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Born to transform? German bioeconomy policy and research projects for transformations towards sustainability

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ABSTRACT

Aiming at fostering the transition towards a sustainable climate-neutral economy, the German Federal Government (GFG) intends to promote the transition towards a sustainable knowledge-based bioeconomy (SKBBE). Bioeconomy policies are adjusted regularly, increasingly focusing on addressing the grand challenges of our time. To analyze whether the German bioeconomy policy, in terms of strategies and publicly funded research projects, actually fosters knowledge creation for the desired transformation, these strategies and projects have to be evaluated. Using a mixed-methods approach, this paper aims at investigating in what way German bioeconomy policy is dedicated to transformations towards sustainability and whether this reflects in the publicly funded research projects. Our study shows that the strategies as well as the publicly funded projects, still have a strong techno-economic orientation, focusing on technologies as problem-solvers, lacking, e.g., normative or transformative knowledge. What is more, the artificially generated R&D network does not show the necessary structure or involvement of stakeholders, lacking, e.g., the involvement of civil society or transdisciplinary research. We argue that future innovation policy has to foster all types of knowledge relevant for transformations towards sustainability, incorporating all stakeholders. Otherwise, the bioeconomy transition might become a purely technological endeavor unable to foster strong sustainability.

1. Introduction

Our current wicked problems are increasingly bearing down our societal, economic and ecological systems (Rittel and Webber, 1973). Our anthropogenic sustainability problems create pressing global challenges in the fields of societal justice, energy provision, mobility, nutrition, raw materials, and many more. In light of this, the German Federal Government (GFG) has started to advocate and initiate the transition towards a sustainable, knowledge-based bioeconomy (SKBBE) (BMBF, 2018; BMBF, 2010; BMBF and BMEL, 2020). They aim to foster a future-oriented, sustainable, and climate-neutral economy while retaining Germany's competitive position (BMBF and BMEL, 2020). Policy measures comprised in this agenda are designed to foster transitions in socially desirable fields and are mainly built around the mechanism of direct project funding (DPF) of research (BMBF and BMEL, 2020; Imbert et al., 2017). Germany is seen as a pioneering nation in advancing a SKBEE, which may exert signaling effects for other governments in Europe and around the world (Imbert et al., 2017). Qualitatively, however, the question arises whether the policy strategies and instruments are suited to foster transformations towards sustainability as well as the politically desired transdisciplinarity and participation. Recent work has highlighted the risk of an elitist creation of technologies substituting non-renewable resources by renewables—thereby potentially establishing unsustainable versions of the German bioeconomy (Urmetzer et al., 2018, 2022).

There is an ongoing debate on the transformative power and the sustainability potential of our current bioeconomy transition endeavors (Pfau et al., 2014; Vivien et al., 2019). Transformative sustainability scientists argue that potential initiation points for transition processes towards sustainability are the systems' knowledge bases (Abson et al., 2017; ProClim, 1997). In this context, additional types of knowledge complementing technologically useful knowledge (Foray and Lundvall, 1998; Lundvall and Johnson, 1994) may need to be integrated to form a base of knowledge explicitly dedicated to sustainability, so-called *dedicated knowledge* (Urmetzer et al., 2018). Urmetzer et al. (2018, p. 9) claim that “knowledge which guided political decision-makers in developing and implementing current bioeconomy policies so far has, in some respect, not been truly transformative.” Their two main points of

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critique are: 1) Bioeconomy policies have shown to be tainted by a strong techno-economic focus, fostering the creation and diffusion of techno-economic knowledge while neglecting other types of knowledge that are necessary for transformations towards sustainability. 2) Bioeconomy policies feature a top-down design that only superficially integrates relevant stakeholders while lacking genuinely participatory approaches (Urmetzer et al., 2018, 2022).

To empirically investigate these points of critique and to analyze the dedication of German bioeconomy endeavors, we are going to answer the following two research questions:

1. How transformative is the strategic orientation of the German bioeconomy strategy in terms of the underlying knowledge bases?
2. How is this orientation reflected in publicly funded research projects?

The present paper aims to propose a framework that helps us to assess whether German bioeconomy policy is dedicated to transformations towards sustainability by empirically investigating the strategic and structural components of German bioeconomy policies and resulting research projects. We seek to capture this complex phenomenon through a case study approach that allows to encompass various data sources and means of analysis (Yin, 2013; Yin and Davis, 2007). In doing so, we follow a recent stream of research mainly concerned with the contents and sustainability orientation of bioeconomy policy strategies and endeavors (e.g., Böcher et al., 2020; Giurca and Metz, 2018; Urmetzer et al., 2018) and integrate it with modern techniques of content analysis to identify represented knowledge types (Abson et al., 2014). We then extend the focus of analysis to the contents of consequently funded research projects utilizing deductive content analysis (Mayring, 2000) and employ social network analysis (Wasserman and Faust, 1994) to identify relevant network parameters emerging as a result of DPF. Lastly, we contextualize our findings with two qualitative interviews with current members of the latest German bioeconomy council (BC). Our paper contributes to the current discussion by confirming the sustainability critique of the German bioeconomy policy using empirical data. Additionally, we propose a new approach based on transformative sustainability science. Our model expands the scope of analysis from upstream bioeconomy strategies captured in policy documents towards investigating how well the strategic orientation and structural mechanisms proposed in or resulting from these strategies (may or may not) translate to the outcome of publicly funded R&D projects. This downstream perspective complements previous studies that have primarily focused on synthesizing national and international bioeconomy strategies. We believe that the proposed analytical framework can be used to analyze other countries' policy efforts and compare them to another.

This paper is structured as follows: Section 2 reflects on transformative innovation policies and presents types of knowledge relevant for transformations towards sustainability. Section 3 expands on the methodological procedures comprised in our case study approach. Section 4 presents the results of the analysis. Section 5 contextualizes the findings using interview data and discusses the most important results. The last Section 6 gives a short conclusion as well as an outlook to future research avenues.

2. Theoretical considerations

2.1. On the need for transformative innovation policies and multiple actor engagement

Considering the wicked problems and grand challenges of our time, transformative sustainability researchers see the necessity for innovation to be explicitly dedicated to sustainability and coined the notions of mission-oriented innovation systems (Hekkert et al., 2020) or dedicated innovation systems (Pyka, 2017). In conventional paradigms, the leading assumption prevails that innovations are desirable per se (Schlaile et al., 2017) and that the dominant values are economic growth, efficiency and competitiveness (Schot and Steinmueller, 2018). Innovation systems dedicated to sustainability build on the assumption that, rather, innovations that contribute to sustainability transformations are desirable. Yet, such innovation systems feature inherent tensions. This is why, when discussing such transformations, many researchers and concepts strongly propose to include all relevant (even marginalized) stakeholders (e.g., citizens, mediators, social, sustainable, and systems entrepreneurs, etc.) for negotiating and shaping alternative future pathways and democratizing knowledge production (Dutrénit and Sutz, 2014; Schot and Steinmueller, 2018). Such stakeholder engagement is explicitly demanded, for instance, in the transformative innovation policy discussion (Schot and Steinmueller, 2018), in the dedicated innovation system discussion (Pyka, 2017), in transition management approaches (Loorbach, 2010; Voß et al., 2006) as well as in the transformative knowledge discussion (Abson et al., 2014). Common to these approaches is the reasoning that there does not seem to be a single best pathway for a contested concept such as sustainability. Identifying, discussing and evaluating alternatives to existing understandings and definitions of desirable futures and the means of getting there should not be left entirely to incumbents or the scientific community (Schot and Steinmueller, 2018). What is more, the resistance of incumbent actors benefitting from the current regime or frames can be strong (e.g., concerning undertaken investments but also values, worldviews and belief systems) (Schot and Steinmueller, 2018). Therefore, sufficiently incorporating all relevant stakeholders is necessary not only for finding the "best" technological solutions but also for preventing unacceptable inequalities resulting from such solutions (Schlaile and Urmetzer, 2019).

Incorporating all stakeholders and democratizing knowledge production undoubtedly is a challenging task. Literature identifies various challenges or risks such as too quickly assuming consensus (Schot and Steinmueller, 2018), dominant actors jeopardizing decision making (van de Kerkhof and Wieczorek, 2005), self-organizing networks providing insufficient opportunities for learning, or that transition themes may already be predefined (van de Kerkhof and Wieczorek, 2005). Likewise, stakeholder participation can lead to simplistic solutions in complex settings, which cannot be scaled up (Hermans et al., 2011) and the results of this participation can be heavily dependent on the chosen case (Hermans et al., 2011). Especially in very uncertain contexts, such as climate change, overly managed forms of inclusion might emerge, which hamper the actual goal of participation (Few et al., 2007). Therefore, it is important to discuss *how* engagement is best facilitated.

Despite these challenges, in the latest strategy, one of the six central strategic goals of the GFG is "societal involvement" and one of the six building blocks of research funding are "inter- and transdisciplinarity" (BMBF and BMEL, 2020). The co-chair of the German bioeconomy council even explicitly stated in an interview: "Sustainable bioeconomy only succeeds with society's participation" (Biooekonomie.de, 2021).

