Even though the derivation of the key indicators and the association with bioeconomy visions was carried out carefully, it cannot be ruled out that a different selection of these would have influenced the results. Ultimately, these steps were necessary to enable practical application within the decision-making context.

In addition, subjective stakeholder opinions can only be expressed to a certain extent through the use of a questionnaire. Therefore, a balance must be struck here between the possibility of practical application and the limits of the chosen approach. As a starting point for a constructive discussion and mutual understanding, the use in the present context appears reasonable and could provide the basis for further evaluations.

Further limitations relate to the data collected through the questionnaire. It should be noted that the sample is not representative. Nonetheless, the observations are generally consistent with previous findings from a focus group workshop, an analysis of existing literature, and the representative survey conducted during *Step I* of the analysis. This consistency highlights the importance of considering diverse stakeholder perspectives when formulating bioeconomy strategies and policies. While the consistency in findings is noteworthy, obtaining additional responses from specific stakeholder groups, such as

Citizens & consumers, Soc. & NGOs, and Farmers, would have been desirable. Diversity in respondents can potentially provide a more comprehensive understanding of the existing landscape concerning diversity of opinions.

Yet, the declared aim was to gain a realistic understanding of the dynamics of the transformation process. The responses obtained do contribute to this realistic picture and underline the unbalanced participation in shaping the transition. Thus, it is noticeable that the results by group are very unbalanced in terms of the number of responses. However, this tends to be the rule rather than an exception in this type of transformation process in connection with the bioeconomy (Dieken et al., 2021). In the sense of the *Plural Grounding* approach underlying this analysis, however, unique opinions and perceptions should also be taken into account in order to make underrepresented groups heard. Even if individual weightings may appear to be too extreme or unreasonable, it does not seem expedient to exclude them from the analysis in this study. Rather, this could be explored in greater depth in a workshop as part of a possible application of the developed approach in order to identify the causes of such evaluations. Building on this, the basis for finding compromises in the sense of *Plural Grounding* could be discussed. Therefore, with regard to compromise formation, this may ultimately lead to beneficial insights from individual, divergent assessments that might not otherwise have become visible.

The consistency in these findings reinforces the importance of incorporating diverse stakeholder perspectives into formulating bioeconomy strategies and policies. This multifaceted approach enhances the robustness of the insights and ensures that the resulting strategies and policies are better equipped to address the multifaceted challenges and opportunities of the bioeconomy.

An additional reason is that the overall intention of the developed approach is for it to be used in the context of a group decision-making setting. Thus, the aim of the study is not to derive generalizations from the findings, as these are highly context-dependent with respect to the decision problem. In this connection, results obtained using approaches such as another representative survey would be questionable given the limited bioeconomy-related knowledge within the overall population (Dallendörfer et al., 2022) beyond the affected regions.

Against the background of the limitations outlined, the results should be regarded as exploratory. Applying the approach in the context of another regional transformation process, nationally and internationally, illustrates a promising research avenue.

8.4 Chapter Summary

In this section, *Step III* of the analytical framework is concluded. By determining the criteria weights using the FAHP methodology, the basis for integrating subjective stakeholder perceptions is provided, and the foundation for the final step of the analytical framework is developed.

Therefore, a goal hierarchy was developed and nine key indicators from the overall monitoring framework were identified. The utilization of key indicators was part of the adaptation to the contextual requirements to facilitate the use of the approach in the regional context of RR. Thereby, negative effects on communication by overwhelming stakeholders through a high number of indicators were avoided, related impact categories were condensed, and the number of pairwise comparisons for stakeholders was kept at a manageable amount.

Based on the created goal hierarchy and derived key indicators, an exploratory questionnaire was developed and used to collect responses for the integration of subjective perceptions. The stakeholders could use linguistic terms to describe the relative importance of a criterion in a pairwise comparison from their perspective. Following the procedure laid out in section 5.10.4, the criteria weights were calculated to be utilized within the subsequent evaluation.

The results indicate an unbalanced representation of engaged stakeholders. The groups *Research, Industry & commerce* and *Government & political actors* are notably more present than the other groups and an underrepresentation of groups from civil society, such as *Social or environmental initiatives & NGOs* and *Citizens and consumers*, is apparent.

Further findings indicating a higher level of importance of ecological aspects associated with *Citizens and consumers* are consistent with *Step I* of the analysis. The same applies to the prioritization of technological aspects associated with actors summarized in the stakeholder group *Government & political actors*.

The balanced indicator weightings of groups *Research* and *Industry & commerce* are unexpected, as these groups are frequently associated with a stronger weighting of resource and technology visions in the literature and prior steps of the analysis.

Overall, the results show differences in stakeholder perspectives and priorities, both with respect to the importance of the respective bioeconomy visions and with respect to individual indicators weights. Thus, the developed approach works well in capturing existing, subjective stakeholder perceptions among divergent stakeholder groups. Yet, limitations need to be taken into account, and it must be noted that the findings are explorative and not suitable to derive generalizations. Still, the findings highlight the importance of incorporating diverse stakeholder perspectives.

The subjective perceptions in the form of weighting factors gathered in this section (*RQ 7*) will subsequently feed into the PROMETHEE method in *Step IV* of the analytical framework. These are then brought together with the developed RTPs to rank the decision alternatives and develop stakeholder profiles.

9 Ranking of Decision Alternatives

This chapter completes the final step of the analytical framework. The objective is to merge the information gathered during the previous steps in order to rank the decision alternatives. In particular, the developed decision alternatives in the form of the RTPs (*Step II*) are brought together with the subjective stakeholder perceptions captured as weighting factors (*Step III*).

For this purpose, stakeholder profiles are developed using the PROMETHEE I and II methodology. Subsequently, the PROMETHEE GDSS is utilized to derive the resulting overall ranking.

9.1 Results

9.1.1 Stakeholder Profiles

The presentation of the rankings follows the procedure described in section 5.8.2 according to the PROMETHEE II ranking. The transformation paths are ranked on the basis of the respective net outranking flow $\phi(a)$. This results in a complete ranking and frequently illustrates the preferred way of communicating results to stakeholders.

In cases where a PROMETHEE I analysis can provide additional information, this information is also introduced and addressed. This situation arises, for example, when incomparability exists and it therefore only results in a partial ranking.

The structure of the stakeholder profiles begins with the corresponding graphic of the individual group's results. For each graphic, the net outranking flow $\phi(a)$ is illustrated as a blue bar, the positive flow $\phi^+(a)$ as a green bar, and the negative flow $\phi^-(a)$ as a red bar. The complete PROMETHEE II ranking is then presented and described. Next, where applicable, additional insights from analyzing the outcome from a PROMETHEE I perspective are highlighted.

Table 20 summarizes the measurement unit as well as whether the indicator is supposed to be minimized or maximized.

Table 20*Overview of Key Indicators and Properties*

Criteria / Properties	2.1.b	6.1.b	15.1	2.2	8.1	11.2.c	7.1.a	7.2.a	9.1.a
Direction	Max.	Max.	Max.	Max.	Max.	Min.	Max.	Max.	Max.
Unit	In %	In %	2030 = 100	In %	2000 = 100	In min.	2008 = 100	In %	In %

Note. Extracted key indicators for the evaluation. The measurement units follow the system laid out in the German Sustainable Development Goals. The years 2000, 2008 and 2030 are used as reference years for the respective indicators. Table X provides an overview of all respective RTPs.

The key indicators used to calculate the rankings are summarized in Table 21.

Table 21*Overview of Key Indicators and Related RTP Values*

Criteria / RTP	2.1.b	6.1.b	15.1	2.2	8.1	11.2.c	7.1.a	7.2.a	9.1.a
RTP 1	20	100	100	31.69	160	15.74	158	30	3.5
RTP 2	12.79	94.25	85.25	25.025	144	16.4	139.1	18.42	2.845
RTP 3	12.79	79.43	85.25	18.3	144	17.07	144.85	16.29	1.89
RTP 4	11.97	94.25	69.22	18.3	144	17.07	139.1	18.42	2.845
RTP 5	11.97	98.39	52.60	31.69	191.95	17.07	139.1	16.29	2.90

Note. Extracted key indicators for the evaluation. Table 13 provides an overview of all respective RTPs.

9.1.1.1 Citizens & Consumers. According to the PROMETHEE II ranking illustrated in Figure 25, RTP 1 achieves the highest net outranking flow $\phi(a)$ and is thus ranked first. RTP 5 is ranked next, followed by RTP 2. The last two places in the ranking are RTP 4 and RTP 3.

PROMETHEE I does not provide additional insights with respect to this stakeholder group since no incomparability or indifference exists.



Figure 25. Ranking for Stakeholder Group Citizens & Consumers. Source: Author.

9.1.1.2 Farmers & Forest Owners. The PROMETHEE II ranking illustrated in Figure 26 shows that RTP 1 is ranked first. In contrast to the previous stakeholder group *Citizens & consumers*, however, RTP 2 has the second highest net outranking flow $\phi(a)$ and is thus ranked second, followed by RTP 5. The last two places in the ranking are occupied by RTP 4 and RTP 3.

PROMETHEE I does not provide additional insights with respect to this stakeholder group.

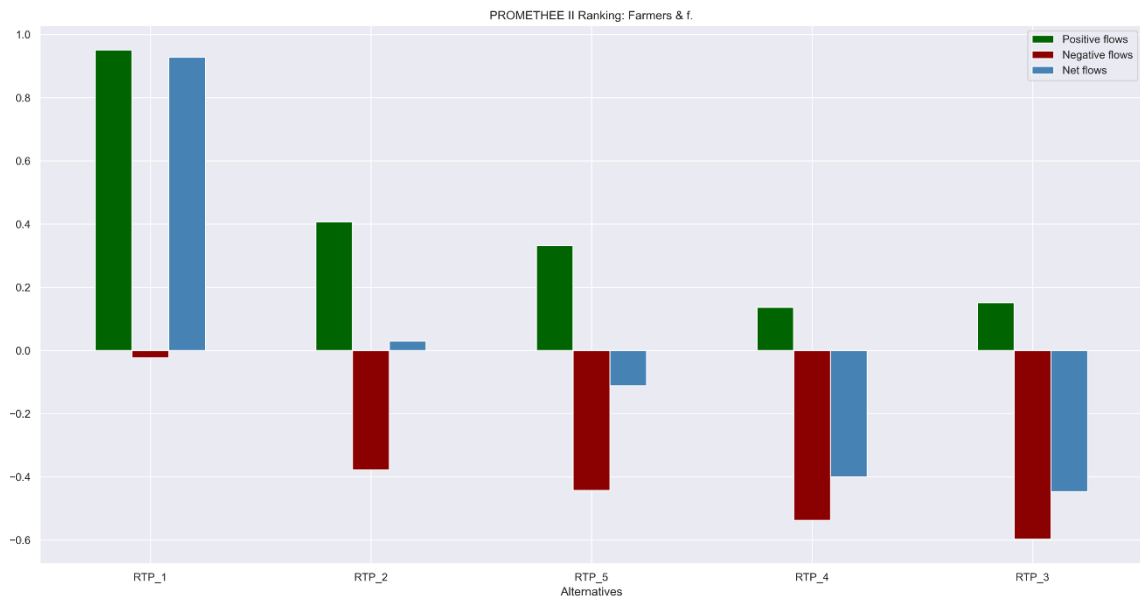


Figure 26. Ranking for Stakeholder Group Farmers & Forest Owners. Source: Author.

