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What Drives a Future German Bioeconomy? A Narrative and STEEPLE Analysis for Explorative Characterisation of Scenario Drivers

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Abstract: A future bioeconomy pursues the transformation of the resource base from fossil to renewable materials in an effort to develop a holistic, sustainable production and provision system. While the significance of this change in the German context is not yet entirely explored, scenarios analysing possible pathways could support the understanding of these changes and their systemic implications. Bioeconomy in detail depends on respective framework conditions, such as the availability of biomass or technological research priorities. Thus, for scenario creation, transferable methods for flexible input settings are needed. Addressing this issue, the study identifies relevant bioeconomy scenario drivers. With the theoretical approach of narrative analysis, 92 statements of the German National Bioeconomy Strategy 2020 have been evaluated and 21 international studies in a STEEPLE framework were assessed. For a future German bioeconomy 19 important drivers could be determined and specific aspects of the resource base, production processes and products as well as overarching issues were exploratively characterised on a quantitative and qualitative basis. The developed method demonstrate an approach for a transparent scenario driver identification that is applicable to other strategy papers. The results illustrate a possible future German bioeconomy that is resource- and technology-driven by following a value-based objective, and which is supplied by biogenic residue and side product feedstocks. As such, the bioeconomy scenario drivers can be used as a starting point for future research like scenario development or modelling of a future German bioeconomy.

Keywords: bioeconomy; drivers; scenario development; explorative; Germany; policy strategy

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Citation: Richter, S.; Szarka, N.; Bezama, A.; Thrän, D. What Drives a Future German Bioeconomy? A Narrative and STEEPLE Analysis for Explorative Characterisation of Scenario Drivers. *Sustainability* **2022**, *14*, 3045. https://doi.org/10.3390/su14053045

Academic Editor: Idiano D'Adamo

Received: 17 December 2021
Accepted: 18 February 2022
Published: 4 March 2022

1. Introduction

Emerging global challenges such as climate change and degradation of ecosystems require the adaptation of various production sectors in an effort to sustain provision systems to satisfy societal demands [1,2]. Bioeconomy is seen as a beneficial and broad concept for this, that interlinks land and marine ecosystems, primary production sectors, and all economic and industrial sectors using biological resources and processes for the production of food, feed, bio-based products, energy, and services [3]. For the support and to ensure the implementation of a bioeconomy, policy activities at the international and national levels have increased in the last years. As an example, several policy developments related to the bioeconomy at the EU level can be mentioned here. Frameworks such as the Sustainable Development Goals (SDG) [4] and European Green Deal with a time horizon of 2030 [5] establishing a wider base for a bioeconomy that addresses sustainability issues [6] that are having longer time frames up to 2050 or 2100 [2]. Several national bioeconomy strategies [7] illustrate that there is not only one specific bioeconomy, but many different ones [2], depending on the respective framework conditions, such as the availability of biomass or technological research priorities, for example [8]. Despite these variations, what is certain is the fact that this multi-sector transformation results in changes of the existing material and energy flow, making it necessary to describe trade-offs and possible synergies of identified promising bioeconomy concepts in a systemic perspective [9].

In the German context, the published German National Bioeconomy Strategy 2020 (GNBS 2020) is a consistent continuation of policy strategies dating back to 2010 [7,10], supporting the development of a German bioeconomy in connection to the overarching European perspective. The present strategy has integrated a broad spectrum of interdisciplinary concepts that make it difficult to identify specific characteristics of a future German bioeconomy. Nevertheless, it includes implicit aspects that can be used to elaborate and clarify distinct objectives and drivers. A more thorough and explicit analysis of these factors could reveal and specify knowledge gaps and open questions, such as the connection between users and producers of bio-based products [11], prioritisation of biomass and resource base issues [8], utilisation options [12], as well as general implementation principles to follow [13,14]. In addition, the aspects explored could support the elaboration of concrete targets and thus promote the transition to a future bioeconomy [15].

For this purpose, holistic and transparent methods have gained importance in recent years in this field, especially scenario and life cycle analyses. Life cycle assessments support decision-making by analysing specific impacts of value chains from a status quo perspective [16], which is less suitable for analysing future aims and objectives. In sectors such as energy, scenarios as future-oriented methods are used widely for elaborating possible outcomes of major transitions (e.g., Refs. [17,18]). The characteristic of scenarios, to connect qualitative and quantitative data in script-like possible stories of a future [19], with attention to causal connections and internal consistency of key aspects in the field of research [20], without the claim of being complete [21], makes them also more applicable for the purpose of the present study. By analysing individual aspects that will drive future developments, gaps of knowledge could be identified, trade-offs communicated and decision-making supported; however, methodical challenges occur through a wide field of possible methodical combinations, integrating qualitative and quantitative data, time-intensive procedures, and overall transparency of the specific methodical steps [22].

Following Kosow and Gaßner [21], it is possible to divide the scenario generation into about five different phases, ranging from scenario field and variable identification to the analysis of the same to the final scenario generation and scenario transfer. The work concentrates on the first steps, in particular, the identification and initial analysis of internal and external influencing variables, also called drivers. To identify these, the most commonly used methods are surveys and assessment by experts and stakeholders [21,23], and the literature reviews of extensive databases [24]. This can lead to difficulties in compiling and deriving drivers, which are influenced by majority decisions, the selection of experts, or the social power relations between participants, or that these depend on the access and extent of databases, the quality of abstracts [25] and boundaries set by the researcher's objective [26]. To address these difficulties in a very interdisciplinary field, such as the bioeconomy, it could be suggested to categorise qualitative aspects of a policy strategy document for the analysis of the system of interest, without applying the extensive methods outlined. The methods of narrative analysis [27] and the analysis of social, technical, economical, ecological, policy, legal and ethical aspects (STEEPLE) [28] are suggested in this context.

Against this background, the goal of the work is to identify and characterise narratives and scenario drivers of a future German bioeconomy in a transparent, replicable, and explorative way. Based on a narrative analysis of the German National Bioeconomy Strategy 2020, overarching narratives and related important aspects are identified, which could be used as building blocks for the creation of scenarios or for further modelling purposes. Linking this method with a STEEPLE analysis of current scientific literature in the research field, supports the assessment of the identified aspects. Based on the explorative description of resulting scenario drivers, a more differentiated picture of a future German bioeconomy could be gained, and the methodical portfolio of scenario generation will be expanded.

To the best of our knowledge, this has not yet been accomplished for the field of scenario analysis and bioeconomy.

2. Materials and Methods

For the purpose of driver elaboration, this work uses the German National Bioeconomy Strategy 2020 as a starting point. As illustrated in Figure 1, a methodical combination of narrative analysis, STEEPLE evaluation, and qualitative and quantitative description of drivers was chosen. This clear methodological starting point for driver identification will increase understanding of the scenario building process in general [26] and support scenario interpretation in further analyses [21].

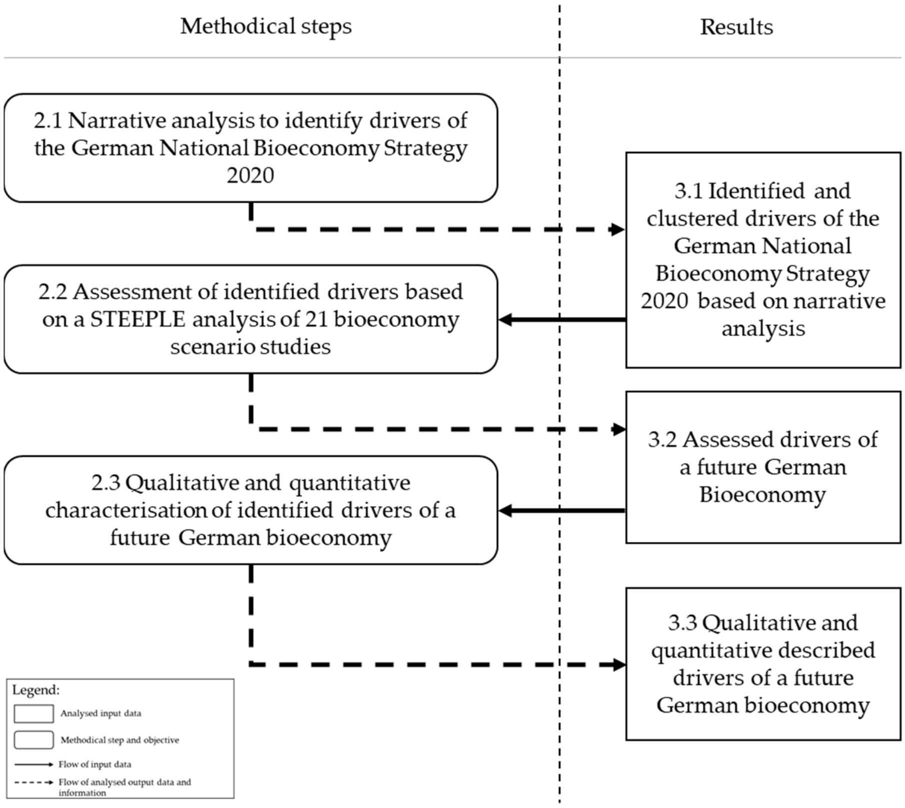

Figure 1. Methodical structure for identification and evaluation of drivers of a future German bioeconomy (numbers correspond to the section headings).