In spite of such progressive ideas, German bioeconomy policy is still strongly framed by what Schot and Steinmueller (2018) call "innovation for growth" (i.e., a strong focus on subsidizing science and technology; advancement of scientific understanding with the assumption that findings will be used in a socially responsible matter; role of the private sector to transform these findings into innovations) and "national systems of innovation" (i.e., centrality of growth of output; employment and competitiveness; foresight; addressing system failure by increasing learning and cooperation between R&D producing actors in the system; greater interest in entrepreneurship). Even though the "national systems of innovation" framing formulates a need for cooperation and knowledge exchange since users of innovation are recognized as valuable contributors, Schot and Steinmueller (2018, p. 1559) warn that "the agency of users is limited to providing input into the knowledge production process by firms and other knowledge providers such as universities." As we will show in Section 4.2, this also is the case in the network of publicly funded projects in the German bioeconomy.

2.2. Dedicated knowledge for sustainability transitions

Already 20 years ago, Michael Gibbons (1999) describes how the relationship between science and society changed and how modern science does not only have to produce 'reliable knowledge', but co-produce 'socially robust knowledge'. He argues that such knowledge not only has a higher validity, is more sensitive to social implications, but is also less contested as society participated in its creation (Gibbons, 1999). Similar arguments can be found in transformative sustainability sciences, where Swiss researchers postulate a vision for science policy, stating that when actually wanting to contribute to sustainability, "science needs to submit three types of knowledge to public debate: Systems knowledge about structures, processes, variabilities, etc.; target knowledge about the targets of future development and scenarios; transformation knowledge about the transition from the current to a future target situation" (ProClim, 1997, p. 3). They go on to state that "for an effective translation of knowledge into action, all the stakeholders need to be involved. The conditions under which science operates and research is funded also need to be adapted accordingly" (ProClim, 1997, p. 3). Similar arguments on the need for these knowledge types for transformative change have been made by other scholars more recently (Abson et al., 2014, 2017; Grunwald, 2004; Urmetzer et al., 2018, 2020; Von Wehrden et al., 2017; or Wiek and Lang, 2016). In the context of the German bioeconomy, this necessity for different types of knowledge, such as transformative knowledge, created in transdisciplinary processes is explicitly highlighted (Knierim et al., 2017).

In this context, knowledge can be defined as the assessment of strategic scenarios to govern the transition towards an SKBBE, which may be based on factual and contra factual predictions of their interconnected effects to support stipulated goals across societal systems. Scholars see the need "to develop tangible strategies to manage ecosystems (based on systems knowledge) towards the societal goals derived from normative knowledge. [...] Transformative knowledge relates not only to specific policy interventions but also encompasses more general strategies such as participation, empowerment, education and communication" (Abson et al., 2014, p. 32). As transformative knowledge (TK) can only result as a combination, it is likely impossible to intentionally intervene in transformation processes successfully without adequately considering all types of knowledge. Systems knowledge (SK) may be described as a comprehensive understanding of the complex dynamics and interactions between (actors in) biological, economic, and social systems (ProClim, 1997). "Systems knowledge needs to be interdisciplinary, integrating knowledge from multiple research strands [...]" (Abson et al., 2014, p. 32). This type of knowledge is sticky and strongly dispersed between many different actors and disciplines (Urmetzer et al., 2018). Thus, to create and disperse systems knowledge, trans- and interdisciplinary approaches are needed (Schlaile et al., 2017). Normative knowledge (NK) "relates to judgements of how a system ought to be. Normative knowledge encompasses both knowledge on desired system states (normative goals or target knowledge) [...] and knowledge related to the rationalization of value judgements […]) (Abson et al., 2014, p. 32). As it is local, path-dependent, and context-specific, there is a need to incorporate actors which help decision-makers in overcoming (mental or emotional) lock-ins and affirm paradigm changes (Schlaile et al., 2017). Techno-economic knowledge (TEK) provides the intellectual basis for producing and distributing goods and services in economies (Foray and Lundvall, 1998; Lundvall and Johnson, 1994). Techno-economic knowledge corresponds to what Lundvall and Johnson (1994) describe as economically useful knowledge and is decisive for the creation of novelties (invention) and their introduction in the market (innovation). It does not only entail the knowledge of scientific facts, the general law of nature, and the technical skills of doing (e.g., producing) something but involves an understanding of market mechanisms in the sense of knowledge of what goods and services will work at the market (and why). It is this type of knowledge that is frequently referred to when universities, research institutions, companies, and policymakers postulate the need for the production, diffusion, and use of new knowledge to increase innovative output.

These types of knowledge in combination are what we argue to be necessary for successful intentional interventions in socio-technical systems, such as policy intervention in bioeconomy transition processes.

3. Methodology

Due to the complexity of sustainability problems and the intricacy of enacting policy agendas, current political efforts to steer an SKBEE need to be analyzed considering the systemic conditions they are embedded in. To do so, a case study methodology allows for a holistic mode of inquiry suited to integrate a variety of different sources of evidence on the design and execution of the bioeconomy policy in Germany (Verschuren, 2003; Yin and Davis, 2007). The present study will employ different analytical tools on different databases embedded in such a case study approach (see Fig. 1). We triangulate the case of Germany's political efforts to steer the bioeconomy by analyzing guiding policy papers (the declared agenda); the structure and content of funded bioeconomy R&D projects (the resulting DPF); and two contextualizing interviews with current members of the new Bioeconomy Council, which is tasked with consulting the government on the design of their strategies and executive mechanisms (BMBF, 2020a). We believe that our approach can easily be transferred to other contexts (e.g., to other countries, programs, policies), to assess the sustainability orientation of not only policies, but also company strategies, research papers, and other types of project descriptions. As 90% of the data available online is stored in unstructured formats and 80% thereof is stored in the form of text (Khan et al., 2010), the ability to contextualize and make use of text becomes increasingly important. What is more, both our quantitative as well as our qualitative analyses allow for relatively easy comparisons between texts. The analytical framework presented in this case study may, e.g., be valuable for assessing the implementation of Bioeconomy policies of other nations. At least 56 nations have published bioeconomy strategies (German Bioeconomy Council, 2015). Here, our framework may be used to investigate both comparisons between countries as well as the longitudinal development of strategies and connected research projects. For comparative analysis, differences in the strategic orientation between countries must be considered.

3.1. Analyzing policy agendas

The analysis of the policy agenda for the German bioeconomy is twofold. First, we provide a qualitative synthesis of the following seminal strategy papers published by the German Federal Government:National Research Strategy BioEconomy 2030 published in 2011 (BMBF, 2011); National Policy Strategy on Bioeconomy published in 2014 (BMEL, 2014); National Bioeconomy Strategy in 2020 (BMBF and BMEL, 2020); and Germany's sustainable development strategies (2002 SDS (GFG, 2002), 2016 SDS (GFG, 2016), 2021 SDS (GFG, 2021)).

The second step is to provide a more concrete measurement of the contents of each of the previously mentioned strategies through a lexicometric analysis (Dzudzek et al., 2009; Wiedemann, 2013). For this, we turn to Abson et al. (2014), who have qualitatively validated indicator words for SK, NK, and TK based on scientific publications. In addition, we compile a lexicon of indicator words for techno-economic knowledge ourselves in the following way: 1) We identify 1691 peer-reviewed articles focusing on techno-economic knowledge using the scientific database Scopus. 2) We retrieve the abstracts of these studies and prune the textual data for meaningless terminology (stop-words), as well as we prepare the text to be processed further (tokenization, removing symbols, lowering capital letters). 3) We identify terms that are frequently and significantly co-occurring with the word 'knowledge' within this textual data (Figueiredo et al., 2011; Wartena et al., 2010).