9.1.1.3 Government & Political Actors. RTP 1 leads the PROMETHEE II ranking as illustrated in Figure 27. RTP 5 and RTP 2 follow while the last positions in the ranking are RTP 3 and finally RTP 4.

For the stakeholder profile of the group *Government & political actors*, ranking according to PROMETHEE I provides additional information. As shown in Figure 27, the green bar associated with RTP 3 is higher compared to RTP 4. Yet, at the same time, the red bar associated with RTP 3 is more pronounced than that of RTP 4. Therefore, RTP 3 has a higher positive flow $\phi^+(a)$ but also has a stronger negative flow $\phi^-(a)$. Thus, following PROMETHEE I, RTP 3 and RTP 4 are considered as incomparable. For the group *Government & political actors* that implies that, following the ranking procedure of PROMETHEE I, only a partial ranking can be achieved and the PROMETHEE II complete ranking is thus connected with a loss of information.

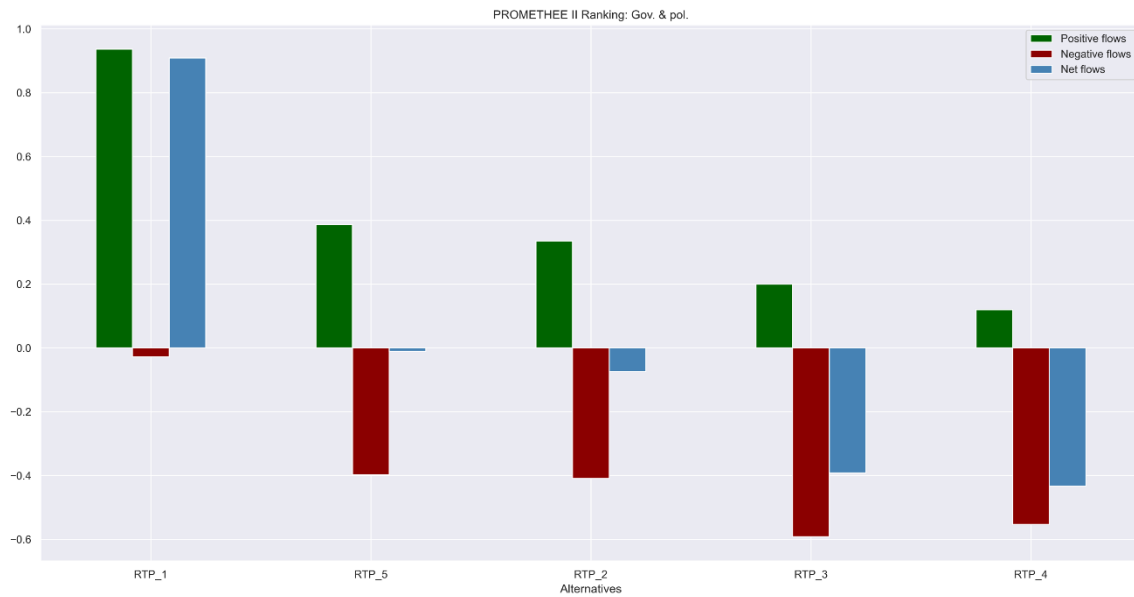


Figure 27. Ranking for Stakeholder Group Government & Political Actors. Source: Author.

9.1.1.4 Industry & Commerce. Figure 28 illustrates that RTP 1 is ranked first according to PROMETHEE II results. Following this, RTP 2 and RTP 5 occupy the subsequent ranks, while RTP 3 and RTP 4 are positioned at the lower end of the ranking.

While RTP 3 is ranked before RTP 4 and obtains a higher net outranking flow $\phi(a)$ and a higher positive flow $\phi^+(a)$, it also has a stronger negative flow $\phi^-(a)$ in comparison between the two RTPs. For the stakeholder group *Industry & commerce* RTP 3 and RTP 4 are thus incomparable according to PROMETHEE I.

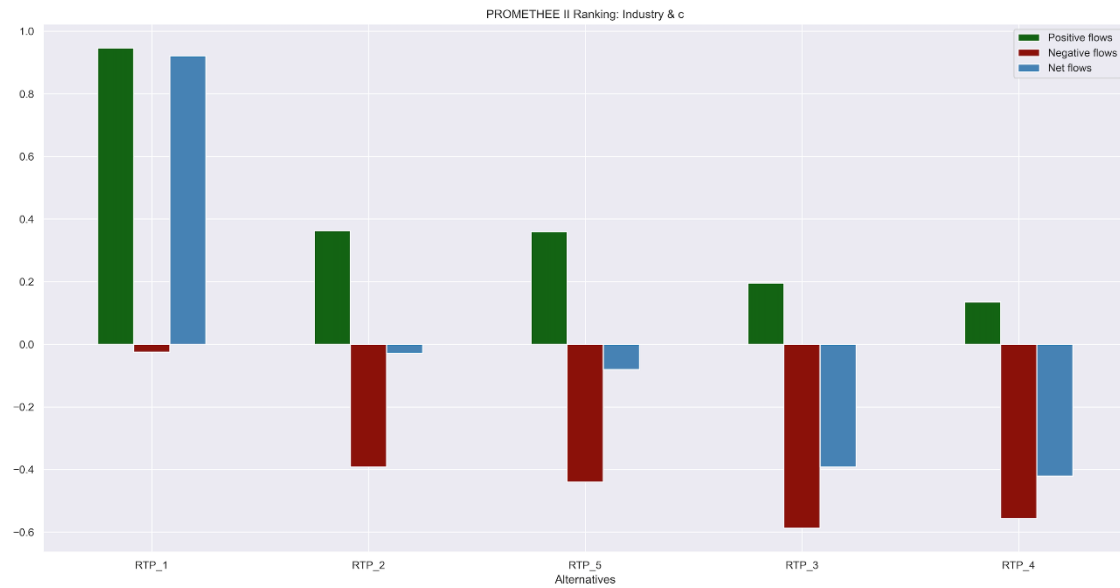


Figure 28. Ranking for Stakeholder Group Industry & Commerce. Source: Author.

9.1.1.5 Media. Ranked according to PROMETHEE II, Figure 29 shows that RTP 1 obtains the first place, followed by RTP 2 and RTP 5. The last two positions in the ranking are held by RTPs 4 and 3.

With regard to this stakeholder group, PROMETHEE I does not provide additional insights.

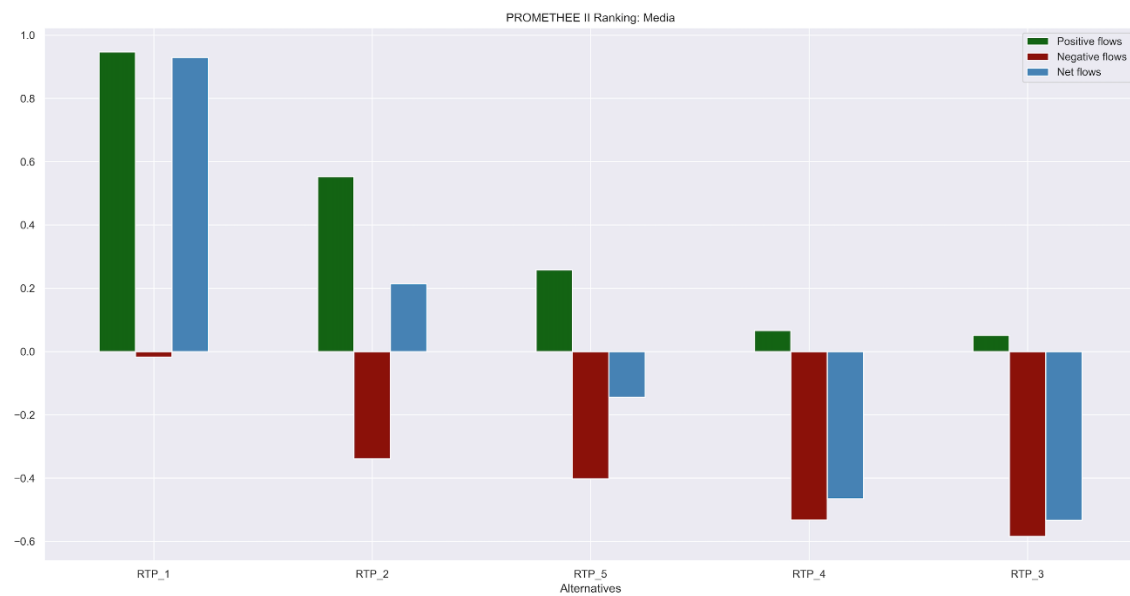


Figure 29. Ranking for Stakeholder Group Media. Source: Author.

9.1.1.6 Research. The PROMETHEE II ranking presented in Figure 30 places RTP 1 in first place, followed by RTP 2 and RTP 5. This is followed by RTP 3 and 4 in the last two places.

With regard to the PROMETHEE I partial ranking, an incomparability can be identified. In particular, RTP 3 and RTP 4 are incomparable since RTP 3 is ranked ahead of RTP 4 according to the net outranking flow $\phi(a)$ and higher positive flow $\phi^+(a)$, but also has a stronger negative flow $\phi^-(a)$.

