Tracking the Evolution of the European Bioeconomy

Maximilian Kardung

Propositions

1. The rate of change of an indicator is more important to policymakers than the level of the indicator.
(this thesis)

2. Income inequality is overlooked as a driver of bioeconomy development in scientific research.
(this thesis)

3. Policymakers want incomplete datasets that quantify progress toward policy objectives.

4. Economists are especially prone to optimism bias regarding climate change impacts because of their belief in rational behavior and technological change.

5. A Ph.D. candidate's dependence on others to conduct research is unrelated to the candidate's ability to gain a doctorate.

6. Researchers working on climate change who fly to conferences prove that individual behavior is not the way to reduce greenhouse gas emissions.

Propositions belonging to the thesis, entitled

Tracking the Evolution of the European Bioeconomy - From Devising a Conceptual Framework to Using Novel Indicators

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Tracking the Evolution of the European Bioeconomy

From Devising a Conceptual Framework to Using Novel Indicators

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Thesis

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CHAPTER 1

General Introduction

1.1. BACKGROUND

European countries have likely overshot their nitrogen, phosphorus, and land system boundaries and emit decreasing but still vast amounts of greenhouse gases (European Environment Agency, 2021; European Environment Agency & Federal Office for the Environment FOEN., 2020; Häyhä et al., 2018). Heatwaves in Europe in 2018, 2019, 2020, and 2022 and an increasing trend of heatwaves since the 1970s have heightened the urgency of tackling climate change (Zhang et al., 2020). Additionally, biodiversity loss and the accompanying ecosystem services have become increasingly evident (IPBES, 2019; Leclère et al., 2020). However, European countries can still steer away from this unsustainable pathway and avoid the severe consequences of climate change and biodiversity loss (Dasgupta, 2021; IPCC, 2022). Their policymakers strive to transform their fossil-based economies and steer them onto a sustainable path by using their natural resources differently (European Commission, 2018b). Keeping track of this path is challenging because it affects many economic sectors, societal aspects, and environmental systems and requires novel, sophisticated approaches and indicators.

One opportunity for a society is to transition towards a bioeconomy, which entails all economic sectors and systems linked to biological resources and their functions and principles (European Commission, 2018b). A bioeconomy in the European Union (EU) could tackle economic, environmental, and social problems if the transition from a fossil-based economy is realized properly (O'Brien et al., 2017). Policymakers have stated that safeguarding sustainable land use and preserving natural capital in the bioeconomy can contribute to sustainable development. This contribution could be achieved by reducing the use of raw fossil materials in order to mitigate climate change, forming new value chains to promote economic growth, and creating jobs in rural areas (European Commission, 2018b). Notably, the transition to a bioeconomy involves the sustainable use of natural resources, high expenditures on research and development of new technologies, and education for new and restructured jobs (Purkus et al., 2018). Policymakers have the power and tools to steer this transition efficiently and sustainably.

The EU has an extensive policy framework with multiple interlinked strategies to reach the Sustainable Development Goals (SDGs) of the United Nations (UN) (European Commission, 2019b). A crucial part of this framework is the European Green Deal, a set of policy initiatives with the aim of making the EU climate neutral by 2050. These initiatives could influence the development of the bioeconomy and vice versa (Palahí et al., 2020), and they are strongly linked to the objectives of the EU Bioeconomy Strategy. The Circular Economy Action Plan, the European Industrial Strategy, the Farm to Fork Strategy, the Biodiversity Strategy for 2030, and New EU Forest Strategy for 2030 are some of the most intertwined policies (European Commission, 2022a).

With regard to bioeconomy policies, the 2012 EU Bioeconomy Strategy constitutes an initial attempt to promote the bioeconomy's development. The 2018 EC Bioeconomy Strategy Update both confirmed that the bioeconomy is high on the political agenda and proposed an action plan with 14 concrete measures (European Commission, 2018b). In 2022, the European Commission (EC) published the EU Bioeconomy Strategy progress report, which identified positive developments and shortcomings of the strategy and action plan. The report found that more national and regional bioeconomy strategies have been implemented focusing on cross-sectoral cooperation and sustainability. The bioeconomy has been expanded in central and eastern European countries, and private investment, research, and innovation in bio-based sectors have increased. A gap in the strategy has been the alignment of ecological limits, e.g., land and biomass demands, with economic development. The strategy also found that greater understanding of promoting sustainable consumption is needed (European Commission, 2022a).

1.2. PROBLEM STATEMENT

The bioeconomy is a broad strategy tackling many different economic, social, and environmental challenges simultaneously (Wesseler & von Braun, 2017; Zilberman et al., 2018). There are tradeoffs with other policies as links between them increase, which makes objectives and elements more complicated. Consequently, as the EU aims to promote the bioeconomy and reach the UN SDGs by establishing an extensive police framework, it is crucial to track this process and its dynamics to ensure that resources are efficiently spent (Calicioglu & Bogdanski, 2021; Linser & Lier, 2020).

The development of the bioeconomy is driven by several forces, and knowing and understanding how these influence the bioeconomy is vital for measuring its development (Wesseler & von Braun, 2017). The bioeconomy has an inter-sectoral, (inter)national, and transdisciplinary nature, which is reflected in varying definitions and delimitations. How the term is defined and its activities delimited depends on stakeholders: scientists, policymakers, non-governmental organizations, or the private sector (Bugge et al., 2016). This ambiguity presents a challenge for measuring the bioeconomy, for which a clear scope is useful (van Leeuwen et al., 2015). Additionally, the bioeconomy has been linked with the circular economy, which can be described as an economy in which products and materials show a high degree of recycling, reuse, and reduction. The circular economy concept shares the rise in popularity of and can work complementarily to the bioeconomy (Carrez et al., 2017). Defining which sectors make up the bioeconomy allows us to identify the specific activities and industries that contribute to it and to track their growth and development over time (Heijman, 2016; Kuosmanen et al., 2020). Additionally, defining the sectors that comprise the bioeconomy can help in identifying potential gaps and overlaps in the existing framework and in developing more comprehensive, accurate measures of the bioeconomy. The Statistical Classification of Economic Activities in the European Community – from the French, Nomenclature Statistique des activités économiques dans la Communauté européenne (NACE) provides a starting point for defining which and to what extent economic activities belong to the bioeconomy. When setting up an indicator framework for the bioeconomy, the driving forces of its development, the scope of the societal objectives, and the specific statistical measures to quantify it are the most important pieces of information to have.

Governments and NGOs widely use indicator frameworks to track progress towards crucial societal objectives, but these frameworks are complex and come with pitfalls (Lyytimäki et al., 2020; Rinne et al., 2013; Sébastien et al., 2014). A prominent example is the UN SDGs, which include 231 indicators to measure progress towards 169 corresponding targets (United Nations, 2022). Researchers have pointed out the risk of overuse, non-use, and misuse of these indicators, which could affect the implementation of the SDGs (Lyytimäki et al., 2020). However, comprehensive, reliable, and user-friendly indicators can be used by policymakers to assess a desired development's current state and direction at the appropriate detail level and implement suitable policy actions. Society can use the same information to hold policymakers accountable for their actions (Biermann et al., 2022). A comprehensive framework has indicators that not only measure development and economic, environmental, and social impacts but also reveal tradeoffs between them (van Leeuwen et al., 2015). Such a framework would hence benefit from accommodating many well-defined quantitative indicators and finding patterns in their evolution (Lier et al., 2018).

When policymakers choose sectors they want to prioritize for the transition to a bioeconomy, they typically assess which sectors have the most potential for a sustainable transition. This potential can be related to, for example, a sector's value-added, its environmental impact, or its regulatory burden (Wesseler & von Braun, 2017). Consequently, when the European Council requested the EC to assess how each economic sector can best contribute to reaching the 2030 greenhouse gas emissions targets, environmental, economic, and social impacts had to be taken into account (European Council, 2020). The EC also presented the "Fit for 55" Package, which contains many legislative proposals to achieve the EU Green Deal. These changes in the legislation, such as in the revision of land use, forestry, and agriculture regulations, can be expected to also affect the bioeconomy sectors (European Commission, 2021).

Regarding bioeconomy development, there is still a knowledge gap between ecological limits and economic development(European Commission, 2022a). Research into the varying social costs and benefits of investing in bioeconomy sectors could address this gap and promote a sustainable, efficient transition. This weighing out relates to measuring sustainable economic development over time and, by that, going beyond macro-statistical analysis like gross domestic product (GDP) (Dasgupta et al., 2015). New frameworks measuring sustainable development include a range of aspects such as capital assets, manufactured goods, services provided by nature, health services, and the needs of future generations (Arrow et al., 2012). Due to its strong relationship with climate change and biodiversity, future rewards and costs of investing in the bioeconomy are uncertain. In addition, investments into the bioeconomy, such as certain forms of land use change or greenhouse gas emissions, are partially or entirely irreversible. Further, the timing for a transition towards the bioeconomy is flexible in that waiting for better future insight is generally possible, especially for novel activities that further process biomass. Considering these three characteristics of investments in the bioeconomy allows policymakers to promote sectors with low investment hurdles and high societal benefits.

Besides measuring the wide development of the bioeconomy, another challenge is quantifying and analyzing its individual aspects. Especially the food sector is a crucial part of the bioeconomy puzzle. While this sector is a conventional manufacturing activity, consumer demand has recently shifted toward new health, functional, and ethnic food, as well as different dietary alternatives and environmentally sustainable choices. This evolving consumer demand and the development of new technologies have led to increased innovation in the food sector in recent decades. When new foods enter the market, the EU regulates them under the novel food regulation (NFR) (European Commission, 2022b). The EC created the NFR within an extensive general EU food regulation. Its elaborate authorization procedure for novel foods (NFs) entails costs and benefits for society (de-Magistris et al., 2015; Lahteenmaki-Uutela, 2007). The innovation developments in this sector and the tradeoffs related to the regulation of new products have wide-ranging implications for the rest of the bioeconomy.

1.3. OBJECTIVE, RESEARCH QUESTIONS, AND METHODS

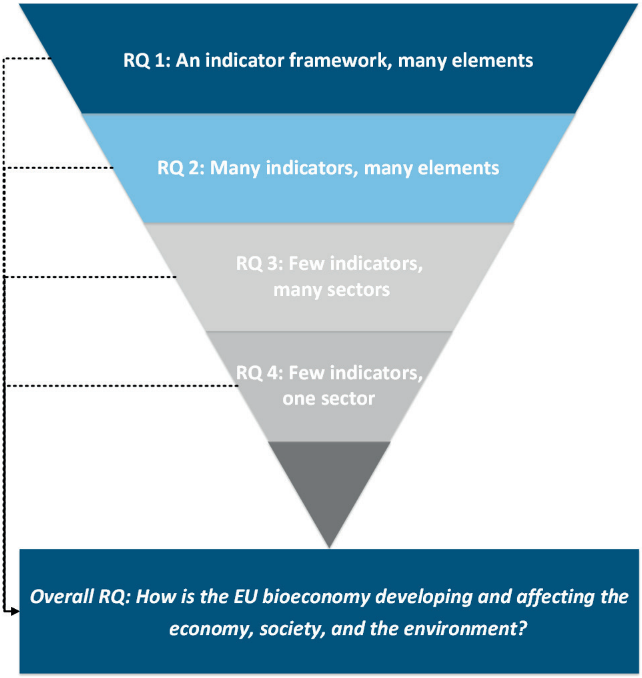
The previous section described the development of an EU bioeconomy as a multi-layered endeavor that can be analyzed from various angles. The objective is to investigate the development of the EU bioeconomy, starting from a broader and ending at a narrower perspective. The thesis begins by presenting a conceptual framework. Then, it empirically investigates how the bioeconomy is developing, assesses the sustainability of bioeconomy sectors, and finally analyses the relationship between regulation and innovation in the food sector.

This combination of angles and approaches allows the thesis to address the overall question:

How is the EU bioeconomy developing and affecting the economy, society, and the environment?

Chapters 2 to 5 of the thesis are based on four articles. These chapters address the following four research questions related to the topic introduced in the problem statement. Figure 1.1 shows the approach used to measure the EU bioeconomy as a reversed pyramid, reflecting the narrowing of the perspective from the first to the fourth research question. Each study contributes equally to addressing the overall research question while offering a different perspective on the bioeconomy.

Figure 1.1: Approach to investigating the development of the EU bioeconomy and its economic, societal, and environmental impacts.



Research Question 1: What is driving the development of the EU bioeconomy, and how can it be measured?

Knowing and understanding how different forces influence the development of the bioeconomy is vital for monitoring and for impact assessment. The focus on the bioeconomy in the EU is evident from the multitude of EU policy initiatives spearheaded by the European

Green Deal and from research programs such as the recent European Bio-Based Industries Joint Undertaking. Recently, the EC introduced the term 'circular bioeconomy' to intertwine bioeconomy and circular economy concepts and emphasize the use of a circular approach to the bioeconomy. Chapter 2 analyses the driving forces of the bioeconomy, grouping them into supply and demand drivers, resource availability, and government measures. A conceptual analysis framework for quantifying and analyzing the development of the EU bioeconomy is proposed. First, the scope of the bioeconomy framework in terms of bioeconomy sectors is derived by following the broad definition of the bioeconomy by the EC and reviewing previous monitoring studies. Then, a set of indicators based on stakeholder feedback and an examination of the literature is outlined. These indicators are subsequently linked to the objectives of the EU's bioeconomy strategy, and whether they measure social, environmental, or economic impacts is investigated. Finally, the chapter suggests several new indicators related to measuring the impact of changes in supply, demand drivers, resource availability, and policies on sustainability goals.

Research Question 2: What patterns can be found in the evolution of the bioeconomies of ten selected EU Member States?

Measuring the development of the bioeconomy requires quantifying a range of indicators to determine its impact on the economy, the environment, and society. Many indicators can measure various development characteristics of a trend, such as the transition from a fossil-based economy to a bio-based one. For example, there are 100 EU SDGs indicators, 232 UN SDGs indicators, and 1600 World Bank World Development Indicators. Chapter 3 devises a method that can accommodate any number of indicators when measuring a trend. The objective is to empirically investigate whether the circular bioeconomies in ten selected EU Member States (MSs) were progressing or regressing over the time frame of 2006 to 2016, as measured by 41 indicators. The chapter models the development of the intra-distribution of the indicators using by Markov transition matrices. These matrices were first used in the cross-country growth and income literature to investigate patterns in income distributions because conventional regression methods were not able to study the dynamics of evolving distributions (Quah, 1996). Later, many researchers adopted this approach to analyze trade-specialization patterns by estimating the intra-distribution dynamics of trade-specialization indices over time. For example, the intra-distribution dynamics of the Lafay index were analyzed, considering the difference between the exports and imports of 208 sectors (Zaghini, 2005). This chapter applies the same approach, but for many indicators instead of one. The examination of the intra-distribution of indicators allows a unique analysis of the dynamics of circular bioeconomies.

Research Question 3: How sustainable is the transition to a bioeconomy in the economic sectors of EU Member States?