2.1. Narrative Analysis to Identify Drivers of the German National Bioeconomy Strategy 2020

To narrow down the GNBS 2020 to specific, essential aspects a narrative analysis was conducted. The development of a future German bioeconomy is influenced and shaped by subjective goals and perspectives of heterogeneous actors from interdisciplinary sectors. As strategy papers are developed by these groups on a cooperative basis, specific measures are often not clearly defined. Narrative analyses, used to categorise descriptive language, can contribute to consolidating data and support the narrowing down of complex fields of interest [27] and reflect specific perspectives on issues under research [29,30].

At first, the policy strategy was broken down into 92 statements. These were sorted into three existing narrative frameworks in the field of bioeconomy, developed by Bugge et al. [31], Hausknost et al. [29] and Dietz et al. [32], which were already used in other analyses in the research field (see, e.g., Refs. [33–35]). The results show which narratives of the three frameworks could be found in GNBS 2020, while a combined view revealed the overarching narrative of the GNBS 2020 (detailed results see Supplementary Materials S1 and S2).

In the next step, specific bioeconomy concepts mentioned in the 92 statements were selected according to the identified narrative and were further used as a first narrowing to the scenario drivers. In general, drivers are factors that have a high impact on the issue under research [36], are measurable as well as describable, and changeable in their specific significance [37]. For better comprehensibility, the identified drivers were grouped into five areas, which are aligned to a supply chain perspective. These areas are further called building blocks (BB) and the identified drivers have been named with identification numbers (ID) from 1 to 19. The building blocks have been chosen with regard to their specific characteristics as part of bioeconomy value chains. Starting with the raw material base, through the production processes to the products themselves, and ending with overarching aspects.

2.2. Assessment of Identified Drivers Based on a STEEPLE Analysis of 21 Bioeconomy Scenario Studies

In preparation for the assessment of the relevance of the drivers in the field of bioeconomy, a STEEPLE analysis of 21 international bioeconomy peer-reviewed scientific studies, project reports, and scenario studies was carried out. The focus was on up-to-date literature, from 2016 to 2020, but with no specific geographical limitations. The STEEPLE framework sorts the reviewed aspects into social, technological, environmental, economic, political, legal, and ethical categories, which provide an extensive overview of macroenvironmental and future trends, and thus of drivers considered in the analysed studies [28]. Identified drivers were used to assess the state of art scientific relevance of drivers identified in the narrative analysis. If one element was mentioned in the study, a connection to the appropriate driver was set. As the results were only used for the assessment of drivers chosen out of the narrative analysis, the specific findings of the STEEPLE analysis can be found in Supplementary Material S3 and have not been further discussed.

2.3. Qualitative and Quantitative Characterisation of Identified Drivers of a Future German Bioeconomy

While the previous steps were applied to identify drivers and assess their relevance in the area of research, this section addresses their characterisation and description.

For this purpose, no in-depth literature review was carried out on databases such as Google Scholar, Wiley, or Science Direct, to provide a first scientifically sound overview of each driver, following an integrative synthesis strategy [38]. The driver titles themselves were used as search terms, with contextual phrases such as "bioeconomy", "potential" or "definition", with a specific geographical scope on Germany, which was only extended when no specific results could be found. The timeframe was set from 2010 to 2020 due to the date of the first published policy strategy for bioeconomy in Germany [10]. About 327 journal articles, university theses, proceedings, databases, books, project reports, discussion papers, and webpages were screened for accessibility, quantifiable data and indication of the theoretical background of the drivers (see Supplementary Material S4 List of reviewed literature); afterward, 123 studies could be included in the study.

The work establishes the first step in scenario development on an explorative basis, which is often conducted in areas that entail a high uncertainty, but low complexity [39]. For scenario building purposes, drivers are described with distinct short names, specific characteristics, and possible trend developments [37]. While point estimations or forecasts are subject to high uncertainties, such as external constant changing conditions, bandwidths, based on empirical data, such as minimum and maximum yields, include these uncertainties within these ranges. Applying "What if" questions [21], the analysis shows, for example, what would happen if all possible areas were planted with perennial production systems. Taken the year 2020 as the base year for the analysis, determined by the completeness of the data found, ranges of minimum and maximum values have been generated for the year 2030 and 2050, where the minimum value was described with the lowered abbreviation of "min" and maximum values with a lowered abbreviation of "max" on the distinctly used unit. If future possible development pathways have been described in the literature, these values were taken for the years 2030 and 2050. In cases where quantifiable data were available but no future development was described, minimum (e.g., minimum yield potential on minimum area potential) and maximum (e.g., maximum yield potential on maximum area potential) values were calculated (for data basis and equations used see Supplementary Materials S5–S7). If no quantifiable data were available or elaboration extended the scope of the work, the development was outlined on a qualitative basis. Elaborated bandwidths are a first data basis for further studies, which could be adapted by including other factors such as, e.g., the legal, political or social aspects.

3. Results

3.1. Identified and Clustered Drivers of the German National Bioeconomy Strategy 2020 Based on Narrative Analysis

The narrative analysis of 92 statements of the strategy paper gives a varying picture, while three narratives, one from each framework, could be identified as leading. The following Table 1 shows the specific characteristics of the three major identified narratives, and demonstrate a resource- and technological-oriented perspective of the GNBS 2020. Harmful influences on the environment should be reduced primarily by technological innovations. A growth and value-based objective is in the foreground, especially for products and processes based on non-food biomasses, e.g., residue and side products. Table 2 illustrates various concepts mentioned in the strategy that corresponds to the elaborated narrative aspects and are used for further analysis as drivers (D), clustered in five building blocks, in relation to the identified objectives.

Table 1. Overview of identified narratives of the German National Bioeconomy Strategy 2020, based on Bugge et al. [31], Hausknost et al. [29] and Dietz et al. [32].

Characteristics of Identified Narratives	Bio-Resource Vision Relating to (Bugge et al. [31] (p. 10–11))	Eco-Growth Vision Relating to (Hausknost et al. [29] (p. 6–7))	New and More Efficient Biomass Relating to (Dietz et al. [32] (p. 4))
Aims/ Objectives	• Economic growth • Sustainability supported by bio-innovations • Capitalising of bio-resources → positive environmental sustainability • Setting standards of procedures and processes	• Growth-based capitalist economy • No proposal of a global transition strategy • Emphasises the importance of organic farming and agroecological practices • Adapted to bioeconomy to not lose out against other sectors for research funding and political influence	• Governance instruments • Supply-side dynamics
Values created	• New bio-based products majorly sourced by residues and side products • Side products are input for renewable energy production or for large-scale biofuel production • Production of higher value-added products combined with externally located knowledge	• Organic entrepreneurship • Agroecological innovation	• Increase of efficiency • Innovations in downstream sectors
Central principle to follow	• Cascade use for increasing efficient use of biomass • Land productivity and use of degraded and marginal lands for biofuel production	• "Sufficiency" → focused on input-side of production and not including restriction of consumption or production, which leads to an understanding more similar to "efficiency"	• Increasing efficiency in biomass utilisation
Actors/ Areas of consideration	• Interdisciplinary research, collaboration between dissimilar or downstream actors, research of consumer preferences, local competency • Spatial focus is on rural areas for based on key location factors	• Small-scale farming practices with the spatial focus on regional structures	• Innovation in downstream sectors to increase efficient use of biomass and recycling of waste streams • Supply dynamics • Consumer behaviour • Regulatory environment
Less considered	• Changes between different land use types • Use of resources and products, as water, fertiliser and pesticides	• Concentrated on the agricultural sector • "Real sufficiency"	• Rebound effects of innovations

Table 2. Identified central aspects in the German National Bioeconomy Strategy 2020 in relation to narrative analysis clustered into five building blocks aligned with the supply chain's perspective.

