Daniela Thrän
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The bioeconomy system

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Foreword

The new, old bioeconomy of today has, since its introduction as the Knowledge-Based Bio-Economy (KBBE) by the EU in September 2005, evolved politically from a research initiative, in preparation for the seventh[1] Framework Programme, to a considerable, comprehensive economic strategy. Around 60 states and more and more regions worldwide have adopted corresponding supporting and promoting strategies, action plans, and roadmaps, which either carry the name "Bioeconomy" directly or represent initiatives with identical content. Some of them, such as the EU, Germany and Italy, have even produced an updated edition of such strategies! And the number of institutions calling for and promoting the bioeconomy system, that is, greater use of and knowledge about biological resources in the broadest sense, continues to grow. Their goal: to contribute to resource efficiency, to sustainability, to the circular economy, and to the achievement of climate goals. Biological resources and knowledge about them can also create or "trigger" products and processes with new, previously unknown properties, that is, deliver highly innovative results.

However, it is becoming increasingly clear that there is and will be not one but many bioeconomies in the world. It is therefore all the more necessary to identify and outline the cornerstones, the commonalities, and unique selling points of the extremely complex system of a bioeconomy and to agree on their significance and relevance: availability of biological resources with their elements of renewability, climate neutrality, circularity, innovation, and relevance of value chains and systems – with implications for collaboration, education, training, financing, and communication. The bioeconomy in the Faroe Islands is just different from that in Finland or South Africa, and the biobased activities of large German chemical companies in the Ruhr region are not comparable to the practiced bioeconomy in the Argentinian pampas or the Austrian Alps.

Many different products are already being produced bio-based today because they have clear advantages in resource efficiency and quality, in cost, in terms of health and environmental impact, and indeed in sustainability. Industry will continue on this path, with or without strategies. Against this background, we need to respond to questions like: What is the changing role of the public sector in, for example, research, licensing, and regulation? Are consumers even aware yet of the benefits of bio-based products and services that are becoming clear? How does this gradually growing reality of a biobased world affect our academic and general education and training system, the so-called *soft skills* including the necessary funding? In view of the competition between the different uses of biological resources, biomass, its impact on the media of soil and water, will we be able to "afford" one or many bioeconomies on a large global scale at all, or will only waste remain as a resource in the end? What role can and will the digital transformation, of which the public is becoming increasingly aware, play here, either on its own or in conjunction with a corresponding biological transformation?

1 ► See https://de.wikipedia.org/wiki/Forschungsrahmenprogramm as well as ► https://www.horizont2020.de/.

All these complex aspects are clearly evident in the approaches and essays of this book. The book differs from many other current contributions in Europe specifically by the following accents:

- The focus is on the bioeconomy SYSTEM with its many facets, not on individual modules (sub-areas), even though these are of course dealt with intensively.
- The differentiation of the individual actors in their roles and relevance, from agriculture to associations, as inventors or consumers, in their various functions and interests, is being scientifically reviewed for the first time , although there is still much research to be done.
- The differentiation according to the economic or instrumental form of bioeconomy applications, from the waste-based bioeconomy to the bioeconomy of microorganisms and fungi, also addresses the digital bioeconomy – a highly interesting attempt to update this topic in view of the increasingly strong debate, at least in Germany, on the biological and digital transformation.
- For the first time, the relevance of the term cluster, also in practical regional examples, is highlighted. This is very important work with regard to the importance of value creation for the bioeconomy, which science has hardly done so far, but which should have quite a few practical consequences for the success of bioeconomies.
- For the first time, new job profiles that are emerging as a result will also be covered.
- Last but not least, the book ventures into the question of the governance of the bioeconomy, a topic in which there is as yet very little that is scientifically robust, both in the German language and international literature. Thus, with regard to the diversity of organizational forms and business models of the bioeconomy, including questions of delimitation, a great deal of work still needs to be done here.

All in all, this work can be described as ambitious, but also as courageous in its choice of topics. It is published at a time when the bioeconomy is approaching a further stage in its development in the competition of ideas, strategies, and conceptual designs for tackling the immense questions of the future on our planet, in our world today. Since its launch in Brussels in 2005 as a research initiative for the EU's Seventh Framework Programme for Research, through its further development as a general economic model, as a "partner" for the achievement of sustainability goals and in the implementation of a circular economy, it now faces the challenge of measuring itself against and allying itself with the potentials and characteristics of the digital world, the world of artificial intelligence, robotics, and automation.

To do this, it must reflect on its own unique qualities and advantages, make them clear, and, above all, make them understandable: this is an easier task for anyone who develops an iPhone or tablet, or who is concerned with autonomous driving. In my opinion, this book can make an important contribution to this.

Whether and how the bioeconomy gains and keeps its momentum does not only depend on the understanding of the bioeconomy as a system. The COVID pandemic has shown that the transformation into a bioeconomy is determined by far more influencing varying factors than presented in this book.

Christian Patermann
Bonn, Germany
April 2020

Preface

The bioeconomy aims to combine the tried and tested with the new. Since 2016, there has been international agreement that this should be done within the framework of the Sustainable Development Goals (SDGs) of the 2030 Agenda. This requires not only scientific knowledge and creative technical solutions but also a sustainable framework for action and comprehensive interaction between stakeholders. In addition, there are many and dynamic developments: Innovations in *genome editing* allow new insights and development and governance opportunities in the bioeconomy; future innovations in synthetic biology are likely to accelerate these opportunities. These developments are associated with great opportunities, but also risks, which must be weighed up not only from a scientific-technical but also from a social point of view.