Measuring the sustainability of the bioeconomy is crucial to evaluate its continuous contribution to societal wellbeing. The overall objective of the 2018 EU Bioeconomy Strategy is to ensure the "prosperity" of EU citizens, and measuring this objective is directly linked with measuring sustainable development. A good understanding of measuring sustainable development is crucial for deriving indicators for monitoring the bioeconomy that can quantify this link (Calicioglu & Bogdanski, 2021). Chapter 4 uses the genuine investment framework to assess the sustainability of bioeconomy sectors. Genuine investment can be expressed as the investments or disinvestments in each of a society's capital assets, where each investment is the product of the change in the quantity of the asset times the shadow price of that asset (K. Arrow et al., 2004). First, genuine investment, based on the seminal paper by Arrow et al. (2012), is introduced and subsequently advanced by explicitly including the concepts of uncertainty and irreversibility. The chapter then applies the framework empirically to the bioeconomy sectors of the EU-28 countries, measuring the sustainability of the transition to a bioeconomy. The hurdle rates for bioeconomy sectors are calculated from their value-added from 2005 to 2015. In investment analysis, a hurdle rate is the minimum rate of return on a project a manager or company is willing to accept before starting a project. In this chapter, a hurdle rate of 1.5, for example, indicates that the benefits of a bioeconomy investment project have to be at least 1.5 times larger than its irreversible costs to be considered sustainable. Additionally, reversible and irreversible costs and benefits of bioeconomy investments are estimated using bioeconomy value-added and greenhouse gas emissions as measures. This estimation allows calculation of the maximum incremental social tolerable irreversible benefit or costs a sustainable transition to a bioeconomy would entail. The indicator quantifies the irreversible costs that can be tolerated with the introduction of a bioeconomy investment project. The larger the value, the more sustainable the bioeconomy will be.

Research Question 4: How is the EU's novel food regulation developing and impacting innovation in the food sector?

The food sector is an important part of the bioeconomy and major technological innovations are expected to occur in it (Kristinsson & Jörundsdóttir, 2019). Consumer demand is shifting towards new health, functional and ethnic food, as well as dietary alternatives and environmentally sustainable choices due to demographic changes, globalization, and income changes (Belluco et al., 2017; Hermann, 2009; Marberg et al., 2017). Consumer demand evolved, and new food products surged into the market. Food consumption and food consumption changes can impact sustainability by reducing food waste, greenhouse gas emissions related to food consumption, and more (e.g., European Commission. Directorate General for Research and Innovation., 2021). The EU regulates new food products under the NFR. Such a regulation must balance safety, regulatory burden, and impacts on the sustainability of the food sector. The more NFs are approved, the more sustainable the food sector can be expected to become; if European consumers replace animal-source foods with these NFs, the environmental impacts might be reduced by more than 80% while meeting nutrition and feasible consumption constraints (Mazac et al., 2022). Chapter 5 empirically analyzes the development of the EU NFR authorization procedure from 1997 to 2020, investigating the number of applications, the duration of the authorization procedure, and the determinants of approval. A unique dataset was gathered from official sources of the EC. An empirical strategy using Bayesian methods is applied to address the shortcomings of the data. The yearly number of applications is modelled through a Bayesian hierarchical model, and the share of applications that received a decision within a certain period is assessed. Finally, the chapter applies a Bayesian logit model to assess the contribution of the new NFR and different applicants' characteristics on the probability that an NF is authorized.

The remainder of the thesis is structured as follows: Chapters 2 through 5 address RQs 1 through 4, respectively. Chapter 6 discusses the research findings, limitations, and policy implications.

CHAPTER 2

Development of the Circular Bioeconomy: Drivers and Indicators[1]

1 This chapter is based on the article: Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., van Leeuwen, M., M'barek, R., van Meijl, H., Piotrowski, S., Ronzon, T., Sauer, J., Verhoog, D., Verkerk, P. J., Vrachioli, M., Wesseler, J. H. H., & Zhu, B. X. (2021). Development of the circular bioeconomy: Drivers and indicators. Sustainability, 13(1), 1–24. https://doi.org/10.3390/su13010413

ABSTRACT.

The EU's 2018 Bioeconomy Strategy Update and the European Green Deal recently confirmed that the bioeconomy is high on the political agenda in Europe. Here, we propose a conceptual analysis framework for quantifying and analyzing the development of the EU bioeconomy. The bioeconomy has several related concepts (e.g., bio-based economy, green economy, and circular economy) and there are clear synergies between these concepts, especially between the bioeconomy and circular economy concepts. Analyzing the driving factors provides important information for monitoring activities. We first derive the scope of the bioeconomy framework in terms of bioeconomy sectors and products to be involved, the needed geographical coverage and resolution, and time period. Furthermore, we outline a set of indicators linked to the objectives of the EU's bioeconomy strategy. In our framework, measuring developments will, in particular, focus on the bio-based sectors within the bioeconomy as biomass and food production is already monitored. The selected indicators commit to the EU Bioeconomy Strategy objectives and conform with findings from previous studies and stakeholder consultation. Additionally, several new indicators have been suggested and they are related to measuring the impact of changes in supply, demand drivers, resource availability, and policies on sustainability goals.

2.1. INTRODUCTION

In the last twenty years, policymakers of the European Union (EU) have placed a high priority on a sustainable and circular (bio)economy with the aim to reduce the use of petrochemicals, to mitigate climate change, to reduce the dependency on imports of natural resources, and to promote local economies. This focus on the bioeconomy is evident from a multitude of EU policy initiatives, spearheaded by the European Green Deal, and research programs, including the recent European Bio-Based Industries Joint Undertaking (European Commission, 2019b; Wesseler & von Braun, 2017). Many bioeconomy strategies on a regional and national level have been developed, most of them in Europe, but also in the United States, South Africa, or Thailand. Those countries are also willing to intensively promote the development of their bioeconomies politically, using enabling policy means (Dietz et al., 2018). Where a designated bioeconomy strategy is missing, the governments have often addressed the topic in related strategies. One example is The Netherlands, where it is linked to the circular economy strategy (Ministry of Economic Affairs and Climate Policy, 2018). The recent EC Bioeconomy Strategy update (European Commission, 2018b) revalidates the objectives of the 2012 Bioeconomy Strategy, which are now accompanied by three main action areas: bio-based sectors, rural development, and ecological boundaries.

Further, the bioeconomy is seen as an important part of sustainable consumption and production, which gains importance on national, EU, and global levels (Knudsen et al., 2015). Sustainable development combines consumption and production and has three major dimensions: economy, society, and the environment. All three dimensions are addressed in the Sustainable Development Goals (SDGs) global framework, which was launched by the United Nations in 2015 and constituted a landmark in the push for sustainable development (Griggs, 2018). To measure the impacts of the bioeconomy on the three dimensions of sustainable development, a monitoring framework is considered crucial (D’Adamo et al., 2020b; O’Brien et al., 2017).

This chapter aims to outline the drivers of the circular bioeconomy based on an analysis of important relations within and outside the bioeconomy. Subsequently, the chapter derives the bioeconomy framework’s scope using definitions of the bioeconomy and set up an indicator framework to measure and monitor its development along with its social, environmental, and economic impacts. This study focuses on the EU and EU bioeconomy policies, but where appropriate references to methods and policies beyond the EU are made.

This chapter proceeds as follows: Section 2 shows how the bioeconomy works as a system’s approach, i.e., which driving forces influence the bioeconomy, what is the impact of the bioeconomy on societal challenges and what are the trade-offs. Section 3 presents various definitions of the bioeconomy, pins it down to related terms, and delimits it using a sectorial view. Section 4 reviews previous efforts on measuring and monitoring the bio-economy and subsequently presents the framework. Section 5 concludes on implications of the previous sections for our framework.

2.2. DRIVING FORCES AND RELATIONS WITHIN THE BIOECONOMY

The development of the bioeconomy is driven by a number of forces and knowing and understanding how they influence the bioeconomy is vital for monitoring and impact assessment (Vivien et al., 2019). Several studies (SAT-BBE, 2015b; Sheppard et al., 2011; Wesseler & von Braun, 2017) identified several major forces steering the development of the bioeconomy. We group these drivers as supply drivers (Sections 2.2.1, 2.2.2 and 2.2.3), demand drivers (Section 2.2.5), resource availability (Section 2.2.4), and the measures of governments to influence the development of the bioeconomy (Section 2.6).

2.2.1. Technology and Innovation

2.2.1.1. Advances in Biological Sciences

Advances in biological sciences are a major supply driver of the bioeconomy. One of the earliest advances was the fermentation of food products, whose underlying biological processes have been refined over the past thousands of years (Wesseler & von Braun, 2017). Following the first successful recombinant DNA experiments in 1973 by Paul Berg and others, commercial ap-plications of modern biotechnology started in 1982 (Nationale Akademie der Wissenschaften Leopoldina, 2019; Tramper & Zhu, 2012).

Today, a wide array of applications of biotechnology and bioengineering, alongside recom-binant DNA technologies, are used for improvements in food and feed sectors, bio-fuels, materials, chemicals, and pharmaceuticals (Wesseler & Zilberman, 2021; Yoshida, 2017). Genetic engineering is likely to play a key role in further developments of non-food ap-plications, but the use of modern biotechnology is not uncontroversial (Paarlberg, 2014). Policies related to the application of modern biotechnology can have wide-ranging impli-cations that need to be considered for assessing impacts (Smart et al., 2015, 2017; Venus et al., 2018; Wesseler et al., 2017). The debate on the use of modern biotechnology has been rekindled by the advent of so-called new plant breeding technologies (NPBTs) for gene editing and related regulatory issues. The regulatory status affects further advances of the CRISPR-based technologies, one of the most important gene-editing tools, as it may disincentivize in-vestments and bring companies to reallocate their research out of the

EU (Nationale Akademie der Wissenschaften Leopoldina, 2019; Wesseler et al., 2019). In a comparison of the worldwide CRISPR patent landscape by Martin-Laffon et al. (2019), it is already apparent that Europe is lagging behind the United States and China. Therefore, the development of regulatory measures is an important factor in the further advances in biological sciences.

Technological advances would not have been possible without investments in the bioeconomy. As outlined in the Updated Bioeconomy Strategy “By capitalising on un-precedented advances in life sciences and biotechnologies, as well as innovations merging the physical, digital and biological worlds, the European industrial base can maintain and enhance its global leadership.” (European Commission, 2018b, p.5). Investments are directly related to the level of research and development that takes place, which again determines the speed of advances in biological sciences and other technological advances relevant to the bioeconomy. An example is the 100 million euro Circular Bioeconomy Thematic Investment Platform, which the EU should deploy shortly (European Commission, 2018b); however, also funding from EC framework pro-grams and public–private partnerships between the European Union and, for example, the Bio-based Industries Consortium. It has formulated a Strategic Innovation and Re-search Agenda that describes the main technological and innovation challenges to over-come in order to develop sustainable and competitive bio-based industries in Europe. Re-search, Demonstration, and Deployment have been identified to meet the common EU goals in the bio-based economy.

To understand the effects of innovation and investment efforts in the bioeconomy, monitoring the impact of technological developments in natural sciences on the performance of the bioeconomy in achieving its objectives has been identified as being important (European Commission, n.d.). Furthermore, the regulatory environment (e.g., the EU legal framework for the application of genetic modification technology) is of relevance as it has a large influence on technological developments.

2.2.1.2. Advances in Information and Communication Technologies

Another important supply driving force related to innovation is the vast and in-creasing application of information and communication technologies (ICTs). Watanabe et al. found that in recent years the bioeconomy has taken major steps driven by digital solutions (Watanabe et al., 2019). Smart (digital) farming such as innovative precision farming uses extensively ICTs and is seen key for the development of a sustainable agriculture (Walter et al., 2017). The biosciences, and especially genome sequencing and analyses, produce significant amounts of data. Data storage and information analysis tools are vital enablers of bioeconomy innovations such as phenotyping, smart breeding, medical diagnostics, genome discovery and exploration, and therapy development. ICTs also move agriculture, forestry, and fishery management forward. The use of Blockchain technologies, for instance via a distributed data-base of records structured in encrypted smaller datasets, promise to improve agri-food supply chains (Antonucci et al., 2019). Agri-food supply chains usually involve a high number of intermediaries between producers and consumers. Blockchains can provide a higher level of transparency, efficiency, and guarantee traceability for all kinds of products such as coffee (Salerno, 2018), fish (Provenance, 2016), or milk (Dongo, 2018).

As ICTs improve, many technologies become more affordable, and their use spreads globally, including in developing countries. New developments allow detection of bio-based material content in consumer goods supporting labeling as well as tracking and tracing of bio-based materials along the supply chain. Their impacts on the bioeconomy and, therefore, on society, will gain in importance.

2.2.1.3. Other Technological Advances

Technological advances are obviously not limited to biological sciences and ICT only, as advances in other sectors also contribute to the development of the bioeconomy. For example, advances in wood construction technologies may increase the use of wood in construction. The use of wood in multistorey buildings has long been difficult and often limited to single-family houses or other small-scale buildings. Particularly, the development of engineered wood products, such as cross-laminated timber (CLT), allows for the increased use of wood in multistorey buildings (Näyhä et al., 2014; Tollefson, 2017). Due to these developments, the markets for engineered wood products—especially CLT –and the use of wood in construction are expected to develop rapidly over the next years to decades (Hurmekoski et al., 2018; UN, 2019). Innovations in the chemical industry have the potential to make the use of biomass more cost-efficient than the use of fossil-based raw materials. In the agriculture and food sector, major developments are already taking place. Vertical and indoor farming becomes possible by improvements in the lighting. Indoor aquaculture is making progress for the production of, e.g., seaweed. Meat substitutes make large progress in providing alternatives that are accepted by a majority of the population and are not a niche product anymore. A similar development can be expected with cultured meat, produced by in vitro cultivation of ani-mal cells.

Altogether, these technological developments are relevant for the bioeconomy and need to be monitored as well as investments in the chemical and wood-based industries. Furthermore, new bio-based materials and products have to be integrated into the standardized classification system and data collecting system.

2.2.2. Market Organization

2.2.2.1. Advances in Horizontal and Vertical Integration

Another supply driver is horizontal and vertical integration of bioeconomy supply chains that can influence the supply and demand on bioeconomy markets and impact the sustainability goals. Therefore, looking at the agricultural sector only and not considering the increase in up- and down-stream linkages with other sectors through different forms of contractual arrangements may create biases in policy analysis. Horizontal integration refers to the acquisition of a business operating at the same level of the value chain in a similar or different industry (Investopedia, n.d.). Through mergers and acquisitions or voluntary collabo-ration at the farm level, horizontal integration can change the market power of agents with economic and distributional effects along the value chain. Vertical integration refers to the process where different parts of the supply chain (e.g., growing raw materials, manufacturing, transporting, marketing, and/or retailing) are arranged for by a single company. It can be seen as a supply-side response to differentiate products and to reduce the potential decrease in producer rents that might result from an increase in product supply. Further integration of the value chain is also achieved by close partnerships between different companies, whereby an important enabling factor is advances in ICTs.

New bioeconomy value chains have emerged based on the increasing use of natural and renewable resources in non-food applications. A central link for these new value chains are bio-refineries, which have been defined as "a facility (or network of facilities) that integrates biomass conversion processes and equipment to produce transportation biofuels, power, and chemicals from biomass" (Cherubini, 2010). In the EU, about 800 biorefineries are running at a different level of maturity (i.e., commercial, demo, pilot, and R&D). However, this number does not include biogas plants, where in Germany alone there are around 12,000 (BNetzA Marktstammdatenregister, n.d.). The highest geographical concentration of biorefineries is in Northwestern Europe and agricultural resources are the most used feedstock [38]. However, the type of inputs and outputs of a biorefinery can vary widely. For examples, in a Kraft pulp mill biorefinery, a broad range of by-products, such as tall oil, turpentine, bioelectricity, product gas, sulphuric acid, and biogas can be produced from woody raw materials, and in a sugar or starch biorefinery, the main primary products are fermentable sugar and animal feed. The bio-refinery concept is an important part of the value chain of many bio-based products and has the advantage of operating at a much lower temperature, allowing for smaller units to be built in comparison to fossil fuel-based refineries (Clomburg et al., 2017). Nevertheless, the conversion of biomass can result in trade-offs that might be intensified by national and international bioeconomy policies (Choi et al., 2019).