Building Block (BB)	Driver_ID (D)	Central Aspects in Relation to Narrative Analysis	Objectives of the Strategy
BB1—Provision of raw materials	D1	Biogenic residues and side products	Increase biogenic resource base in a sustainable manner for a future bioeconomy (low or no impact on land use, greenhouse gas (GHG) reduction, ecological and ethical aspects, degraded and unused areas, urban concepts)
	D2	Urban agriculture and gardening	
	D3	Degraded and unused land	
	D4	Algae	
	D5–D6	Perennial cultivation (short rotation coppice, agroforestry, paludiculture)	
	D7	Forest areas	
BB2—Production systems and principles	D8	Microorganism	Fulfil societal demands based on sustainable and responsible use of resources
	D9–D10	Agricultural production systems	Production processes and systems that are used by humans to transform biogenic resources into products that can be used in and for a future bioeconomy in relation to ecosystem service functions (e.g., land and soils, biodiversity, water)
	D11	Ecosystem services	
BB3—Infrastructure and technologies	D12	Technological concepts	Biorefineries as a central concept for production of high-value products
	D13	Digitisation	Digitisation is a major key for precision and smart farming practices, microorganism, data sciences in the synthetic biotechnology or climate change adaptation
	D14	Cascade principle	Development of value chains or networks with cascade and closed-loop capability
BB4—Sustainable products	D15	Fully recyclable biopolymers	Development of new, resource-saving processes and products Cascade principles and bio-based value pyramid products have to be analysed Reduction of fossil resources within the material sector
	D16	Environmentally-friendly chemicals	Fulfil societal demands based on sustainable and responsible use of resources
BB5—Bioeconomy and society	D17	Population development	Research of technologies and resource-based aspects must be connected to social and ecological systems (scarce resources, population growth and changing values, lifestyles and consumption patterns, knowledge base)
	D18	Behavioural changes	
	D19	Rural development	

3.2. Assessed Drivers of a Future German Bioeconomy

Connecting the identified drivers of the STEEPLE analysis of the 21 international bioeconomy peer-reviewed scientific studies, project reports, and scenario studies [2,8,40–58] and of the narrative analysis, shows that, at the minimum, in one study, at least two drivers could be found (see Figure 2).

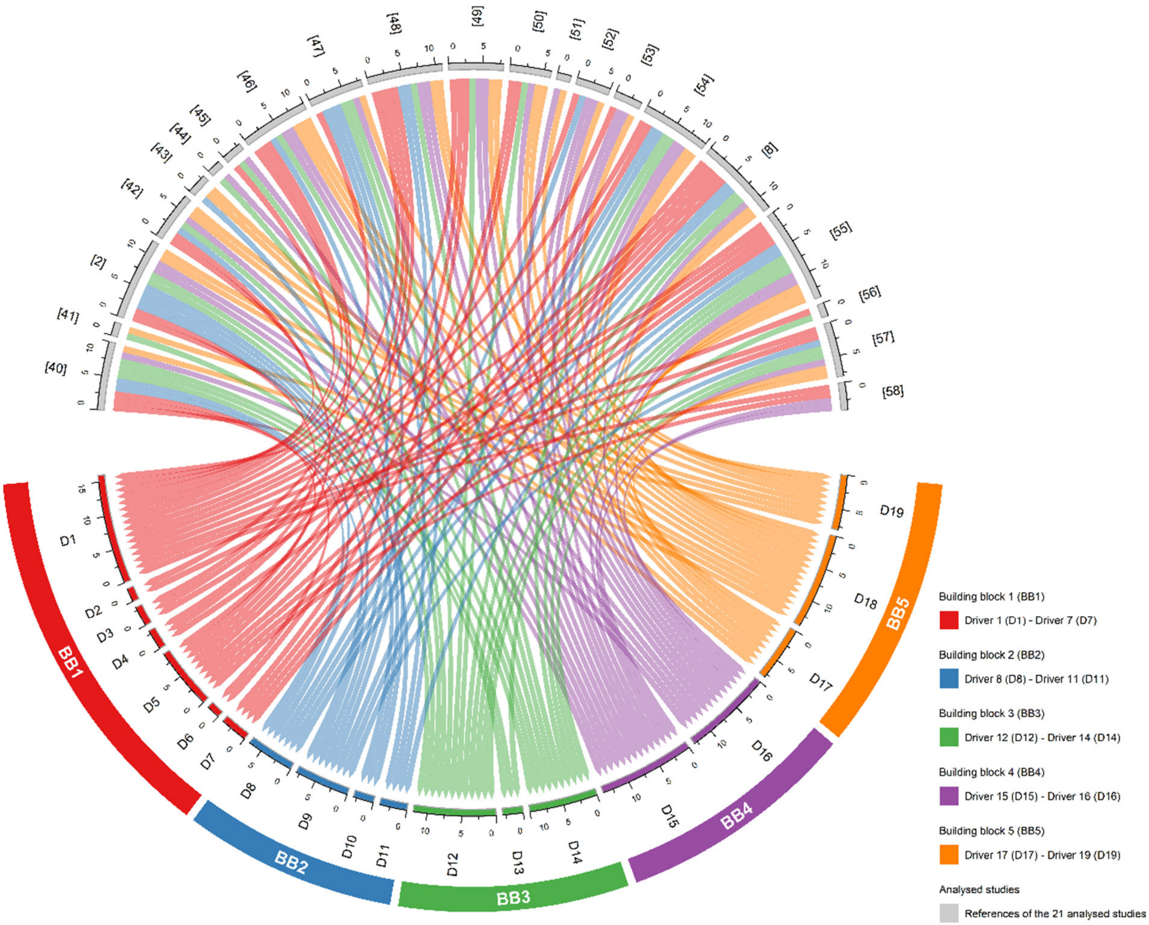

Figure 2. Chord diagram illustrating the connection of the drivers identified with the STEEPLE analysis of the 21 studies to the identified drivers (D1–D19) and associated building blocks (BB1–BB2) from the narrative analysis.

Based on this assessment, it can be stated that the identified drivers from the strategy are also those used in present scientific discourse. Although the weighting of the individual drivers is not the priority of the study and will not be explored in depth, a first approximation of relevance can be made based on their connection amounts. High relevance could be stated for driver D1 (biogenic residues and side products) 16 times, D5 (perennial production systems) 9 times, D10 (organic farming practices) 8 times, D12 (production plants of bioeconomy products) 12 times, D14 (cascade principle) 10 times, D15 (fully recyclable biopolymers) 14 times, D16 (environmentally-friendly chemicals and fuels) 13 times and D18 (behavioural change) 14 times.

3.3. Qualitative- and Quantitative-Described Drivers of a Future German Bioeconomy

The analysis of the individual drivers shows a high variability of quantifiable data based on different research methods and units used in the studies. The results and used units are meta-analytical summarised in Table 3, while quantitative findings of the explorative assessments are listed at the end of the section in Table 4 (for data basis and equations see Supplementary Materials S5–S7). The detailed explanation for each driver is given in the following section.

Table 3. Identified drivers of the German National Bioeconomy Strategy 2020 and meta-analytical characteristics.

Building Block (BB)	Driver_ID (D)	Bioeconomy Driver	Short Description	Unit	Unit Explanation
BB1 Provision of raw materials	D1	Biogenic residue materials	Biogenic residue and side products occur in several sectors, e.g., agriculture or forestry from production and utilisation processes, and are a feasible resource base for a future bioeconomy [59].	Mg_{dm}	Potential usable volume in tonnes of dry matter
	D2	Urban agriculture	Urban agricultural is an emerging concept which increases food production and farming activities within urban context [60,61].	ha	Possible land gains for other purposes by implementation in hectare
	D3	Degraded and unused land	Abandoned, degraded areas, old industrial sites and marginal areas are considered as economically unprofitable due to physically inaccessible, soil or climate restrictions and low productivity [62,63], but could be used as cultivation opportunities for raw materials for a future bioeconomy [64].	ha	Possible usable land in hectare
	D4	Algae	Algae are organisms that consume CO_2 and produce oxygen and biomass [65] and are seen as potential resources for 3rd generation biofuels [66] or nutrition products in a future bioeconomy [67].	Mg_{dm}	Possible usable production volume in tonnes of dry matter
	D5	Perennial production systems	The integration of fast growing, perennial biomasses such as Short Rotation Coppice (SRC) or Miscanthus could lead to beneficial land use change [68] and could increase lignocellulosic biomass for use in a future bioeconomy [69].	Mg_{dm}	Possible usable production volume in tonnes of dry matter
	D6	Paludiculture	Paludiculture is the agricultural use of wet bogs and fens by cultivating reeds, which could provide lignocellulosic biomass for use in a future bioeconomy [70,71].	Mg_{dm}	Possible usable production volume in tonnes of dry matter
	D7	Forest areas	Due to the high relevance of lignocellulosic materials for a future bioeconomy, forests are an important source of raw materials, accounting for 30% of the area in Germany [72].	Mio. m^3	Possible usable potential in cubic meter yield