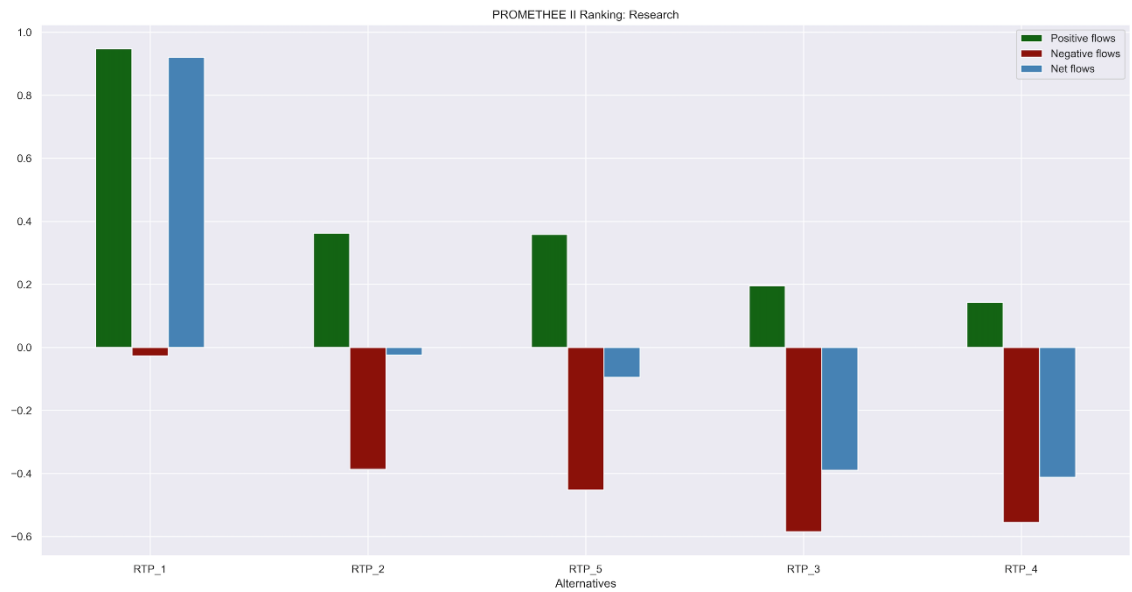


Figure 30. Ranking for Stakeholder Group Research. Source: Author.

9.1.1.7 Social and Environmental Initiatives & NGOs. The PROMETHEE II ranking presented in Figure 31 shows RTP 1 in the first place, followed by RTP 5 and RTP 2. The last-ranked alternatives are RTP 4 and RTP 3. PROMETHEE I does not provide further information concerning this group.

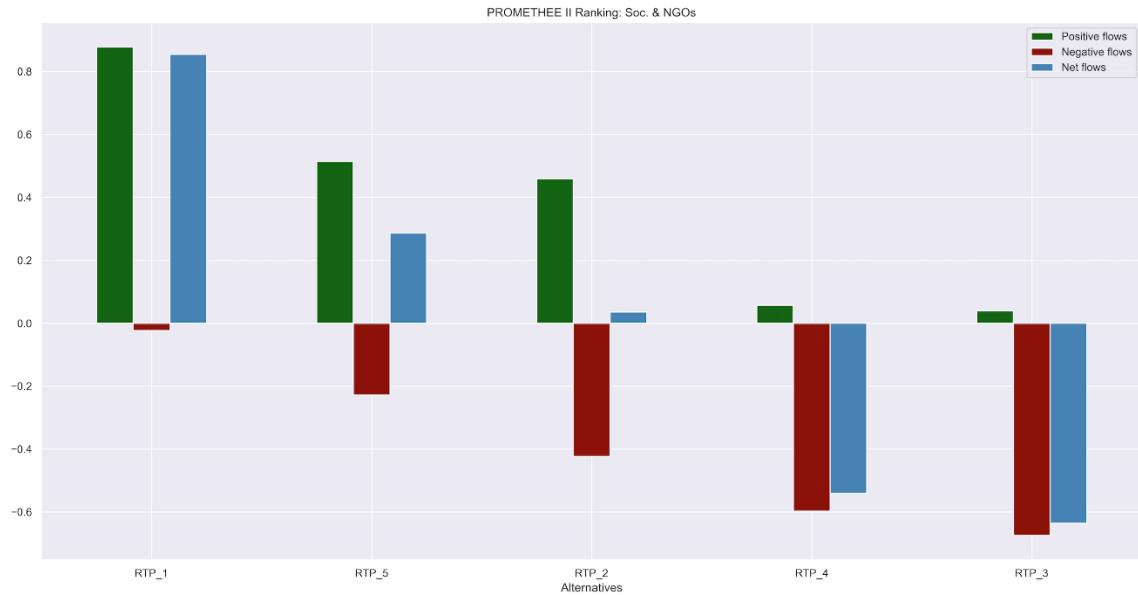


Figure 31. Ranking for Stakeholder Group Social & Environmental Initiatives& NGOs. Source: Author.

9.2 Result Group Evaluation

Subsequently to the individual evaluations of the respective stakeholder groups, utilizing the PROMETHEE GDSS allows for ranking the alternatives from a group perspective. Following the procedure laid out in section 5.8.4, the individual results are merged into a comprehensive decision matrix consisting of the entire group of investigated stakeholders.

Table 22*PROMETHEE II Results of Stakeholder Groups*

Stakeholder Group / RTP	Gov. & pol.	Media	Farmers & f.	Research	Industry & c.	Citi. & c.	Soc. & NGOs
RTP 1	0,909	0,930	0,928	0,921	0,921	0,902	0,855
RTP 2	-0,074	0,214	0,029	-0,024	-0,028	-0,004	0,035
RTP 3	-0,391	-0,533	-0,446	-0,390	-0,392	-0,472	-0,635
RTP 4	-0,433	-0,465	-0,400	-0,412	-0,421	-0,470	-0,541
RTP 5	-0,010	-0,145	-0,111	-0,095	-0,080	0,044	0,286

Note. These individual results illustrate the decision matrix for the PROMETHEE GDSS.

For the general evaluation, all groups and their subjective perspectives are considered to be of equal importance. Thus, the groups are weighted equally within the GDSS. Combining the individual results in the decision matrix (Table 22) for the PROMETHEE GDSS forms the basis for the overall ranking of transformation trajectories.

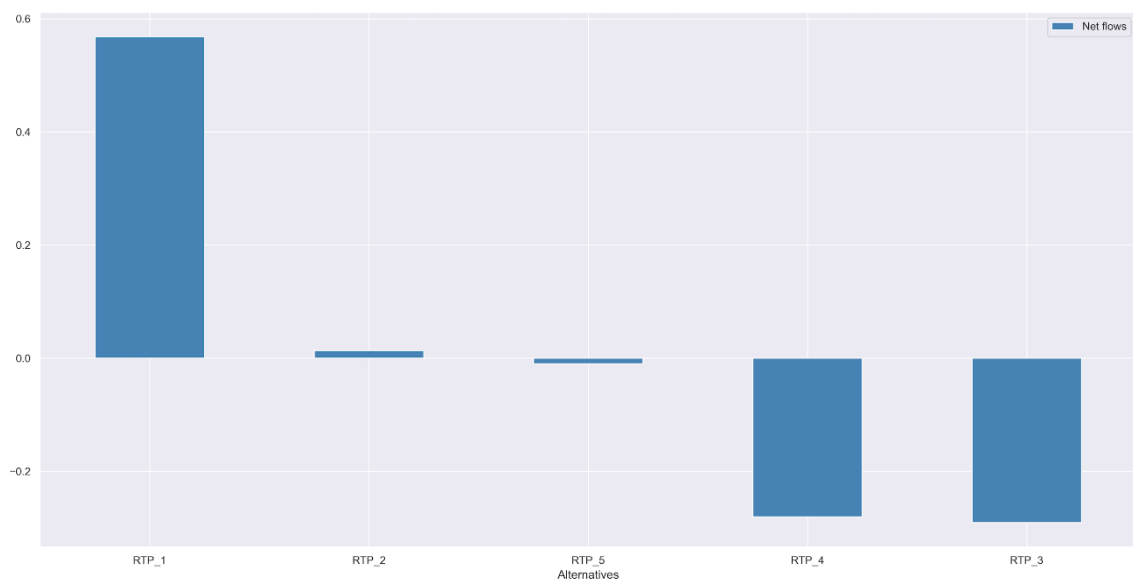


Figure 32. Illustration of the PROMETHEE GDSS Ranking. Source: Author.

The resulting ranking is illustrated in Figure 32 and summarized in Table 23.

Table 23*Group Results According to the PROMETHEE GDSS*

Ranking	Net Flow ϕ	RTP	Title
1	0,568	RTP 1	SDG Pathway
2	0,013	RTP 2	Incremental Progression
3	-0,010	RTP 5	Technology Pathway
4	-0,280	RTP 4	Transformational Divide
5	-0,291	RTP 3	Strained Cooperation

Note. For the related narratives, see Table 12.

According to this PROMETHEE GDSS ranking, RTP 1 is ranked first from the perspective of all stakeholder groups. RTP 2 is in second place, followed by RTP 5 in third place. This is followed by RTP 4 and RTP 3 as the last-ranked transformation path.

9.3 Discussion

9.3.1 Individual Results

The individual rankings according to PROMETHEE II show that RTP 1 is consistently ranked first among all stakeholder groups. However, notable differences arise among the respective groups in the following rankings. RTP 2 is ranked second in four instances while RTP 5 is ranked second three times. Thus, RTP 2 and RTP 5 alternate in second and third place in the ranking.

A similar setting can be observed with respect to RTP 3 and RTP 4. RTP 3 is ranked fourth on three occasions, while RTP 4 is ranked in this position four times. As a result, RTP 3 and RTP 4 alternate between the fourth and fifth place, depending on the respective group observed. Overall, both RTP 3 and RTP 4 consistently occupy the bottom two positions in the ranking.

The results further confirm that using the additional ranking of PROMETHEE I can, in some cases, provide additional information. In the present case, incomparabilities concerning the ranking order of RTP 3 and RTP 4 are affected. This is particularly evident in the stakeholder groups of *Government & political actors*, *Industry & commerce* and *Research*. These groups are especially influential in terms of shaping the transformation process and tend to have balanced weighting factors with regard to the weighting of the

criteria. From a conceptual point of view, this highlights the potential of providing individual stakeholder groups with more information. For the present analysis, however, the additional insights are unlikely to be decisive, since both RTPs in question are ranked lower than all other existing decision alternatives. Thus, from an analytical standpoint, these alternatives are considered less favorable than all other alternatives in question and should, therefore, not be pursued.