On the other hand, the environmental situation is also deteriorating dynamically: climate change, degradation of agricultural land, and biodiversity loss are progressing unabated so far and are fueled by the increasing demand for food, products, and energy. For the bioeconomy, this means on the one hand a clear limitation of its future development within the framework of the natural resource base, but on the other hand also a higher expectation for the future contribution of bio-based products in an economy increasingly based on renewable resources: for food, building materials, basic chemicals, specialty products, and energy. These expectations are linked to the great hope of being able to anchor the bioeconomy comprehensively in a circular way for the transformation into a new economic system, as well as the concern that the bioeconomy, as a supposedly greener economy, will further accelerate the plundering of the planet. Many expectations and interactions – both positive and negative – must therefore be taken into account in order to embark on the path to a sustainable bioeconomy.

This is only possible with a system perspective that embeds the scientific-technical activities of the bioeconomy along the biogenic material flows in the societal context and takes into account future development opportunities and conflicting goals.

This book attempts to describe the bioeconomy system for Germany (and beyond) and to bring together the different levels of resource use, actors, and framework conditions. Because the bioeconomy is inconceivable without plants, wood, microorganisms, aquatic biomass, waste use, and data/information, we have chosen these as the starting point for describing the subsystems of the bioeconomy. In order to describe the concrete movers and shakers of the bioeconomy, individual perspectives are portrayed, and the networks and clusters are presented as nodes of joint action. The framework for action in which the bioeconomy is developing is also described. These include, for example, understandings of innovation, national and international governance, scenarios and models, monitoring activities, professional fields, and bioeconomy discourses.

Finally, a look is taken at the bioeconomy as a whole and its future developments – both for Germany and beyond. The book does not provide contradiction-free perspectives or a unique understanding of the system but gives an insight into the often very dynamic contexts of action of current bioeconomy actors and their own understanding of how they define and shape "the bioeconomy system." This illustrates the diversity of the bioeconomy but also makes it possible to see where conflicting goals exist and how they can be overcome.

This book is aimed at actors from politics, administration, and civil society, entrepreneurs, and communicators as well as students and young professionals. It provides them with a quick, comprehensible, and interdisciplinary overview of the most important interrelationships of the bioeconomy. It is intended as an "orientation in the bioeconomy" and thus as a helpful support for understanding and action. It complements the books *Bioeconomy for Beginners* by Joachim Pietzsch and *Bioeconomy Shaping the Transition to a Sustainable, Biobased Economy* by Iris Lewandowski, which focus primarily on the utilization of biomass. This book is being published to coincide with the launch of the "Bioeconomy Science Year 2020" – another milestone in the German bioeconomy. We hope that in this context it will contribute not only to the scientific advancement but also to the practical introduction of the sustainable bioeconomy. The bioeconomy has the potential to sustainably shape necessary transformation processes. It is now also important to develop these more strongly in system contexts.

We would like to take this opportunity to thank the many people who have contributed to the creation of this book. First and foremost, we thank the authors of this book, who have painstakingly attempted, in some cases for the first time, to present their interrelationships in a compact manner. The authors represented in this book were supported by numerous other persons: by ideas, contributions, references, and reviews. Even if they are not mentioned here individually, they deserve special thanks. In addition, we would like to thank some people in particular. First and foremost, we thank Mr. von Braun, who has supported and accompanied this book in terms of content and concept from the very beginning. We also thank Dr. Eva Leiritz (PtJ) and Dr. Grit Zacharias (Freie Leiritz); Grit Zacharias (freelance editor and environmental scientist), who provided the original impetus for this book; Ms Diana Pfeiffer (DBFZ), whose comments contributed to a significant sharpening of the book concept and the quality of the content of the individual texts; and Mr Björn Schinkel (UFZ), whose graphic work created a coherent, overall visual image of the book and thus helped to illustrate the many ideas and concepts of the authors. Our special thanks also go to Ms. Maxie Wolf (UFZ), who checked all texts for their linguistic and formal consistency and correctness and also took over all accompanying work of the book production up to the handover to the publisher.

Finally, we would also like to thank our publisher, Springer, for making it possible for us to publish this book and always supporting us through Ms. Carola Lerch and Dr. Stephanie Preuss. Our thanks also go to you, for holding this book in your hands and having placed your interest and trust in us.

With our book, we would like to provide you with an introduction to the exciting world of the bioeconomy.

Daniela Thrän
Leipzig, Germany

Urs Moesenfechtel
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January 2020

Contents

Supplementary Information

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Daniela Thrän

(born 1968) studied technical environmental protection at the University of Berlin and earned her doctorate at Bauhaus University Weimar. She researches how biomass can be produced and utilized as sustainably as possible. Since 2003, she has been heading the Bioenergy Systems Division at the German Biomass Research Centre in Leipzig. Since 2011, she has headed the Department of Bioenergy at the Helmholtz Centre for Environmental Research (UFZ) in Leipzig and has since held the Chair of Bioenergy Systems at the University of Leipzig. She contributes her expertise on the sustainable use and production of biomass to numerous committees. She leads research projects in the field of bioenergy, bioeconomy, and spatial effects of renewable energies and has developed, among other things, the Smart Bioenergy concept.