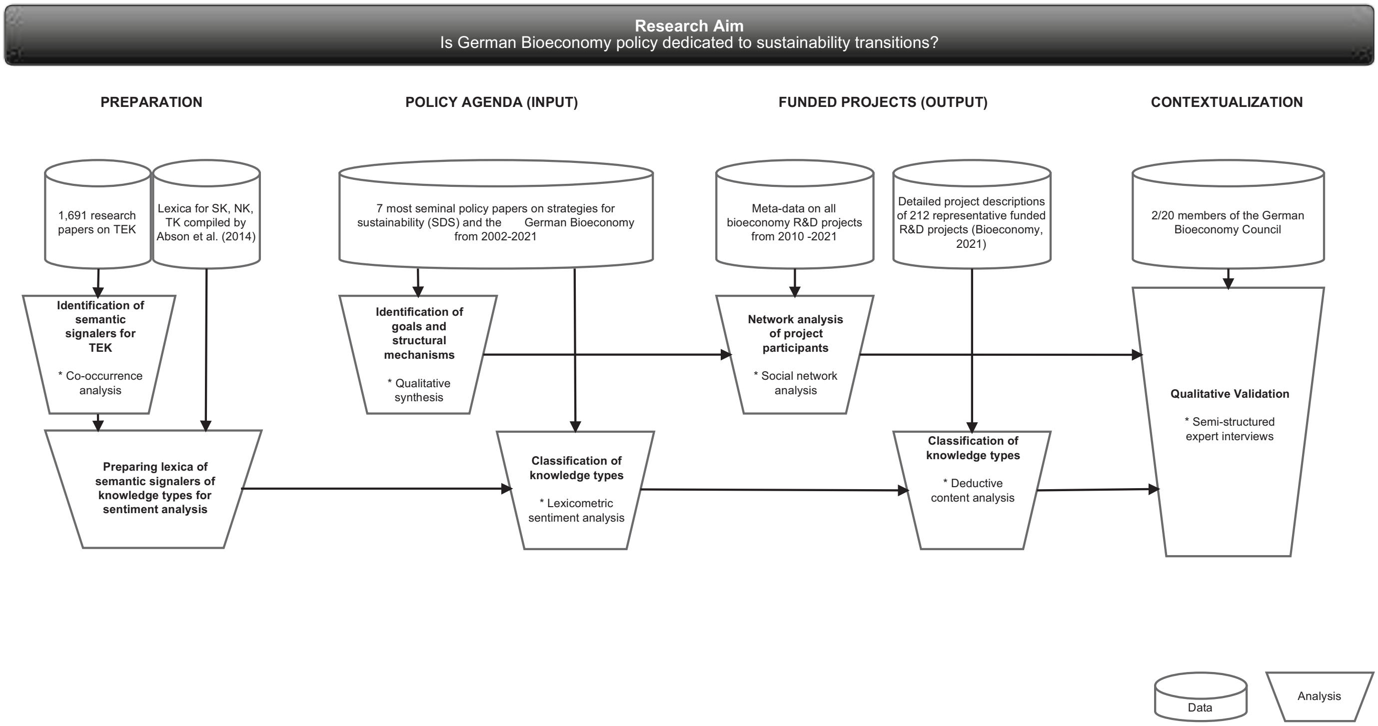

Fig. 1. Flowchart of methodological procedures encompassed in the case study.

These significant co-occurrences of words then form our lexicon of semantic signalers for a sentiment containing TEK. The complete list of terms used in our lexicometric analysis is reported in Appendix A.

3.2. *Analyzing publicly funded research projects*

We are analyzing how the bioeconomy strategies reflect in DPF in two parts. First, we conduct a social network analysis on the project data to assess the structure of the R&D network and identify the most important actors. To build the network of project participants, we extract meta-data on funded projects from the catalogue of funded projects by the GFG and create a network out of the 1019 joint or individual bioeconomy research projects and the 919 actors involved. We conduct a social network analysis (Wasserman and Faust, 1994) by considering the frequency of co-occurrences of actors in a joint project. Moreover, we calculate the degree centrality as in the number of links connected to a given actor (Freeman, 1979), which acts as a measure of immediate and direct influence within a network (Borgatti, 2005).

Second, we conduct a qualitative content analysis (Mayring, 2000) of the detailed project description of all projects to assess the representation of the above-mentioned knowledge types. We follow the technique proposed by Krippendorff (2004) to inform our process of sampling and coding. For this qualitative assessment of project contents, we scrape web data from the official bioeconomy-website hosted by The Federal Ministry of Education and Research (BMBF, 2020b), offering in-detail project descriptions of a subset of 20% of all projects (212 projects). We go on to manually code the project descriptions, relying on the expertise of the leading author of this study to classify all segments and passages of the 212 full-text project descriptions. We develop a codebook based on the indicator words used for our lexicometric analyses. Appendix A provides an overview of the sub-categories assigned to the four overarching knowledge types. Appendix B shows some exemplary coding for different knowledge types.

3.3. *Qualitative contextualization*

We cannot assess how the latest policy strategy will influence future research projects. Thus, we seek to provide contextual information on the process of designing and enacting the Bioeconomy strategies. We conduct in-depth interviews with two current members of the German Bioeconomy Council. The BC constitutes an independently operating body consulting the GFG on the creation and implementation of bioeconomy policies. The two interviews were designed in a semi-structured manner. Relevant contextual information and quotes taken from the interviews will be presented in the discussion section of this study, where they will be interwoven with complementary scientific evidence to reinforce or contrast the interpretation of our results. We indicate a reference to contents taken from either of the two interviews with the abbreviations I1 and I2.

4. The case of the German bioeconomy

4.1. *German bioeconomy policy strategies*

In 2002, the GFG presented its first draft of a policy document that would later become the basis for subsequent sustainable development strategies. In the last 20 years, Germany has assumed a leading role in developing political guidelines to drive respective endeavors forward. Under the German presidency of the European Council, a first roadmap for the KBBE was agreed upon in the so-called Cologne paper in 2007 (*European Union*, 2007). Germany installed a national bioeconomy council to consult the federal government in 2009 and published their '*National Research Strategy for the BioEconomy 2030*' in 2010 (BMBF, 2010), introducing a six-year plan bolstered by 2.4 billion Euros in research funding. Since then, we can observe an evolution of strategies for the bioeconomy and sustainable development to become more inclusive and participatory. While the 2010 strategy almost exclusively relied on financial grants for research and R&D activities, with only sporadic mentions of goals to build strategic alliances of different stakeholder groups (mainly focused on industrial partners), the 2014 '*National Policy Strategy for the Bioeconomy*' (BMEL, 2014) strengthened the focus on close cooperation between markets, academia, as well as ecological and societal actors, e.g., for considering social or ecological sustainability. This sustainability orientation had been pushed further by the introduction of the '*German Sustainable Development Strategy*' (SDS) in 2015 (GFG, 2016) to embrace the goals stipulated in the 2030 Agenda. The strategy is targeting "achievement of intergenerational equity, social cohesion, quality of life, and the acceptance of international responsibility" (GFG, 2016, p. 7), and highlights actors within civil society as one of five major interest groups to participate in this dialogue.

The previously described strategies of the GFG build the foundation upon which the updated '*National Bioeconomy Strategy*' published in 2020 is based on (BMBF and BMEL, 2020). Goals continue the path of developing solutions for the *2030 Agenda for Sustainable Development* and try to reconcile economic growth of the bioeconomy with limited capacities of ecological systems. Previous focal points are enriched through specific instruments to foster interdisciplinary collaborations, strongly support start-ups and small to medium enterprises as well as promote clusters and model regions. The involvement of various societal actors has been newly added and prominently phrased as one of six major goals for the strategy. To meet this goal, specific instruments include the creation of an advisory committee representing civil society, increased efforts to initiate a dialogue with interest groups, increased (financial) support of (accompanying) social science research for the bioeconomy. The most recent 2021 update of the SDS reemphasizes the need for genuine transformative changes in society and calls for an increased speed of implementation of measures targeting the realization of the SDGs. Besides a newly added focus on resilience to crises (due to the COVID-19 pandemic), the strategy presents the involvement of social stakeholders as one of six central tenets in achieving societal coordination of implementing sustainability efforts.

Despite the thematic development of strategies for the bioeconomy and sustainable development to become more inclusive and participatory, an analysis of even the most recent strategies reveals that technocratic goals and measures remain dominant. Beyond a qualitative impression, we visualize the representation of knowledge types found in each strategy in Fig. 2, which depicts the results of our lexicometric sentiment analysis of the relevant policy documents. Overall, the sentiment analysis reveals that the composition of knowledge types found in the different iterations of strategies has not changed much over time and seems to be heavily skewed towards TEK. We observe a strong and sustained dominance of TEK for all SDS and bioeconomy strategies across the years (only slightly decreasing for the SDS). Besides this finding, the SDS show a rather constant and low coverage of other knowledge types with a slightly higher representation of NK, a severe underrepresentation of SK, and a rather high frequency of sentiments connected to TK. In these relations, the high representation of indicator words connected to TK may signal that transformative instruments may be proposed within strategies, but are likely to be based on imbalanced knowledge types and may be lacking real transformative quality. For the bioeconomy strategies, we see an even stronger focus on TEK and a slightly better representation of SK, which is especially true for the 2020 strategy. The representation of SK seems to be primarily driven by consideration of system functions and processes, while NK is rather underrepresented. These findings may be explained by the current objective of bioeconomy strategies as techno-economic operationalizations of sustainability goals.

4.2. *Direct project funding in the German bioeconomy*

In the last eleven years, the GFG funded 1160 joint or individual bioeconomy research projects with more than 937 actors (universities, other research institutions, companies, associations and other actors) involved. Fig. 3 shows how the number and types of actors, as well as the number of funded projects and the subsidies, have developed over time. Subsidies rose by the factor of 7. Spending this enormous amount of money on Bioeconomy research is in line with Germany's bioeconomy strategies (BMBF and BMEL, 2020) and shows government's keen interest in fostering the creation of (new) knowledge. Not only the amount of money but also the number of different actors has grown. Over time, also the number of actors besides the traditional ones (universities and research institutions) increased to some extent, such that in 2020, instead of zero, 31 actors belong the categories 'associations' or 'other' (e.g., chambers of agriculture, regional offices, different associations, and consumer advice offices). In addition, the number of companies increased by the factor 4 from 2010 to 2020.