With respect to the group *Citizens & consumers*, the strong emphasis on ecological aspects was to be expected with regard to both *Step I* and *Step III* of the analytical framework. An interesting observation concerning the individual ranking of this group is that RTP 5 slightly outperforms RTP 2. This could be attributed to the significant weighting of resource-related aspects within the sample, particularly concerning indicator 2.2, as this is the most important indicator according to the weighting, and RTP 5 performs better in this respect.

Step I and *Step II* indicated a generally balanced evaluation for the group *Farmers & forest owners*, with slightly more importance associated with resource-related aspects compared to technological or environmental issues. This is also reflected in the ranking, as RTP 2 performs better here than the technology-oriented RTP 5.

The high perceived importance of technological aspects related to the bioeconomy for *Government & political actors* was indicated during *Step I and II* and is also reflected in the individual ranking for this stakeholder group since RTP 5, the Technology Pathway, is ranked second.

While *Step I* highlighted the greater importance of resource- and technology related aspects of the bioeconomy for the stakeholder groups *Industry & commerce* and *Research*, the subjective perceptions integrated as weighting factors gathered in *Step III* pointed towards a more balanced evaluation for these groups. Consequently, both groups place RTP 2 as second in the ranking, following RTP 1 and before RTP 5. The higher importance associated with ecological aspects thus led to the outcome that RTP 5, the Technology Pathway, only ranks third. One possible explanation for this could be that the direct inquiry into the importance of ecological factors led to a heightened perception of their importance.

The findings during *Step I* and *Step III* indicated an increased focus on resource-related aspects for the stakeholder group *Media*, although only a few publications and survey responses were available. RTP 5 performs better in two of the three indicators related to resource aspects, while RTP 2 only performs slightly better with respect to indicator 11.2.c. Yet RTP 2 achieves a better position in the ranking. This is due to two factors. First, within the indicators associated with the bio-resource vision, high importance is attached to the performance of 11.2.c. The second factor contributing to RTP 2's a better position in the overall ranking is related to the choice of the preference function T1. While the use of this preference function is beneficial with respect to ease of use, minor differences concerning indicator performance can result in a complete preference of one option over the other. PROMETHEE offers the flexibility to adjust the choice of preference functions to allow for a more nuanced assessment. However, this also increases the need to integrate further parameters and thereby increases complexity. Depending on the context, it could therefore be weighed up whether the choice of a different preference function seems appropriate, or whether the unexpected results are a reason to question the unbalanced evaluation of the individual indicators, potentially offering a constructive basis for further enriching discussion.

The PROMETHEE II ranking associated with group *Social and environmental initiatives & NGOs* ranks RTP 5, the *Technology Pathway*, ahead of RTP 2, the *Incremental Progression* path. Given the findings from *Step I*, this result was not to be expected. Yet, the collected responses from *Step III* within the explorative sample revealed a strong focus on resource-related topics, especially regarding indicator 2.2. The result could thus be linked to the thematic focus of the respective organizations. Moreover, similar to the *Media* group, the strong, one-sided weighting of resource-related indicators also contributed to the shifts in the ranking. This illustrates a fruitful starting point for constructive discussion and potential reflection concerning the choice of weighting factors.

9.3.2 Group Results

Concerning the group results based on the PROMETHEE GDSS, various observations can be pointed out. First, all stakeholder groups rank RTP 1, the *SDG-Pathway*, as the highest ranked decision alternative. Given that RTP 1 was ranked first among all groups

individually, the outcome that RTP 1 is ranked first from a group perspective was to be expected. Generally, this could indicate that a consensus can be found in the perception that pursuing RTP 1 illustrates the best option possible.

Following as second in the overall group evaluation, RTP 2, *Incremental Progression*, is followed by RTP 5, the *Technology Pathway*. Yet, the outcome of RTP 2 being ranked ahead of RTP 5 might not necessarily be the most crucial insight in this regard. More importantly, RTP 2 and RTP 5 frequently alternate between second and third place across different stakeholder groups with respect to the individual rankings, suggesting a general agreement on their relative importance. Potentially, this could indicate a tension between focusing on technological elements of the bioeconomy (RTP 5) and only striving towards incremental progression towards the SDGs (RTP 2). Thus, a discussion could be centered around those alternatives, evaluating respective advantages and disadvantages.

Another notable observation concerns the frequent low-ranked alternatives RTP 3, *Strained Cooperation*, and RTP 4, *Transformational Divide*. The observation that these two alternatives consistently occupy the last two positions highlights a shared perception of their limitations among stakeholders. This could indicate that there is a consensus that transformational divide and strained cooperation are not desirable and should be avoided wherever possible. In this context, it is ultimately not decisive that RTP 4 is placed ahead of RTP 3. Rather, it can be stated that if RTP 1 is not achievable, RTP 2 and RTP 5 would be preferable to the alternatives RTP 3 and 4.

Furthermore, variability in stakeholder priorities is recognizable. For example, the group *Citizens & consumers* places a greater emphasis on environmental issues, which affects the RTP rankings differently than is the case for groups such as *Industry & commerce*. Overall, it is evident that weighting factors influence rankings in the present case. The subjective weighting factors in Step III lead to variations in rankings, particularly for RTPs 2 and 5, but also for RTP 3 and 4, suggesting that stakeholder perspectives notably influence outcomes.

Another noteworthy observation concerns the impact of resource-related aspects. The emphasis on these across several groups suggests a growing recognition of the importance of resource management within the bioeconomy discourse. Furthermore, the use of PROMETHEE II and the ability to integrate additional rankings, such as the partial

ranking according to PROMETHEE I, demonstrates the flexibility of the framework. However, in direct interaction with stakeholders, may become overwhelming for stakeholder groups that are not familiar with related approaches.

Taken together, these observations can serve as a foundation for a comprehensive discussion of the individual rankings and group results, highlighting both consensus and divergence among stakeholder perspectives. Exploring the results of individual group before assessing the overall group results contributes to a more nuanced understanding of stakeholder dynamics, which can lead to more informed decision-making processes. However, it is important to note that the findings are intended to provide decision support, not prescriptive.

9.3.3 Limitations

The explorative application of the developed framework allows for generating various qualitative and context-specific findings. The resulting ranking is thus valuable for obtaining preliminary insights, illustrating patterns and trends and establishing a structured understanding of the decision problem. In doing so, it can provide a solid foundation for constructive public reasoning and mutual understanding between the involved parties.

Yet, it faces several limitations. The explorative nature of this approach does not allow for generalization of the findings. The utilized sample size is not intended to be representative but rather to illustrate the potential to adopt the methodology and contribute to understanding complex problems associated with societal transformation processes in relation to the bioeconomy. Generalization of respective findings and rankings is not possible. Thus, deriving definitive conclusions or attempting to predict the outcome of decision-making processes on the basis of this work is not feasible.

Operationalization for the decision context requires numerous steps in the analysis that can affect the results, such as the way subjective stakeholder perceptions are collected, the choice of preference function, and the development of decision alternatives. Transparency is therefore vital. As discussed in section 5.2.1, decision support systems face limitations and are intended to support decisions and not take decisions. Despite careful conceptualization and application, the absence of an optimal decision implies that

every decision is associated with compromises and trade-offs. However, this does not necessarily represent a negative property. On the contrary, awareness and careful weighting of associated trade-offs and compromises might notably contribute to an improved understanding of the decision context, potentially leading to a more nuanced perception and understanding of the decision problem itself. In this way, it can thus contribute to a constructive framework for public reasoning, as intended in this work.

10 Discussion

The previous chapters illustrated how to apply the developed research approach to the RR case study, divided into four steps. This chapter extends the analysis and is divided into two parts. The first part derives policy implications based on the findings of the overall analysis. The second part provides a critical discussion of the general aspects of the developed approach.

10.1 Policy Implications

The development of the policy implications is structured along the associated research questions. Policy implications are then derived on the basis of and with reference to the related insights gained throughout the analysis.

10.1.1 Derived from Step I

10.1.1.1 Fair Share of Burdens. Societal change and transformation processes of the scale needed to shift towards more sustainable pathways will have profound implications that are associated with various forms of burdens. With respect to *RQ 1*, the objective was to gain insights into the priorities and concerns of affected stakeholders in relation to the transformation process towards a sustainable bioeconomy in the RR. In this connection, the focus group workshop conducted allowed for interesting insights into respective subjective perceptions.

During the work with stakeholders, it became apparent that three aspects were considered particularly important. Those concerned regional added value, environmental sustainability and a fair share of financial burdens. These concerns should be taken into consideration and addressed appropriately, as change processes can also place a disproportionate burden on individual groups, while others benefit disproportionately. This must be avoided, as such developments could hinder the progress of politically desired transformation processes. Thus, the following policy recommendation can be derived:

Implication: Ensure a fair share of burden associated with the transition processes towards a sustainable bioeconomy.

10.1.1.2 Underrepresented Stakeholders. Stakeholder perceptions play an important role for the progress of societal transformation processes (Section 3.2.2). Considering social transformation processes as wicked problems clearly shows the importance of actors' perceptions when it comes to finding possible solutions or an overarching understanding of the problem (Section 3.2.1). The aim related to *RQ 2* was thus to determine which stakeholder groups are frequently addressed in relation to the bioeconomy.

The analysis based on the systematic literature review as part of *Step I* revealed that the groups *Government & political actors*, *Industry & commerce*, and *Research* were assessed almost twice as often as *Citizens & consumers*, *Farmers & forest owners*, or stakeholders from *Social and environmental initiatives & NGOs* (Dieken et al., 2021). The disparity extends to the analysis of stakeholder groups and their expertise since experts are examined much more frequently than laypersons (Dieken et al., 2021). Therefore, most research on stakeholder perceptions focuses predominantly on expert groups while civil society and their respective perceptions remain comparatively underexplored (Dieken et al., 2021).

The responses based on the explorative sample, gathered using the questionnaire of subjective stakeholder perceptions in *Step III*, pointed in a similar direction. An unbalanced overall picture emerged, and it became apparent that stakeholders from the groups *Research*, *Industry & commerce* and *Government & political actors* are visibly more present than the other groups. In contrast, the groups *Social or environmental initiatives & NGOs*, *Farmers & forest owners* and *Citizens and consumers*, were underrepresented.

Overall, this indicates that the perceptions of civil society stakeholders are insufficiently represented. This observation aligns with findings in the literature (Section 6.2). Given that these perceptions can also play an important role in the long-term success of a sustainable transformation to a bioeconomy, it would appear to make sense to include them to a greater extent. Hence, the following *PI* can be derived:

Implication: Increase efforts to include underrepresented stakeholder groups.