Urs Moesenfechtel

(born 1978) studied German language and literature, adult education, and political science at the universities of Cologne and Leipzig from 1998 to 2005 and has since been working at the interfaces of press and public relations, event organization, and education management. The communication of environmental and nature conservation topics is a focus of his work. He has been working at the Helmholtz Centre for Environmental Research (UFZ) since 2013, where he has already served as press and public relations officer for the projects "Natural Capital Germany (TEEB DE)," "Soil as a Sustainable Resource for the Bioeconomy (BONARES)," and "Network Forum on Biodiversity Research Germany (NeFo)." Likewise, he has been working at the UFZ Department of Bioenergy since 2013 as a science communicator with a focus on the bioeconomy. There, he managed the communication activities within the framework of the accompanying research of the Bioeconomy Cluster of Excellence as well as the Bioeconomy Information Office.

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Introduction to the Bioeconomy System

Daniela Thrän

Contents

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1

1.1 The Challange of Transformation

Humans have been gathering and storing knowledge for millions of years, using it to improve their lives. Knowledge, wealth and also humanity have grown dramatically in the past. However, such growth as we know from the past is considered finite, especially by environmental scientists. Already in 1972, the Club of Rome pointed out in its paper "Limits to Growth" that unlimited growth was impossible in a world with limited resources (Meadows et al., 1972). Today, the various impacts of resource depletion have been demonstrated manifold (International Resource Panel, 2017). The most pressing global challenges that will arise for humanity in the future, or that already exist, are above all

1. preserving of a diverse, efficient natural environment as a basis for life,
2. overcoming the high dependence on fossil raw materials and the associated climate change with its global consequences,
3. the care of a growing world population with increasingly ageing societies and
4. reducing the contradictions between economic growth and sustainability (BMBF, 2014).

The goal of using the earth in the future in such a way that all countries of the world receive equitable development opportunities and without thereby diminishing the development opportunities of future generations (Vereinte Nationen, 2015a) was already adopted by the United Nations (UN) in the Declaration of Rio de Janeiro in 1992 (Vereinte Nationen, 1992). As a result of this declaration – in response to increasingly complex global challenges – the *Sustainable Development Goals* (SDGs) were ratified in autumn 2015 (Vereinte Nationen, 2015b), which apply to all states and are to be implemented by 2030. The 17 goals and 169 subgoals underpin the guiding vision of sustainable development in a comprehensive way, even if they have not yet been fully differentiated and are sometimes contradictory (Pfau et al., 2014). They form a globally agreed framework that includes the resource base as well as society and the economy in their development opportunities (■ Fig. 1.1) Although the living conditions (life expectancy, water scarcity, economic growth, poverty, etc.) of many people have improved significantly globally in the last decade,[1] the global challenges for a sustainable economy are more precarious than ever before. The Global Footprint Network calculated that the time span in which globally available resources are consumed for the year has shortened by 1–6 days every year since 1987, and in 2018 fell on August 1 (Mosbergen, 2016).

To overcome the challenges, the many smaller drivers must be turned – in the right direction and in a coordinated interplay. This requires both keeping an eye on the big picture and activating the right adjust key levers. To stay in the technical picture: The engine room of the transformation towards a sustainable society is a complex system that must be kept in view as a whole, but also adjusted in the right places. It is a space in motion, in which not only adjustments and controls are made, but in which the system is also constantly being rebuilt so that something fundamentally new emerges.

This is our motivation for writing this book: We want to outline the bioeconomy as a system, using Germany as an example, in terms of its opportunities and risks for meeting the global challenge, but also to shed light on the subsystems that set the necessary wheels in motion with their various achievements, and expectations. We want to organise the vast amount of information on bioeconomy, make it understandable for dif-

1 For more information see: ► https://ourworldindata.org/

Fig. 1.1 The United Nations (UN) Sustainable Development Goals. (Source: Vereinte Nationen, 2015c)

ferent actors, and thus reduce the "impenetrable" complexity so that development perspectives become clearer. System knowledge is the crucial prerequisite for shaping a sustainable bioeconomy.

1.2 Bioeconomy as an Opportunity for the Future

The constant emergence of new life, the interaction with nature and the balance of biological processes are the central basis for human existence. The natural balance has provided these over millions of years. Using these principles of living nature as a model for human economic activity is seen as an important approach to dealing with global challenges (Biodiversity in Good Company, 2016).

Looking at biological processes in detail, a comprehensively better understanding has also developed over the past centuries and especially in recent decades: Genetics, biotechnology and material sciences now offer the possibility not only of replicating natural processes, but also of developing them further, thus opening up a wider view of the contribution that the natural balance can make to solving global challenges.

The idea of the bioeconomy is located precisely in this area of tension. Even if the term "bioeconomy" is used in different ways (Infobox: What Is Bioeconomy?), at least the more comprehensive definitions include an important element of social change towards a sustainable economy. The bioeconomy is generally based on natural cycles and the claim that these should be preserved in the interests of environmental protection and resource conservation (Berger, 2018).

Accordingly, the bioeconomy should not be understood as a branch of industry, but rather as evidence of a rethinking process towards a "green economy", which should be complemented by other important elements (Bioökonomierat, 2019): If sustainable management of the natural resources water, air and soil, the protection of biodiversity and the consideration of social aspects are included, the bioeconomy can contribute to climate protection, resource conservation and global food security.