Fig. 4 shows a visualization of the R&D network in the German bioeconomy from 2010 to 2021. Node size is determined by nodes' average degree (Wasserman and Faust, 1994), i.e. the number of connections they have to other actors in terms of the number of projects they participate in. The link thickness shows the number of connections

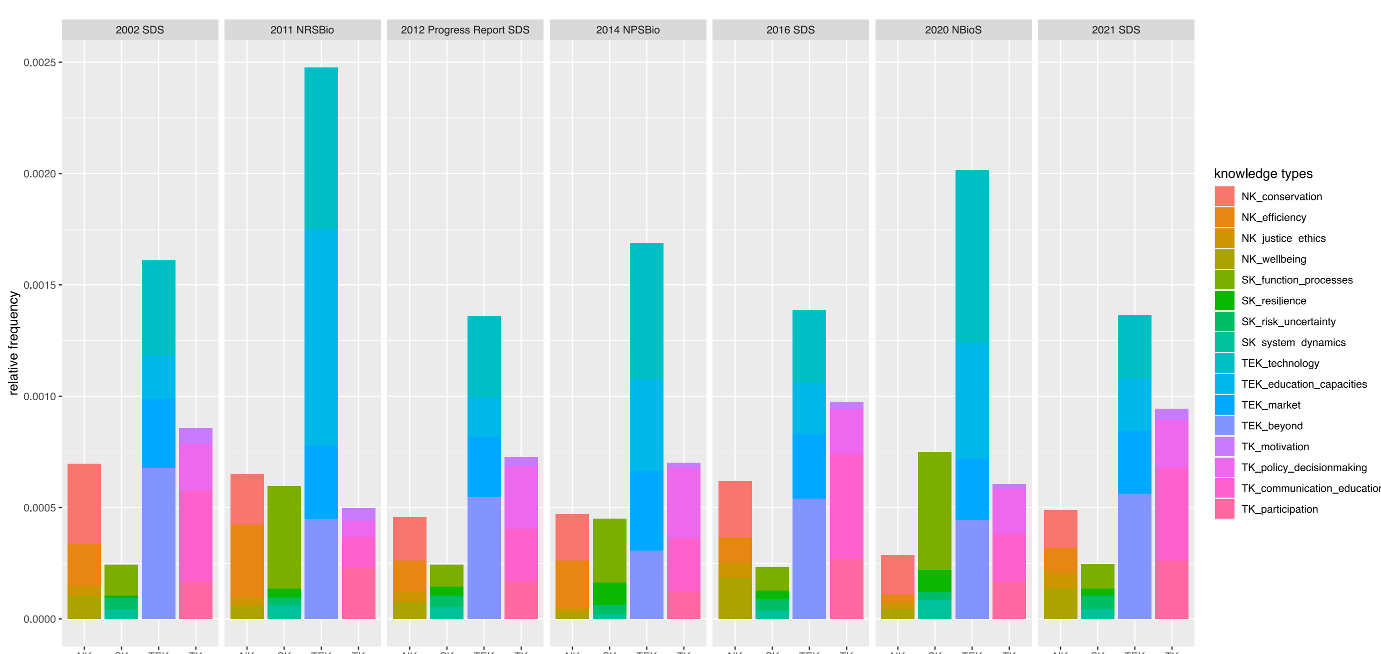

Fig. 2. Lexicometric sentiment analysis indicating the relative dominance of knowledge types represented in relevant policy documents.

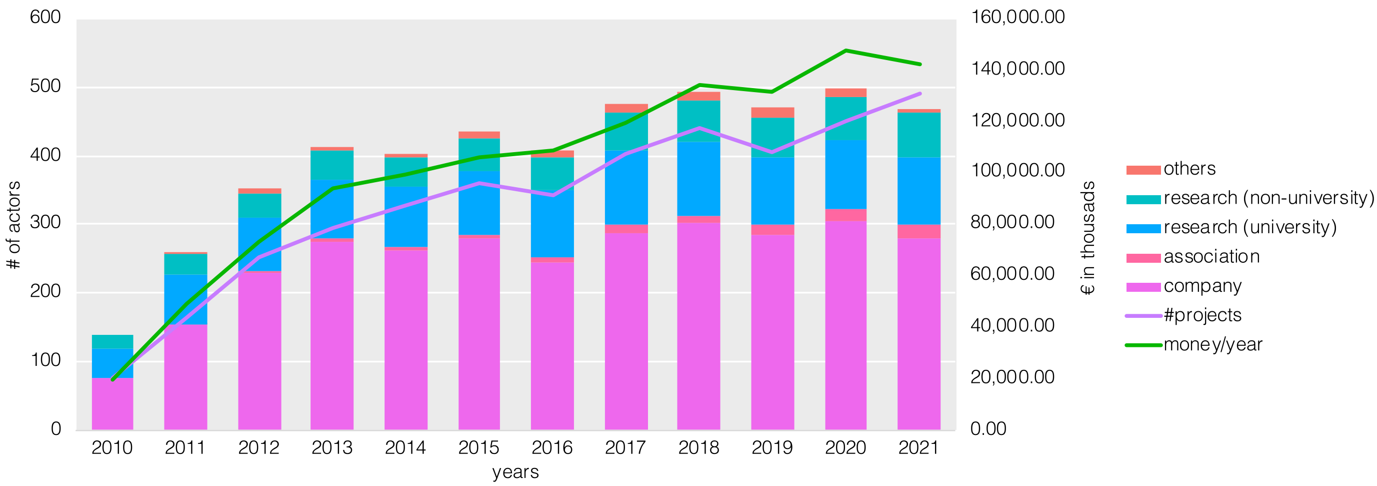

Fig. 3. Number, types of actors, funded projects and subsidies from 2010 to 2021.

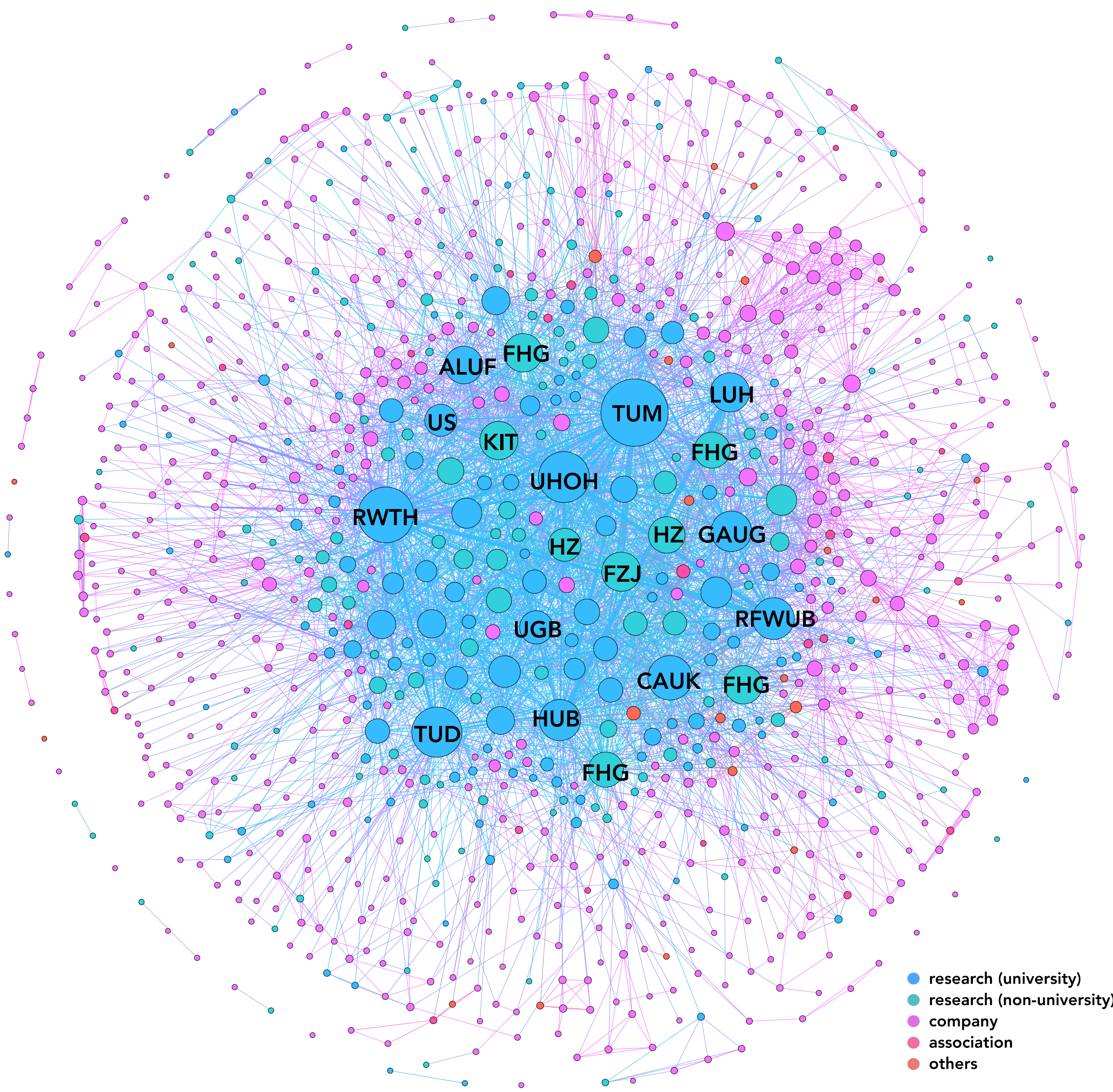

Fig. 4. Visualization of the publicly funded R&D network representing projects from 2010 to 2021. Light blue nodes represent universities, turquoise nodes represent other research institutions, pink nodes represent companies, red nodes represent associations and orange nodes represent other actors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