2.2.2.2. Globalization

A further important driving force that influences the markets is globalization, which can be understood as "a process of interaction and integration among the people, companies, and governments of different nations, a process driven by international trade and investment and aided by information technology. This process has effects on the environment, on culture, on political systems, on economic development and prosperity, and on human physical well-being in societies around the world" (Levin Institute, n.d.). Globalization goes beyond the increase in international trade and vertical and horizontal integration. This process contributes to the harmonization of value chains and consumer attitudes around the world. Globalization also affects the geographic location of production and consumption of goods. For example, intensively managed forest plantations in the southern hemisphere are replacing boreal and temperate forests as a source of raw material (Hurmekoski et al., 2018). Furthermore, the consumption of packaging paper and paperboard is shifting from North America and Western Europe to emerging countries such as China, and these shifts are linked to changes in the location where goods are manufactured (Hetemäki & Hurmekoski, 2014).

The pervasive forces of digitization and globalization of the socioeconomic system change the framework condition of the bioeconomy. Standards for biorefineries and bio-based products can be expected to be increasingly harmonized and foster positive externalities by reducing approval costs and length and trade disruptions caused by asynchronicity in product approval (Purnhagen & Wesseler, 2021). Examples are related to the labeling of food, feed, and other bio-based products (Venus et al., 2018). This implies trade in products and innovations related to the bioeconomy as well as the regulatory environment at the international level needs to be monitored.

2.2.3. Increase in Importance of Climate Change and Pressure on Ecosystems

Climate change is a particularly complex driving force in the context of the production of biomass for the bioeconomy. On the one hand, it is a major challenge for the agricultural and forestry sectors because a change in climatic conditions as well as more extreme weather events will affect forest and crop growth and wood production (Lindner et al., 2010). Climate change also increases uncertainty in these sectors and can potentially cause market disruptions (Challinor et al., 2017). The development of the bioeconomy is considered to reduce emissions and to mitigate climate change, as the use of biological resources, such as wood, manure, food waste, and algae, for producing materials and energy is generally considered to reduce emissions compared to fossil-based, emission-intensive products. Furthermore, the bioeconomy could offer an opportunity to develop new value chains, which could attract private and public investments into improved management practices that could increase the resilience of forests to climate change (Verkerk et al., 2018). The use of new breeding technologies pro-vides tools to develop crops that are suitable for a wide range of micro-agroclimatic conditions much faster and thereby can respond to climate change more effectively. Bio-based products typically have much smaller carbon dioxide (CO2) footprints compared to functionally-equivalent products made from fossil-based or fossil-intensive materials (Leskinen et al., 2018; Spierling et al., 2018). However, bio-based products may have greater water, eutrophication, and land-use footprints (Spencer et al., 2017) and bio-based products may not always be more environmentally friendly or more sustainable than fossil-based products.

2.2.4. Resource Availability

A variety of resources are needed to fuel the economy such as land, water, air, or skilled labor. The most important resource for the bioeconomy is biomass, either domestically produced or imported. Besides the quantity, also the type and quality of available biomass are important. Biomass can originate from agriculture, forestry, marine environment, and waste. The biomass is then used as food or feed, but also to produce bioenergy and bio-based products. Different uses require different types of biomass. The majority of experts consider the competition of biomass for food and non-food use an important conflict that needs to be addressed by bioeconomy strategies (Issa et al., 2019). A large future potential lies in waste biomass, especially agricultural residues and food waste. Monitoring the flow of biological and other materials within the economy provides information about the potential availability and current stream of biomass (Van Berkel & Delahaye, 2019). Such monitoring can be used to measure resource efficiency, resource dependency, production of solid waste and recycling, pressure on the environment, and footprints (Capasso & Klitkou, 2020; D'Adamo et al., 2020a).

2.2.5. Demographics, Economic Development, and Consumer Preferences

The strong world population growth is another important determinant on the de-mand-side. Naturally, a growing population leads to an increase in demand for all kinds of products. For example, the pressure on cropland use further expands due to a higher demand for non-food biomass that is induced by the evolution towards a bioeconomy. The increasing competition for cropland happens at the expense of shrinking grasslands, savannahs, and forests, primarily in tropical countries (Bringezu et al., 2009), and potentially leads to bio-diversity losses and greenhouse gas emissions. Next, a shifting consumer demand based on the awareness of the need to ensure sustainable production and consumption is expected to be a major factor driving future markets in the EU. For example, rising aware-ness on environmental issues like climate change and plastic pollution could lead to a change in consumer preferences, resulting in higher demand for bio-based products (von Braun, 2018). Previous studies have shown that consumers value the health and environmental attributes of novel food products (Dolgopolova & Teuber, 2016) and that fully bio-based products result in greater purchase intentions (Reinders et al., 2017).

Other consumer studies, however, have shown great confusion of consumers regarding the term "bio-based products" and many misunderstandings regarding, e.g., biodegradability or organic content (Sijtsema et al., 2016). Product labels have been introduced to respond to consumer preferences and they enable the monitoring of expected shifts in demand. So far, this paper has demonstrated that several driving forces affect the developments of the bioeconomy and its impacts on the economy, society, and the environment. The following two sections will discuss the resources that act as an important constraint and the policy measures that can be used to steer the development.

2.2.6. Policies, Strategies, and Legislation

2.2.6.1. Global, EU and National Policies

Agricultural, fisheries, and forestry policies steer the primary production sector, which is influential to the whole bioeconomy. Furthermore, policies on both, renewable energy and energy from fossil fuels, are driving the bioeconomy. Renewable energy targets and subsidies generally result in an increase in bioenergy production. The focus on bioenergy in the policy landscape could also affect other parts of the bioeconomy, lead to distortions within the bioeconomy (such as over-cultivation of energy crops), and hinder environmental benefits and cascading use of biomass (Keegan et al., 2013). Bioeconomy strategies take a big role as they outline the visions and intentions of countries and regions (Choi et al., 2019; Nițescu & Murgu, 2020). The market mechanisms of the bioeconomy are of high complexity and policy measures targeted to-ward single effects involve trade-offs, leakage, and rebound effects (SAT-BBE, 2015a). This implies that also policies not directly targeted at the bioeconomy can have a considerable effect. For example, tax policies on fossil fuel can lead to substitution effects between fossil fuel-based products and bio-based products and are a key determinant of bioeconomy development (Tsiropoulos et al., 2017).

Moreover, policies related to the circular economy are influential for the bioeconomy because of the synergies between both approaches (see Section 3.2 for details). The European Commission's 2015 CE action plan addressed the transformation of EU MS into a circular economy focusing on the supply-side for production, consumption, secondary raw materials, innovation and investment, and monitoring (European Commission, 2015). The 2020 EU Circular Economy action plan, which was published as part of the Communication on a European Green Deal, followed up with more focus on the consumer-side and the aim to establish a coherent product policy framework and promote sustainable products, services, and business models (European Commission, 2020).

2.2.6.2. Regional Policies

Bio-based products and industries offer new opportunities for European rural and coastal regions due to their local biomass resources such as agriculture, marine ecosystems, and forests, which can be supplemented by municipal waste streams. Investments in new bio-based industries can be best planned at the regional level where efforts can be targeted and based upon regional attributes, strengths, and opportunities. At the regional level, the bioeconomy could endorse a positive impact in terms of job creation and building a circular economy. The regional dimension of the bioeconomy is especially supported by EU initiatives like the EU Bioeconomy Strategy, the EU Cohesion Policy, and the introduction of Regional Innovation Strategies for Smart Specialisation (RIS3). With RIS3, regions are challenged to make strategic choices for their own socioeconomic development based on their regional characteristics and assets. The EU supports this trajectory by offering H2020 funding for exploring innovations and the European Regional Development Fund for piloting and implementing regional initiatives.

Although many European regions have expressed ambitions to valorize agricultural, forest, marine, or urban biomass and waste into new bio-based products (i.e., 100–170 regions have a bioeconomy related focus in their RIS3, depending on the selection criterion), only a few regions have successfully been through the development path and succeeded in establishing bio-based industries to date (e.g., Hauts-de-France and Grand Est regions in France as part of IAR cluster in France, Central Finland, Biobased Delta in the Netherlands). Most of these success cases exist in regions with established chemical, energy, and paper and pulp industries, which provided the foundation for building new bio-based industries and clusters to attract investors and to bring sustainable bio-based products to the market (Van Leeuwen, 2016).

2.2.6.3. Legislation

Legislation can act as a strong policy tool to steer the bioeconomy. There are a large number of legislative acts that are relevant for the bioeconomy in the EU, but no specific EU bioeconomy legislation exists (Ronzon et al., 2016). The European Agricultural Guarantee Fund (EAGF) provides direct payments to farmers, based on the type of biomass they produce and compliance with basic standards concerning the environment (e.g., food safety and animal welfare). Furthermore, green direct payments can be received for practices that benefit the environment and climate. The European Agricultural Fund for Rural Development (EAFRD) finances the so-called agri-environment-climate measures, which affect the availability, prices, and price stability of biomass and the environmental impact of agri-cultural commodities. The Common Fisheries Policy regulates fisheries management, international policy, market organization, and the European Maritime and Fisheries Fund has high relevance for biomass from the maritime environment. The EU food and feed safety legislation is a very comprehensive regulation that the food industry has to comply with (Ronzon et al., 2016). The Renewable energy directive sets targets for renewable energy shares, which promotes the uptake of bioenergy and biofuels. The Waste Framework Directive and many further legal acts regulate the management of waste in the EU. These regulations have a large impact on the development of the bioeconomy because they steer the handling of bio-waste streams.

2.2.7. Relations within the Bioeconomy

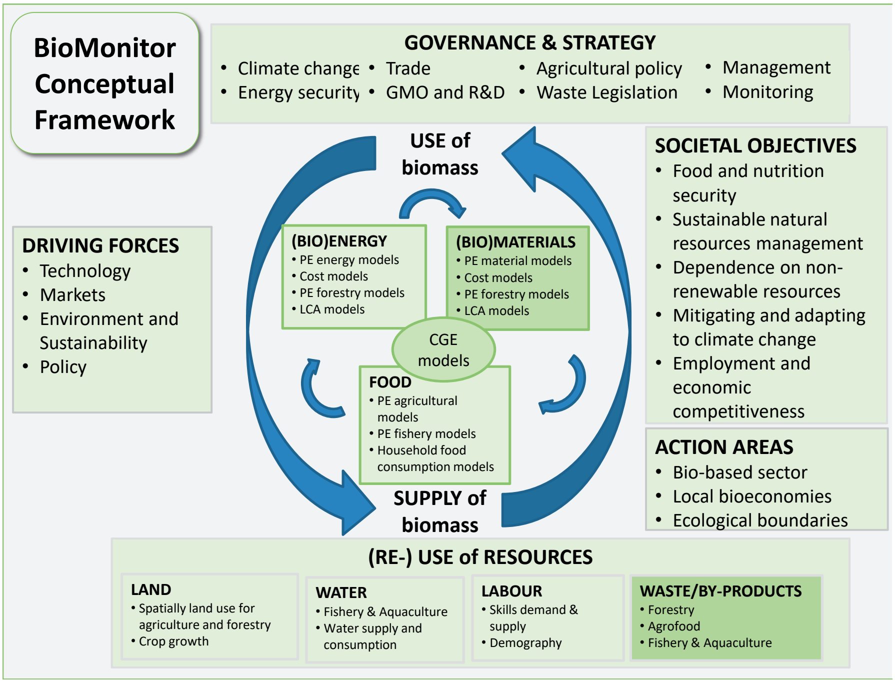
Figure 2.1 summarizes the issues discussed in the previous sections of our conceptual framework. This should be seen as a dynamic and not as a static process. The Drivers-Impact-Results (DIR) framework has been adapted from the SAT-BBE project (SAT-BBE, 2015b). On the left side are the supply and demand drivers, which determine the development of the bioeconomy. Policies, strategies, and legislation on the top constitute the measures of governments to influence this development. At the bottom, we can see the different resource availabilities for biomass production, like land, water, and labor, which influence the biomass market in the center. In the center of the framework are the different supplies and uses of biomass, which are endogenously determined through the aforementioned three boxes of driver types. Furthermore, waste/by-products, whose usage is the key to a sustainable and circular bioeconomy, have been taken into account. In combination, the drivers, policies, and resources have an impact on the demand and supply of the bioeconomy which in its turn determines to what extent it will contribute to achieving sustainable and policy targets of the objectives (right-hand side).

To make the impacts on the objectives measurable, they must be transformed into criteria or targets. For example, the objective ‘mitigating climate change’ could be reflected in the criteria ‘reduce greenhouse gas (GHG) by 40% by 2030 as compared to 1990’. Therefore, meaningful indicators must be assigned that can measure the development and impacts of the bioeconomy in relation to the criteria and policy targets. For example, the indicator ‘% CO2 in bio-based and fossil-based sectors’ could be applied to measure the impact on the target ‘reduce GHG with 40%’.

Insights into the impacts on the targets of the objectives will likely trigger responses from policymakers (i.e., by reforming the policy or introducing new measures) or from stakeholders in the private sector (i.e., by investing in techniques or changing their management). In their turn, the responses might influence the drivers behind the development of the bioeconomy again, such as consumer preferences, economic development, innovation, and technological change. Policy targets are thus quite closely connected to drivers as they are answers that anticipate the affected sustainable objectives caused by the status of drivers and resource availabilities so far. In their turn, adapted policy targets in conjunction with the drivers will again influence the sustainable objectives behind the bioeconomy. This iterative process will continue until the environmental, economic, and social sustainable objectives will be sufficiently satisfied

This process shows that the bioeconomy is a complex system and therefore its monitoring requires a comprehensive systems analysis. Both dynamics within the bioeconomy and interactions and pressures from the outside influence the development. These factors include the changes in existing sectors and products, changes in interactions between sectors, and the creation of new bio-based products. It is not possible to foresee all new developments, but a look at the driving forces of these developments provides an insight into what parts of the bioeconomy deserve closer attention. A priority is to be able to capture the level of sustainability and circularity of the bioeconomy. Furthermore, the monitoring has to be spatially explicit to analyze the development of the local bioeconomy. As the advances in technology constitute an important driving force of the bioeconomy, monitoring must include private and public efforts to advance these technological developments.

Figure 2.1: Overview of the relations within the bioeconomy.



Source: Adapted from SAT-BBE (2018).

2.3. DEFINING AND DELIMITING THE BIOECONOMY

2.3.1. Definition

The bioeconomy has an inter-sectoral, (inter)national, and transdisciplinary nature, which is reflected in varying definitions and delimitations. The way in which the term is defined and in which its activities are delimited depends on the stakeholders: scientists, policy-makers, NGOs, or the private sector. Bugge et al. (2016) identified three visions of the bioeconomy, that is a biotechnology vision, a bio-resource vision, and a bio-ecology vision, which are associated with different actors and reflect their priorities in the bioeconomy (Bugge et al., 2016). Furthermore, the bioeconomy is considered as being of pervasive nature, not only a sector but more and more integrated into day to day life, similar to digitalization (Wesseler & von Braun, 2017). This presents a challenge for monitoring and measuring the bioeconomy, for which a clear scope is necessary.