10.1.1.3 Divergent Value Systems. As discussed in section 3.2.1, the way we perceive a wicked problem strongly influences the way we address and intent to solve a given problem. In a societal transformation process with diverse groups, interests and value systems, striving for a sustainable approach to foster change implies that it is important to include various stakeholders and account for diverse perspectives and interests. The underlying objective associated with *RQ 3* was therefore to understand what conflicts of values exist between stakeholder groups.

The analysis in *Step I* indicated that the most commonly investigated stakeholder groups from industry, politics or research tended to be equally supportive of both the bio-technology and bio-resource understandings (Dieken et al., 2021). In contrast, citizens and consumers indicated notable support for the bio-ecology vision, which was only marginally present in the findings on other stakeholders (Dieken et al., 2021). This divergence highlight a conflict of values concerning the noticeable gap in the consideration and regarding the importance of the ecological dimension. This value conflict is further underscored by findings showing that citizens familiar with the concept of the bioeconomy generally associated it primarily with eco-friendly production or nature-related aspects (Dallendörfer et al., 2022).

Step III and *Step IV* further illustrated differences in the weighting of the indicators and the ranking of the various RTPs. The results indicating a higher level of importance of ecological aspects associated with *Citizens and consumers* are consistent with the previous steps of the analysis and seem to reinforce the relevance of this value conflict. Moreover, the prioritization of the technological aspects associated with the actors categorized in the stakeholder group *Government & Political Actors* is also consistent with the observations made in the previous steps of the analysis and indicates another existing value conflict.

Yet, as discussed in the context of *RQ 2*, stakeholders from civil society appear to be notably less involved in transformation processes related to the bioeconomy. However, their interests seem diverge from those of stakeholders actually shaping the transition process. *RQ 2* and *RQ 3* are thus interrelated.

As Sen pointed out, a consensus based on *Plural Grounding* does not require an identical, shared reasoning on an entire political conception of justice, but does emphasize the importance of integrating multiple perspectives to reach mutual agreement on actions

taken (Sen, 2017a). Thus, divergent value systems should be accounted for. Overall, by more actively engaging civil society, policymakers can better align the goal of implementing a sustainable bioeconomy with the values of citizens and hence foster a more holistic and broadly supported transition. This leads to the following policy implication:

Implication: Address concerns resulting from different value systems equally.

10.1.1.4 Communication Strategies. As discussed in the sections 2.2 and 3.1, there is frequently ambiguity connected to terms and concepts such as sustainability, GE, CE and bioeconomy. The definitions, underlying properties, and associated implications differ connected to a normative concept such as sustainability or a broad concept such as bioeconomy. The objective of *RQ 4* was thus to arrive at an understanding of what the German population knows about the bioeconomy and what is commonly associated with it. The survey revealed that public understanding of the term *bioeconomy* is limited and ambiguous (Section 6.3.3), often diverging from fundamental concept of substituting fossil resources with renewable, bio-based resources – a notion frequently emphasized in policy documents and strategies as outlined frequently from definitions found in policy documents and strategies (Dallendörfer et al., 2022; Dietz et al., 2023; Meyer, 2017; Proestou et al., 2024). Yet, when it comes to supporting a transformation characterized by the replacement of fossil resources with renewable alternatives (BMBF & BMEL, 2020a; EC, 2018c), the core concept and its underlying aspirations are widely supported by the population (Dallendörfer et al., 2022).

The survey further revealed that there is a widespread expectation within the general population that a sustainable bioeconomy is a solution to many environmental problems (Dallendörfer et al., 2022). However, while ecological aspects are an important part of the bioeconomy, the analysis also indicated the importance of those is not as pronounced with respect to stakeholders that notably shape the transition process (Section 6.3.3). This, too, is consistent with results of further research (Dietz et al., 2023).

Overall, these findings suggest that communicating core elements of the bioeconomy holds the potential to build broad support for the planned transformation process. At the same time, there is also considerable risk that large sections of the population will be disappointed, as they have different hopes, expectations and perceptions of a sustainable bioeconomy. These appear particularly relevant concerning fairness and justice connected

to the transformation process. Justice frequently illustrates a central concern of several stakeholder groups in the context of energy system transitions (Kalt, 2021; Newell et al., 2022). A fair share of burden resulting from the transition process further constituted a key take-away from the focus group workshop conducted. The perceived fairness can vary considerably and is closely linked to issues of communication. In this connection, the perceived burden and perceived injustice can turn out to be higher or lower in comparison to the actual burden itself. Here in particular, an open and constructive discourse appears to be necessary since Sen and Rawls both closely relate their understanding of public reasoning to justice.

In addition, the ambiguity of complex concepts such as the bioeconomy or sustainability hold potential for misperception and problems such as *green washing*. Honest, transparent communication is thus vital to prevent unrealistic expectations and contribute to avoiding societal backlash. This results in the following policy implication:

Implication: Develop clear and transparent communication strategies to align expectations and actual policy goals.

10.1.2 Derived from Step II

10.1.2.1 Monitoring Systems. Sustainability as a normative concept, requires continuous adaptation over time, with related indicators needing to be able to respond in a timely manner to technological changes. Thus, related concepts and measurement approaches require continuous work and will never reach a point of finality or final definition since they need to remain dynamic and have to account for changing societal or technological realities. Digitization or the developments related to the Fourth Industrial Revolution are good examples in this connection (Siekman et al., 2023).

Early recognition of developments also plays a key role with regard to the bioeconomy. Not least because a large number of related developments are based on KETs and are connected to questions of acceptance concerning bio-based technologies (Macht, Klink-Lehmann, & Hartmann, 2023; Macht, Klink-Lehmann, & Venghaus, 2023; Waßenhoven et al., 2023).

The rationale of RQ 5 was hence to investigate how a comprehensive monitoring system can be established that accounts for sustainability while addressing key parts of the bioeconomy.

Linking the bioeconomy to sustainability and using a holistic monitoring system is thus vital since the bioeconomy affects multiple sectors and the implementation of a sustainable bioeconomy influences affected communities as a whole. Comprehensive measurement approaches can reduce the potential for overlooking essential parts beyond issues immediately addressed. This presents the danger of unawareness regarding maldevelopments and can contribute to silo-thinking of involved actors.

The SMLFA developed in *Step II* illustrates that the connection between the bioeconomy and multiple SDGs can be holistically integrated using a systematic approach (Section 7). This approach can also be replicated in various contexts and thus provides a viable foundation for further related monitoring systems. Given the importance of accounting for the bioeconomy comprehensively and the availability of the developed approach, the following policy implication can be derived:

Implication: Ensure that monitoring systems are up-to-date and account for the bioeconomy comprehensively.

10.1.2.2 Narratives and Pathways. Regional transitions and related shifts in economic activities have profound implications for the way resources are produced, distributed and consumed (Coal Commission, 2019; Diluiso et al., 2021; Font Vivanco et al., 2019). To develop effective policies that prioritize sustainability and resource efficiency, policymakers must consider how structural changes will affect these systems.

In this context, transformation pathways constitute a practical tool for understanding and evaluating potential policy options (Turnheim et al., 2015; Werners et al., 2021; Wolff et al., 2023). They further allow for improved communication with stakeholders by simplifying complex concepts (Section 3.2.3 as well as Wolff et al. (2023)). However, established pathways, such as the SSPs, differ concerning the addressed time frame, sectors and governance level. The motivation behind *RQ 6* was hence to develop an approach that builds on recent advancements connected to climate science, and particularly the SSPs, while at the same time adapting to the needs of decision-makers in a regional context and making them more tangible.

Against this background, transferability of the underlying approach used to develop the RTPs in *Step II* was an important consideration from the outset. The development of the narratives was therefore based on the steps that were also used in the conceptualization of the SSPs. Similarly, the SMLFA used to build a balanced indicator system is also

adaptable to different contexts. And using SDG data to quantify the values of RTPs further contributes to a transferable framework that can be used beyond the RR.

The RTPs thus present a range of possible future paths, in a coherent way, with both narrative and data, making possible directions comprehensible. In particular, it can be utilized to inform key stakeholders in policy, industry and research who, according to the results gathered in this work, frequently play a central role in shaping transformation processes in relation to the bioeconomy.

As highlighted in *Step II*, the developed approach offers potential to contribute to strategic processes related to regional bioeconomy transformations in three ways. First, by supporting the development of monitoring systems to track regional progress. Second, it provides a robust methodology that can be utilized to assist policy development at various levels and create supportive frameworks that promote sustainable practices. Lastly, by supporting communication efforts that raise awareness, engage communities in decision-making, and seek to distribute benefits equitably, while taking into account stakeholder perspectives.

The comparability and adaptability of this approach make it a valuable tool for further research and decision-making processes, presenting promising potential for broader application. This leads to the following policy recommendation:

Implication: Develop region-specific transformation pathways and account for transferability.

10.1.3 Derived from Step III

10.1.3.1 Importance of Decision Criteria. As discussed in relation to *RQ 3*, conflicts of values between stakeholder groups exist and can be expected in the context of societal transformation processes. The question remains, however, as to how these differences can be integrated within an MCDA-based decision support system. To do this, it is frequently necessary to determine the different, subjective assessments of individual criteria. The purpose of *RQ 7* was thus to explore how this can be pursued in the context of the present research framework.

The methodological basis for integrating subjective stakeholder perceptions in this work was FAHP. To prevent negative effects on communication by overwhelming stakeholders with a large number of indicators and limit the required number of pairwise

comparisons, it was necessary to adapt to the contextual requirements of the decision problem in the RR. To this end, a goal hierarchy based on nine key indicators from the overall monitoring framework was developed. An exploratory questionnaire was subsequently developed based on the goal hierarchy and key indicators to gather stakeholder input. Stakeholders were able to use linguistic terms to express the relative importance of each criterion in pairwise comparisons.

Although the explorative results cannot be generalized, interesting insights emerged. Those include that stakeholders from the groups *Research* and *Industry & commerce*, frequently associated with more pronounced weighting of resource and technology visions in the literature and prior steps of the analysis, indicated rather balanced weightings. Another notable observation is the emphasis on resource-related aspects across several groups, suggesting a growing awareness of the importance of resource management within the bioeconomy discourse. However, other findings from the previous analysis also seem to be confirmed, such as the stronger weighting of ecological aspects by *Citizens and consumers* and the higher weighting of technological aspects linked to actors from group *Government & political actors*. Overall, a more nuanced understanding could thus be achieved compared to solely relying on literature-based analysis. This points to the following policy recommendation:

Implication: Utilize measures to integrate subjective stakeholder perceptions in addition to literature analysis.