Table 3. *Cont.*

Building Block (BB)	Driver_ID (D)	Bioeconomy Driver	Short Description	Unit	Unit Explanation
BB2 Production systems and principles	D8	Microorganism	Adaptation of metabolic activity of microorganisms based on synthetic biotechnological tools could increase production opportunities in a future bioeconomy [73].	-	-
	D9	Smart farming	The digitalisation of agricultural processes, understood as "smart-farming" [7] could increase efficiency of in- and output processes in the agricultural sector [74].	%	Possible development of in- and outputs of agricultural systems in percentage
	D10	Organic farming	Organic farming practices have the aim of creating closed nutrient cycles and reducing negative impacts to the environment [75,76].	%	Yield development by implementation of these systems in percentage
	D11	Ecosystem services	Ecosystem services are provision and production systems of nature raw materials from which humans benefit [7] and are therefore necessary to sustain a future bioeconomy [77].	-	-
BB3 Infrastructure and technologies	D12	Production plants of bioeconomy products	Biorefineries could be a cluster of facilities or processes that convert biomass [78] into chemicals, fuels, or marketable products, as well as power and heat [79].	-	-
	D13	Digitisation	Digitisation is a major key for enabling the full potential of several technological solutions, e.g., synthetic biotechnologies (D8) [80] or smart farming activities (D9) [7].	%	Connection rate in percentage
	D14	Cascade principle	Following cascade principle, biomass has to be used over several stages in order to maintain materials in the economic system as long as possible and is a central principle of a future bioeconomy [57].	-	-
BB4 Sustainable products	D15	Fully recyclable biopolymers	Fully recyclable biopolymers are understood as "materials that are completely degraded to carbon dioxide and water by the action of naturally occurring microorganisms, such as bacteria, fungi, and algae", Iwata [81] (p. 3210).	%	Possible production volumes in comparison to reference year in percentage

Table 3. *Cont.*

Building Block (BB)	Driver_ID (D)	Bioeconomy Driver	Short Description	Unit	Unit Explanation
	D16	Environ. friendly chemicals and fuels	Chemicals and polymers from renewable resources are an essential factor for reducing the share of fossil raw materials in material flows [82].	%	Possible production volumes in comparison to reference year in percentage
BB5 Bioeconomy and society	D17	National population development	All bioeconomy drivers are linked to consumption patterns of people and therefore to the development of number of people included in the evaluation of specific concepts [40].	Mio. pers.	Possible population development in Millions
	D18	Behavioural changes	Changing dietary habits and reduced animal production could set free additional areas for a future bioeconomy [2,83,84].	kg_{head} $litre_{head}$	Possible development of consumption in kilogram and litre per person and year
	D19	Rural development	Rural areas are suppliers for renewable materials, which makes them indispensable in the bioeconomy context [85] and connects resource base to social change and a sense of local identity of business models [86].	-	-

Table 4. Summarised characterisation of explorative, quantitative of bioeconomy drivers, their assessment methods and bandwidths (minimum and maximum values) (for data basis and equations, see Supplementary Materials S5–S7).

ID	Drivers	Assessment Method (L/O/Q) *	Minimum in 2050	Maximum in 2050	Unit	Unit Explanation
D1	Biogenic residue materials	L	10,216,000	137,550,000	Mg_{dm}/a	Potential usable volume in tonnes of dry matter
D2	Urban agricultural	O	5532	181,089	ha	Possible land gains for other purposes by implementation in hectare
D3	Degraded and unused areas	O	4,372,971	5,371,906	ha	Possible usable land in hectare
D4	Algae	O	291,000	582,000	Mg_{dm}/a	Possible usable production volume in tonnes of dry matter
D5	Perennial production systems	O	29,392,042	162,644,402	Mg_{dm}/a	Possible usable production volume in tonnes of dry matter
D6	Paludiculture	O	3,060,000	26,805,600	Mg_{dm}/a	Possible usable production volume in tonnes of dry matter

Table 4. *Cont.*

ID	Drivers	Assessment Method (L/O/Q) *	Minimum in 2050		Maximum in 2050		Unit	Unit Explanation
D7	Forests for raw materials	L	Deciduous tree: Coniferous tree:	0.7 31	Deciduous tree: Coniferous tree:	12 43	Mio. m^3 a^{-1}	Possible usable potential in cubic meter yield
D8	Microorganism	Q	-		-		-	-
D9	Smart farming	L	Yields: Water usage: N_2O emissions: Plant protection:	+1 −20 −10 −11	Yields: Water usage: N_2O emissions: Plant protection:	+15 −25 −34 −90	%	Possible development of in- and outputs of agricultural systems in percentage
D10	Organic farming	L	Yields:	−15	Yields:	−25	%	Yield development by implementation of these systems in percentage
D11	Ecosystem services	Q	-		-		-	-
D12	Production plants of bioeconomy products	Q	-		-		-	-
D13	Digitisation	L		100		100	%	Connection rate in percentage
D14	Cascade principle	Q	-		-		-	-
D15	Fully recyclable biopolymers	O	PLA prod. (Source: Lignocellulosic; Base year: 2020)	77	PLA prod. (Source: Lignocellulosic; Base year: 2020)	1772	%	Possible production volumes in comparison to reference year in percentage
		O	PLA prod. (Source: Food wastes; Base year: 2020)	0.01	PLA prod. (Source: Food wastes; Base year: 2020)	0.48	%	
D16	Environ. friendly chemicals and fuels	O	Ethanol cons. (Source: Lignocellulosic; Base year: 2019)	314	Ethanol cons. (Source: Lignocellulosic; Base year: 2019)	8634	%	Possible production volumes in comparison to reference year in percentage
		O	Biodiesel cons. (Source: Microalgae; Base year: 2018)	3	Biodiesel cons. (Source: Microalgae; Base year: 2018)	7.3	%	
D17	National population development	L		74,000,000		84,000,000	Pers.	Possible population development in Millions
D18	Behavioural changes	O		35 361		31.2 270	kg_{head} a^{-1} l_{head} a^{-1}	Possible development of consumption in kilogram and litre per person and year
D19	Rural development	Q	-		-		-	-

*: L, values taken without any alteration from literature; O, values calculated based on quantitative examinations of the literature; Q, qualitative description.

3.3.1. Building Block 1—Provision of Raw Materials

The following building block contains seven drivers: biogenic residue materials, urban agriculture concepts, abandoned and degraded areas and old industrial sites and marginal areas, algae, integrated cropping systems, paludiculture, and forest areas.

D1—Biogenic Residue Materials

The quantitative potential analysis is based on Krause et al. [87], which monitored occurrence of these specific material streams in Germany. For minimum potential, the mobilisable potential (Technical biomass potential deducted by technical biomass potential used, in dry matter (Mg_{dm}) [88]) is considered, and for maximum potential, the technical potential (Time- and location-dependent quantity of usable biomass potential for material or energetic purposes from a technical point of view, in dry matter (Mg_{dm}) [59]) of all investigated biogenic raw materials of the year 2015 is used, which leads to the following results of 10,216,000 Mg_{dm}/a_{min} and 137,550,000 Mg_{dm}/a_{max} available resources. Due to the fact that bioeconomy will increase the usage of more biogenic resources in several appliances, occurrence of biogenic residues could be assumed to be stable by 2050 but with changing characteristics.

D2—Urban Agricultural

The quantitative potential analysis distinguishes between two production systems for fruits and vegetables, which are implemented in the example on abandoned inner city areas (see Driver 3). It is assumed that the introduction of these systems results in savings of agricultural areas outside the urban context. The first system consists of allotment gardens and controlled urban agricultural practices as greenhouses or community gardens. Based on the analyses of McClintock et al. [89] and Edmondson et al. [90], a potential production capacity of 2.9% minimum to 15% maximum of inner city areas relative to consumption is assumed by 2050, which would result in a gain of about 5532 ha_{min} and 28,612 ha_{max} spaces (Further reference used for the calculation: Ref. [91]). The second one is based on cultivation of plants within a closed setting on nutrient rich mediums, mostly soilless, controlled in a strong technical environment. Due to crop yields from 71 Mg/ha ${a^{-1}}_{min}$ to 155 Mg/ha ${a^{-1}}_{max}$ [92], it would be possible to produce the whole vegetable production for Germany (average German production from 2015 to 2019 [93]) within an urban setting. Therefore, based on the minimum yield, about 50,937 ha_{min} and, based on maximum yield, about 23,332 ha_{max} of areas would be needed. Thus, until 2050, all of the 181,089 ha_{max} of areas previously used for vegetable cultivation could be reclaimed for other purposes. Thus, until 2050, about previously used 181,089 ha_{max} could be gained. The reported high energy consumption of these systems, high prices of products, and stable supply of fruit and vegetables in Germany inhibit a wider dissemination in the present state [94]. Therefore, the emphasis of the role of these concepts is on the years after 2030, when the challenges of climate change will increase, especially for the agricultural sector [95,96].

D3—Degraded and Unused Areas

The quantitative potential analysis distinguishes between areas in an urban context and the primary production sector. About 120,000 ha_{min} to 175,000 ha_{max} areas are actually classified as abandoned in urban surroundings in Germany [97,98]. Reduce this with values calculated in Driver 2, about 47,832 ha_{min} up to 90,817 ha_{max} could be available for biomass cultivation in 2050. Based on a GIS assessment of marginal areas in the primary sector, by Gerwin et al. [64], about 3.3 Mio. ha_{max} could be used for biomass cultivation until 2050. These results need to be interpreted with caution because other aspects, e.g., biodiversity, are not considered [99].