Fig. 1.2 Opportunities and risks of the bioeconomy. (Source: Own representation)

The opportunities arising from the concept of the bioeconomy are aimed at different fields of action (Fig. 1.2):

- The secure nutrition of a growing world population requires both the continuous further development of existing agricultural production and the development of new production systems, for example for the provision of proteins from aquacultures, algae, insects and other raw materials or the establishment of production systems in growing cities *(urban farming)*.
- The substitution of fossil raw materials is a central challenge for achieving the internationally agreed climate protection targets. Biological building materials, but also bio-based chemical products produced in biorefineries, are considered important fields of action here. Energy from biomass can substitute fossil fuels, but is limited by the amount of biomass available, so that widespread use will not be possible. Appropriate use of biomass as an energy source should therefore be targeted, for example to close material cycles or supply gaps in a sustainable energy system.
- New, smarter products and processes offer opportunities for innovation and competitiveness. Materials with improved properties compared to those made from petroleum or concrete can, for example, enable less material-intensive and at the same time more durable construction. In medicine and pharmacy, therapies and active ingredients that are individually tailored to the individual person achieve greater healing success than products that have been commonly used to date. However, much of the potential for innovation still lies in the dark: For example, only a very small proportion of the estimated several hundred million species of microorganisms living on earth have been classified (Kallmeyer et al., 2012).
- The sustainable production and processing of biogenic resources also offers the opportunity to maintain jobs in rural areas or to create new decentralised value chains. As the past has shown, this requires not so much technical innovations as new organisational and social concepts.
- The bioeconomy can serve as a building block for "green growth" if the larger material cycles are designed accordingly. Recycling and circular economy form important elements here. The bioeconomy, which is oriented towards natural material budgets, also requires a reduction in consumption and a change in consumer behaviour (Grefe, 2016). This requires the necessary changes in the attitudes of each individual.
- The bioeconomy is particularly dynamic due to its speed of development – currently in the field of industrial biotechnology and genetics. This can be illustrated, for example, by the development of the cost of genome sequencing.

The increase in performance and reduction in costs is much faster than in the case of Moore's Law, which described the speed of doubling of performance in the IT industry in its establishment phase (Schaller, 1997). In 2006, genome sequencing cost about US$14 million; in 2015, it cost only US$1500 (Thrän & El-Chichakli, 2017). In the short term, a further reduction in cost to US$100 is expected (Ropers, 2018). It is widely assumed that with the help of biotechnology and information technology, technical developments will become possible in the coming years "that are beyond the imagination of previous generations" (Fritsche and Rösch 2017 in Berger, 2018, p. 7; Harari, 2018; MPG, 2019).

In line with the potential and the challenges, bioeconomy strategies have been adopted not only in Germany (BMBF, 2010), but also in many countries in recent years (Fig. 1.3).

While in many parts of the world the potential for innovation is seen as unreservedly positive, not least because of these prospects for new markets (Zinke et al., 2016), there is also considerable criticism of the bioeconomy, particularly in Germany and the European Union, which addresses a whole range of risks:

- The use of plants and their products in a wide range of applications entails conflicts over biomass and the land needed to provide it. Species loss and soil degradation are the consequences of intensive agricultural production worldwide.
- Restrictions on the distribution of and access to land and food also pose considerable risks, as the so-called "plate-or-tank" debate in the 2000s showed. At that time, political incentives in many countries simultaneously propagated and promoted the cultivation of energy crops, especially palm oil and maize, for biofuel production. Because there was a simultaneous increase in demand for food, world market prices for agricultural products rose dramatically within a short period of time. Even if the actual effects on food security are disputed, the image of starving people next to the fuel

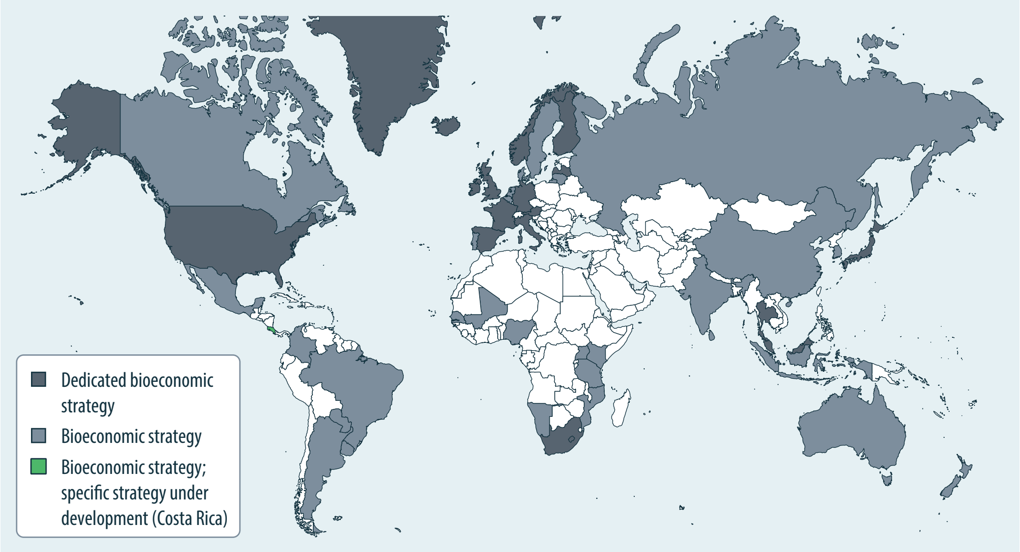


Fig. 1.3 Overview of adopted bioeconomy strategies around the world. (Source: Own representation)

cap of a high-priced car has consolidated the impression of ethically unjustifiable competing uses.