Within Europe, one of the most used definitions is the one by the European Commission, who define that "The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries, and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy, and services" (European Commission, 2018b, p.4).

The Commission's definition of the bioeconomy in its 2018 Bioeconomy Strategy Update expands on the Commission's 2012 definition by including a wider array of products, sectors, and value chains. Furthermore, the strategy stresses that "to be successful, the European bioeconomy needs to have sustainability and circularity at its heart," (European Commission, 2018b, p.4) thereby emphasizing sustainability and circularity.

The Global Bioeconomy Summit provides another frequently used definition. The summit brings together ministers and government representatives from Asia, Africa, Eu-rope, South and North America, international policy experts from the United Nations, the Organization for Economic Co-operation and Development and the European Commission, as well as high-level representatives from science and industry. The 2018 Global Bioeconomy Summit defined the bioeconomy as "[...] the production, utilization, and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes, and services across all economic sectors aiming toward a sustainable economy" (BIOÖKONOMIERAT, 2018, p.2).

The European Bioeconomy Alliance, a cross-sector overarching alliance of various bioeconomy industries associations (e.g., The European Vegetable Oil and Protein Meal Industry), has a comprehensive definition of the bioeconomy:

“The bioeconomy comprises the production of renewable biological resources and their conversion into food, feed, bio-based products, and bioenergy via innovative, efficient technologies. In this regard, it is the biological motor of a future circular economy, which is based on optimal use of resources and the production of primary raw materials from renewably sourced feedstock” (European Bioeconomy, 2016, p. 1).

This definition includes the concept of the circular economy and emphasizes the relationship between the circular economy and the bioeconomy in that the progress in the bioeconomy is stimulating the transition to a circular economy.

Another perspective comes from organizations representing different sectors within the bioeconomy. They emphasize the role of their sectors and how those sectors can contribute to the overall objectives of the bioeconomy on the one hand, and how their sectors can benefit from the bioeconomy on the other hand. An example is the Confederation of European Forest Owners:

“Sustainable, multifunctional forest management and the forest-based sector play a key role in achieving Sustainable Development Goals, for example, by providing climate action, sustaining life on land, delivering work and economic growth, enhancing responsible production and consumption, boosting industry innovation and infrastructure, creating sustainable cities and communities, enhancing good health and well-being, and providing clean energy. The bioeconomy is a key concept to boost the potential of the forest sector to deliver solutions to these multiple challenges.” (Confederation of European Forest Owners, 2017, p. 2).

In this definition, the Sustainable Development Goals are the primary objective and the bioeconomy is considered a viable solution for their achievement.

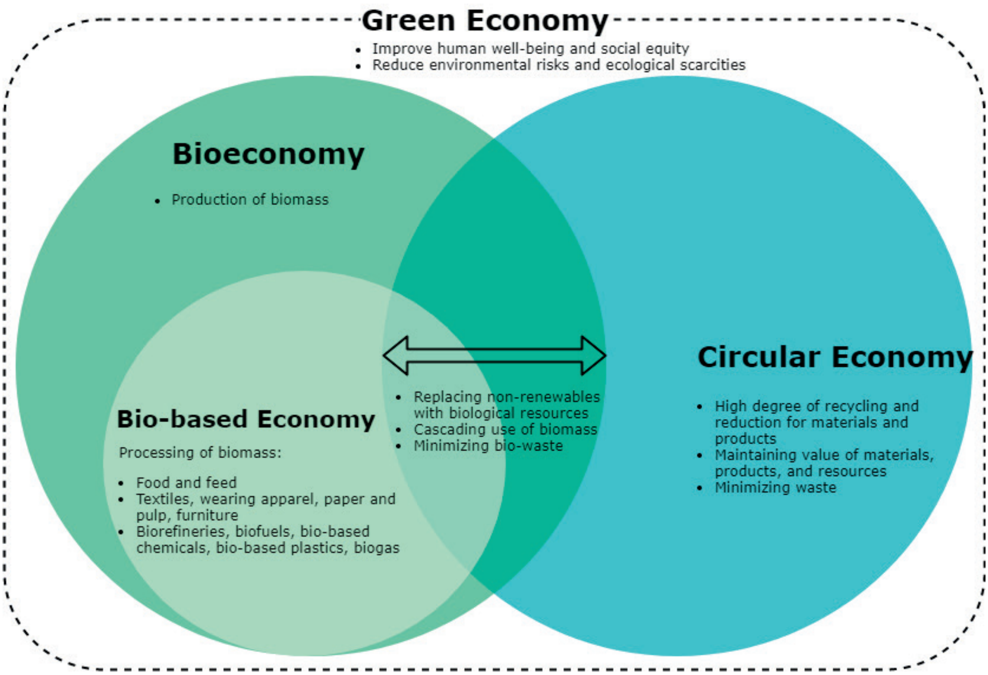
In summary, this non-exhaustive selection of definitions provides additional information to and confirm the EC’s perspective on the scope of the bioeconomy. The 2018 Global Bioeconomy Summit specifically mentions the conservation of biological resources to be included in the bioeconomy. The European Bioeconomy Alliance emphasizes the importance of the synergies between the bioeconomy and the Circular Economy. Moreover, the Confederation of European Forest Owners highlights the potential of the bioeconomy to contribute to the Sustainable Development Goals. Hence, a wide range of stakeholders supports the EU bioeconomy not only within the EU but also beyond.

2.3.2. Bioeconomy, Bio-Based Economy, Green Economy, and Circular Economy

In addition to the term ‘bioeconomy’, there exist several related terms, such as ‘bio-based economy’, ‘green economy’, and ‘circular economy’. Figure 2.2 shows the relation and overlap between the terms. The green economy is generally considered as being an umbrella concept (D’Amato et al., 2017) and is understood to “result in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. In its simplest expression, a green economy can be thought of as one which is a low car-bon, resource-efficient and socially inclusive” (Unep et al., 2012, p. 1). The bioeconomy is generally considered to be part of the green economy (Figure 2.2). Generally, the bioeconomy is often more related to promoting global economic growth and technological development than purely focusing on limits to growth as a consequence of resource scarcity, depletion, and expected population growth (Pülzl et al., 2014).

The concept of the bioeconomy has early-on been linked with the concepts of the bio-based and the circular economy. The bio-based economy is seen as part of the bioeconomy and relates to the conversion of biological resources into products and materials. This is also referred to as bio-based production. In some definitions of the bio-based economy, an emphasis is put on innovative bio-based products such as biopolymers and bioplastics (Dubois & Gomez San Juan, 2016) while in others, traditional bio-based products such as

Figure 2.2: Relations between bioeconomy, bio-based economy, green economy, and circular economy.



bio-based textiles, wood products, pulp, and paper are explicitly included as well (Carus & Dammer, 2018). Figure 2.2 summarizes the different concepts being used and uses the latter definition of the bio-based economy and additionally includes the food and feed sector in the bio-based economy. The production of food and feed usually involves the processing of agricultural goods and, therefore, fits into the bio-based economy.

The circular economy, which shares the rise in popularity and can work complementary to the bioeconomy (Carrez et al., 2017), can be described as an economy in which products and materials used show a high degree of recycling and reduction, contrary to a linear economic model that builds on a 'take-make-consume-throw away' pattern (Buongiorno, 2018). Substitution of non-renewables with sustainably produced biomass is also an important part of the circular economy. The concept of circularity is not new and has been the foundation for economy-wide modeling dating back at least to the works of François Quesnay and the Physiocratic school of the 18th century in France. The Ellen MacArthur Foundation, a strong supporter of the circular economy concept, defines it as "an industrial economy that is restorative or regenerative by intention and design" (Ellen MacArthur Foundation, 2013, p. 14). Similarly, the European Commission defines the circular economy as an economy "where the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste minimized, [it] is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource-efficient and competitive economy" (European Commission, 2015, p. 2).

The synergies between the bioeconomy and circular economy concepts are significant. Several European industry associations such as CEPI (Confederation of European Paper Industries) and EuropaBio (The European Association for Bioindustries) use and support the concept of a 'circular bioeconomy' and promote greater integration of both concepts instead of developing both in parallel (Confederation of European Forest Owners, 2017; EuropaBio, 2017). Recently, the term circular bioeconomy has been introduced by the EC, among others, to intertwine the bioeconomy and circular economy concepts and emphasize the use of a circular approach to the bioeconomy, but also to show limitations of the overlap (Carus & Dammer, 2018; European Commission, 2018a; Hetemäki et al., 2017).

2.3.3. Sectors in Bioeconomy and Bio-Based Economy

To monitor the bioeconomy and considering the broad definition of the bioeconomy by the European Commission, there is a need to define which sectors make up the bioeconomy (Heijman, 2016; Kuosmanen et al., 2020). Bioeconomy-related activities can be broadly classified as (i) Natural-resource based activities that directly exploit a biological resource (e.g., the primary sectors agriculture, fishery, and forestry) and provide biomass for further processing; (ii) Conventional manufacturing activities that further process biomass (e.g., food or wood processing sectors); and (iii) Novel activities that further process the biomass and/or bio-mass residues (bioenergy or bio-based chemical sectors). The NACE provides a useful starting point for defining which and to what extent economic activities belong to the bioeconomy. Its divisions A01–A03 (i.e., agriculture, forestry, and fishery) are unambiguous as they constitute entire sectors and cornerstones of the bioeconomy. Apart from the primary sectors in Section A, the main part of the bioeconomy can be located in Section C—Manufacturing. Divisions C10 (food products), C11 (beverages), C12 (tobacco products), C16 (wood and wood products), and C17 (paper and paper products) are conventional bioeconomy sectors that further process biomass and can be attributed to the bioeconomy. C13 (textiles), C14 (wearing apparel), C15 (leather and related products), C19 (coke and refined petroleum products), and C31 (furniture) are traditional sectors that to some extent use bio-based input. In the case of C19, the sector includes the blending of biofuels with petroleum products. Like in most other studies, they are part of the bioeconomy, but only for their share of bio-based production. C20 (chemical products), C21 (pharmaceutical products), and C22 (rubber and plastic products) are sectors, which include novel activities that further process biomass, often as a substitute for fossil-based raw material. This substitution is an important objective of the bioeconomy and, therefore, these potential bio-based sectors are included in the list. In order to measure the development of new, innovative industries that make novel use of biomass, biorefineries and cascading use of biomass are two essential concepts that should be captured.

Apart from the manufacturing sectors, several additional service-related sectors partly use processed biological resources. These are D35 (electricity, gas, steam and air conditioning supply), F41 (construction), F42 (civil engineering), G46 (wholesale trade), G47 (retail trade), I55 (accommodation), and I56 (food and beverage service activities). For service sectors, it is a challenge to determine which share of the use of biological resources (and therefore part of the bioeconomy) can be assigned to them. However, the importance of the service sector for GDP and employment in the EU has become so substantial that a large proportion of the bioeconomy would be omitted from the analysis if it would be ignored. Efken et al. (2016) use estimates from different market research companies to calculate the share of biobased related activities in total turnover for G46 (wholesale trade), G47 (retail trade), I55 (accommodation), and I56 (food and beverage service activities) for Germany [84]. However, for the case of restaurants, they do not find any reliable estimates on the share of turnover related to biological resources and, therefore, consider restaurants completely as part of the bioeconomy.

Table 2.1 summarizes the sectors that we consider to belong to the bioeconomy ac-cording to previous efforts (Efken et al., 2016; Fumagalli & Trenti, 2014; Lier et al., 2018; Piotrowski et al., 2018; Ronzon et al., n.d., 2017; SAT-BBE, 2015a). For example, Ronzon et al. (n.d.) in their report use 16 sectors, and the major indicators applied include turnover, value-added, and jobs (Ronzon et al., n.d.). Statistics and methods measuring the contribution of the bioeconomy to reaching the global societal objectives are relatively well equipped and developed for its traditional sectors and products like food, feed, pulp and paper, and bioenergy chains (Lier et al., 2018), but there are gaps for the innovative biobased sectors. For example, according to Ronzon et al. (n.d.), the EU-28 bioeconomy was responsible for 18 million full-time jobs, generated €2.3 trillion of turnover, and contributed to a value addition of €620 billion in 2015 (Ronzon et al., n.d.).

Table 2.1: Sectors of the bioeconomy and the bio-based economy.

	NACE	Fumagalli and Trenti (2014)	SAT-BBE (2015)	Efken et al. (2016)	Ronzon et al. (n.d.)	Piotrowski et al. (2018)	Ronzon et al. (2017)	Our FRAME-WORK
A01	Crop and animal production, hunting and related service activities	✓	✓	✓	✓	✓	✓	✓
A02	Forestry and logging	✓	✓	✓	✓	✓	✓	✓
A03	Fishing and aquaculture	✓	✓	✓	✓	✓	✓	✓
C10	Manufacture of food	✓	✓	✓	✓	✓	✓	✓✓
C11	Manufacture of beverages	✓	✓	✓	✓	✓	✓	✓✓
C12	Manufacture of tobacco	✓	✓	✓	✓	✓	✓	✓✓
C13	Manufacture of textiles	X	✓	✓	✓	✓	✓	✓✓
C14	Manufacture of wearing apparel	X	✓	✓	✓	✓	✓	✓✓
C15	Manufacture of leather and related products	X	✓	✓	✓	✓	✓	✓✓
C16	Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	✓	✓	✓	✓	✓	✓	✓✓
C17	Manufacture of paper and paper products	✓	✓	✓	✓	✓	✓	✓✓
C19	Manufacture of coke and refined petroleum products	X	✓	X	X	X	X	✓✓
C20	Manufacture of chemicals and chemical products	✓	✓	✓	✓	✓	✓	✓✓
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	X	X	✓	✓	✓	✓	✓✓

Table 2.1: Sectors of the bioeconomy and the bio-based economy.

	NACE	Fumagalli and Trenti (2014)	SAT-BBE (2015)	Efken et al. (2016)	Ronzon et al. (n.d.)	Piotrowski et al. (2018)	Ronzon et al. (2017)	Our FRAME-WORK
C22	Manufacture of rubber and plastic products	X	✓	X	✓	✓	✓	✓✓
C31	Manufacture of furniture	X	✓	X	✓	✓	✓	✓✓
D35	Electricity, gas, steam, and air conditioning supply	X	✓	X	✓	✓	X	✓✓
D3511	Production of electricity	X	✓	X	X	X	✓	✓✓
E36	Water collection, treatment, and supply	X	X	X	X	X	X	✓
E37	Sewerage	X	X	X	X	X	X	✓
E38	Waste collection, treatment, and disposal activities; materials recovery	X	X	X	X	X	X	✓
E39	Remediation activities and other waste management services	X	X	X	X	X	X	✓
F41	Construction of buildings	X	✓	X	X	X	X	✓
F42	Civil engineering	X	✓	X	X	X	X	✓
G46	Wholesale trade, except for motor vehicles and motorcycles	X	X	✓	X	X	X	✓
G47	Retail trade, except for motor vehicles and motorcycles	X	X	✓	X	X	X	✓
H	Transportation and storage	X	X	X	X	X	X	✓
I55	Accommodation	X	X	✓	X	X	X	✓
I56	Food and beverage service activities	X	X	✓	X	X	X	✓
M7211	Research and experimental development on biotechnology	X	X	X	X	X	X	✓✓
R9104	Botanical and zoological gardens and nature reserves activities	X	X	X	X	X	X	✓

ote: “X” specifies sectors that were not considered as part of the bioeconomy in the respective study; “✓” specifies sectors that were included; “✓✓” specifies sectors that are considered as part of the bio-based economy in our framework.