D4—Algae

The quantitative potential analysis distinguishes between open ponds and closed production systems, both of which are land-based [65,66,100]. Due to the limited potential of macroalgae farming in Germany [101], only microalgae farming is considered. The bandwidth of yields is from about 3.5 $Mg_{dm}/ha\ a^{-1}{}_{min}$ (open systems) up to 100 $Mg_{dm}/ha\ a^{-1}{}_{max}$ (closed systems). While the production depends on surrounding conditions (e.g., radiation intensity, temperatures) for Germany, a minimum yield of about 30 $Mg_{dm}/ha\ a^{-1}{}_{min}$ up to 60 $Mg_{dm}/ha\ a^{-1}{}_{max}$ [66] on suitable areas of about 9700 ha_{max} would be feasible [100]. Exploiting the full potential, a maximum production scale of 582,000 Mg_{dm}/a_{max} is assumable until 2050.

D5—Perennial Production Systems

The quantitative potential analysis distinguishes between SRC (short-rotation coppice) and miscanthus planted on agricultural areas, marginal land and on areas gained due to implementation of other systems, e.g., Driver 2. It was assumed that a share of both perennial systems remains at the status quo in Germany (about 60% SRC and 40% miscanthus [84]). In the agricultural sector, the bandwidth of usable land spreads from about 170,000 [102] to 500,000 ha [57] (see Figure 3: SRCAG, MISCAG). This results in a biomass potential from 510,000 Mg_{dm}/a_{min} to 5,400,000 Mg_{dm}/a_{max} for SRC (Further references used for the calculation: Refs. [103,104]) and from 408,000 Mg_{dm}/a_{min} to 5,200,000 Mg_{dm}/a_{max} for miscanthus (Further reference used for the calculation: Ref. [105]) on agricultural areas in 2050. In marginally abandoned and gained areas, the potential spreads from 15,818,912 Mg_{dm}/a_{min} to 77,456,582 Mg_{dm}/a_{max} for SRC and from 12,655,130 Mg_{dm}/a_{min} to 74,587,820 t_{dm}/a_{max} for miscanthus in 2050. To date, these potentials have been highlighted in several studies (e.g., Refs. [68,102,106]); however, based on the development from 2015 to 2021 (increase from 100 to 11,200 ha) in Germany, it can be considered that there is a significant divergence between scientific analysis and practical dissemination of these systems [84]. Enhancement of information about the advantages of these systems and specific incentives could support dissemination, as already elaborated in detail by Böhm et al. [107]. Given the status quo, widespread use of these systems is not expected before 2025.

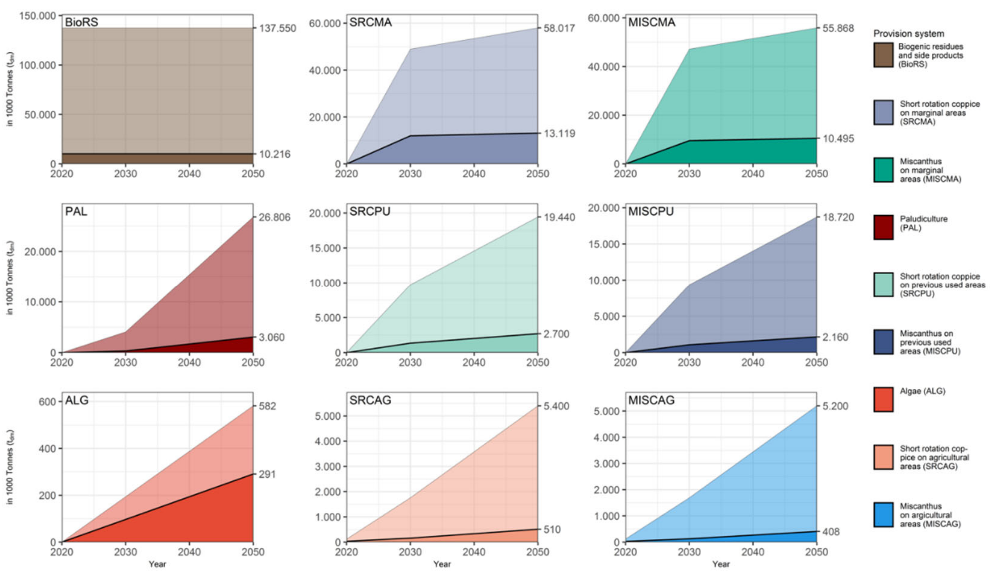

Figure 3. Analysed possible biogenic raw material sources of a future German bioeconomy with linear gradient or extrapolated values of minimum and maximum potentials until the year 2050.

D6—Paludiculture

The quantitative potential analysis is based on Abel et al. [70] and describes a necessity of rewetting about 1,789,000 ha drained areas until 2050, of which about 1,314,100 ha_{max} could be used for the cultivation of lignocellulosic biomass in the form of paludiculture. Until 2030, half of the area should be rewetted for reaching agriculture climate sector goals [83], and until 2050, the whole area is assumed to be rewetted. With yields from about 3.6 $Mg_{dm}/ha\ a^{-1}{}_{min}$ to 20.4 $Mg_{dm}/ha\ a^{-1}{}_{max}$ until 2050, about 26,805,600 Mg_{dm}/a_{max} of lignocellulosic biomass could be generated [108].

D7—Forest Areas

The quantitative description of future possible yields from German forests was not systematically reviewed, and is based on the national WEHAM scenario study [72,109]. Based on the evaluation of forest development, a raw wood potential for material usage from about 0.7 Mio. m^3/a_{min} to 12 Mio. m^3/a_{max} of deciduous tree wood and about 31 Mio. m^3/a_{min} to 43 Mio. m^3/a_{max} of coniferous tree wood until 2052 is reachable [110]. These numbers have been already reduced by dead wood and wood for energy purposes. Nevertheless, these material streams have not been considered in the example calculation because they are already mostly in use [40]. Only residues from the forest have been integrated into Driver 1, which will change in a specific characteristic (more deciduous trees than coniferous) but not in quantity due to no majorly changing forest area in total [72].

Figure 3 summarises the results for the explorative potential analysis of the specific biomasses of Drivers 1 to 6. Therefore, it is necessary to consider that this is only an excerpt of biomass material flows in a future German bioeconomy. A more systematic overview of about several biomass material flows could be seen in Bringezu et al. [40] or Szarka et al. [111]; however, the quantitative description of bandwidths shows high relevance, especially for biogenic residues and side products (Driver 1) based on the overall share of the analysed biomass sources (share of overall resource base: 2030_{min}: 29%; 2030_{max}: 53%; 2050_{min}: 24%; 2050_{max}: 42%). While residues and marginal areas can be identified as an already available resource for a bioeconomy, urban agriculture concepts, perennial biomasses or algal systems have yet to be developed, which makes their implementation expected at a later point in time. By integrating analysed biomasses as short-rotation coppice or paludiculture (Drivers 5 and 6), the perspective could be extended to the subject of beneficial land use change [68].

3.3.2. Building Block 2—Production Systems and Principles

The following building block contains four drivers: microorganisms, smart farming, organic farming, and ecosystem services.

D8—Microorganisms

The qualitative description highlights the necessity of further research in this sector and the less available data about possible production capabilities [112]. Tools such as metabolic engineering, directed evolution, automated strain engineering, metagenomic discovers, gene circuit design and genome editing increase the possibilities to modify microorganisms and to produce bioherbicides, organic acids for fuel, and more efficient chemicals [112,113]. Some of these technologies have already reached a high technological readiness level and are used in, e.g., biorefineries (Driver 12) for fuel or chemical production [11,78,79]. These could gain high relevance in the next decade, but microbial production systems are still in development and are connected to high uncertainties for applying these technologies on a wider industrial level for the mentioned purposes within the next decade.

D9—Smart Farming

The quantitative description is literature-based, without setting the evaluated data into a systemic context. With the aim of increasing efficiency, smart farming technologies can support the reduction of inputs while increasing or maintaining yields. Real-time support by processing data, e.g., historical farm-level data or weather forecasts, is one opportunity to achieve these efficiency gains [114]. On the input side, a reduction of up to 25% of expenditures is feasible to reach [74]. Following Ref. [74] herbicide reductions of 11 to 90% are indicated and 3–25% reductions in fertiliser use are described in Ref. [115], each in relation to the crops and systems cultivated. Reduction of nitrous oxide (N_2O) emissions up to 34% in Germany is possible [115], while about 10% on average could be realistic. Further positive aspects are a reduction of soil compaction, runoff, and erosion [116]. On the output side, yields could increase by 1–15% regarding the cultivation system [74,117] (Further references used for calculation: Refs. [118–121]). It should be considered that these technologies are mostly applied in conventional agricultural practices at the current state-of-the-art. Rebound effects, which can have a negative impact on ecosystem services (Driver 11) in the long term, should be taken into account [122]. Due to this, low-cost unmanned aerial vehicles (UAV) or remotely piloted aerial systems (RPAS) could gain more importance in the production of crops and biomass in the future [123].