- The possibilities of targeted modification of the genetic material of microorganisms, plants and other organisms using molecular biological tools *(genome editing*[2]*)* have significantly changed the breeding of crops and the conversion of their products. Many biotechnology processes were made possible in the first place. Newer techniques – in particular CRISPR/Cas[3] – have enormous potential for development and application, as they are less complex and more precise to use than previous methods, and their application is associated with considerable time and cost savings. It is foreseeable that this technology will decisively shape, multiply and accelerate the transformation process towards a bioeconomy. The central question of the twenty-first century will be how the economy and society can best face these developments regionally, when this technology will change our entire agricultural and bioproduction systems (and possibly also ecosystems) worldwide and thus affect all areas of social life. *Genome editing* already triggers moral questions of great significance. For example, the use of the biological information of the individual person carries the risk of endangering individual fundamental rights. The question of how to deal with personal genetic information has not yet been decided in society.
- The consistent exploration and exploitation of biological principles and processes also harbours further social dangers of a comprehensive economisation of nature. The sequencing of genes as the basic building blocks of life and their release for commercialisation through patenting are described as a revaluation of all living things into the raw material "biomass", which subjects life to short-term profit targets and thus represents a continuation and expansion of the system oriented towards quick profits (Gottwald & Krätzer, 2014).

Given the range of expectations, it is not surprising that extensive and contradictory interactions are seen between the SDGs and the bioeconomy. In Germany, stakeholders from science, business and civil society interested in the bioeconomy expect the bioeconomy to contribute above all to "No Hunger" (SDG 2), "Clean Water and Sanitation" (SDG 6), "Responsible Consumption & Production Patterns" (SDG 12), "Climate Protection Measures" (SDG 13) and "Sustainable Development" (SDG 13). "production patterns" (SDG 12), "Climate action" (SDG 13) and "Life under water and on land" (SDGs 14 and 15) are unanimously rated as very important, while opinions differ significantly, for example, on "No poverty" (SDG 1), "Affordable and clean energy" (SDG 7) and "Industry, innovation and infrastructure (SDG 9)" (Zeug et al., 2019).

The diverse interactions with the SDGs also point to a central area of tension. Actors in the most diverse areas of life are involved with the bioeconomy: Bioeconomy is understood in the context of agriculture, forestry, microbiology, the marine economy and their respective products, but also as part of waste management, energy management and digitalisation.

2 We understand this term here as a collective term for the application of new molecular biological tools (such as zinc finger nucleases, TALEN and CRISPR/Cas. See also: ▶ https://www.dialog-gea.de/de/themen/inhalte and ▶ https://de.wikipedia.org/wiki/Genome_Editing

3 For more information, see: ▶ https://www.mpg.de/11018867/crispr-cas9

In the system, different actors interact in the various economies or economic sectors. They base their actions on their respective achievements and expectations – and this can lead to tensions, but it can also inspire them: In order to seize the future opportunity of the bioeconomy, it is precisely these sectors and actors that must interact in an appropriate manner, i.e. turn the adjusting screws described in the previous chapter. The second part of this book is therefore devoted to a systemic view of the sub-sectors of the bioeconomy.

However, looking beyond the experts' horizons also provides a very different picture: In the past, according to survey results from 2013 (IfD, 2013), the majority of Germans were unaware of the concept of the bioeconomy (Bioökonomierat, 2013). More recent surveys are not available, but there is little evidence that the picture has fundamentally changed. To date, there is a lack of clear visions or guiding principles of what a bioeconomic future should look like. For example, although the European Union's 2018 revised strategy aims to take a comprehensive view of the bioeconomy in a healthy environment and also to pay attention to urban and rural environments, it still does not include concrete targets or transformation pathways (EC, 2018). The new national bioeconomy strategy also has a similar tenor. Public dialogue and discourse events are rare and critics describe the bioeconomy as a smokescreen (denkhausbremen, 2018). Recent research among actors in the forestry and timber sector also found that there is a great deal of uncertainty about what future developments will look like (Stein et al., 2018).

Nevertheless, the bioeconomy is developing – driven by actors and in regional cooperations – with different motivations and fields of action across the economies. We dedicate the third part of this book to these movers and organisational forms of the bioeconomy in Germany.

What Is Bioeconomy?

Bioeconomy is derived from the terms bios (life), oikos (house) and nomos (law). As a principle, the term was first used in the 1960s by Zeman (Bonaiuti, 2014), who used it to highlight the biological basis of almost all economic activities. Another genesis of the term is described in connection with the discoveries of genetics in the late 1990s and the associated expectation of a comprehensive revolution in the industrial sector.

Today, the Bioeconomy Council of the German Federal Government defines the bioeconomy as the production and utilisation of biological resources (including knowledge) to provide products, processes and services in all sectors of trade and industry within the framework of a sustainable economy (Bioökonomierat, 2019). It identifies agriculture and forestry, the energy industry, fisheries and aquaculture, chemicals and pharmaceuticals, the food industry, industrial biotechnology, the paper and textile industry, and environmental protection as important fields of application. In its economic breadth, its consideration of the most diverse uses and future needs, this definition represents a comprehensive (systemic) claim. This is why we follow it in this book – both in the overall consideration of the bioeconomy in Germany and in the presentation of individual aspects.

In addition, there are many other definitions that span between this broad definition and a much narrower understanding of the further development of industrial biotechnology. The term "bio-based economy" is often used synonymously.