2.4. MONITORING AND MEASURING THE BIOECONOMY

2.4.1. Stocktaking of Monitoring Systems

There are efforts of monitoring the EU bioeconomy and single country bioeconomies. The European Commission provides its monitoring results for the EU bioeconomy and single MS online at https://ec.europa.eu/knowledge4policy/bioeconomy/monitoring_en (Robert et al., 2020). Several countries (Argentina, Australia, Germany, Malaysia, the Netherlands, South Africa, and the United States) are measuring the contribution of the bioeconomy to their overall economy or country objectives (Bracco et al., 2018). Germany is working on a comprehensive approach to monitor the bioeconomy by a joint inter-ministerial undertaking with three research projects. In the Netherlands, a bio-based economy monitor protocol to quantify the size and monitor its development was established already in 2013 (Meesters et al., 2013). However, so far there is, except for the efforts by the EC, no common and holistic approach to monitor and measure the bioeconomy across EU states and, therefore, it is not possible to compare the results between countries (Bracco et al., 2018; Linser & Lier, 2020). Furthermore, the majority of countries measure their bioeconomy not comprehensively using only economic indicators (Bracco et al., 2018).

To monitor physical investments, they need to be differentiated by the kind and amount of biomass used, the production capacity as well as the bio-based products produced, and their intended use. For the products produced, prices and quantity are of importance as well as their destination: are they further processed within the region, processed outside the region but within the country, within the EU, or exported outside the EU, and what are countries of destination? To assess the future potential of the bioeconomy not only the investments into physical capital and related non-physical capital are important but also in research and development. In addition to the amount of private and public capital spent, another important aspect is to measure the impact and success of such kinds of investments with patent applications being an important indicator in this respect. The Organisation for Economic Co-operation and Development (OECD) patent data can be used as a source to identify the number of patents filed over time and space in the EU differentiated by the different sectors of the bioeconomy. Again, the sectors identified in Section 2.3.3 provide guidance for the classification of patent applications.

For monitoring the bioeconomy, a sectorial perspective is a very useful approach. One reason is that usually data are collected on an annual basis at the sectoral level, so that creates a good base for monitoring, measuring, and benchmarking. This has been followed by a number of previous projects (Efken et al., 2016; Ronzon et al., n.d.). For example, Ronzon et al. (n.d.) provide valuable information on economic indicators such as value added, but a more regional disaggregation, as well as disaggregation by products, has been expressed as a need by stakeholders (Piotrowski et al., 2019).

2.4.2. Indicators

To monitor and measure the development of the bioeconomy, a set of indicators is essential. An indicator is a quantitative or qualitative measure, which must be measurable, comparable, replicable, and responsive to fluctuations in the development. They can help policymakers and other stakeholders to understand and interpret results, reveal trade-offs between policy measures, and formulate clear targets for their policies. There are several bioeconomy monitoring-related initiatives (BERST, 2014; SAT-BBE, 2015b) that proposed a set of indicators and other organizations are already collecting data for their indicators (e.g., by EUROSTAT, Forest Europe, European Environment Agency). EUROSTAT has 100 indicators related to the SDGs and ten indicators for the circular economy and in particular on biomass flows (Eurostat, 2019). The ten indicators for the circular economy are part of a monitoring framework on the circular economy, which entails four thematic areas (i.e., production and consumption, waste management, secondary raw materials, competitiveness, and innovation). SDG indicators are important as some of them measure the bioeconomies contribution to sustainable development. This is supported by Ronzon and Sanjuan (2020), who found that the 2018 EU Bioeconomy Strategy Update could contribute to 53 targets in 12 of the 17 SDGs by semantically mapping the action plan of the strategy with SDGs.

When defining our set of indicators, we considered a number of criteria. First, we focus on the bio-based industry and, therefore, gave preference to indicators for which a plausible link with bio-based production could be assumed (i.e., there should be a measurable effect). For instance, when looking at 'Greenhouse gas emissions', we are interested in the carbon removal capacity of forestry and emission reductions by agriculture and the bio-based industry. Second, we strive to have a balance of Main Indicators across the societal objectives from the 2018 Bioeconomy Strategy. Third, we aim at addressing all three dimensions of sustainability (i.e., environmental, social, and economic) as much as possible, although our focus is on the economic dimension of sustainability in particular. Especially the economic sustainability of the bioeconomy at the product level is neglected thus far (Bracco et al., 2019). Fourth, we include indicators that are considered important now (e.g., employment), as well as indicators that might become important in the future (e.g., education and investment) (Philippidis et al., 2018; Urmetzer et al., 2020). Table 2.2 presents the selected main and sub-indicators for our measuring and monitoring framework.

We assign the indicators to the five societal objectives based on the EC's 2018 Bioeconomy Strategy and distinguish between Main Indicators and Sub-Indicators. Based on consultation with stakeholders (in October 2018), we restrict the number of Main Indica-tors to 25 to provide a condensed view on, respectively, the transition of the bioeconomy, and on the realized (ex-post) and potential (ex-ante) effects of the EU bioeconomy. The Main Indicators can be disaggregated to Sub-Indicators, which offer a more detailed view. Our selection of indicators is based on stakeholder feedback and examination of the literature. As a starting point, we rely on indicators identified by Lier et al. (2018)., who proposed indicators for assessing and monitoring the progress of a bioeconomy at the national level using a survey among ministries and research organizations responsible for national bio-economy strategies, policies, and/or related initiatives (Lier et al., 2018). We elaborated this set by evaluating the indicators that are used in the literature and monitoring projects to measure the five themes from the societal objectives. Based on the four before-mentioned criteria, we created a comprehensive framework of indicators, which considers social, environmental, and economic impacts.

A significant aspect of measuring the potential of sustainable bioeconomy is to con-sider indicators for innovation, supporting policies, strategies, and legislation. Policy measures can be implemented at a regional, national, supranational, or global level.

Table 2.2: Proposed list of indicators by societal objective for our framework.

Main Indicator	Rationale	Sustainability Dimension	Source
1. Food and nutrition security			
Availability of food	To assess the contribution of the bioeconomy to food and nutrion security based on the widely accepted four dimension of food security	Society	FAO (2009)
Access to food			
Utilization			
Stability			
2. Sustainable natural resource management			
Sustainability threshold levels for Bioeconomy Technologies	New indicator based on genuine investment theory with a focus on the bio-based economy	Environment	Own elaboration, Bartolini et al. (2017), Wesseler et al. (2007)
Biodiversity	Indispensable to assess the impact of biomass production at the genetic, species, and ecosystem level	Environment	SAT-BBE (2015b), Bartolini et al.(2017), Plieninger et al. (2019), Strohbach et al. (2015), Weikard et al. (2006)
Land cover	To assess land use conflicts	Environment	Lier et al. (2018)
Primary Biomass production	To assess biomass availability	Economy	BERST(2014)
Sustainable resource use	To assess the sustainability of biomass production	Environment	Lier et al. (2018)
3. Dependence on non-renewable resources			
Bio-energy replacing non-renewable energy	To assess the direct substitutability of fossil resources with biological resources	Environment	Own elaboration
Bio-material replacing non-renewable resources	To assess the direct substitutability of fossil resources with biological resources	Environment	Lier et al. (2018)
Biomass self-sufficiency rate	To assess independence from biomass imports.	Economy	Own elaboration
Material use efficiency	To assess the degree of circularity	Economy	Lier et al. (2018)
Certified bio-based products	To assess the variety of products from bio-based production.	Environment	Own elaboration
4. Mitigating and adapting to climate change			
Greenhouse gas emissions	Traditional indicator applied to bioeconomy sectors	Environment	EUROSTAT (2019)
Climate footprint	To assess CO2 emissions for sectors based on life cycle assessments of bio-based production	Environment	Own elaboration

Table 2.2: Proposed list of indicators by societal objective for our framework.

Main Indicator	Rationale	Sustainability Dimension	Source
Climate change adaptation	More indicators of adaption to climate change impacts are needed.	Environment	Own elaboration
5. Employment and economic competitiveness			
Innovation	Traditional indicator applied in more sectorial and spatial detail	Economy	Lier et al. (2018); SAT-BBE (2015); Own elaboration
Investments	To assess biomass flows within the EU between the rest of the world	Economy	Lier et al. (2018) Bartolini et al. (2017)
Value Added of the bioeconomy sectors	To assess product uptake of bio-based production	Economy	Lier et al. (2018)
Comparative advantage	To assess biomass flows within the EU between the rest of the world	Economy	Own elaboration
Production and consumption of non-food and feed bio-based products	Traditional indicator applied in more sectorial and spatial detail	Economy	Own elaboration
Import and export of bioeconomy raw materials and products	To assess biomass flows within the EU between the rest of the world	Economy	Own elaboration
Employment	Traditional indicator applied in more sectorial and spatial detail	Society	Lier et al. (2018)
Bioeconomy-driving Policies	To assess policies, strategies, and legislation on the bioeconomy	Society	Own elaboration

These can make a significant contribution to promote the bioeconomy and often provide the foundation for establishing new bio-based industries. We suggest new spatially differentiated indicators for revealing these effects, measuring inter alia, 'Innovation' via 'Number of patents submitted by field and sub-field' and 'Innovation hurdle for different industries', and 'Policies' via 'Policy-induced investment hurdles' and 'Country level strategies'. As previously stated, it is desirable to measure the degree of circularity of the bioeconomy as well as its contribution to the Sustainable Development Goals. We use indicator measures, among others, 'Material use efficiency' and 'Sustainable resource use'. By measuring 'Bio-energy replacing non-renewable energy' and 'Bio-material replacing non-renewable resources ', we assess whether the bioeconomy reduces emissions compared to fossil-based, emission-intensive products. This can be done using bioeconomy transition indicators to quantify the substitution of fossil resources (Jander et al., 2020).

Bracco et al. stress the need for trade-related indicators to link national and global sustainability performances and ensure sustainable production of imported biomass (Bracco et al., 2019). We try to fill this gap by taking into account 'Import and export of bioeconomy raw mate-rials and products' and 'Comparative Advantage' of countries for biomass production, which is not only relevant for environmental sustainability but also for biomass availability.

Several authors highlight the importance of environmental indicators for monitoring the sustainability of the bioeconomy (Bartolini et al., 2017; Plieninger et al., 2019; Strohbach et al., 2015). We address this by including the availability of biomass and biological diversity used for producing the biomass by employing the index proposed by Weikard et al. (2006). Their index consists of the number of different sources of biomass and the abundance as well, which can be presented using different kinds of metrics such as at regional or national level as well as a share in land use and more. An important sub-indicator will be related to ecosystem resilience. This can be measured by changes in the maximum incremental social tolerable irreversible costs (MISTICSs) (Wesseler et al., 2007). Habitats, landscape elements, and regulatory services are further important sub-indicators. They will be included by differentiating the different forms of land use as commonly done.

The methodologies and indicators described in this paper will contribute to the development of the EU Bioeconomy Monitoring system (Robert et al., 2020).

2.4.3. Regulatory Challenges

One of the important factors for the success of the EU Bioeconomy Strategy is the regulatory environment. Many of the new technologies for circular bioeconomy use methods based on new developments in the biological sciences such as CRISPR-Cas. The use of these technologies is heavily regulated and, in particular, application in plant breeding has become difficult under the current regulatory environment (Purnhagen & Wesseler, 2021). In some areas, recent improvements have been observed such as for the approval of microbial biological control agents (Frederiks & Wesseler, 2019) or novel foods (Zarbà et al., 2020). Still, at the international level, approval for new products of importance for the circular bioeconomy in the EU is more time consuming (Jin et al., 2019) and hence much more expensive (Purnhagen & Wesseler, 2019) and reforms are urgently needed (Eriksson et al., 2019). Monitoring progress on regulatory issues will be important. They can be measured by identifying investment hurdles and how they change over time (Wesseler et al., 2017), the impacts of policies on those hurdles (Wesseler & Zhao, 2019), and because of their importance for the success of the bioeconomy need to have priority. The measurement of the investment hurdles provides a quantitative measure, but qualitative measures such as changes in policies are important as well as they indirectly affect the sectorial growth (Acemoglu & Azar, 2020).

2.5. CONCLUSIONS

This paper shows the bioeconomy receives wide support within the EU and beyond. Most stakeholders apply a sectorial view, defining the bioeconomy according to the sec-tors to be included and excluded. We developed a conceptual analysis framework for quantifying and analyzing the development of the bioeconomy, determined the general scope for the framework, and derived a set of indicators. Using the European Commission's definition as a basis for monitoring and measuring the bioeconomy framework, a wide range of sectors are part of the bioeconomy, including biomass producing activities, conventional biomass processing activities, novel biomass processing activities, and service-related activities that use biomass (European Commission, 2018b). However, we emphasize the need for improvements in the methodologies for monitoring and measuring bio-based production. In the corresponding sub-sectors of the bioeconomy, existing data collecting methodologies and available data sets are lacking the most. A major issue is that national statistical agencies seldom distinguish between bio-based and non-bio-based products (Jander et al., 2020). Furthermore, we expect at least some of these sectors to undergo a rapid and volatile development driven by technological change. A good monitoring system can support public policymakers to assess and steer these developments and for industrial stakeholders to manage their investment plans. This requires that statistical offices in the EU collect data differentiated by product at member state and regional level. This may allow to provide a more detailed picture of the contribution of the circular bioeconomy toward regional growth (D'Adamo et al., 2020a).

The inclusion of innovation, policies, strategies, and legislation in the monitoring and measuring framework is important because these influence the development of the bioeconomy. Policy measures can be implemented at the regional, national, supranational, or global level. They can make an important contribution to the promotion of the bioeconomy and provide the foundation for establishing new bio-based industries. New indicators have been suggested for monitoring innovation, policies, strategies, and legislation. The indicators measure the changes over time. The indicators can be combined into time-series datasets and put onto a standardized scale that allows further transformation to compare developments among EU member states or even beyond as commonly done in the literature on economic growth (Quah, 1996) or trade (Zaghini, 2005).

It is widely considered crucial for society to achieve sustainable development on national, EU, and global levels, and the bioeconomy has an important role in that achievement. The sustainability of the bioeconomy is mostly attached to its environmental dimension, especially when it comes to sustainable production and use of biomass. To ensure that biomass is used sustainably, the bioeconomy needs to include strategies from the circular economy. A prominent example of this is the recycling of bio-based products. Our proposed set of indicators is designed to be able to measure the degree of circularity of the bioeconomy as well as its contribution to the Sustainable Development Goals.

However, many new bio-based products can be expected to enter the market, but not all can be explicitly singled out in statistics. First of all, procedures to collect new data for new products need to be adjusted, which is a long and expensive process. Secondly, the market of new bio-based products is still very volatile in the sense that many new initiatives appear and disappear from the market. Therefore, a selection needs to be made, which should be based on sound market analysis. A monitoring framework relies on data that is collected regularly and in a detailed manner.