10.1.4 Derived from Step IV

10.1.4.1 Potential for Consensus. Striving for compromise is an essential part of democratic decision-making. Yet, especially in the context of wicked problems and complex transition processes, finding consensus appears to be increasingly challenging, not least due to divergent value systems and diverse stakeholder groups confronted with multiple challenges simultaneously.

Embedded in this context, the analysis conducted in this work revealed several differences concerning the importance of factors related to the transition towards a sustainable bioeconomy. For example, the population's overall understanding of the bioeconomy is notably lower compared to other stakeholder groups (Dallendörfer et al., 2022). And the understanding of the rationale for concepts such as bioeconomy and the

connection to underlying visions often varies widely from group to group (Dieken et al., 2021).

As per definition of a wicked problem, the way we perceive a problem strongly influences our idea of how to address it (Rittel & Webber, 1973). The motivation for *RQ 8* was to investigate whether a potential compromise solution can be identified, even if the perception of related problems and solutions differs.

The ranking of respective decision alternatives pursued in *Step IV* showed that RTP 1, the Sustainability Pathway, is ranked as the first alternative in each individual ranking as well as in the overall group ranking using the PROMETHEE GDSS. Yet, to see this immediately as a compromise solution is an incomplete perspective. On the one hand, because aspects of RTP development and methodology also play a role here. But more crucially, the ranking based on an MCDA approach intended to support decisions in this work is not intended to prescribe any solution. Instead, it is meant to help structure a constructive reasoning process.

It is thus reasonable, as Sen pointed out, to also regard the insights originating from partial rankings, such as those obtained through the use of PROMETHEE I, and consider further positions in a ranking. *Step IV* illustrated that RTP 5 and RTP 2 alternate frequently depending on the stakeholder group considered, while RTP 2 is associated with notably fewer negative impacts on a number of dimensions and is more closely aligned with the Sustainability Pathway RTP 1. Addressing these issues can potentially help to steer the discussion in a constrictive direction. Ideally, this could even lead to those involved questioning their weightings and priorities.

Furthermore, Sen noted that excluding inferior alternatives can already be considered a success. In this connection, the analysis suggests that there is a broad consensus of avoiding the alternatives RTP 3 and 4. This observation, too, might contribute to a fruitful process of public reasoning.

As pointed out in section 4.3.8, it is vital to reflect on the kind of consensus that is strived for. In particular, the complexity of the problems addressed in this work suggests that a broader understanding of consensus, one where stakeholders can agree from their own perspective and for their own reasons, appears to be a more suitable approach. A consensus on *Plural Grounding* might be less stable than an *Overlapping Consensus* as defined by Rawls. Yet it might be attainable, while Rawls' *Overlapping Consensus*

appears to become increasingly more difficult to relate to given the shifts and increasing polarization in various democratic societies. Thus, pragmatically speaking, it is better to strive for a form of weak compromise than prevailing with a complete absence of compromise. The following policy recommendation emerges from this:

Implication: Foster public reasoning and a consensus on the basis of plural grounding.

Table 24 summarizes the derived policy implications.

Table 24

Overview of Derived Policy Implications

Nr.	Description
1	Ensure a fair share of burden associated with the transition processes towards a sustainable bioeconomy
2	Increase efforts to include underrepresented stakeholder groups
3	Address concerns resulting from different value systems equally
4	Develop clear and transparent communication strategies to align expectations and actual policy goals
5	Ensure that monitoring systems are up-to-date and account for the bioeconomy comprehensively
6	Develop region-specific transformation pathways and account for transferability
7	Utilize measures to integrate subjective stakeholder perceptions in addition to literature analysis
8	Foster public reasoning and a consensus on the basis of plural grounding

Note. The number of the policy recommendation derived refers to the respective RQ, see section 5.11.

10.2 Research Approach

The application of the developed analytical framework yielded well-structured information and illustrated results allowing for a comprehensive overview of existing stakeholder perceptions in the context of a societal transformation processes. This approach provides valuable insights for supporting decision-making in the context of a wicked problem embedded in a dynamic environment with various affected stakeholders. Using this holistic perspective provides notably more information for forward-looking decision-making compared to approaches only investigating individual stakeholder

groups, as frequently pursued in current bioeconomy literature, as well as compared to approaches focusing only on a single sector or industry at a time.

The advantages include the possibility of developing communication strategies tailored to the intended stakeholder group and thereby provide targeted information related to respective issues of interest or concern based on the prevailing perceptions. Divergent perspectives can also be taken into account in order to enable mutual understanding. Stakeholders from civil groups could be made aware, for example, that the concept of the bioeconomy is not just a vision for an ecological future, but also addresses technological issues and resource constraints. Similarly, stakeholders from groups strongly engaged in the actual shaping of the transformation process could be made more conscious of existing perceptions across society. At the same time, the group perspective contributes to a better and more comprehensive understanding of the forces that drive the transformation process. The overview it provides of the commonalities and differences with regard to the respective weightings but also of tendencies with regard to possible under-representation and involvement in the process reveals a much more differentiated understanding of the dynamics of transition.

The overall research approach developed in this thesis followed a clear and structured path. The individual chapters and work steps built on and connected to each other in order to ultimately ensure coherence in terms of content and methodology. In addition, key advances in the progress of the work were captured continuously in the form of summaries at the end of the respective chapters. This type of structure is helpful for relating each analysis step and its place in the overall context of the analysis. In view of the complexity of the research focus and the scope of this work, this structure has proven to be advantageous.

This work started by introducing the foundations of the bioeconomy concept, vital developments and related critiques of the concept to allow for a comprehensive overview (Section 2). Given the various definitions of the term bioeconomy and multiple related concepts, delineation from the GE and CE was necessary to avoid misinterpretations and allow for analytical clarity. A crucial analytical building block for the developed framework could be identified in the bioeconomy visions introduced by Bugge et al. (2016). Their distinction between bio-technology, bio-resource and bio-ecology visions proved particularly useful with regard to the systematic literature review (Section 6.2)

conducted (Dieken et al., 2021). The usefulness of this approach is also demonstrated by the fact that further research is based on the corresponding distinction between visions (see e.g., Proestou et al., 2024). They were also of great use in categorizing the indicator system in *Step II* and for operationalizing the indicators in the context of gathering weighting factors in *Step III*.

Sustainability serves as a guiding principle for developing a future-oriented bioeconomy and was of vital importance for this work (Section 3). It played a crucial role in the development of the analytical framework and the choice of the MCDA method, for example with regard to questions of compensation (Section 5.5). Moreover, it was of particular relevance for the development of the monitoring system. In order to ensure a comprehensive, holistic monitoring of the bioeconomy and its linkage to sustainability, the development of the SMLFA was closely aligned with the SDGs and the GSDD (Section 7).

Understanding societal transformation processes, such as the transition to a sustainable bioeconomy, as a wicked problem as defined by Rittel and Webber (1973) highlighted the importance of perceptions in relation to policy planning (Section 3.2.1). The interdependent relation between comprehending a problem and resolving it points out that such problems are essentially unique and strongly context dependent. This insight is all the more crucial in situations in which an optimal solution cannot be determined. Thinking of planning as a process of ongoing discussion among stakeholders that leads to a better understanding of the problem and possible solutions, as brought forward by Rittel and Webber (1973), aligns with the foundational approach of this work.

Sen's work allowed for a novel interpretation and operationalization of addressing collective choices, especially with respect to environmental issues (Section 4.4). The crucial role of public reasoning in collective decision-making should also be emphasized here. Sen's remarks on completeness, maximality, and commensurability, played a decisive role, particularly with regard to the choice of specific MCDA methods within the research framework (Section 5.1.2). Also with regard to dealing with complete and, in particular, partial rankings as a common outcome in ethical and policy evaluation the insights gained contributed substantially to the selection of PROMETHEE I and II. In addition, the considerations concerning *Plural Grounding* were a major factor in favor of using the PROMETHEE GDSS.

As pointed out by Roy (1996a), decision aid is intended to help form, establish, and justify beliefs. It is thus consistent with the idea of a public reasoning framework that contributes to the understanding of complex decision problems. Against this background, the application of the developed framework in the context of the RR allowed for multiple findings.

Step I served to establish a clear understanding of the decision problem. Methodologically, this step of the analysis was based on a focus group workshop, a systematic literature review of stakeholder perceptions of the bioeconomy, and a representative survey of the German population (Dallendörfer et al., 2022; Dieken et al., 2021). This provided a comprehensive picture of the decision-making context and existing lines of conflict, as well as a differentiated picture of the actors involved. The combination of a local, small group in the focus group workshop, intensive literature research and a survey of the population's perception of the bioeconomy ensured a broad and multifaceted overview.

In *Step II*, structuring the developed regional narratives along the SSPs proved to be a fruitful approach, as it allowed for a reasonable limitation concerning the number of RTPs to be developed. Moreover, preceding this way provided a clear foundation for structuring the underlying core ideas and thus facilitated a traceable and transparent way to distinguish the respective transformation trajectories. The newly developed SMLFA for deriving the indicator framework further illustrated a viable, replicable approach to connect the SDGs with the requirements for a sustainable bioeconomy (Siekmann & Venghaus, 2024). This made it possible to develop a comprehensive approach that not only covers the bioeconomy, but also related contributions to sustainability as outlined in the SDGs. By combining the narratives and the indicator system, it was possible to carry out a plausible quantification and thereby complete the RTP development.

The FAHP methodology provided the basis for determining subjective stakeholder perceptions in *Step III*. For instance, the development of the goal hierarchy contributed to adapting to the contextual requirements to facilitate the use of the approach in the regional context of the RR. The operationalization of key indicators subsequently allowed for a viable approach for integrating subjective stakeholder perceptions. The exploratory survey further illustrated how the approach can be applied in a current transformation process.

The stakeholder profiles based on PROMETHE I and II in *Step IV* illustrated how the approach can be used to depict individual rankings and nuanced analysis on a stakeholder basis. The use of the GDSS showed subsequently how the differences in the individual rankings affect the overall ranking. The combination of individual and group perspectives complements each other and was able to present both preferred alternatives and undesired alternatives. Therefore, the intended task could be accomplished.

Overall, the developed analytical framework was thus capable of answering the RQs and allowed for deriving policy recommendations. The methodology of MCDA thus proved to be of great use for this study. By grounding the analytical framework in the basic steps of pursuing an MCDA, a foundation for the framework could be established. The steps of definition, structuring, evaluation, and analysis were thus a clear way to approach the decision problem. A key feature is the ability to bring together stakeholder perceptions and decision alternatives in an organized manner. It can therefore act as a connecting element throughout the analysis.