D10—Organic Farming

The quantitative description centres on the present state and possible future developments in the agricultural sector, and it distinguishes between organic farming and an agroecological perspective without analysing the systemic impacts on material or energetic flows. Until 2030, 20% of agricultural area should be cultivated under organic farming practices. Therefore, about 3.3 Mio. ha_{max} of land is needed (based on 16.68 Mio. ha usable area (2020)), which results in an increase of about 1.6 Mio. ha of organically cultivated land until 2030 (base year 2019) [124]. Based on the growth rates from about 2010 to 2019, without any incentives, the aim of 20% in 2030 is not possible to reach. The results show that about 2.4 Mio. ha would be cultivated on trend extrapolation in 2030, reaching the aim for 2030 in the years 2045–2050 [83]. In addition, organic or agroecological systems are associated with a reduction in productivity per hectare of about 15% to 25% compared to conventional farming methods, but this depends on the context and cannot be generalised [40,46,125]. Therefore, effects of land gains through behavioural changes in diet (Driver 18) are reused to offset the higher land requirements for organic farming. Due to the necessity to adapt agricultural production processes for mitigation purposes of climate change [95], a higher dissemination of these systems is assumed until 2050, which would lead to yield reduction up to 25%.

D11—Guiding Principle: Ecosystem Services

The qualitative description explains the role of ecosystem services as a leading concept in the strategy. Ecosystems consist of plants, animals and microorganisms living in biological communities, interacting with each other and the physical and chemical environment due to the driving force of solar energy [77]. Ecosystem services include material as well as immaterial goods and can be divided into four general categories: supporting systems, e.g., soil generation, nutrient and water cycle, oxygen production, carbon storage or primary production; regulation systems, e.g., regional climate and air quality, water balances and quality, soil formation and development or occurrence of pests or diseases; provision systems, which enable people to use renewable resources in the form of food, wood, fibre, drinking, and process water; and cultural systems, which satisfy immaterial human needs arising from aesthetic, contemplative, spiritual, religious, cognitive, educational and recreational aspects. Overall, ecosystem services are only generated if the relevant capacity of an ecosystem (ecosystem services supply) meets a corresponding individual or societal expectation (ecosystem services demand) that can be realised. Ecosystem services are the connection between the natural resource base and society demands, desired or not [126], which leads to the conclusion that they have to be integrated as a leading principle of a future bioeconomy.

3.3.3. Building Block 3—Infrastructure and Technologies

The following building block contains three drivers: production plants of bioeconomy products, digitisation, and cascade principle.

D12—Production Plants of Bioeconomy Products

The qualitative description of central technical bioeconomy applications distinguishes between biorefineries and biogas plants, while biogas plants are also partly described on a quantitative basis due to the already wide systemic implementation in Germany. Biorefineries are a central key industrial process with the possibility to generate diverse products from diverse biogenic sources. Used raw materials are quite heterogenous, including starch and sugar crops, whole crops (e.g., corn and straw), oil crops, lignocellulosic and wet biomass (e.g., green crops, leaves, grass, lucerne), and marine biomass, such as microalgae and macroalgae products [79]. Quantitative examples are given in Drivers 15 and 16. It is assumed that the potentials of these plants will be fully developed by the beginning of 2030 due to the necessary time of product development as well as necessary incentives for increasing market share [11,127].

About 9000 biogas plants in Germany use microbial production systems to convert cultivated energy plants, manure, and biogenic residues into biogas, which are then utilised in the power or heat sector [128]. As they are already multi-output facilities, they are establishing a first step into a future bioeconomy [129]. With a share of about 40% of all renewable energies in Germany, biomass contributes about 8% to German gross power generation [130]. More important is production for the heat sector, where about 15.2% of heat is generated by renewable energies, and from this, about 10.7% is in the form of gaseous biomass from biogas plants [131]. Biogas plants will, within the next two decades, still have an important role in the transformation of energy systems [132]. Besides the heat sector, based on smart energy concepts (e.g., flexible bioenergy) [133], biogas could be used in sectors where the substitution of fossil fuels is resource intensive. These could be, e.g., the transport sector, sectors with fluctuating electricity generation, or to realise negative emissions [12,134].

D13—Digitisation

The qualitative description outlines the need for a digital infrastructure to realise the full potential of a future German bioeconomy, while the quantitative data illustrate the actual status quo of development. An increasing amount of data are used in several sectors, e.g., forestry or agricultural, for monitoring purposes, reducing the input of processes (Driver 9), or securing sustainable feedstock production, which is also highly important for a future bioeconomy [80]. Further applications of synthetic biotechnology required to alter metabolic production systems are highly complex and generate a large amount of data. Therefore, technology (bioeconomy) developments such as DNA data storage systems or blockchain technology are increasingly needed [135]. A precondition to enable this potential is an infrastructure of fast data connection. In German rural areas, about 20,2% of the population has the opportunity to connect to fibreglass with a connectivity of >1000 Mbit/s, while in urban areas, the share is about 76,6% [136]. The slow extension leads to difficulties for several actors, as highlighted by the latest infrastructure report of the Federal Ministry for Economic Affairs and Climate Action (BMWK) [137], where about 72% of industrial actors stated to have economic deficiencies because of missing opportunities to connect to high-speed data networks. With the aim of having a "Gigabit" society in 2025, the necessary infrastructural need for improvement is clear. It is assumed that a complete connection in rural areas to >1000 Mbit/s networks could be reached by 2025, or at the latest, 2030.

D14—Guiding Principle: Cascade Principle and Circular Economy

In the qualitative characterisation, the discourse of the cascade principle is examined in the context of the hierarchy for products and the cascade factor. The aim of cascade usage is the reduction of resource overuse by applying principles of efficiency (using less resource for the same output) and consistency (using renewable resources instead of finite resources) [138]. Cascade use includes multiple uses of materials with decreasing value added and at the end of the life cycle for energy or composting purposes. It is a leading concept of the bioeconomy and the connection to the circular economy [7]. Until now, cascade use has mostly been oriented towards the bio-based value creation pyramid. This shows the product hierarchy for bioeconomy products based on product values, the possibility for cascade usage, and mass volume from high to low [13], with products such as pharmaceuticals and nanocellulose at the top, and energy at the bottom [139]. Cascade factors were developed for the analysis of the reduction potential of primary raw materials and greenhouse gas emissions. They are applicable in distinct product portfolios, but less so for overarching assessment [57].

In general, cascade use pursues a value-based objective without knowing whether it will reduce negative impacts on the resource base and environmental systems. For this reason, it must be taken into account that an anthropocentric, use- and process-oriented view is associated with weaker sustainability perception [6], and thus the cascade principle is not intrinsically sustainable [13]. Extending the perspective on the cascade principle by the integration of an ecosystem service perspective could be a favourable to increase integration of sustainability aspects and would also shift the focus from product side to downstream processes at the supply side [140]. Further research to expand the cascade principle in relation to sustainability concepts would also increase sustainability in the orientation of a future bioeconomy.

3.3.4. Building Block 4—Sustainable Products

The following building block contains two drivers: fully recyclable biopolymers and environmentally-friendly chemicals.

D15—Fully Recyclable Biopolymers

The qualitative description of biopolymers is supported by a quantitative example of possible production capacity of polylactic acid (PLA). Polymers have advantageous properties such as formability, hardness, elasticity, rigidity, heat resistance, and chemical resistance, and they are lighter and more economical, which is why they can be used in a variety of applications [141,142]. As the state-of-the art, they are mainly produced by petrochemical processes and are associated with fossil fuel depletion, environmental impacts due to longevity of degradation processes, and GHG emissions due to incineration as end-of-life treatment [143]. Fully recyclable biopolymers could solve several environmental and waste management challenges as well as accelerate cascade usage (Driver 14) of products. The production of PLA could be used as an example because it is also based on a so-called platform chemical (Driver 16). PLA is chemosynthesized from lactic acid that could be produced from various raw materials such as lignocellulose, microalgae, or food wastes [144]. While the production potentials from food wastes with $0.01\%_{min}$ to $0.48\%_{max}$ is neglectable, based on analysed potentials of lignocellulosic materials in BB1, about $18.25\%_{min}$ (2020) to about $1772\%_{max}$ (2050) would be feasible to be produced based on plastic production capacity in 2020 in Germany (Further references used for the calculation: Refs. [145–148]). The calculation includes no boundary conditions (e.g., lignocellulosic materials of residue streams already in use) and therefore have to be taken with caution, but shows opportunities for substituting fossil-based polymers.