CHAPTER 3

Full Speed Ahead or Floating Around? Dynamics of Selected Circular Bioeconomies in Europe[2]

2 This chapter is based on the article: Kardung, M., & Drabik, D. (2021). Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe. Ecological Economics, 188, 107146. https://doi.org/10.1016/J.ECOLECON.2021.107146

ABSTRACT.

Measuring the progress of the circular bioeconomy requires quantifying a range of indicators. Contrary to previous studies that analyzed only a few indicators, we devise a method that can accommodate any number of them. Our objective is to empirically investigate whether the circular bioeconomies in ten selected European Union Member States were progressing or regressing over 2006–2016 as measured by 41 indicators. We model the development of the intra-distribution of the indicators using Markov transition matrices. We find that the ten circular bioeconomies mostly progressed. Moreover, research and development quickly progressed in the private sector but regressed in the public sector, suggesting substitution between them. Our cross-country comparison reveals that Germany is the front-runner in the circular bioeconomy, but circular bioeconomies in Slovakia, Poland, and Latvia also developed quickly.

3.1. INTRODUCTION

The size of a country's economy is commonly measured by its GDP and other comparable indicators (Kubiszewski et al., 2013). A part of the economy is the bioeconomy, which entails all economic sectors and systems linked to biological resources and their functions and principles (European Commission, 2018b). Measuring the development of the bioeconomy requires quantifying a range of indicators to determine its impact on the economy, the environment, and society (Wesseler & von Braun, 2017).

The bioeconomy in the European Union (EU) can potentially tackle economic, environmental, and social problems if the transition from a fossil-based economy is approached in the right way (O'Brien et al., 2017). Sustainable land use and natural capital preservation within the bioeconomy could be promoted by following the principles of a circular economy, which is defined as an economy "[...] where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised" (European Commission, 2015, p. 2). Applying the principles of a circular economy in the bioeconomy, the advancement of the circular bioeconomy can contribute to sustainable development by reducing the use of raw fossil materials to mitigate climate change, forming new value chains to promote economic growth, and creating jobs, especially in rural areas. Recent European heatwaves in 2018, 2019, and 2020 and an increasing trend of heatwaves since the 1970s have heightened the urgency to tackle climate change (Zhang et al., 2020). The circular bioeconomy is expected to mitigate the effects of climate change by reducing fossil fuel consumption and adapt to it by reducing heat stress and flood risks by increasing tree and vegetative cover (Bell et al., 2018). However, the transition to a circular bioeconomy requires the sustainable use of natural resources, high expenditures on research and development (R&D) of new technologies, and education for new and restructured jobs (Purkus et al., 2018). These challenges emphasize the need for policy actions to steer this transition in a structured and sustainable way. Hence, the EU and several EU Member States (MSs) as individual countries have launched and adopted bioeconomy policy strategies to achieve long-term sustainable development, such as the EU Green Deal in December 2019 (European Commission, 2019b; German Bioeconomy Council, 2018).

The bioeconomy policy strategies show that the transition to a circular bioeconomy is a political aim deepened by the world's pressing environmental problems. Still, it comes with economic, environmental, and social impacts that must be considered, so the progress of circular bioeconomies in EU MSs should be tracked and compared (Jander & Grundmann, 2019). In the last decade, several large frameworks have been developed to monitor the trends and progress of various policy objectives, such as the UN SDGs.

Many indicators can measure various development characteristics of a trend, such as the transition from a fossil-based economy to a bio-based one. For example, there are 27 indicators to support the Europe 2020 Strategy, 100 EU SDGs indicators, 231 UN SDGs indicators, or 1,600 World Bank World Development Indicators. In the same vein, Bracco et al. (2019) reviewed existing monitoring approaches to the bioeconomy and collected 269 distinct indicators from 19 sources that measured a wide range of impact categories, such as food security, biodiversity conservation, and the resilience of biomass producers. Among others, Lier et al. (2018) proposed 161 indicators and the BioMonitor project 84 indicators for a bioeconomy-monitoring framework.

In previous quantitative assessments of circular bioeconomy development, researchers have selected a few economic and social indicators to track their developments. Ronzon and M'Barek (2018) examined the temporal dynamics of the EU bioeconomy and provided a spatial analysis of the EU circular bioeconomy, comparing different EU MSs and grouping them according to the labor market specialization and the apparent labor productivity of their circular bioeconomies. Ronzon and M'Barek (2018) considered only four indicators: the number of people employed, turnover, value added, and apparent labor productivity. D'Adamo et al. (2020b) compared the socio-economic performance status of bioeconomy sectors in EU MSs using the same indicators as Ronzon and M'Barek (2018) except for apparent labor productivity. Furthermore, they introduced a new composite dimensionless indicator to measure and compare socio-economic performance between EU MSs. Efken et al. (2016) measured the importance of the bioeconomy within the economy as a whole in Germany from 2002 to 2010 using employment and gross value added as indicators. Other studies have also been limited to economic indicators and employment (e.g., Piotrowski et al., 2016) or provided only snapshots in time instead of temporal development (e.g., Iost et al., 2019).

Unlike to the previous literature, we devise a theoretical framework that accommodates any number of well-defined quantitative indicators and empirically analyze 41 of them. We investigate their distribution to find patterns in the evolution of the circular bioeconomies of ten selected EU MSs. A similar approach to ours has been used in other fields of economics with a single indicator for many regions or sectors. Quah (1993; 1996) was the first in the cross-country growth and income literature to investigate patterns in income distributions using Markov transition matrices. Later, many researchers adopted this approach to analyze trade-specialization patterns by estimating the intra-distribution dynamics of trade-specialization indices over time (e.g., Alessandrini et al., 2007; Chiappini, 2014; Fertö & Soós, 2008; Zaghini, 2005). Zaghini (2005) analyzed the probability of new EU MSs moving between different degrees of trade specialization. He examined the intra-distribution dynamics of the Lafay index, considering the difference between the exports and imports of 208 sectors. The variation of the relative ranking of sectors by the Lafay index over time depicts these intra-distribution dynamics.

In our exploratory research, we paint a picture of the development of the EU circular bioeconomy between 2006 and 2016 and analyze its specificities in Finland, France, Germany, Italy, Latvia, The Netherlands, Poland, Portugal, Slovakia, and Spain. Our research objective is to investigate whether the circular bioeconomies in these countries are progressing or regressing over the ten-year period. We selected these EU Member States, from now on referred to as the EU-10, on several grounds. First, we considered the (potential) importance of the circular bioeconomy to their economies. Countries such as The Netherlands and Finland already have highly competitive agricultural and forestry sectors and consider the circular economy an approach to consolidate their positions and be more environmentally sustainable (Ministerie van EZ, 2013; Ministry of Employment and the Economy, 2014). Others, such as Latvia and Italy, focus on increasing per capita income competitiveness in their bioeconomy sectors (Italian Presidency of Council of Ministers, 2017; Latvian Ministry of Agriculture, 2018). Second, the selected countries cover the whole range of agricultural intensification, from intensive agriculture in The Netherlands and Germany to extensive agriculture in Latvia and Portugal (European Commission, 2019a). Third, we wanted to achieve good geographical coverage across the EU, including the distinction by the entry date into the EU—before and after 2004. Finally, we were constrained by the availability of coherent data for the included indicators. The data sources of Eurostat did not contain consistent time series for all indicators, in all EU Member States, and all years. Therefore, our choice of the countries and the period is a result of a compromise that respects the three qualifications above. That said, our framework allows including additional countries and years if the necessary data is available.

Our article contributes to the current literature by including a wide range and a high number of indicators to provide a more comprehensive view of the circular bioeconomy's progress and economic, social, and environmental impacts in ten EU countries. Our analysis of the dynamics of circular bioeconomies is unique by examining the intra-distribution of indicators.

3.2. BACKGROUND

3.2.1. Circular bioeconomy policy actions

The circular bioeconomy is high on the political agenda, and many policymakers have proposed and already implemented policy actions to support and steer its development. Table 3.1 presents an overview of policy actions related to the bioeconomy in the EU and

Table 3.1: Overview of actions related to the bioeconomy from 2007 to 2017 by countries in this study

Title	Type	Level	Target policy area	Year
European Union				
En route to the Knowledge-Based Bioeconomy	Consultation document	Supra-national	Yes	2007
Innovating for Sustainable Growth: A Bioeconomy for Europe	Policy Strategy	Supra-national	No	2012
Bio-based Industries Consortium	Investment program	Supra-national	No	2012
Germany				
Erneuerbare Energien Gesetz 2009	Policy measure	National	Yes	2009–2011
Erneuerbare Energien Gesetz 2012	Policy measure	National	Yes	2012–2016
Nationale Forschungsstrategie BioÖkonomie 2030	Research strategy	National	No	2010–2016
Bioeconomy. Baden-Württemberg Path Towards a Sustainable Future	Policy strategy	Regional	No	2013
Nationale Politikstrategie Bioökonomie	Policy strategy	National	No	2014
Finland				
The Natural Resource Strategy	Policy strategy	National	No	2009
Distributed Bio-Based Economy – Driving Sustainable Growth	Policy strategy	National	No	2011
Sustainable Bioeconomy: Potential, Changes and Opportunities for Finland	Policy strategy	National	No	2011
The Finnish Bioeconomy Strategy – Sustainable growth from bioeconomy	Policy strategy	National	Yes	2014
The Finnish Bioeconomy Strategy	Policy strategy	National	No	2014
The Netherlands				
Groene Groei – Van Biomassa naar Business	Innnovation contract	National	Yes	2012
Framework Memorandum on the Bio-Based Economy	Framework paper	National	Yes	2012
Groene Groei: voor een sterke, duurzame economie	Green growth strategy	National	Yes	2013
France				
National Biodiversity Strategy 2011–2020	Research & innovation	National	Yes	2011
The new face of Industry in France	Research & innovation	National	Yes	2012
National Biodiversity Strategy 2011–2020	Research & innovation	National	Yes	2011
The new face of Industry in France	Research & innovation	National	Yes	2012
France Europe 2020	Research & innovation	National	No	2014

Table 3.1: Overview of actions related to the bioeconomy from 2007 to 2017 by countries in this study

Title	Type	Level	Target policy area	Year
Stratégie nationale de transition écologique vers développement durable	High-tech	National	No	2014
A Bioeconomy Strategy for France	Holistic bioeconomy development	National	No	2017
Italy				
Bioeconomy in Italy: A unique opportunity to reconnect economy, society, and the environment	Holistic bioeconomy development	National	No	2017
Spain				
Horizon 2030	Holistic bioeconomy development	National	No	2016
Extremadura 2030	Regional bioeconomy development	Regional	No	2017
Portugal				
Estrategía Nacional para o Mar	Blue economy	National	Yes	2013–2020
Latvia				
Latvian Bioeconomy Strategy 2030 (LI-BRA)	Holistic bioeconomy development	National	No	2017

Note: Poland and Slovakia did not implement an action related to the bioeconomy in this period.
Source: German Bioeconomy Council (2018)

EU-10. Policymakers in the EU have made the bioeconomy a priority to reduce the use of petrochemicals, mitigate and adapt to climate
change, reduce dependency on imports of natural resources, and promote rural development (European Commission, 2018b). At the EU level, this is reflected in a multitude of EU policy initiatives and research programs, including the EU Bioeconomy Strategy and the European Bio-Based Industries Joint Undertaking (Wesseler & von Braun, 2017). At the MS level, most countries in this study have developed dedicated bioeconomy strategies or other policy initiatives and research programs related to the bioeconomy from 2006 to 2016. The exceptions are Italy and Latvia, who published their bioeconomy strategies only afterwards in 2017, and Slovakia and Poland, who have not yet developed a bioeconomy strategy while it is under development (Joint Research Centre, 2019). However, in Slovakia and Poland, bioeconomy development is recognized in regional and smart specialisation strategies (RIS3 SK, 2013; Sosnowski et al., 2014).

While bioeconomy strategies target the whole bioeconomy, policy actions can also target specific policy areas. An example of the latter is the German Erneuerbare Energien Gesetz (EEG), which targeted the promotion of renewable energy. The promotion of bioenergy in the EEG then affected other parts of the bioeconomy, such as agriculture and electricity production.

3.2.2. Measuring performance with indicator frameworks

Governments have taken numerous policy actions on the circular bioeconomy that they must monitor, such as the SDGs. Policymakers have used monitoring frameworks with a diverse set of indicators for many policy objectives. The 17 UN SDGs are a widely used framework and include 232 indicators to measure progress towards 169 corresponding targets. However, measuring progress towards the SDGs is complicated by the fact that there are no specific targets for SDG indicators (United Nations, 2017). Nevertheless, three prominent methods to measure SDG performance have been developed: the Bertelsmann Index (BI) by Bertelsmann Stiftung and the Sustainable Development Solutions Network (Lafortune et al., 2018; Sachs et al., 2018), the Organisation for Economic Co-operation and Development's (OECD) distance measure (OECD, 2016), and progress measures based on Eurostat's report (Eurostat, 2019). Substantial discrepancies exist between these methods (Miola & Schiltz, 2019); the normalization of indicators is a significant one.

The SDG indicators must be normalized to enable aggregation and comparison because they measure different economic, environmental, and social targets and therefore have different units and dimensions. Accordingly, researchers subtract the minimum value across all countries from the indicator value and divide the difference by the range of values across all countries for the BI (Lafortune et al., 2018). This procedure generates a score which relates to the indicator values in all included countries but means little for the development of a single country independently. For the OECD's distance measure, the latest value of an indicator is subtracted from the target value and is divided by the standard deviation across all countries (OECD, 2019). Again, the resulting score is related to all included countries, and importantly, target values for each indicator are necessary. The progress measure based on Eurostat's report linearly interpolates the value of a specific indicator for 2030. For that, the difference between the latest and the first observation is divided by the difference in years and then multiplied by the difference between 2030 and the latest observation and added to the value of the latest observation (Miola and Schiltz, 2019). All indicator values are then rescaled between zero and one and aggregated to obtain a performance measure at the goal level. This method is sensitive to outliers in the time-series data because only two observations are included in its calculation. The z-score (standard score) is another method for normalization and is common for composite indices of development, which integrate various social, political, and economic aspects of the development of a country (Booysen, 2002). Its calculation is straightforward and uses the mean and standard deviation of an indicator (see Section 3.4.1 for details).

For our framework, we needed to normalize because of our selected data and methodology. We analyzed the development of the circular bioeconomy in the EU and its MSs independently and compared the development among countries, but targets were not available for a significant number of indicators, so we used z-scores to normalize the indicators. Before we could do that, we needed to gather and prepare our dataset, which the following section describes.

3.3. DATA

We used time-series data from Eurostat's 'indicator set to measure the progress towards the SDGs' and 'monitoring framework on the circular economy.' From the 232 SDG indicators, we chose those related to the bioeconomy according to Ronzon and Sanjuan (2020). To select bioeconomy-related indicators, they identified any meaning-based equivalence or similarity between SDG targets and the EU Bioeconomy Action Plan that is part of the Updated Bioeconomy Strategy 2018.