actors have. The thicker the link between two actors, the higher the number of joint research projects (as is the case with HUB and LUH, which cooperate many times in joint research projects). The link color is determined by the node types this link connects, i.e., a link between two universities colored in blue will appear blue as well. The visualized network shows a group of well-connected actors (mainly research institutions, see Appendix C) in the center, surrounded by the majority of other peripheral actors. We see a rather skewed degree distribution with a high number of connections distributed to a small group of actors (Appendix D). The well-connected actors at the core show a high degree centrality, i.e., they are the actors that are participating in most projects. The top-20 actors are participating in 83.9% of all projects. What is more, the core of the R&D network dominates not only research in this field but also policymaking. 12 out of 17 members of the former German bioeconomy council, which supported the government in policy making since 2009, are affiliated with a university or research institution, and 15 out of 17 members hold a position as a professor at a university (BMBF, 2020a). There is not one single member representing an NGO or other type of societal group. In the new bioeconomy council, 15 out of 20 experts hold a position as a professor. However, the new council without a doubt is more diverse, including, e.g., a political scientist, a researcher on ethics and responsibility or an expert from organized civil society. Despite funding more interdisciplinary research groups, traditional research projects only insufficiently integrate relevant system actors such as NGOs, sustainability movements (e.g., #FridaysForFuture), or other citizens (if at all). Not only is this at odds with the goals of the latest strategy but for integrating systems and normative knowledge, incorporation and empowerment of other actors (citizens) is needed to combine indigenous knowledge with scientific knowledge. This may help to overcome path dependencies, avoid lock-ins and to embrace uncertainty (accepting that the behavior of systems can never be completely understood and anticipated) (Schlaile et al., 2017).

4.3. Types of knowledge in subsidized R&D projects

To dive deeper into the question of which knowledge types are present in this structure, in this sub-chapter we are going to present the results of our qualitative content analysis of the project descriptions of the 212 selected research projects. Fig. 5 presents an overview of the different knowledge types and to what extent they have been considered in the analyzed bioeconomy projects. Fig. 6 additionally gives information on which combinations of knowledge types have been found in the project descriptions.

Most of the investigated projects (99%) also focus on the creation and diffusion of techno-economic knowledge. That is, for finding new or improved technological applications (162 projects), for educating actors on technological applications, and for improving their technological competencies (90). We also document a rather strong focus on market-related aspects (34) such as increasing market acceptance for products or processes. This comes as no surprise as the funded projects are purpose-based R&D projects with the declared goal to produce new products or processes or to find technical solutions to certain problems. Only three projects primarily focus on other aspects of techno-economic knowledge, which relate to socio-economic effects of certain technologies as, e.g., acceptance of bioenergy, or economic crises. Therefore, the representation of knowledge types within the projects is quite in line with the representation in the strategies (Fig. 2), except for a stronger representation of normative knowledge in the projects. Additionally, Fig. 6 shows that 44% of all projects exclusively address techno-economic knowledge. These projects most often are (or describe) biotechnological projects, in which a certain technology (e.g., opto-sensors) shall be found or improved. Whether or not these technologies might also have negative (environmental, social) effects or are desirable at all, is not explicitly addressed. Other projects that did not exclusively focus on techno-economic knowledge most often also focused on systems knowledge (39 projects), on normative knowledge (32) or on both systems and normative knowledge (26). We found various ways of how these different knowledge types are addressed and understood. Projects can already be classified as addressing systems knowledge, techno-economic knowledge and normative knowledge if it is simply stated that the desired technology might have unexpected effects but that project partners want to proceed as fast as possible nonetheless, as they do not want to waste time or money (normative knowledge - category efficiency). On the other hand, projects can be classified in the exact same category if their research motivation is to prevent waste in the first place, e.g., by making use out of waste materials (as waste from pepper plants) but not using unsustainable or wasteful production methods. In general, we find that projects dealing with issues related to circular

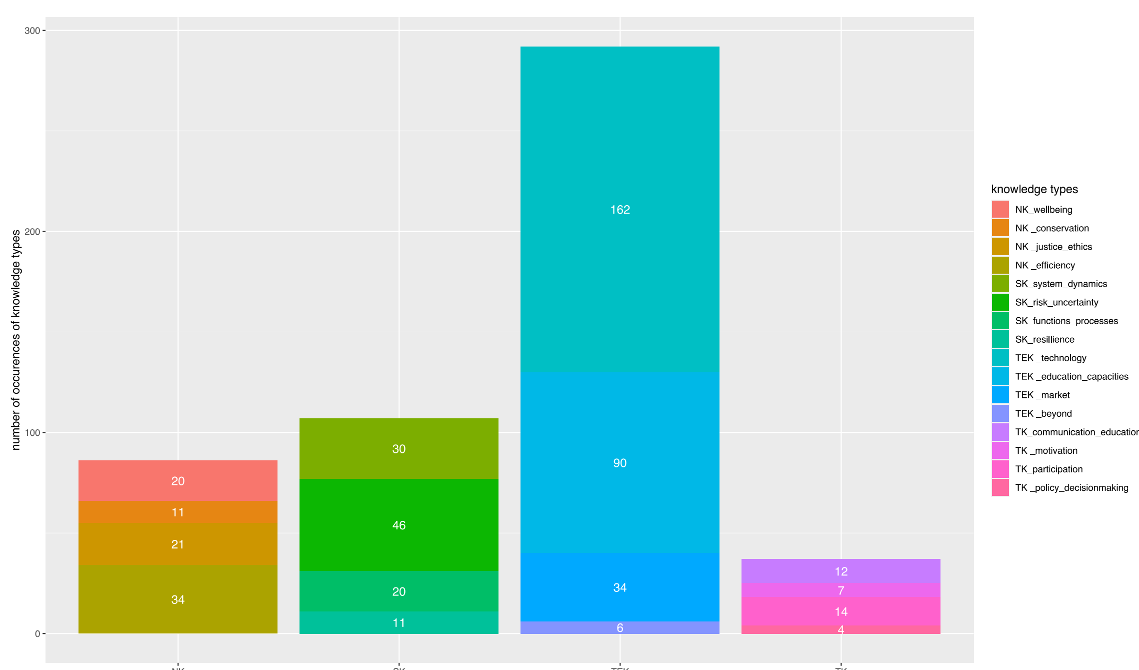

Fig. 5. Different knowledge types (TEK, SK, NK, TK) and respective sub-categories found in the projects.

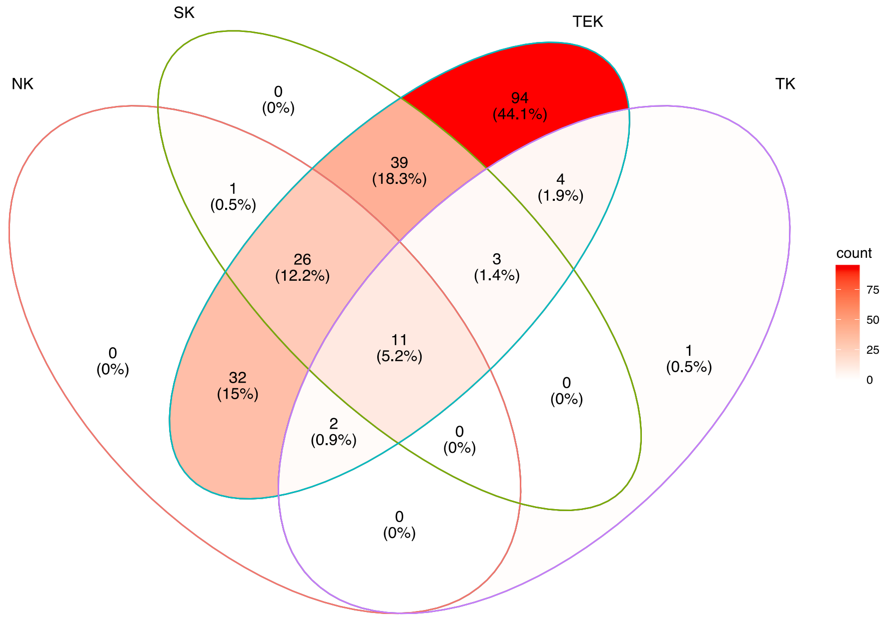

Fig. 6. Different combinations of knowledge types in project descriptions.

economy and waste prevention are more frequently addressing different kinds of knowledge comprehensively.