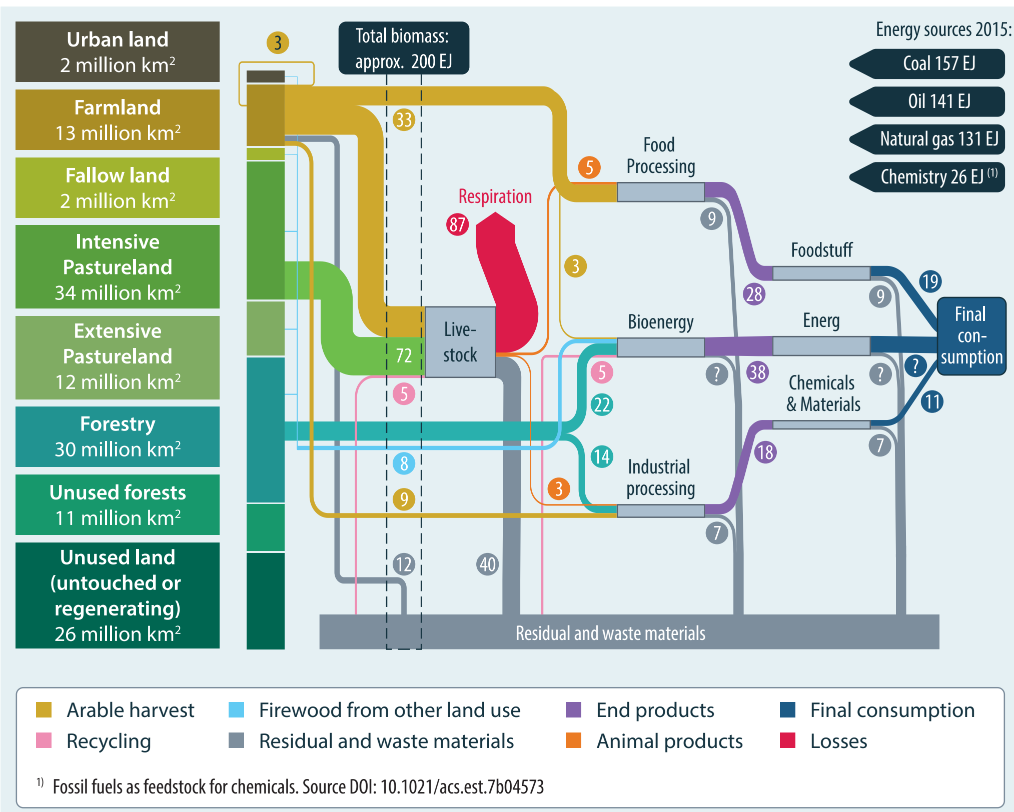
The term "biological transformation" (biologisation) is a collective term for the increasing integration of principles of nature into modern economic sectors, or the development of products or solutions to problems, driven by the knowledge gained in the life sciences and especially biotechnology. For example, there is talk of the biologisation of the economy, the biologisation of industry or the biologisation of technology.

1.3 The Resources of the Bioeconomy

Land, biomass, microorganisms, technologies, knowledge, etc. form the resources of the bioeconomy. They are provided by nature again and again or can be generated by closing the loop at the end of human use. Both elements together form the resource base.

Biomass is traded as a raw material in a wide variety of processing stages and is also frequently imported into Germany. A national consideration of raw materials always remains incomplete. ▪ Figure 1.4 therefore provides an overview of land use and global biomass flows utilised by humans. The data shown are from the year 2000, as no more recent consistent balances are available. The total amount of biomass harvested has increased since 2000; however, the overall picture, particularly with respect to land use and the magnitudes and relations of fluxes to each other, should still be essentially valid (Angerer et al., 2016).

Three quarters of the global land area – with the exception of Greenland and Antarctica – is already used by humans (Erb et al., 2017). The still unused land areas consist on the one hand of unproductive soils such as deserts, and on the other hand of the last untouched primeval forests. Additional land areas can and should therefore largely not be cultivated (Angerer et al., 2016).



▪ **Fig. 1.4** Flow chart of harvested global biomass fluxes in exajoules per year for the year 2000. The left column illustrates the use of global land areas. (Source: Own representation, based on data from Angerer et al., 2016)

A total of 235 EJ/year of biomass is harvested globally by humans (Zeddies & Schönleber, 2014). Half of this amount consists of crops grown on arable land, half of which is used as livestock feed. The harvested biomass further includes one third grasses consumed by livestock and one sixth wood. Thus, a total of 135 EJ, i.e. more than half of the total biomass used, is used to feed livestock. Of this, in turn, only 5 EJ (4%) enter the human diet in the form of animal products. The rest is consumed by the animals or ends up as a waste product (Angerer et al., 2016).

These figures show the strong influence of dietary habits on current and future land requirements for food production. For example, a purely plant-based diet could feed about twice as many people worldwide from the same amount of land as today.

Agricultural land would be freed up for bioenergy production or other uses. For example, if meat consumption were halved, biofuel production could increase by 7.7 times, which would curb 14% of greenhouse gases in the transport sector (Zech & Schneider, 2019). However, in light of population growth and rising demand for animal foods in populous countries such as India and China, the Food and Agriculture Organisation of the United Nations (FAO) projects that global agricultural production will need to increase by 60% by 2050 compared to 2005 levels (Alexandratos & Bruinsma, 2012).

Figure 1.4 also shows that less than half of the harvested biomass (86 EJ/year) reaches humans in the form of food, energy sources, chemicals and materials. Much of the residues from crop and wood harvesting remain in the field or forest and contribute, among other things, to the natural fertilisation of the soil, humus formation and the preservation of biodiversity (for example, deadwood beetles) (IEA, 2017). Usable residues and waste materials are generated during harvesting and further processing of biomass, but also during or after use (Angerer et al., 2016). For example, consumers in Germany throw away about 70–90 kg of food per inhabitant per year (Kranert et al., 2012). At the same time, a comparable amount of used and waste wood is produced at the end of the use phase, which can be reused in use cascades (Umweltbundesamt, 2019).