The selected 41 'bioeconomy-related' and circular-economy indicators cover not only a multitude of aspects of the circular bioeconomy but also different periods. The largest data gaps occur before 2005 and in the recent years 2017–2019. The former data gaps likely come from indicators that were introduced later and for which data collection needed to be implemented in all EU MSs; the latter is likely due to the time it takes to collect the data. For a consistent data set, we finally considered the period of 2006–2016 and filled in remaining data gaps by predicting missing values using linear regression. The indicators from the circular economy monitoring framework were either coded as 'cei' (competitiveness and innovation) or 'wm' (waste management), followed by a classification number. In contrast, SDG indicators were coded as 'sdg' with a goal number between 1 and 17, followed by a classification number.

In most cases, we avoided the same indicator being represented multiple times with different dimensions or measurement units in the data. For example, the indicator 'Employment rates of recent graduates' from SGD 4 – Quality Education contains disaggregated data for males and females, but we only kept the aggregated total. However, we kept the disaggregated data for indicators that can provide additional insights. For instance, we included the indicators disaggregated by sectors as well as the total for 'Share of renewable energy in gross final energy consumption by sector' because they likely move in different directions. Table 3.2 provides a list of all our indicators and specifies which are aggregated and which are not.

In the next step, we checked the indicators for consistency in their interpretation. For some indicators such as agricultural factor income per annual work unit, a higher value means either the bioeconomy is progressing or has a positive impact on society, while for others such as ammonia emissions from agriculture, a higher value means the bio-economy is regressing, has a negative impact on society, or both. To make all indicators consistent, we had to ensure that a higher indicator value indicates a move in the desired direction. Therefore, we assigned a negative sign to the indicators whose desired direction was negative. A similar approach was taken, for example, by the OECD (2019) and Ronzon and Sanjuan (2020). In the case of indicators whose optimal value is zero, we took their absolute value and assigned a negative sign to it.

Table 3.2: List of the indicators used in this study

Code	Description	Desired Direction
cei_cie010	Value added at factor costs (Mio Euro)	+
cei_cie010	Value added at factor costs (% of GDP)	+
cei_cie010	Gross investment in tangible goods (Mio Euro)	+
cei_cie010	Gross investment in tangible goods (% of GDP)	+
cei_cie010	Persons employed (umber)	+
cei_cie010	Persons employed (% of total employment)	+
cei_wm030	Recycling of biowaste (kg per capita)	+
sdg_02_20	Agricultural factor income per annual work unit	+
sdg_02_30	Government support to agricultural research and development (Mio Euro)	+
sdg_02_30	Government support to agricultural research and development (Euro per inhabitant)	+
sdg_02_40	Area under organic farming - % of utilised agricultural area (UAA)	+
sdg_02_50	Gross nutrient balance on agricultural land by nutrient (nitrogen)	0
sdg_02_50	Gross nutrient balance on agricultural land by nutrient (phosphorus)	0
sdg_02_60	Ammonia emissions from agriculture (tonne)	-
sdg_02_60	Ammonia emissions from agriculture (kg/ha)	-
sdg_04_20	Tertiary educational attainment by sex (total)	+
sdg_04_50	Employment rates of recent graduates by sex (total)	+
sdg_04_60	Adult participation in learning by sex (total)	+
sdg_07_10	Primary energy consumption (Mio tonnes of oil equivalent)	-
sdg_07_30	Energy productivity (Euro per kg of oil equivalent)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (total)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (transport)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (electricity)	+
sdg_07_40	Share of renewable energy in gross final energy consumption by sector (heating and cooling)	+
sdg_08_30	Real GDP per capita – Chain linked volumes (% on previous period, per capita)	+
sdg_08_40	Long-term unemployment rate by sex (total)	-
sdg_09_10	Gross domestic expenditure on R&D by sector – Higher education sector	+
sdg_09_20	Employment in knowledge-intensive services	+

Table 3.2: List of the indicators used in this study

Code	Description	Desired Direction
sdg_09_20	Employment in high- and medium-high technology manufacturing	+
sdg_09_30	R&D personnel by sector - Business enterprise sector (% of active population)	+
sdg_09_30	R&D personnel by sector - Government sector (% of active population)	+
sdg_09_30	R&D personnel by sector - Higher education sector (% of active population)	+
sdg_09_40	Patent applications to the European Patent Office (number)	+
sdg_09_40	Patent applications to the European Patent Office (per million inhabitants)	+
sdg_11_60	Recycling rate of municipal waste (% of total waste generated)	+
sdg_12_41	Circular material use rate (% of material input for domestic use)	+
sdg_13_10	Greenhouse gas emissions (base year 1990)	-
sdg_13_10	Greenhouse gas emissions (tonnes per capita)	-
sdg_14_10	Surface of marine sites designated under NATURA 2000 (km^2)	+

Note: "+" denotes indicators that progress with a higher value; "-"denotes indicators that regress with a higher value; and "0" denotes indicators whose desired value is zero.

In this way, the positive and negative deviations from the optimum were treated equally. Table 3.2 shows the desired directions of all the indicators; we adopted the directions of SDG bioeconomy indicators from Eurostat (2019). The circular economy indicators are all designed so that an increase means a move in the desired direction. Having prepared our data, we applied our methodology to the indicator framework, as outlined in the following section.

3.4. METHODOLOGY

3.4.1. Z-scores

We analyze the evolution of the bioeconomies in Finland, France, Germany, Italy, Latvia, The Netherlands, Poland, Portugal, Slovakia, and Spain in the period of 2006–2016. We first examined the movements over time of all circular bioeconomy indicators together and compared them across countries. We then analyzed the dynamics of circular bio-economy indicators using Markov transition matrices.

As all indicators have different units and magnitudes, they need to be normalized for meaningful comparison and aggregation. Although several normalization methods exist, they suffer from deficiencies, as pointed out in Section 3.2.2. We calculated the z-score (standard score) for each indicator to put our data onto a standardized scale. The z-score of a given indicator in a given year measures how many standard deviations the indicator value is away from the indicator's mean. A positive z-score denotes a value above the mean, and a negative z-score corresponds to a value below the mean over the whole period. The z-score of indicator *i* in year *t* is given by

$$z_{it} = \frac{x_{it} - \overline{x}_i}{s_i} \quad (1)$$

where x_{it} is the value of an indicator, $\overline{x}_i$ is the temporal mean of indicator *i*, and s_i is the indicator's temporal standard deviation. Using equation (1) for normalizing our indicators allowed us to aggregate them, giving equal weight to all indicators, and track their movement over time. To rank the normalized indicators according to the 'speed' of their development over time, we calculated the slope parameter of a linear regression of a z-score of indicator *i* on time as shown in equation (2)

$$\hat{\beta}_i = \frac{Cov[t, z_i]}{Var[t]} \quad (2)$$

We used parameter $\hat{\beta}_i$ as a measure to rank the indicators and did not examine whether there was a statistically significant relationship. A larger value of $\hat{\beta}$ corresponds to a faster-progressing indicator.

3.4.2. Markov transition matrices

To analyze the dynamics of the circular bioeconomy, we needed to understand the development of the intra-distribution of indicators over time. Z-scores allowed us to rank the indicators according to their change over years and define a distribution of these changes. We calculated the quartiles of the z-scores across all indicators for each year and used them as boundaries to divide the indicators into quarters: from Q_1, the indicators with the lowest z-scores, to Q_2 and Q_3, with the medium-low and medium-high z-scores, to Q_4, the indicators with the highest z-scores. We then used the quarters to construct Markov transitions matrices.

Following Quah (1993; 1996) and Zaghini (Zaghini, 2005), we modeled the development of the intra-distribution of indicators over time using Markov transition matrices. These matrices were used in the cross-country growth literature to analyze income convergence (e.g. Quah, 1993; 1996). To build a Markov chain, we need a transition matrix and an initial distribution. Assuming a finite set $S = \{1, \ldots, m\}$ of states, a real number p_{ij} must be assigned to each pair $(i, j) \in S^2$ of states, ensuring that the properties

$$p_{ij} \geq 0 \quad \forall (i, j) \in S^2 \quad (3)$$

$$\sum_{j \in S} p_{ij} = 1 \quad \forall i \in S \quad (4)$$

are satisfied. The transition matrix **P** can be defined as follows:

$$P = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{pmatrix} \quad (5)$$

where the value of each cell is a transition probability, that is, the probability that an indicator from segment *i* moves to segment *j* in the next year. We calculated the transition probabilities for each period by counting the number of transitions between intervals of the relative change of indicator levels.

3

We compared the mobility (i.e., the extent of indicator movement among quarters) between different periods and countries with two metrics proposed by Shorrocks (1978):

$$M_1 = \frac{n - \mathrm{tr}(\mathrm{P})}{n-1} \tag{6}$$

and

$$M_2 = 1 - \left|\det(\mathrm{P})\right| \tag{7}$$

where *n* is the order of a square transition matrix P, *tr(P)* is its trace (i.e., the sum of elements on the main diagonal), and *det*(*P)* is its determinant.

For both metrics, a higher value suggests a higher indicator mobility between segments, while zero indicates no mobility at all. However, both metrics can still lead to different outcomes, as they measure different types of mobility. M_1 relates only to the trace of the transition matrix and therefore measures the ratio between diagonal and off-diagonal transition probabilities. The metric M_2 uses the determinant of the transition matrix and therefore measures all changes in the matrix.

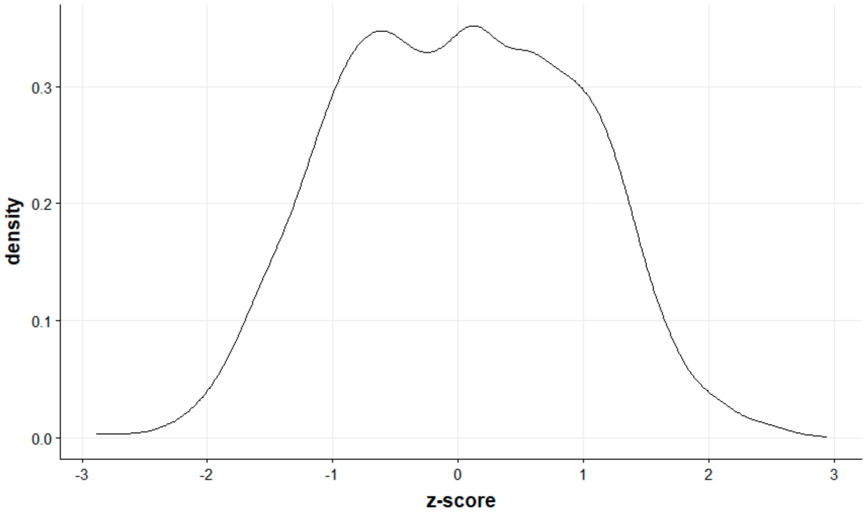
3.5. RESULTS

3.5.1. The external shape of the distribution of circular bioeconomy indicators

To analyze the movement of all circular bioeconomy indicators, we examined the external shape of the z-score distribution across all countries over time. The graph in Figure 3.1 shows that the aggregated distribution comes close to a normal distribution, which results from the calculation of a z-score, and that most indicators have a z-score between -2 and 2. In the graph in Figure 3.2, the distribution for each consecutive year shifts to the right and therefore peaks at a higher z-score level. Circular bioeconomy indicators, on average, improve over time for the EU-10 aggregate.

To further describe and analyze the external shape of the distribution of circular bioeconomy indicators, we present brief descriptive statistics for the EU-10 in Table 3.3. It shows that the EU-10 mean z-score progressed from -0.622 in 2006 to 0.466 in 2016.

Figure 3.1:Indicator distribution over the whole period for all countries (Kernel density estimates)



Note: The graph shows the density estimates for the z-scores aggregated across all indicators and years.

This progression is nearly continuous over the whole period except for an interruption between 2008 and 2010. The national bioeconomies' developments confirm this positive trend to varying extents. Germany progressed from a mean of -1.001 in 2006 to 0.769 in 2016; Slovakia increased its mean by 1.504 from 2006 to 2016 and Portugal by 1.186. Finland progressed the least, from a mean of -0.35 in 2006 to only 0.045 in 2016.

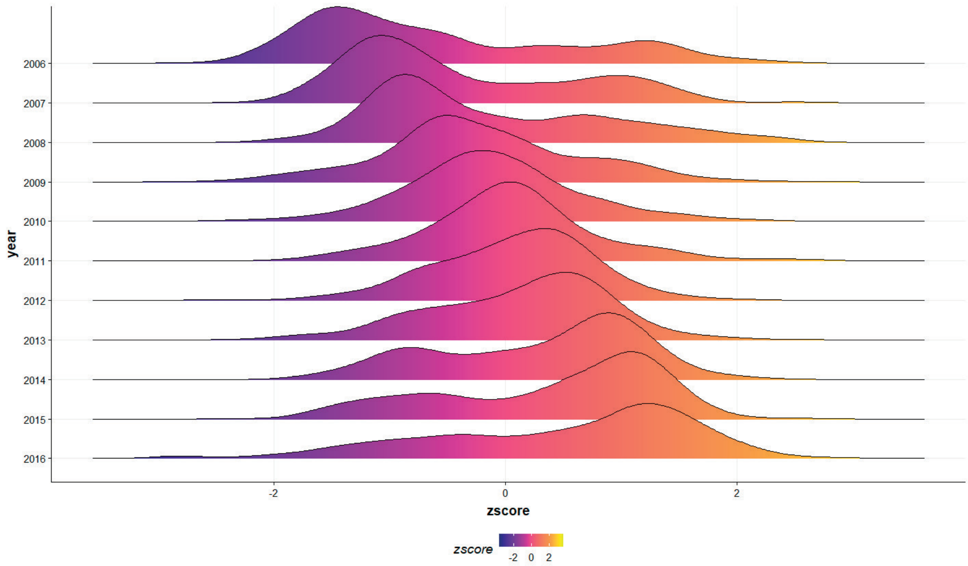
Latvia, The Netherlands, Poland, Italy, Spain, and France have successively greater progress but still lag behind Germany and Slovakia. The range of z-scores for the EU-10 is generally higher in the first four years of the examined period, then relatively low around 2.5 from 2010 to 2013, before increasing again in 2014 and 2016.

Figure 3.3 confirms the generally positive trend as the median (the band inside the box) increases over time in the EU-10. The interquartile range (the width of the box) is comparable to the range and shows a similar picture. In the middle of the period (2010–2012),

Table 3.3: Descriptive statistics from the standardized indicator distribution

	EU-10										
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Mean	-0.622	-0.430	-0.122	-0.155	-0.122	0.052	0.081	0.138	0.310	0.405	0.466
Median	-0.954	-0.758	-0.476	-0.248	-0.164	0.029	0.175	0.286	0.555	0.706	0.733
St. dev.	1.113	0.953	1.005	0.842	0.735	0.716	0.677	0.761	0.858	0.941	1.134
Range	5.339	4.972	4.359	5.044	4.885	4.621	4.554	4.800	4.096	4.832	5.747

Figure 3.2: Indicator distribution by year for all countries (Kernel density estimates)

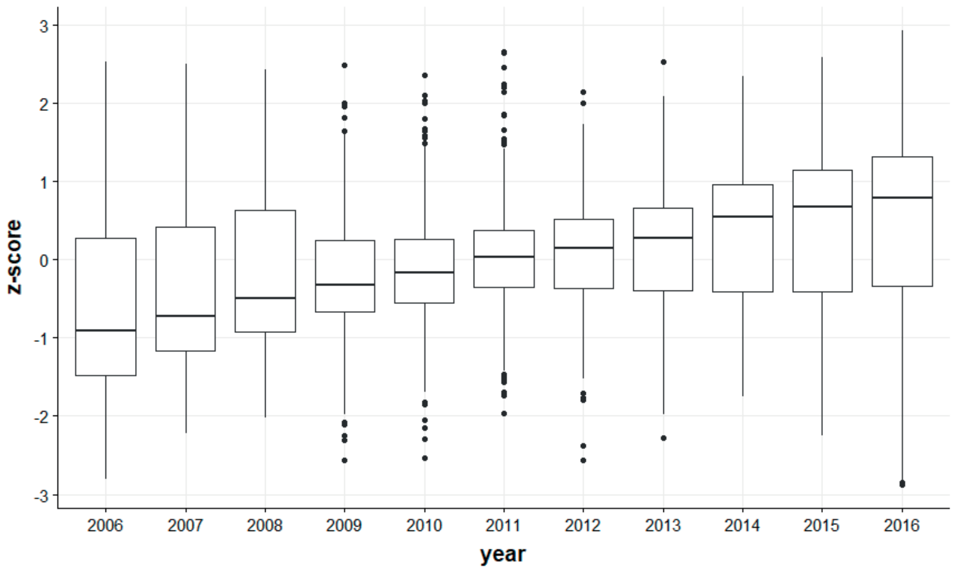


Note: The graph shows the temporally disaggregated z-scores for all indicators.

it is generally lower than at the beginning and end. With some small deviations, the same trend can be seen in the development of circular bioeconomy indicators in each country (Appendix A).