MCDA can constitute a beneficial tool, especially in the context of sustainability. Yet certain things need to be addressed carefully. Employing MCDA for decision-making requires various steps along the way of the analysis, including the choice of the specific method, development of decision alternatives, selection of indicators and more. As long as these choices and their underlying reasoning are transparent, traceable and comprehensible for the actors involved; it can turn out to be beneficial since it raises awareness of issues that need to be addressed. However, blindly following the resulting rankings without reflection should be avoided, as this undermines the iterative nature of the decision-making process.

The transferability of the approach gives rise to a number of starting points for future research, three of which are particularly noteworthy and connected to the development of the RTPs (Section 7). First, the narrative development building upon central aspects of the SSPs is flexible and can be utilized in different regional settings. Second, the SMLFA, used to derive a balanced indicator system, can also be applied beyond the case study considered in this thesis. The third aspect concerns the approach for quantifying the RTPs using SDG data, which holds considerable potential for deployment in further cases. Comparative approaches utilizing MCDA methods and addressing questions of subjective stakeholder criteria weights in relation to structural change processes for the

implementation of bioeconomy constitute a fourth avenue for future research. Those could provide interesting insights into regional characteristics, differences and commonalities. Lastly, further applications of the developed framework in constructive public reasoning processes illustrate promising options for future research projects.

11 Conclusion

This work presents a novel approach to bridge stakeholder perceptions and regional transformation trajectories within a decision support system. Based on this stakeholder-centered approach it contributes by deriving policy implications needed to foster progress towards a sustainable economy and society. It thus provides crucial support for achieving the objectives in a policy-driven structural change process for a sustainable bioeconomy.

The operationalization of Amartya Sen's work on collective choice guided the development of the research framework in this thesis. The developed approach allows for a comprehensive analysis and understanding of transition processes striving for a sustainable bioeconomy in a regional setting. In order to support navigating complex transitions, it supports structuring the context the decision is embedded in and allows for illustrating divergent stakeholder perspectives.

By addressing research gaps in subjective stakeholder perceptions and developing a holistic monitoring system that integrates social, economic, and environmental dimensions, this study contributes to a more inclusive and informed approach to managing transformation. A core feature of the proposed methodology consists of its transferability, which played an integral role in the overall development from the outset. In this connection, the procedure towards developing the RTPs is particularly noteworthy. The tree-step procedure consisting of regional narrative development based on core properties of the SSPs, a systematic approach to derive a sustainability-oriented monitoring, and SDG-based quantification, obtains potential to increase comparability between cases.

The application of the developed approach in the RR as a region strongly affected the phase-out of coal and the aspired implementation of a sustainable bioeconomy allowed for deriving insightful policy implications. Among the most important is the need to ensure a fair distribution of the burdens associated with the transition in order to avoid disproportionate costs being placed on individual groups, which could potentially impede the progress of the transformation. In addition, underrepresented civil society actors should be more closely involved, as their perspective on environmental and social impacts is crucial for promoting a holistic and widely accepted transition.

While the bioeconomy can play a vital role in a forward-looking transformation, it is not inherently sustainable on its own. The analysis revealed that knowledge and

perceptions of stakeholder understandings differ, especially with respect to the role of environmental aspects. Therefore, clear and transparent communication strategies should be developed to align public expectations with policy objectives, minimize misunderstandings and foster support for bioeconomy initiatives. If the bioeconomy is promoted as a sustainability concept, it should be grounded and reflected in related monitoring approaches. Without this, despite good intentions, there is a risk of misunderstandings and disappointment across various stakeholders.

Despite the multifaceted contributions, the limitations associated with the study must also be taken into account. Those concern the interpretation of the results in the context of the application in the RR. Parts of the application are explorative in nature. Thus, a generalization of the results is not possible. Yet, they can hint at potential issues and provide a way to structure complex decision problems. Thereby, they allow for a more nuanced understanding of respective decisions and the context they are embedded in. This, after all, broadens the available information and illustrates a constructive starting point for practiced public reasoning.

Further limitations relate to the utilization of approaches based on MCDA or DA in general. Related approaches cannot be entirely impartial. The utilization requires a large number of decisions that could potentially influence subsequent results. Thus, despite the utmost care, it can never be ruled out that the objectivity and consistency of the results may be affected by subjective judgments or biases. However, being aware of this limitation can actually be beneficial, as it encourages constructive discussion and reasoning concerning respective choices. Thereby, it might highlight issues that otherwise go unnoticed. In line with Sens's line of thought, decisions could be reflected upon and, if necessary, adjusted.

While these limitations exist, they also open up a number of possibilities for prospective research efforts. Further studies could explore the use of this approach in subsequent, interactive workshops to engage stakeholders directly. Promising studies could also apply the decision support system in different regions, both within Germany, and especially in an international context. This could contribute to a more nuanced understanding of collective choice in different settings and enhance the adaptability and utility of the framework. Following the structured procedure could additionally lead to

interesting comparative insights of how stakeholder perceptions and developed transformation trajectories vary across cultural or political landscapes.

Another key contribution of this work lies in the linking of the bioeconomy with sustainability in the form of a comprehensive monitoring system. Research and technology development in the context of the bioeconomy is promising and can contribute to addressing and mitigating numerous challenges, including resource scarcity and climate change. The societal implications of modern, innovative technologies, however, are frequently unclear. Technologies in relation to the bioeconomy are no exception. A thorough analysis of the individual technologies and their associated impacts is therefore important. However, this is not sufficient, as system changes also need to be considered and further implications may arise in the context of sustainability. Comprehensive approaches are thus crucial to navigate towards desired pathways and allow for course correction if necessary.

Decision-making in the context of social transformation processes is complex. Identifying transformation trajectories that are feasible, desirable, and acceptable from the perspectives of different stakeholders is a challenging task. However, these issues need to be addressed. Avoiding or postponing decisions can also be considered a form of decision-making but narrows the space of opportunity for future generations. The concept of sustainability implies a responsibility to take action in order to protect resources and secure livelihoods for generations yet to come. Thus, it is frequently better to decide despite potential uncertainty or gaps concerning the information available. Amartya Sen's reflections on collective choice provide constructive guidance in addressing challenges of integrating diverse human interests and values into decision-making processes. These can serve as a valuable foundation for steering future-oriented policy.

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Appendix

Questionnaire used for weight determination.



Wahrnehmung des Strukturwandels

In diesem Teil der Umfrage geht es um Ihre Wahrnehmung des Strukturwandels im Rheinischen Revier, insbesondere um die Umsetzung durch die Politik.

1. Wo würden Sie sich zuordnen?

- ☐ Forschung
- ☐ Medien
- ☐ Allgemeine Bevölkerung
- ☐ Land- und Forstwirtschaft
- ☐ Industrie und Unternehmen
- ☐ Politik und Verwaltung
- ☐ Bürgerinitiativen und NGOs

2. Betrifft das Thema Strukturwandel im Rheinischen Revier Sie in Ihrem beruflichen/privaten Umfeld?

	überhaupt nicht 1	2	3	4	5	6	extrem stark 7
Der Strukturwandel betrifft mich in meinem beruflichen Umfeld	☐	☐	☐	☐	☐	☐	☐
Der Strukturwandel betrifft mich in meinem privaten Umfeld	☐	☐	☐	☐	☐	☐	☐

3. Wie wichtig schätzen Sie die Rolle der Politik für den Strukturwandel des Rheinischen Reviers zu mehr Nachhaltigkeit ein?

- | | | | | | | |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1 extrem unwichtig | 2 | 3 | 4 | 5 | 6 | 7 extrem wichtig |
| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

4. Wie zufrieden sind Sie insgesamt mit der Umsetzung des Strukturwandels durch die Politik?

- | | | | | | | |
|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 1 extrem unzufrieden | 2 | 3 | 4 | 5 | 6 | 7 extrem zufrieden |
| ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

5. Wie bewerten Sie folgende Aussagen zur Rolle der Politik im Strukturwandel?

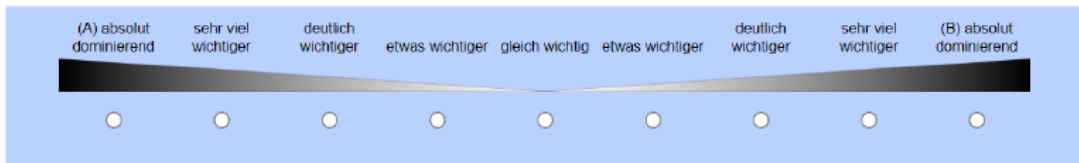
	Stimme überhaupt nicht zu	Stimme eher nicht zu	Stimme eher zu	Stimme komplett zu
Die Politik sollte dafür sorgen, dass die Konsumenten ihr Verhalten ändern und z.B. biobasierte und innovative Produkte (auch zu einem höheren Preis) kaufen.	☐	☐	☐	☐
Die Politik sollte eindeutige und verlässlichere Regeln und Vorschriften für Unternehmen schaffen, z.B. um Rohstoffe im Kreislauf zu führen.	☐	☐	☐	☐
Die Politik sollte mehr (finanzielle) Anreize für Forschung und Innovationsentwicklung bieten.	☐	☐	☐	☐
Die Politik sollte Landwirte mehr unterstützen, damit diese höhere Erträge bei gleichzeitig strengeren Umweltschutzauflagen erzielen.	☐	☐	☐	☐

Wandel im Rheinischen Revier

Mit dem Transformationsprozess sollen verschiedene Ziele nachhaltiger Entwicklung verfolgt werden. In den folgenden Fragen möchten wir Sie daher bitten, die unterschiedlichen Aspekte hinsichtlich ihrer Relevanz für die angestrebte Transformation im Rheinischen Revier miteinander zu vergleichen. Dabei können Sie angeben, ob Sie einen der genannten Aspekte als wichtiger erachten, oder beide als 'gleich wichtig' bewerten.

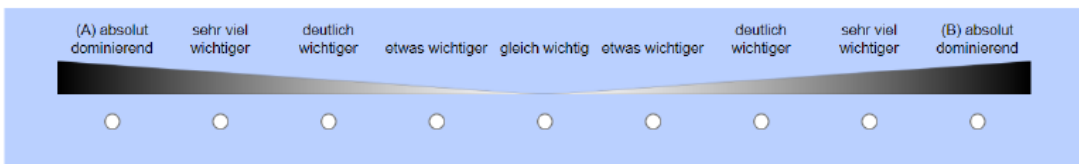
6. Welche Bedeutung hat Ihrer Ansicht nach eine höhere Wertschöpfung je eingesetzter Energie (A) verglichen mit einem höheren Anteil erneuerbarer Energien am Energieverbrauch insgesamt (B)?