The figures show impressively that biomass use by humans in the big picture has so far been little cycle-oriented and resource-conserving. However, there are already successful niche products: Phosphorus is one of those substances whose occurrence is very limited, but which is of great importance for soil fertilisation and food production. Microorganisms enable the recovery of phosphorus from sewage sludge. For example, in a waste water treatment plant operated by Berliner Wasserbetriebe, phosphorus compounds are biologically extracted from municipal wastewater with the help of microorganisms and then crystallised using a chemical-physical process. The resulting recycling product is called magnesium ammonium phosphate (MAP). Wasserbetriebe also sells it as a long-term mineral fertiliser at a low price to farmers or small customers under the brand name "Berliner Pflanze" (Berliner Wasserbetriebe n.d., in Thrän & El-Chichakli, 2017). To conserve resources, future approaches to develop nutritious, tasty and healthy food alternatives can make an important contribution. One example lies in the development of other protein sources such as plant-based egg, milk and meat substitutes, foods made from fungal or insect proteins, or lab-grown meat (Bioökonomierat, 2015).

Also, the comparison of biomass and fossil material flows clearly shows that it is unsustainable to supply our current economy entirely with biomass: the total biomass harvest of 235 EJ/year contrasted with fossil fuel consumption of 440 EJ/year in 2000, which increased to 550 EJ/year by 2015 (Our Finite World, 2018).

The comparison of material flows provides an assessment of the resource availability, efficiency and substitution potential of the bioeconomy. However, material flow analyses have the representation problem that small material flows with a high value creation potential are difficult to identify, and thus the opportunities arising from a very raw material-efficient use of biomass are easily overlooked. Biological knowledge is naturally not included in the analyses.

A sustainable bioeconomy – so the conclusion – must therefore understand the limited resources as a starting point and push technical and social innovations with strong emphasis in order to conserve resources, close cycles and at the same time meet the needs of a growing world population. The description of possible innovations and their chances of realisation are therefore a central element in the coming chapters. The process principles on which they are based are presented in the following chapters.

1.4 Process Principles of a Knowledge-Based Bioeconomy

Metabolic activities of various organisms are the starting point for life on our planet, for microorganisms, plants, animals and humans. Natural *photosynthesis* represents a central metabolism: Plant cells use solar energy to convert CO_2 from the air together with water into oxygen and hydrocarbons. The latter form the basis for plant growth: Roots, stems and stems, leaves, flowers and fruits are formed (biological synthesis) as well as the transport of nutrients, information and defense substances is organised. Because the plant has to fulfil a wide variety of tasks, energy production from sunlight is only carried out to the extent necessary. The effectiveness of photosynthesis in relation to the total sunlight falling on the earth is less than 3%. More than 5.5% are never reached (Chemie Lexikon, n.d.). Photosynthesis forms a central basis for all process principles of the knowledge-based bioeconomy by providing plant-based hydrocarbons (◘ Fig. 1.4).

Humans, like many other living creatures, use the hydrocarbons of plants for their own metabolism – as an energy supplier. Because sunlight only produces a good mood and/or possibly skin irritations. And humans are also choosy about plant biomass: they can only digest and use fruits and seeds as well as selected leaves and roots. Straw, husks and wood are not usable energy suppliers. Unlike many other creatures, however, man has understood over thousands of years how to cultivate plants and how to reproduce the desired characteristics in plants through *breeding*. The beginning of the cultivation of plants and thus also of plant breeding began about 12,000 years ago in Mesopotamia (today mostly Iraq) with barley (Pflanzenforschung Lexikon, n.d.). Einkorn, a type of primordial wheat, bears 500 g of grain on 1 kg of straw (Konvalina et al., 2014). Today's wheat has more than 1.1 kg of grain on 1 kg of straw (Weiser et al., 2014). And with the new methods of *genome editing* (► Sect. 1.2), things may go much further: not only more grain to straw, but also more valuable ingredients such as vitamins and trace elements in the grain, lower susceptibility to pests and rapid ripening could make plant biomass an even more affordable human food.

Biomass is also constantly transformed in the natural cycle, both in the individual cell and the individual organism, but also along food chains: Biomass is eaten by insects, for example, which then serve as food for snails, which are on the menu of rodents, for example, etc. Metabolism is complex, but there are always very special structures that ensure a survival advantage for the individual species, for example, defensive substances against pests, special enzymes for wood decomposition in the digestive tracts of beavers or rubber-like substances in Caucasian dandelions that protect against frost damage (Global Bioeconomy Summit, 2018).

The list is arbitrarily long and much is still largely unexplored today. However, man began a very long time ago to extract, ferment and preserve these special ingredients and to use them especially in the fields of art, culture and medicine. Frankincense, for example, the air-dried gum resin from the frankincense tree, is considered one of the oldest remedies in the world. References to the use of frankincense can be found in three and a half thousand year old texts from the Nile Valley. The Egyptians used frankincense for ointments and wound treatment, but also for the mummification of pharaohs (Pfeifer, 2018). The processing of food with the help of certain microorganisms and enzymes, such as those contained in yeasts, has also been known for thousands of years (Biotechnologie.de, 2019b). For example, the tradition of brewing beer has already been proven in the Mesopotamian culture 6000 years ago (Hirschfelder & Trummer, 2016), and viticulture in the comparable period in Georgia (McGovern et al., 2017).