A share of 37% of the projects address dimensions of systems knowledge. Most of these projects (46) cover topics that deal with risks such as associated risks of biogas production or the risks that biomass production faces due to climate change. 30 projects also focus on system dynamics, i.e., how certain interventions in the system might lead to undesired effects. An example for this would be the import of new plants anticipated of being more robust to changing climate conditions and diseases, however, potentially leading to so far unknown diseases of other plants and, in the end, worse biomass production. Ten projects cover aspects related to how the systems work and which processes take place in the system—for example, by analyzing dynamics of sponges in trying to find applications for other systems. Six projects entail research that also tries to find out how the system (or parts of it) can be made more resilient (e.g., how intercrops can be used to make soils more resilient). It must be noted that systems knowledge is strongly dispersed and that all these projects and actors only hold parts of systems knowledge, mostly understanding the respective parts of the systems and the dynamics that they are directly subjected to or which they have made the subject of investigation. Fostering a more comprehensive form of systems knowledge requires incorporating and enabling all actors of the different systems to collaborate or at least share their knowledge with these other actors.

It is noteworthy that almost 34% of all projects entail normative knowledge. The largest part of these projects (34) is interested in aspects related to the efficient use of resources and waste prevention. As already mentioned before, what efficient use and waste prevention means from a sustainability point of view differs between the projects. Another important aspect comprises considerations of social justice and ethics, such as a just distribution of resources or the need to produce sustainable goods in form of frugal innovations. This is not only considered for satisfying own consumption habits but also focused on helping others (e.g., refugees). Additional points of interest focus on the well-being (20) of humans and other animals (e.g., by producing milk powder which is easier to digest for babies) and the conservation of our system (11) (e.g., by finding innovative concepts of forest usage which help the conservation of our forests). We found that most projects that deal with parts of normative knowledge mainly focused on their (the researchers') value judgements and desired future states. As normative knowledge is intrinsically local, path-dependent, and context-specific, the normative knowledge of these researchers (and those that evaluate project proposals) in some ways manifests as value judgements in the German bioeconomy (e.g., concerning the desirability and need to do research concerning certain types of biotechnology). Therefore, it seems to be of utmost importance to also invite other actors like NGOs, civil society, sustainability groups and so on in defining desired future scenarios and states (Wilke et al., 2021).

As transformative knowledge is conditional on the concurrent presence of TEK, NK and SK, it is consequently addressed rarest in these projects. This is also in line with what Abson et al. (2014) found when analyzing ecosystem services literature. However, at least in 9% of all project descriptions investigated, some elements of transformative knowledge can be found. For instance, researchers deal with how they can make other actors in the system participate in their research (8), how they can communicate with (and not only to) civil society (12), and how they can help other actors engage in the participation of environmentally friendly behavior (14). Policy and decision making are only of minor importance (4 projects), which is in line with what Urmetzer et al. (2020) found when analyzing knowledge types in academic bioeconomy programs. Projects in our sample that are categorized as dealing with transformative knowledge often have a rather broad focus and despite being purpose-based, they mostly do not intend to produce technology or technological solutions in the end. Their purpose seems to revolve around investigating social inequalities in the bioeconomy; risks and downsides concerning the production and use of bioenergy; or explicitly want to invite societal actors to collaboratively find new ideas for forest use and protection. It stands out that these projects do not intend to find (technological) solutions and seek to inform society or increase social acceptance ex-post. Rather, the projects seek to incorporate various societal actors in the search process for solutions to make use of societies normative and transformative knowledge.

5. Discussion

From the 1972 Limits to Growth (Meadows et al., 1972) to the 2018 #FridaysForFuture movements (Fridays for Future, 2021)—much has happened in the last 50 years concerning sustainability-related problems. Looking at the SKBBE in Germany, we see an increase in sustainability efforts and declared political will to foster this transition. Taking new scientific findings and circumstances into account, political strategies and measures have been adjusted and improved tremendously over the last ten years. Knowledge and insights from different scientists seem to be recognized with increasing importance when designing policy strategies and measures. Especially the updated version of the National Bioeconomy Strategy (BMBF and BMEL, 2020), which explicitly aims at fostering interdisciplinary collaborations, the involvement of various societal actors and the creation of the latest bioeconomy council, as well as the increased (financial) support of accompanying social science research for the bioeconomy, can be seen as a silver lining.

However, when analyzing the case of the German bioeconomy policy for transformations towards sustainability, we also see two major risks.

(1) The general strategic orientation: The analyzed strategies and the resulting projects feature a dominant focus on the techno-economic dimension of the triple bottom line, which is represented by reoccurring themes around competitiveness, technology, eco-efficiency, innovation, economic output, industrial applications. These policies seem to rather produce top-down technological solutions than engaging in participatory problem framing or solution finding. We may presume that this orientation originates in the policy strategies and the knowledge bases represented there, showing a lack of normative or transformative knowledge in strategies but also the analyzed R&D projects. In this context, the strategies translate well into the funded projects, however, the strategic orientation is not dedicated to sustainability. The reason for this strategic orientation is the fact that the German concept of the bioeconomy did not emerge as a sustainability program but as an alternative form to achieve profits for the economy (I2), born out of biotechnology. It is one approach to maintain the current economic paradigm, albeit slightly more sustainable (I2). German bioeconomy policy is effectively technology and growth-driven, but not a transformative innovation policy (I2). Although the contents of policy strategies have changed over the years, our analysis reveals that the iterations constitute mere refinements without straying too far from the initial strategic orientation of economic growth.

(2) The chosen policy measures and the implementation in research projects: Despite the will to foster cooperation, participation, increased societal involvement, and transdisciplinary research, funded projects do not fully reflect this. We find an overwhelming representation and centrality of traditional and established actors conducting publicly funded projects. If at all, participation and multi-actor involvement can only be found in a small number of so-called accompanying research projects. Still, even in these projects, it is not always about co-designing, discussing and collectively negotiating alternative pathways, or having real power over the chosen direction. Our results suggest that structural dependencies seem to have emerged in the actornetwork for public project funding. Based on this observation, it is at least questionable whether a potential strategic reorientation of bioeconomy policies may be enacted within an actor network historically shaped by techno-economic considerations. Interview data affirms this notion as the political decision for bioeconomy as a solution seems to have been made, and there is little room for public debates on a reorientation (I2). Hence, public participation can, if at all, only be found in implementing solutions.

Our results are in line with the current discourse in literature (e.g., Abson et al., 2014; Urmetzer et al., 2020; Urmetzer et al., 2022; Von Wehrden et al., 2017) and can be confirmed by the insights we gathered in our experts' interviews (I1, I2). Previous research continuously highlighted the theoretical potential but practical challenges of a bioeconomy dedicated to strong sustainability (Bennich et al., 2021; de Vries et al., 2021; Heimann, 2019; Meyer, 2017). In this context, researchers directly pointed to the fact, that current economic policy frameworks do not sufficiently support the relevant changes necessary for transitions towards strong sustainability in all three dimensions, both in general (Dietz et al., 2018; Kircher, 2021; Meyer, 2017; Zeug et al., 2019) as well as in Germany in particular (Heimann, 2019; Prochaska and Schiller, 2021). Heimann (2019) also finds that Germany has a rather ambitious strategy, but lacks solutions, binding regulations or concreteness to be considered as strong sustainability. State Secretary at the Federal Ministry of Education and Research Georg Schütte (2018, p. 82) even explicitly stated "(…) bioeconomy research policy will have to be aimed more strongly towards achieving international goals such as the Sustainable Development Goals (SDGs) and to showing what contribution the bioeconomy can make in this context. The success of the bioeconomy requires a societal discourse on how our society can reconcile economic growth and sustainability in the future. This requires the adaptation and continued development of national agendas and initiatives as well as efficient international cooperation."

Taking the results of our research into account, we deem it reasonable to give the following two policy recommendations:

(1) In the short run and on the micro-level, publicly funded R&D projects may need to be funded in a way that fosters the creation of transformative knowledge. There is an apparent need for more participatory transdisciplinary research projects and more social scientists, even in more traditional biotechnology projects (I2 also pointed to this). Systems knowledge is extremely sticky and strongly dispersed between disciplines. This is why there is a need for research projects that explicitly support the knowledge combination and creation of rather different actors, not only but also different in discipline and profession. Normative knowledge is intrinsically local, path-dependent, and context-specific and, thus, the normative orientation of individual researchers likely manifests as value judgements in the German bioeconomy (e.g., concerning the desirability and need to do research concerning certain types of biotechnology, genome editing, etc.). One possible group of actors to include could, for instance, be the #FridaysForFuture movements, which traditionally had not been invited in research projects despite having very pronounced value judgements and ideas on pathways towards sustainability. Transformative knowledge is context-specific, strongly sticky, and path-dependent. It therefore is necessary to incorporate all relevant actors in the right way. This is also explicitly in line with the strategies and the aim of the bioeconomy council (I1). Therefore, projects may need to incorporate more heterogeneous actors to foster inter- and transdisciplinary knowledge co-creation. These actors may need to be different in age, gender, social and educational background in order to allow for different solution options and overcome paradigmatic "lock-in" in unsustainable value systems as well as the issue of bounded morality of systemic actors (Schlaile et al., 2017). These actors may need to be empowered and educated to stay actively engaged, but not in the sense of informing them or increasing acceptance (ex-post), but in the sense of incorporating them in the solution-finding process (sometimes even agreeing to disagree). However, challenges of participatory formats, such as power imbalances and the fact that voluntary work has its limits, have to be taken seriously (I2) to allow them to unfold their potential.