← (A) Höhere Wertschöpfung je eingesetzter Energie | Anteil erneuerbarer Energien am Energieverbrauch insgesamt (B) →



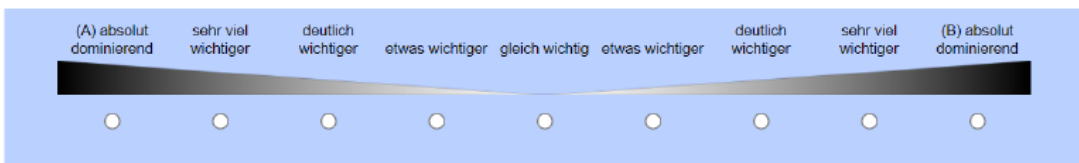
7. Für wie wichtig halten Sie eine höhere Wertschöpfung je eingesetzter Energie (A) im Vergleich zu höheren öffentlichen und privaten Ausgaben für Forschung und Entwicklung (B)?

← (A) Höhere Wertschöpfung je eingesetzter Energie | Öffentliche und private Ausgaben für Forschung und Entwicklung (B) →



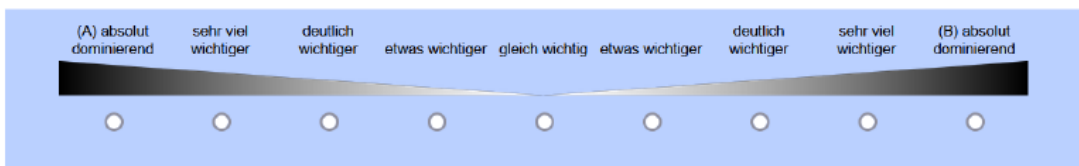
8. Für wie wichtig halten Sie höhere öffentliche und private Ausgaben für Forschung und Entwicklung (A) verglichen mit einem gesteigerten Anteil erneuerbarer Energien am Energieverbrauch insgesamt (B)?

← (A) Öffentliche und private Ausgaben für Forschung und Entwicklung | Anteil erneuerbarer Energien am Energieverbrauch (B) →



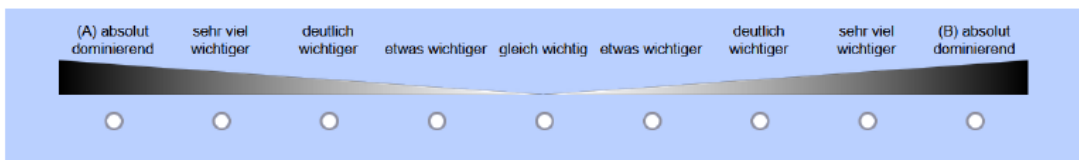
9. Welche Bedeutung hat Ihrer Ansicht nach der effizientere Einsatz von Ressourcen in der Produktion (A) verglichen mit einem gesteigerten Beitrag Deutschlands zur Ernährungssicherheit weltweit (B)?

← (A) Effizienter Einsatz von Ressourcen in der Produktion | Beitrag Deutschlands zur Ernährungssicherheit weltweit (B) →



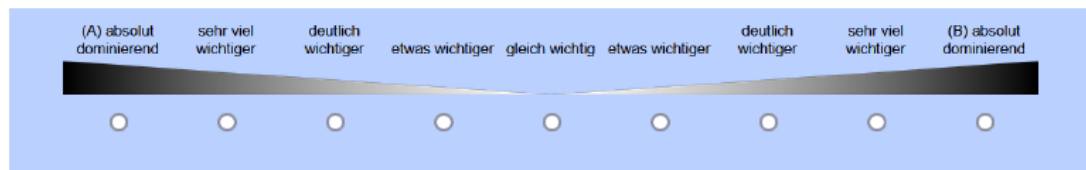
10. Für wie wichtig halten Sie eine bessere Anbindung an den ÖPNV (A) verglichen mit einem gesteigerten Beitrag Deutschlands zur Ernährungssicherheit weltweit (B)?

← (A) Bessere Anbindung an den ÖPNV | Beitrag Deutschlands zur Ernährungssicherheit weltweit (B) →



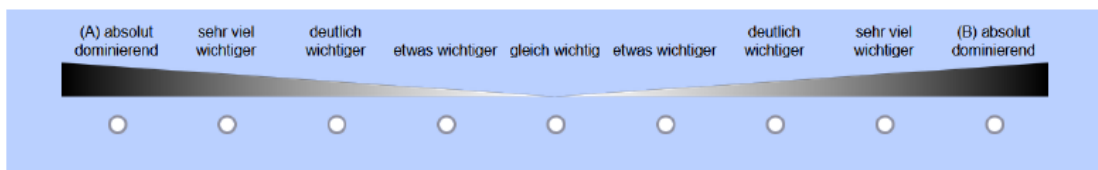
11. Wie wichtig ist Ihnen eine bessere Anbindung an den ÖPNV (A) im Vergleich zu einem effizienteren Einsatz von Ressourcen in der Produktion (B)?

← (A) Bessere Anbindung an den ÖPNV | Effizienter Einsatz von Ressourcen in der Produktion (B) →



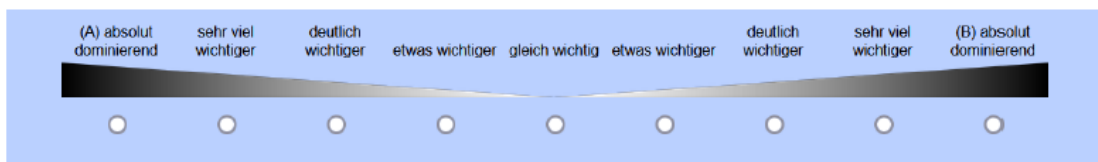
12. Wie wichtig ist Ihnen ein höherer Anteil an landwirtschaftlichen Betrieben, die nach Prinzipien des ökologischen Landbau produzieren (A), verglichen mit einer Verringerung der Schadstoffbelastung in Flüssen und Grundwasser (B)?

← (A) Anteil ökologischer Landbau | Verringerung der Schadstoffbelastung in Flüssen und Grundwasser (B) →



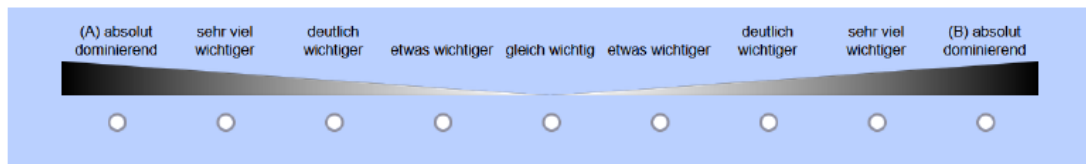
13. Welche Bedeutung hat Ihrer Ansicht nach ein höherer Anteil an landwirtschaftlichen Betrieben, die nach Prinzipien des ökologischen Landbau produzieren (A), verglichen mit einem gesteigerten Engagement zum Schutz großer Artenvielfalt und dem Erhalt der Landschaftsqualität (B)?

← (A) Anteil ökologischer Landbau | Artenvielfalt und Erhalt der Landschaftsqualität (B) →



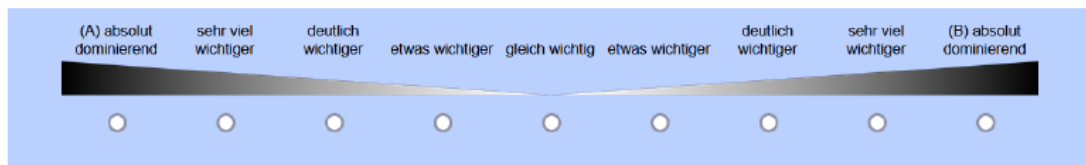
14. Für wie wichtig halten Sie eine Verringerung der Schadstoffbelastung in Flüssen und Grundwasser (A) verglichen mit einem gesteigerten Engagement zum Schutz großer Artenvielfalt und dem Erhalt der Landschaftsqualität (B)?

← (A) Verringerung der Schadstoffbelastung in Flüssen und Grundwasser | Artenvielfalt und Erhalt der Landschaftsqualität (B) →



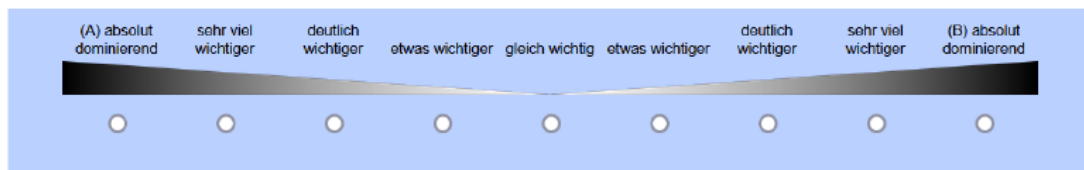
15. Für wie wichtig halten Sie Verbesserungen in Aspekten der Biodiversität und Ökologie (A) im Vergleich zu Fortschritten in den Bereichen Forschung und Entwicklung sowie Kommerzialisierung von Produkten auf Basis von bio-technologischen Prozessen (B)?

← (A) Biodiversität und Ökologie | Produkte auf Basis bio-tech. Prozesse (B) →



16. Wie bewerten Sie die Wichtigkeit von Aspekten zur Förderung der Biodiversität und Ökologie (A) verglichen mit gesteigerten Engagement bezüglich dem verantwortungsvollen und ressourcenschonenden Einsatz biologischer Rohstoffe (B)?

← (A) Biodiversität und Ökologie | Verantwortungsvoller und ressourcenschonender Einsatz biologischer Rohstoffe (B) →



17. Welche Bedeutung hat Ihrer Ansicht nach Fortschritt in den Bereichen Forschung und Entwicklung sowie Kommerzialisierung von Produkten auf Basis von bio-technologischen Prozessen (A) im Vergleich zu gesteigerten Engagement bezüglich einem verantwortungsvollen und ressourcenschonenden Einsatz biologischer Rohstoffe (B)?

← (A) Produkte auf Basis bio-tech. Prozesse | Verantwortungsvoller und ressourcenschonender Einsatz biologischer Rohstoffe (B) →