D16—Environmentally-Friendly Chemicals and Fuels

The qualitative description is supported by a quantitative example that distinguishes between ethanol production in the chemical sector and biodiesel production in the fuel sector. Chemicals are mainly produced based on fossil resources [82], which goes along with negative impacts to the environment and atmosphere [143]. Analyses show that about 15 chemicals are promising as platform chemicals for several applications addressing the defossilisation of material flows [82]. Due to the necessity of reduction of GHG emissions in the German fuel sector, this sector is next to the chemical sector highly relevant for further analysis [12]. Following the examination by Michels [149] and the evaluated biorefinery concept by Budzinski et al. [150], nearly all lignocellulosic materials could be used depending on the pre-processing steps for ethanol production. With the same raw material potential as in Driver 15, about 32.17% of German ethanol consumption (2018) could already be produced. With a higher dissemination of the technology in 2030, it would be possible to generate the entire German ethanol consumption (2018) from considered feedstocks (Further references used for the calculation: Refs. [151–158]). Microalgae could be a feasible feedstock for second- and third-generation fuels; however, the analysed production potential could have a share of about 3% to 7% of the German biodiesel market (2018), which shows limited potential in comparison to other biogenic feedstocks used for fuel production [66] (Further references used for the calculation: Refs. [151,159]).

3.3.5. Building Block 5—Bioeconomy and Society

The following building block contains three drivers: national population development, behavioural changes, and rural development.

D17—National Population Development

The quantitative description is based on the latest scenario studies of the German Federal Statistic Office about a possible population development by 2050 [160]. The bandwidth extends from an old to a young population structure, with inhabitants from about 74 Mio. people at a minimum to about 84 Mio. people at a maximum. In the minimum scenario, the group of working people consists of about 43 Mio. people, and in the maximum, it is about 47 Mio. people.

D18—Behavioural Changes

The quantitative description emphasises the effects of dietary habits on land use in Germany. Following a recommended reduction of meat and dairy consumption [161] and the trend of development in the last years, areas are calculated gained through this assumed decrease. The average meat consumption is about 55.4 kg_{head} a^{-1} (2021) [162]. For dairy products, actual consumption is about 361 l_{head} a^{-1} (2017), which is about 13% below the maximum and 25% above the minimum of recommended level by the German Nutrition Society [163]. Reaching the minimum level would reduce the amount of dairy cows by about 13% (base year 2016) with constant exports [83]. Based on the trend of the years 2015 to 2019, a reduction in meat consumption could be observed, and following this trend, in 2050, the average consumption level would be about 35 kg_{head} a^{-1}. A first analysis shows that a reduction to the level of 30 kg_{head} a^{-1} [162] could possibly set free about 2.15 Mio. ha_{max} of land, previously used for production of feed for animal production (Further reference used for calculation: Ref. [164]). A second case shows that a reduction of 25% of meat and milk consumption (2017) could set about 1.75 Mio. ha_{min} of land free [83]. On the minimum bandwidth, no change would be assumed until 2030, and areas would be set free until 2050 due to the necessity for adaptation processes in relation to accelerating climate change impacts [96,165]. In the maximum, the recommended level of meat consumption would be reached by 2030. In the analysis for biomass potential, these gained areas were not considered, as it is assumed that they would be needed to compensate for a decline in production output due to wider dissemination of organic farming methods (Driver 10).

D19—Rural Development

The qualitative description highlights points of consideration for implementation of a bioeconomy in the rural area context. Regional availability of resources, infrastructure and industrial factors, and research and innovation, as well as public and institutional structures, could serve as multipliers of benefits for regional development based on different bioeconomy concepts [166]. Next to the rural areas, urban–rural metabolism is important for transformation aspects. It is necessary to consider the exchange of various flows of people, goods, and knowledge, and the intensive alteration of these flows due to the increasing international and global trade and a stronger shift to a spatial decoupling [167,168]. Thus, strategies for land saving developments, zoning of agricultural priority areas, zoning of ecological priority areas, optimisation of resource use, and planning processes are decisive factors [169]. Integrating these strategies into a future bioeconomy could broaden the perspective from the level of individual actors to a more landscape-based approach [170].

4. Discussion

Based on the applied methodology of combining narrative and STEEPLE analyses, about 19 scenario drivers, compiled into five building blocks, could be extracted from the German National Bioeconomy Strategy 2020. The majority of the drivers (14 of 19; see Table 4) could be quantified based on an integrative synthesis research strategy in an exploratory way. Based on the generated bandwidths of minimum and maximum values, possible boundary conditions of the analysed drivers could be outlined and specific characteristics of a future German bioeconomy were described in more detail. As the identified narratives concentrated on resource and technology perspectives, the description of drivers focused on physical constraints. The advantage of this is that they could be used in different scenario studies as a starting point, which is also supported by the transparent and thorough description of the methods used. The list of drivers includes known drivers, that have been already used in the context of scenario analysis in the research field of bioeconomy, such as SRC, biogenic residues [8,40] or forest raw materials [72], but also integrates new potential drivers such as urban agriculture concepts, paludiculture, direct comparison between organic farming and smart farming practices, algal biomass, and example calculations for biopolymers and fuels. In addition to the quantitative drivers, the qualitative drivers highlight the challenges and gaps that need to be considered much more in the analysis of a future bioeconomy.

4.1. Building Blocks and Drivers

The overarching narrative analysis shows that the GNBS 2020 sets implicit priorities for specific bioeconomy concepts, which have to be discussed in a systemic context. We see that specific preconditions and tools are required, that the current bioeconomy cannot create on its own, and that consequently, governance and management frameworks are needed [16,32]. Therefore, in addition to the resource-related and technological dimensions, political and social aspects have to be discussed.

Following the identified resource- and technology-oriented perspective, our conviction is strengthened regarding the importance of residues and side product streams for a future German bioeconomy. While in some previous studies, the energy potential of these was in the foreground [59], the present study also shows the significance of the dry matter potential for first material use. This is also confirmed by the evidence that these material streams are named in about 16 out of 21 analysed international studies as a major raw material source (see Figure 2). In addition, the concept of beneficial land-use change [68] was highlighted in the work (Driver 5 and 6). With this concept, the focus is not solely on the output of the respective system, but stronger on the systemic effect and resulting synergies. This could change the perspective that bioeconomy concepts only increase land-use pressure, to the understanding that they also increase diversity, which could be favourable for the maintenance of ecosystem services (Driver 11) and thus the resource base of a future bioeconomy.

It should be noted that these material streams are influenced by various factors as e.g., legal regulation, consumption patterns or trade-offs between material and energy sectors. A change in these areas could lead to an alteration of the material flows in quantity or quality and influence the sustain provision as raw material for a future bioeconomy. To ensure the supply of raw materials, the promotion of a market formation for residues and side product streams could be favourable; however, it would be questionable whether this would reduce the negative environmental impacts, if the dynamics of supply and demand follow the identified value- and growth-oriented perspective and do not shift towards a stronger internalisation of the externalities of resource production [13]. Addressing this challenge, the circumstances of resource production could be considered more strongly, as emphasised by Olsson et al. [13]. A stronger policy prioritisation of incentives and penalties for practices that have a negative impact on the environment could promote the implementation and diffusion of different bioeconomy concepts, such as the cascade (Driver 14) valorisation of residue and side products or cultivation of new introduced biomasses (e.g., Driver 4, 5 and 6). Moreover, the innovation potential of the bioeconomy concepts themselves could be a key variable for incentives, as analysed for example by Gatto et al. [171]. Possible conflicts of interest with existing production processes need to be acknowledged, as well as the high diversity of feedstock carriers (BB1). Next to the focus directly on the resource base, increased information for consumers could also accelerate a higher dissemination of bioeconomy in several sectors, which could be slower without any measures, as shown in drivers 10 and 18. Therefore, a general rethinking of the waste pyramid paradigms might be necessary, as e.g., Teigiserova et al. [172] have done for food wastes. Furthermore, there is only a vague reference to CO_2 emissions, associated taxes, or cost increases, although a major goal of a future bioeconomy should be the reduction and storage of CO_2 emissions, as can be seen in the example of bioenergy by Tsiropoulos et al. [45]. A stronger connection to the aspects of reaching national and international climate goals in general is necessary to consider.

Since the work mainly focuses on Germany and the objective is to generate bandwidths that can be further used, the impact of regulatory frameworks, geopolitical developments, or import biomass on drivers were not explicitly considered. Minor integration of regulatory frameworks that have a high impact on the future development of material flows, could be stated. Nevertheless, the results illustrate that a future bioeconomy is a holistic concept that connects different strategies on the national and international level, which could be included in future evaluations. Connection could be seen in several aspects to the Renewable Energy Directive of the EU (RED II) [12] for e.g., residue and side product valorisation (Driver 16), the Farm to Fork strategy [173] for e.g., reduction of used pesticides and change in agricultural systems (Driver 9 and 10) as well as to the latest COVID-19 recovery program NextGenerationEU [174] supporting e.g., diversification (Driver 5, 6 and 10) and digitisation of on-farm activities (Driver 9) and setting in specific in Germany focus on support defossilisation of industries (Driver 15) and integration of alternative fuels (Driver 16) in the transport sector [175].