It is further necessary to highlight the need for accompanying research programs as already funded by the government (e.g., "Bioeconomy as societal change") to not be strictly accompanying but integrated with different research types. For example, normative considerations of social scientists must not stay unconnected to actual technology development carried out by engineers. The risk of funding two different, unconnected types of bioeconomy research streams is also recognized by I2. The data shows that it is indeed possible to fund promising technology-oriented research projects, which facilitate the creation of transformative knowledge and exhibit awareness for system dynamics or normative considerations. We see a very small amount of transformative participatory projects with the overall goal of fostering public participation in developing bioeconomy visions—e.g., using scenario analyses, storytelling processes or games with students. A much greater number of these types of projects may need to be fostered and realized. I2 states that even though the number of social science projects increased, this increase had been much lower than the increase in more traditional technological projects, reinforcing the underrepresentation of social science in this societal transition process.

(2) In the long run, and more on a macro-level, we care to suggest that policy frames themselves need to be subject to change and, therefore, we follow many of our colleagues in calling for paradigmatic changes and transformative innovation policies (Fagerberg, 2018; Schot and Steinmueller, 2018; Steward, 2012). Socio-technical systems transformations, need more than just new radical technological solutions. "(...) (I)t is necessary to engage in frame reflection for designing and implementing effective policy solutions for complex policy problems." (Schot and Steinmueller, 2018, p. 1554).

6. Conclusions and future research avenues

In the light of wicked problems and the current grand challenges, researchers and policymakers alike call for transformations towards sustainability. However, unsustainable bioeconomies are likely to emerge (Pfau et al., 2014) and the transformative power of bioeconomy policies is dependent on the ideological understanding and the implementation of these bioeconomy policies (Schlaile et al., 2021; Vivien et al., 2019). This is why the German bioeconomy policy has been criticized as not fostering sustainability transformations (Heimann, 2019; Prochaska and Schiller, 2021; Urmetzer et al., 2018). Some authors doubt that the German bioeconomy is even a policy field. It rather can be described as a conceptual umbrella for a number of already existing policies, which consequently seem to have little tangible effect (Töller et al., 2021). This is especially relevant as Germany is perceived to be a frontrunner in its bioeconomy efforts that is ranked high in its performance (D'Adamo et al., 2020). Therefore, Germany has an even higher responsibility for being considered a beacon for other countries. In fact, especially due to the changes in recent years, Germany shows some good approaches. The prominent emphasis on the importance of sustainability, the explicit acknowledgement of potential conflicts and the very clear statements about the need to involve society can serve as a model for other countries (I1). However, it must be clearly emphasized that the German bioeconomy policy, in its current implementation, is not a sustainability policy but an economic growth policy, based on a policy frame that still has a strong techno-economic focus. Therefore, it may fail at fostering transformations if the right measures and instruments (e.g., concerning public funding) and shifts in policy framing are not taken.

The transferability of our result is subject to certain limitations. Although we were able to assess all policy strategies up to the most recent versions, the analysis of research projects is naturally limited to projects that have been concluded or are currently running. As these projects were initiated based on previous iterations of the strategies, we are not able to see how the latest strategy influences future projects. Second, while our network analysis is based on the full set of funded R&D bioeconomy projects from 2010 onwards, our content analysis is restricted to a subset (around 20%) of projects, for which textual data is available. This subset only entails project descriptions offered by the editors of the official German bioeconomy web-platform. While these projects are specifically published as representatives of the funding program, the results of the content analysis might lack comprehensiveness or inherit a selection bias.

Besides the already existing monitoring projects, which are also investigating focal points of sustainability efforts in the bioeconomy (Bringezu et al., 2020; Budzinski et al., 2017; Jander and Grundmann, 2019; Lier et al., 2018; O'Brien et al., 2017; Zeug et al., 2019), future research should dive deeper into the questions of how bioeconomy policy can become more transformative and contribute to sustainability, e.g., by more participatory transformative innovation policy frames. Since the German approach of steering their national bioeconomy is heavily relying on direct funding of research projects, future research may focus on comparing the results of the German case to other bioeconomy policies and measures. In addition, future research should investigate to which degree the latest bioeconomy strategy affects publicly funded projects.

The bottom line of our research confronts us with the fact that a majority of sustainability endeavors for the German bioeconomy do not do justice to the multi-dimensional dynamics of grand societal challenges, which are inherently complex and interconnected. These challenges may rather be met by converging societal actors and combined knowledge bases—for the simple reason that we cannot adequately address anthropogenic wicked problems following the same lines of thinking that helped to create them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Knowledge types, sub-categories and indicator terms

Systems knowledge (SK)	Normative knowledge (NK)	Transformative knowledge (TK)	Techno-economic knowledge (TEK)
Function & process: function, functional, functional group, functioning, functions, interrelatedness, interrelations, interrelationships, lifecycle, process, processes, driver, drivers, functionalities, functionality, functionally, interact, interacted, interacting, interaction, interactions, interconnected, interconnectedness, interdependencies, interdependency	Efficiency: efficiencies, efficiency, efficient, efficiently, inefficiency, inefficient, optimal, optimality, optimisation, optimised, optimization, optimizations, optimize, optimized, optimizing, optimum	Communication & education: communicable, communicate, communicating, communication, communications, communicative, education, educational, learn, learned, learning	Technological education / capacities: absorb, absorbed, absorptive, academic, academia, access, accessed, accessible, Accumulate, accumulated, accumulative, acquisition, acquisitions, capability, capabilities, science, theory, theories, think, thought, university, universities, understand, understood, idea, ideas, research, insight, insights, empirical evidence, student, students, stock, stocks, pedagogical, prior, provide, provided, literacy, mechanism, mechanisms

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Systems knowledge (SK)	Normative knowledge (NK)	Transformative knowledge (TK)	Techno-economic knowledge (TEK)
System dynamics: cycle, cycles, cycling, destabilized, dynamic, dynamical, dynamically, dynamics, equilibria, equilibrium, feedback, feedbacks, flow, instabilities, instability, irreversibility, stabilisation, stabilising, stabilities, stability, stabilization, stabilize, stabilized, stabilizers, stabilizing	Conservation: protected, protecting, protection, protective, protects, conservancy, conservation, conservationists, conserve, conserved, conserving, nature conservation, preservation, preserve, preserved, preserving, restoration, restorations, restorative, restoring	Participation: democracy, democratic, empower, empowerment, inclusive, inclusivity, institution, institutional, institutions, participant, participants, participate, participated, participating, participation, participatory, pluralism, pluralistic, practitioners, stakeholder, stakeholders, transdisciplinary, engage, engaged, engagement, team, collaborative, collaborate, cooperation, cooperate	Technology: advance, advancing, advanced, process, processes, product, products, progress, progressed, radical, creation, create, created, new, product development, transfer, transfers, transferred, turbulence, turbulences, generation, generations, diversity, evolution, evolve, evolved, evolutionary, improvement, improvements, incremental, trajectory, trajectories, relatedness, old, organizational, organizational, performance, performances, stage, stages, orientation
Risk & uncertainty: exposed, exposure, exposures, hazard, hazardous, hazards, risk, risks, shock, shocks, vulnerabilities, vulnerability, vulnerable, riskoptimizer, riskscapes, riskscape, uncertain, uncertainties, uncertainty	Well-being: affluence, antipoverty, benefit, benefited, benefiting, benefits, benefitted, enjoy, enjoyed, enjoying, enjoyment, happiness, hunger, income, livelihood, livelihoods, pleasure, poverty, utilitarian, utility, welfare, wellbeing, wealth	Policy & decision-making: decision, decisionmaker, decisionmakers, decision-makers, decision-making, decisions, deliberation, deliberative, enforcing, govern, governance, governed, governing, legislation, legislative, multicriteria, policies, policy, policymaker, policymakers, policymaking, facilitate, facilitated, facilitates, facilitating, facilitation, facilitative	Market: adoption, adopt, adopted, diffusion, diffuse, diffused, diffusing, diversification, diversify, diversified, domestic, domestically, growth, trend, trending, trended, opportunity, opportunities, patent, patents, innovation, innovations, license, licenses, condition, conditions, emerge, emergent, emerging, emerged, financial, financials, financially, enter, entered, exist, existed, focus, focused, foci, alliance, alliances, business, businesses, competition, competitive, communication, communicative, research and development, r&d, venture, ventures, invest, investment, investments, invested, relationship, relationships, intra-firm, project, projects, external, externally, firm, firms, foreign, subsidiary, subsidiaries, involve, involved, involvement, multinational
Resilience: adapt, adaptability, adaptation, adaptations, adapted, adapter, adapting, adaption, adaptive, cascade, cascades, cascading, collapse, collapsed, collapses, fragile, fragility, irreplaceable, irreversible, persist, persisted, persistence, persistent, persisting, perturbations	Justice & ethics: consequentialist, deontological, ecocentric, egalitarian, equalities, equitable, equity, ethical, ethics, fairness, goodness, inequalities, inequality, inequitable, injustice, intergenerational, intra, intrinsic, justice, liberty, moral, norm, normative, norms, obligation	Motivation: activists, advocacy, aspiration, attitude, attitudes, attitudinal, belief, beliefs, idealism, idealistic, ideals, incentive, incentives, inspiration, leadership, legitimacy, legitimate, motivate, motivated, motivation, motivations, motives, encourage, encourages, transformability, reflection, reflect, reflexive, reflective	Beyond: useful, usefully, social, socially, effect, effects, affect, affected, affecting, nonprofit, non-profit, impact, impacted, impacts, future, futures, political, politically, crisis, crises

Note: The table presents indicator terms for different types of knowledge to facilitate in-text classification of paragraphs. Indicator terms adopted from Abson et al. (2014) for SK, NK and TK. Added potential indicator terms for TEK.