Biotechnology has developed from these approaches, using enzymes, cells and whole organisms in technical applications. Since the nineteenth century, modern biotechnology has increasingly drawn on microbiological findings and methods and, since the middle of the twentieth century, increasingly on molecular biological, genetic and genetic engineering findings and methods (Biotechnologie.de, 2019a). This has made it possible to develop manufacturing processes for chemical compounds, for example as active pharmaceutical ingredients, basic chemical substances, biosensors, diagnostic methods or new plant varieties (Biotechnologie.de, 2019b). Biotechnological processes can be applied in a variety of ways in different areas. In some cases, attempts are made to sort these processes according to areas of application, such as

- Medicine (Red Biotechnology),
- plants and agriculture respectively (green biotechnology) and
- industry (white biotechnology) (Kafarski, 2012).

In some cases, a distinction is also made according to the living beings to which the methods are applied, such as in blue biotechnology or yellow biotechnology, which refers to applications based on marine organisms or insects. The term brown biotechnology, which is used primarily to refer to waste management, is also used (ibid.).

In the 1980s, the combination of an ever better understanding of molecular biology and biotechnology made genetic engineering possible as a new field of technology. Its aim is to specifically modify the properties of organisms by interfering with their genetic material in order to achieve desired properties or products in a targeted manner. To this end, methods have been developed to transfer individual genes from organism A to organism B, for example. The first genetic modifications were realised in the USA in 1972 (Wu & Taylor, 1971). The cloned sheep Dolly was born in 1998 (Wilmut et al., 2001). With increasingly precise genetic engineering methods, tools for so-called *genome editing* have been available since the mid-2000s (Chandrasegaran & Carroll, 2015). With the aid of special enzymes (so-called designer nucleases), it is possible to open the DNA at specific target sequences and, for example, to remove, exchange or add gene sequences there. Applications of genetic engineering and *genome editing* are already being used in important areas of biotechnology (e.g. white biotechnology, green biotechnology, red biotechnology) (Sampson & Weiss, 2013; Voytas & Gao, 2014; Laible et al., 2015).

The synthetic biology approach uses the tools of *genome editing,* but goes beyond intervention in existing organisms. It is a field at the interface of molecular biology, organic chemistry, engineering, nanobiotechnology and information technology.

The goal is to create biological systems at the level of molecules, cells and organisms that do not occur naturally and that possess novel properties (EC, 2005). Different strategies are being pursued: On the one hand, artificial, biochemical systems are integrated into organisms, which thereby acquire new properties; on the other hand, chemical systems are gradually constructed in accordance with biological models in such a way that they exhibit certain properties of living organisms (biomimetic chemistry). Other approaches aim to reduce organisms to the most essential system components (minimal genomes), which serve as a kind of "scaffolding" to create biological circuits by incorporating so-called *bioparts* (ibid.). What both approaches have in common is that they aim to create complete artificial biological systems – an intervention in the natural system that clearly goes beyond the previous considerations of genetic engineering. Synthetic biology approaches are also used to develop mechanisms for artificial photosynthesis. This can significantly exceed the efficiency of natural photosynthesis and thus offers very high innovation potential for the production of hydrocarbons. However, their development is still at the basic research stage (Fischer, 2017).

Finally, the oldest cultural technique of man is biomass combustion for the generation of heat. Until about 200 years ago, it was the main source of energy for humans for millions of years (Goudsblom, 1992). However, it was – and in some developing countries still is – not particularly effective in providing energy in open fireplaces: less than 10% of the heat from an open fire actually reaches the inside of the cooking pot. Process engineering developments have also made it possible to achieve better efficiencies in the bioenergy sector, to expand the products into electricity, heat and fuels and other products. Also, today, not only thermal processes are used to convert biomass, but also fermentation and digestion processes as well as chemical processes. The principle of the biorefinery developed from this is comparable to that of a petroleum refinery, in which the complexly composed raw material petroleum is separated and processed into individual fractions (methane, petrol, diesel, kerosene, etc.), which can be used as fuel, energy or chemical raw materials (Grühling, 2013). Depending on the regional boundary conditions and the biomasses used, very different biorefinery concepts can be realised (Lindorfer et al., 2019). First biorefineries are based on the conversion of biomasses containing sugar, oil and starch into bioethanol, among others. Lignocellulosic biorefineries that process straw and wood, green biorefineries and refinery concepts based on algae are still at the pilot stage (Lamers et al., 2016; Pietzsch, 2017).

After thermal conversion to heat and energy, the biomass is converted back into the initial product CO_2. CO_2 forms the basis for new photosynthesis. However, due to the additional emission of CO_2 from the combustion of fossil hydrocarbons, the natural system is disturbed. New considerations on the processes of the knowledge-based bioeconomy therefore go beyond the elements in ◘ Fig. 1.5: permanently removing CO_2 from photosynthesis from the atmosphere could help to keep global warming within the maximum two degrees Celsius agreed in Paris. One option is to capture carbon dioxide in bioenergy plants and store it permanently underground (BECCS) (Angerer et al., 2016).

The products of the bioeconomy fulfil a variety of functions in our society. On the one hand, they satisfy the basic needs of food, clothing, housing and communication and, on the other, they provide the basis for the further development of fundamental knowledge and increasingly existential options for shaping the environment. Under the claim of sustainability, however, the benefits of the bioeconomy must go beyond