With regard to social aspects, the inclusion of the guiding principle of ecosystem services (Driver 11) is beneficial. It not only extends the perspective of the cascade principle (Driver 14) to downstream processes as well [2,140], but underlines the connection between nature and social systems, as cultural systems are one of the service functions provided. Although the focus of the study was on a first exploratory characterisation of the identified drivers, their wider implications for social dimensions are also evident. Urban agriculture concepts (Driver 2) with orientation towards on increasing the food sovereignty of people involved, support further social services as community-based city district development or social participation in general, though, this is not only about social aspects, but also about ethical aspects, such as enabling people to participate more in their own food production [60,61]. In rural areas, bioeconomy concepts could mitigate the negative impacts of changing urban-city metabolism (Driver 19) [167,168]. A stronger alignment with regional planning strategies [169] could enhance the participation of actors, job creation in rural areas as well as knowledge transfer between science and society in general [11]. A landscape-based approach [170] can be used to address challenges arising from bioeconomy concepts that will have a significant impact on the status quo of land use (e.g., Driver 6). Including these aspects within assessment frameworks, as life cycle analysis (see e.g., Refs. [14,176]), benefits of a future bioeconomy for the people themselves as well as for their social environment will become more apparent. We addressed this issue by elaborating drivers in a comprehensible way, that could be used for further discussion.

Next to overarching political and social aspects, several factors have to be considered for further usage of the drivers and their bandwidths. The quantitative analysis for residue and side product streams includes all resources, whether used or not, for the exploratory consideration. While the maximum values of the ranges suggest that biomass can be used for a variety of purposes, it is important to ensure that constraints, such as the impact on ecosystem services (Driver 11), are respected in order to efficiently integrate the biomass streams into different material flows. Contradictions occur in consideration of algae biomass potential, which is lower than their assumed future relevance, as highlighted e.g., in the GNBS 2020 [7]. A limitation of this analysis could be that the emphasis was on land-based systems rather than highly technical or integrated systems. Within the strategy, the objective is to have no reduction in production in the agricultural sector but to have more organic farming areas in general. Based on the analysed yield development in organic farming and reviewed smart farming concepts, a yield gap of about 10–14% can possibly occur (see Table 4).

Despite these discussed aspects, the results are consistent and align with the exploratory outline of the study. Furthermore, they underline challenges in the data basis that could be analysed and integrated in further studies.

4.2. Materials and Methods

The elaborated drivers support the synthesis of the broad field of the German bioeconomy into specific aspects that have a high impact; however, as the aim of the study was also to develop a transparent and replicable method, further limitations need to be discussed.

We used the German National Bioeconomy Strategy 2020 as a starting point for elaboration and certainly such a document is not available in all countries [177], which can reduce the methodical application. Integrating participatory inputs could enrich the concept in further analyses (see e.g., Refs. [178,179]).

The used method of narrative analysis, to quantify the qualitative information, was favourable for the aim of narrowing down the strategy paper to specific aspects as well as to elaborate an overarching objective. Within our work, we addressed the challenge of using narrative frameworks that analysing a state in the past, by assessing the driver with results from a STEEPLE assessment of current literature. As this showed similar pattern, it could be concluded that this constraint does not have a significant impact on the present work. To not over- or under-estimate specific aspects, a normalisation method was used, which could be in the future accompanied by sensitivity analysis [180].

The STEEPLE method was used successfully for driver assessment and to identify drivers of scenario literature. Its limitations are that it is limited to the six external variables and that the analysis relies on an extensive database. For further analysis, we would recommend increasing the database.

The specific characterisation of the drivers itself on a qualitative and explorative quantitative base, illustrates how scenario methods could be used to describe possible boundary conditions, in this case, of a German bioeconomy. The greater attention to physical constraints of the ranges, instead of other factors, allows them to be easily integrated into further analyses. With this, questions of the resource base, prioritisation of biomass, and sustainability impacts could be elaborated much further. Overall, however, we can state that the methodology is favourable for holistic analysis purposes.

4.3. Further Aspects to Consider

We believe that the results lead to a reasonable data basis as a starting point for further system analysis of a future German bioeconomy. The method could be used as guideline and could be applied to other strategy papers in other countries and regions. Further research on strategies from other European countries could validate how the driver identification changes, if strategies integrate already action plans [178], first measurement indicators [179], or have a specific time frame of consideration [181].

While in the present work the objective was set on the identification and characterisation of individual drivers, analysis of the relational context of the drivers in the next step could support decision-making at the political, economic, and especially at the general sustainability level and to promote the formulation of action plans and concrete goals [15].

Methodologies as a complete scenario analysis including analysis of the significance of the drivers [21,39], system dynamics, which emphasises causal relationships [182], or Multi-Criteria Decision Analysis (MCDA) [171] could support this objective and assist actors to integrate presented concepts into regional strategies and investment schemes, considering the use of local resources and long-term trends.

The results show the importance of residue and side products streams as sources of raw materials. Thus, it is necessary to investigate whether the use of these in a future bioeconomy would support overall systematic sustainability. Analyses of distinct production processes in terms of residue and side product streams connected with the cascade principle could be a supporting work. Furthermore, the specific consideration of residue and side product streams as a viable option for the reduction of GHG emissions in the energy sector directly (see Ref. [59]), must be analysed in relation to the environmental impacts and in its contradiction to the guiding principle of cascade use (Driver 14) in a future bioeconomy. To achieve this, an overview of status quo of quantity and quality of the distinct material streams is necessary. A resource database, based on transferable methodologies, as established by Brosowski et al. [88] was a key and decisive element of the present analysis and could be recommended as transferable concept. We showed that sociological aspects are often underrepresented in technology-focused bioeconomies. The importance of integrating rural value creation and socio-technical aspects, as discussed recently in the research field of energy scenarios (see, e.g., Ref. [26]), must be given greater attention. A much stronger connection to the normative SDG framework [14], which supports the communication of specific results on comparable regional [183], national [7], and international levels [184], could be beneficial for this.

5. Conclusions

With this study, we provided an extensive overview of the current status and potentials of the bioeconomy and examine specific aspects of a possible future bioeconomy in Germany. For this purpose, we identified drivers of the bioeconomy, based on the German National Bioeconomy Strategy 2020 and other literature, and present a methodology that can be used for future evaluation in the research field, such as scenario analysis or modelling. The applied methodical combination out of narrative and STEEPLE analysis in connection with the explorative characterisation of quantitative ranges is efficient without involving stakeholders. With this, we build a transparent and traceable knowledge base for different stakeholder groups to facilitate the actual decision-making, but also built long-term implementation strategies for a sustainable bioeconomy. The detailed description of drivers illustrates that the bioeconomy of the future is a highly interdisciplinary field that expands the view beyond the mere substitution of input materials of production processes. While several bioeconomy concepts could increase the resource base, such as paludiculture or perennial systems, and generate products from it, like biopolymers or fuels, governance and management tools are needed to increase synergies and reduce trade-offs between them. Within the transformative concept, social and ethical factors such as participation in decision-making processes or regional value creation are decisive factors in enabling a future German economy, that is oriented towards sustaining ecosystems as resource base.

These aspects can now be better considered into discussion of a future German bioeconomy for the identified drivers. The elaboration of the work allows for a more systematic development of scenarios in the biomass sector that goes beyond the energy focus and takes a more holistic and material perspective. This, in turn, could accelerate the transition and adaptation of production systems for the purpose of scoping with future global challenges.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14053045/s1, S1: Narrative analysis; S2: Results of Narrative analysis; S3: STEEPLE analysis; S4: List of reviewed literature S5: Parameters; S6: Equations; S7: Data basis 2020, 2030 and 2050 for exploratory quantitative analysis.

Author Contributions: Conceptualization: S.R. and N.S.; Methodology: S.R.; Formal analysis and investigation: S.R.; Writing—original draft preparation: S.R.; Writing—review and editing: S.R., N.S., A.B. and D.T.; Funding acquisition: D.T. and N.S.; Supervision: N.S., A.B. and D.T. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by DBFZ—Deutsches Biomasseforschungszentrum gGmbH. Further financial support was received from the Helmholtz Association of German Research Centres through the PoF 4 program Changing Earth–Sustaining our Future, Topic 5 Landscapes of the Future (A.Bezama).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in supplementary materials S1–S7.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

SDG	Sustainable Development Goals
GNBS2020	German National Bioeconomy Strategy 2020
BB	Building Blocks
STEEPLE	Social, Technical, Environmental, Economical, Policy, Legal, Ethical
GHG	Greenhouse gas (emissions)
SRC	Short rotation coppice
PLA	Polylactic acid
MCDA	Multi-Criteria Decision Analysis

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