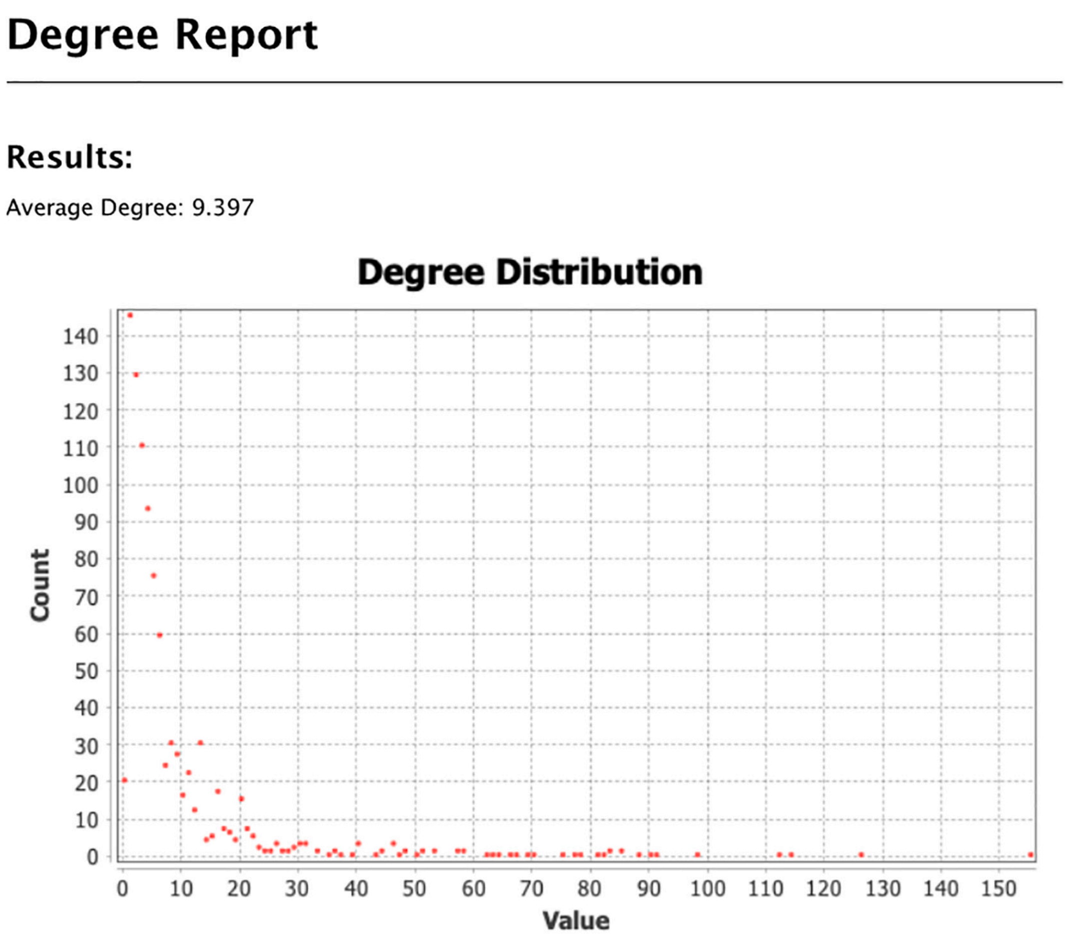
Appendix B. Exemplary coding of project descriptions

Text	Coded as Knowledge Type
"(...) using intelligent monitoring technology, inspections of bee colonies should be reduced to a minimum. (…) We spoke with beekeepers' associations, federations and economic experts and have established that there is a need and that such a system really does make economic sense" (Project: The digital beehive, translated by the authors).	TEK
"In his opinion, the format of the funding programme also played a large part in this success. "The researcher tandem is a brilliant idea. It forces you to learn and understand each other, but it pays off by strengthening the border areas of a subject!""(Project:, translated by the authors).	SK, TEK
"(…) consumers must develop the will and the insight that bio-based materials are much more worth because they are higher quality, long lasting due to better properties and good for the environment. (…) The sustainability aspect must be positive in the minds and appear valuable" (Project: Bioplastics with wood fibres, translated by the authors).	NK, TEK
"To this end, the idea of the art project is to be discussed and sounded out in a broad discourse with experts from the forestry industry and the interested public in so-called 'ForestLabs'. The results, in turn, are to flow into the development of an online platform that focuses on the topic of 'forest self-governance' and reflects the progress of the project. In addition to discussion forums, the website will also include a computer game. 'We first want to introduce people to the topic in a playful way and show them in a kind of simulation what it would mean if such a system existed, what decisions the system would have to make and what the consequences would be,' explains Wagenknecht." (Project: Digital self-government in the forest, translated by the authors)"	SK, TK

Appendix C. Top-20 Actors in the R&D-Network

Rank		Top-20 actors in the R&D network according to their degree centrality	type of actor	degree centrality
1	TUM	Technische Universität München	research (university)	155
2	RWTH	Rheinisch-Westfälische Technische Hochschule Aachen	research (university)	126
3	UHOH	Universität Hohenheim	research (university)	114
4	TUD	Technische Universität Dresden	research (university)	112
5	CAUK	Christian-Albrechts-Universität zu Kiel	research (university)	98
6	RFWUB	Rheinische Friedrich-Wilhelms-Universität Bonn	research (university)	91
7	HUB	Humboldt-Universität zu Berlin	research (university)	90
8	GAUG	Georg-August-Universität Göttingen	research (university)	88
9	FZJ	Forschungszentrum Jülich GmbH	research (non-university)	85
10	LUH	Leibniz Universität Hannover	research (university)	85
11	FHG	Fraunhofer-Gesellschaft - Institut für Grenzflächen- und Bioverfahrenstechnik	research (non-university)	83
12	FHG	Fraunhofer-Gesellschaft - Institut für Verfahrenstechnik und Verpackung	research (non-university)	83
13	KIT	Karlsruher Institut für Technologie (KIT)	research (non-university)	82
14	ALUF	Albert-Ludwigs-Universität Freiburg	research (university)	81
15	HZ	Helmholtz Zentrum München Deutsches Forschungszentrum für Gesundheit und Umwelt (GmbH)	research (non-university)	78
16	FHG	Fraunhofer-Gesellschaf - Institut für Molekularbiologie und Angewandte Oekologie	research (non-university)	77
17	FHG	Fraunhofer-Gesellschaft - Institut für Umwelt-, Sicherheits- und Energietechnik	research (non-university)	75
18	UGB	Universität Bielefeld	research (university)	70
19	HZ	Helmholtz-Zentrum für Umweltforschung GmbH	research (non-university)	69
20	US	Universität Stuttgart	research (university)	67

Appendix D. Degree distribution of the R&D network



Appendix E. List of included strategies with references

Abbreviation	In-text citation	Original German Reference on which the English publication is based
2002 SDS	GFG (2002)	Die Bundesregierung, 2002. Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung.
2011 NRSBio	BMBF (2011)	Bundesministerium für Bildung und Forschung (BMBF), 2010. Nationale Forschungsstrategie BioÖkonomie 2030. Unser Weg zu einer bio-basierten Wirtschaft.
2012 Progress Report SDS	GFG (2012)	Die Bundesregierung, 2012. Nationale Nachhaltigkeitsstrategie - Fortschrittsbericht 2012.
2014 NPSBio	BMEL (2014)	. Nationale Politikstrategie Bioökonomie: Nachwachsende Ressourcen und biotechnologische Verfahren als Basis für Ernährung, Industrie und Energie.
2016 SDS	GFG (2016)	Die Bundesregierung, 2016. Deutsche Nachhaltigkeitsstrategie - Neuauflage 2016.
2020 NbioS	BMBF and BMEL (2020)	Bundesministerium für Bildung und Forschung (BMBF), Federal Ministry of Food and Agriculture (BMEL), 2020. Nationale Bioökonomiestrategie.
2021 SDS	GFG (2021)	Die Bundesregierung, 2021. Deutsche Nachhaltigkeitsstrategie - Weiterentwicklung 2021.

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