We ranked all 41 indicators from best to worst according to the development of their z-scores over time. Table 3.4 presents the five best and worst indicators for all countries, which shows how their circular bioeconomies are progressing or regressing. The rate of progress was among the highest for the share of renewable energy in gross final energy consumption in all countries except Italy. The indicators for the share of renewable energy do not differentiate between the type of renewable energy and do not allow to assess the progress with respect to bioenergy only. However, in 2017, the largest part of renewable energy was still biofuels and renewable waste in all EU-10 countries and therefore, it is likely that bioenergy played a major role in the progress of the share of renewable energy (Bórawski et al., 2019). Also, biowaste recycling, the recycling rate of municipal waste, and the circular material use rate were among the most-improving indicators in seven of the ten countries. By contrast, a negative development took place for ammonia emissions and the nutrient balance on agricultural land in Germany, Latvia, and Slovakia. At least one economic indicator for private investments, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

Figure 3.3: Developmentof circular bioeconomy indicators in the EU-10 from 2006 to 2016 as box plots.



Note: A box plot illustrates the z-scores for each year. The band inside the box corresponds to the median and the width of the box to the interquartile range. The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to outliers beyond the range of the whiskers

In contrast, the percentage of total employment for circular economy sectors increased sharply in Spain, Latvia, and Portugal. This development is ambiguous for indicators related to R&D. The indicators for patent applications are among the worst in Germany, Italy, and France, while they are among the best in Poland. On the one hand, indicators related to public expenditure, agricultural research and development, higher education, and government are among the worst in Spain, Finland, The Netherlands, and Poland, but indicators related to R&D personnel or R&D expenditure in the business enterprise sector are among the best in Germany, France, and Italy.

Table 3.4: The most progressing and the most regressing indicators in the period 2006–2016

Most progressing indicators		Most regressing indicators	
	β		β
Germany			
Share of renewable energy in gross final energy consumption – electricity	0.300	Patent applications to the European Patent Office (total number)	-0.291
Share of renewable energy in gross final energy consumption – all sectors	0.299	Patent applications to the European Patent Office (number per million inhabitants)	-0.288
Employment rate	0.294	Ammonia emissions from agriculture (kg per hectare)	-0.288
Recycling of biowaste	0.293	Ammonia emissions from agriculture (tonnes)	-0.278
R&D personnel – business enterprise sector	0.292	Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP	-0.172
Finland			
Area under organic farming	0.298	Employment in knowledge-intensive services	-0.295
Recycling rate of municipal waste	0.296	Circular material use rate	-0.294
Share of renewable energy in gross final energy consumption – heating and cooling	0.295	R&D personnel – government sector	-0.277
Share of renewable energy in gross final energy consumption – all sectors	0.292	R&D personnel – higher education sector	-0.272
Employment in high- and medium-high technology manufacturing	0.292	Gross domestic expenditure on R&D – higher education sector	-0.234
The Netherlands			
Share of renewable energy in gross final energy consumption – all sectors	0.296	Government support for agricultural R&D (million euros)	-0.267
Tertiary educational attainment	0.291	Government support for agricultural R&D (euros per capita)	-0.264
Share of renewable energy in gross final energy consumption – heating and cooling	0.286	Long-term unemployment rate	-0.246
Recycling rate of municipal waste	0.284	Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	-0.242
Share of renewable energy in gross final energy consumption – transport	0.282	Employment rate of recent graduates	-0.236

Most progressing indicators	β	Most regressing indicators	β
France			
R&D personnel – higher education sector	0.302	R&D personnel – government sector	-0.302
R&D personnel – business enterprise sector	0.302	Employment in high- and medium-high technology manufacturing	-0.290
Recycling rate of municipal waste	0.301	Long-term unemployment rate	-0.258
Share of renewable energy in gross final energy consumption – heating and cooling	0.299	Employment rate of recent graduates	-0.253
Employment in knowledge-intensive services	0.298	Gross domestic expenditure on R&D – government sector	-0.250
Poland			
Tertiary educational attainment	0.299	Energy productivity	-0.294
Share of renewable energy in gross final energy consumption – electricity	0.298	Surface of marine sites designated under NATURA 2000	-0.293
Patent applications to the European Patent Office (number per million inhabitants)	0.298	Gross domestic expenditure on R&D – business enterprise sector	-0.280
Patent applications to the European Patent Office (total number)	0.298	Adult participation in learning	-0.255
Share of renewable energy in gross final energy consumption – heating and cooling	0.296	Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP	-0.183
Slovakia			
Tertiary educational attainment	0.297	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – % of GDP	-0.229
Energy productivity	0.295	Adult participation in learning	-0.223
Share of renewable energy in gross final energy consumption – electricity	0.292	Gross nutrient balance on agricultural land – phosphorous	-0.206
Greenhouse gas emissions (index 1990 = 100)	0.290	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – million euros	-0.194
Share of renewable energy in gross final energy consumption – all sectors	0.289	Employment rate of recent graduates	-0.091
Italy			
Recycling rate of municipal waste	0.298	Patent applications to the European Patent Office (number per million inhabitants)	-0.278
Gross domestic expenditure on R&D – business enterprise sector	0.296	Long-term unemployment rate	-0.278
Recycling of biowaste	0.296	Private investments, jobs and gross value added related to circular economy sectors - percentage of total employment [V16111]	-0.277

Most progressing indicators		Most regressing indicators	
	β		β
Circular material use rate	0.296	Employment rate of recent graduates	-0.274
Tertiary educational attainment	0.295	Private investments, jobs and gross value added related to circular economy sectors - Persons employed - number	-0.272
Spain			
Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	0.297	Circular material use rate	-0.293
Share of renewable energy in gross final energy consumption – all sectors	0.294	Long-term unemployment rate	-0.267
Share of renewable energy in gross final energy consumption – heating and cooling	0.292	Government support for agricultural R&D (euros per capita)	-0.265
Share of renewable energy in gross final energy consumption – electricity	0.291	Government support for agricultural R&D (million euros)	-0.259
Energy productivity	0.285	Employment rate of recent graduates	-0.252
Portugal			
Employment in knowledge-intensive services	0.300	R&D personnel – government sector	-0.283
Tertiary educational attainment	0.299	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – % of GDP	-0.266
Share of renewable energy in gross final energy consumption – electricity	0.298	Gross domestic expenditure on R&D – government sector	-0.249
Share of renewable energy in gross final energy consumption – all sectors	0.294	Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – million euro	-0.249
Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	0.294	Employment rate of recent graduates	-0.241
Latvia			
Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111]	0.299	Ammonia emissions from agriculture (tonnes)	-0.286
Surface of marine sites designated under NATURA 2000	0.298	Ammonia emissions from agriculture (kg per hectare)	-0.266
Tertiary educational attainment	0.293	Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP	-0.264
Share of renewable energy in gross final energy consumption – electricity	0.288	Private investments, jobs, and gross value added related to circular economy sectors – ross investment in tangible goods – % of GDP	-0.252
Circular material use rate	0.282	Gross nutrient balance on agricultural land – nitrogen	-0.245

3.5.2. Intra-distribution dynamics of the circular bioeconomy

To analyze the dynamics of the selected circular bioeconomies, we model the development of the intra-distribution of indicators over time using Markov transition matrices. The matrices are constructed by tracing how each indicator changes its position relative to other indicators between two periods. To keep things manageable and to ease the interpretation of the results, in each year, we assign the indicators to quarters according to the quartiles for a given year, based on the value of an indicator's z-score. Indicators in the first quarter (Q1) have the lowest z-scores and those in the fourth quarter (Q4) have the highest z-scores. The indicators in Q2 perform better than in Q1 but worse than in Q3, which in turn performs worse than in Q4.

Now we are in a position to follow each indicator between any two points in time (e.g., t and t + 1 or t + 10) and determine whether the indicator has stayed in the same quarter or has left it for some other quarter. By calculating the proportions of individual moves from a given quarter at time t into any quarter at t + 1, we estimate the transition matrices as presented in Table 3.5.

The left-hand side of Table 3.5 presents averages of one-year transition matrices in the period 2006–2016, while the right-hand side presents one transition matrix for each country over the whole period (i.e., ten years). To ease the interpretation of results, let us have a look at the one-year transition probabilities of Germany. For example, the value 0.50 (Q1, Q1) means that 50 percent of indicators that were in Q1 in one year, stayed in Q1 also in the next year. Similarly, 11 percent (Q1, Q4) of indicators that started in Q1 in one year improved their performance by moving to Q4 in the next year. The final example shows that 14 percent (Q4, Q1) of highly-ranked indicators that started in Q4 in one year worsened their performance by moving to Q1 in the next year.

The diagonal values of the transition matrices depict how dynamic a circular bioeconomy is in a country. If the diagonal values are higher than the non-diagonal values, more indicators stay in their quarters from one year to the next. Hence, the indicators grow or decline in a homogenous manner.

We can illustrate a country that has been less dynamic in the short term by comparing the one-year transition matrices of Portugal and Germany. For Portugal, the diagonal values are relatively high; for example, 65% of the indicators stayed in the best-performing quarter (Q4) from year to year. In contrast, in Germany, the probability for indicators to stay in their initial quarters was generally lower, with 53% staying in Q4 and approximately 25% staying in Q2 and Q3. This comparison shows that the intra-distribution of circular bioeconomy indicators fluctuates less in Portugal.

Table 3.5: Short-term and long-term transition matrices for all countries

One-year transition matrix					Ten-year transition matrix				
Germany									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.50	.24	.18	.08	Q_1	.00	.30	.10	.60
Q2	.34	.43	.16	.07	Q_2	.10	.30	.30	.30
Q3	.07	.23	.37	.33	Q_3	.10	.30	.40	.20
Q4	.09	.10	.26	.55	Q_4	.73	.09	.18	.00
Ergodic	.250	.248	.242	.260	Ergodic	.245	.244	.243	.269
France									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.46	.32	.12	.10	Q_1	.00	.30	.50	.20
Q2	.26	.37	.22	.16	Q_2	.00	.10	.30	.60
Q3	.15	.17	.42	.26	Q_3	.20	.30	.20	.30
Q4	.12	.13	.24	.52	Q_4	.73	.27	.00	.00
Ergodic	.243	.243	.250	.263	Ergodic	.245	.243	.244	.268
Poland									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.58	.28	.09	.05	Q_1	.00	.30	.40	.30
Q2	.23	.35	.23	.18	Q_2	.00	.45	.27	.18
Q3	.14	.17	.38	.32	Q_3	.33	.11	.11	.44
Q4	.07	.17	.20	.56	Q_4	.73	.18	.00	.09
Ergodic	.254	.242	.218	.286	Ergodic	.252	.288	.211	.249
Slovakia									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.47	.27	.13	.13	Q_1	.00	.40	.50	.10
Q2	.27	.32	.23	.17	Q_2	.10	.10	.30	.50
Q3	.14	.29	.32	.25	Q_3	.20	.30	.10	.40
Q4	.11	.11	.29	.50	Q_4	.64	.18	.09	.09
Ergodic	.245	.245	.243	.267	Ergodic	.245	.244	.244	.268
Italy									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.55	.27	.11	.07	Q_1	.00	.00	.50	.50
Q2	.26	.40	.23	.11	Q_2	.10	.10	.50	.30
Q3	.12	.22	.33	.33	Q_3	.30	.40	.00	.30
Q4	.06	.11	.30	.53	Q_4	.55	.45	.00	.00
Ergodic	.243	.248	.244	.265	Ergodic	.245	.243	.244	.268
Spain									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.53	.33	.10	.04	Q_1	.30	.10	.40	.20
Q2	.28	.39	.24	.09	Q_2	.00	.00	.40	.60
Q3	.13	.17	.41	.29	Q_3	.30	.30	.10	.30
Q4	.05	.10	.22	.63	Q_4	.36	.55	.09	.00
Ergodic	.241	.243	.242	.275	Ergodic	.243	.245	.244	.269
Portugal									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.53	.30	.13	.04	Q_1	.10	.20	.50	.20
Q2	.30	.38	.19	.13	Q_2	.10	.20	.20	.50

Table 3.5: Short-term and long-term transition matrices for all countries

One-year transition matrix					Ten-year transition matrix				
Q3	.09	.19	.48	.25	Q_3	.30	.10	.20	.40
Q4	.06	.10	.19	.65	Q_4	.45	.45	.09	.00
Ergodic	.233	.234	.246	.288	Ergodic	.244	.244	.244	.268
Latvia									
	Q_1	Q_2	Q_3	Q_4		Q_1	Q_2	Q_3	Q_4
Q1	.53	.22	.18	.07	Q_1	.10	.10	.40	.40
Q2	.22	.37	.26	.16	Q_2	.20	.10	.30	.40
Q3	.16	.26	.33	.25	Q_3	.00	.60	.20	.20
Q4	.08	.14	.22	.56	Q_4	.64	.18	.09	.09
Ergodic	.243	.244	.247	.267	Ergodic	.245	.243	.244	.268

Source: own calculations

Comparing short- and long-term matrices, it is evident that over a ten-year period, the probability of an indicator to shift from one quarter to another is more likely than over a one-year period.

This disparity is intuitive because one would expect that, over a longer period, indicators progress or regress at different speeds. However, what stands out in this table is the extent of the disparity between short- and long-term matrices. Not a single probability exceeds a 50% likelihood of staying in one quarter; the highest is for Poland to stay in Q2 with a probability of 45%. The probability of staying in the medium-performing quarters (Q2 and Q3) is also higher than in the least-performing quarter (Q1) and the best-performing quarter (Q4). In contrast, for the short-term matrices, this tendency is, to a lesser extent, the opposite.

Table 3.6 provides an overview of short-term mobility for one-year matrices (in M1 and M2) divided into averages for two periods: 2007–2011 and 2012–2016. This overview allows us to see whether mobility was higher in the first five or second five years of the given period. In 2007–2011, the country with the highest mobility (0.832) was Germany, which decreased to 0.810 in 2012–2016. The table shows a decline in short-term mobility in seven of the ten countries. The decline was especially substantial in Finland and The Netherlands, each going down by 0.18. In Italy, however, short-term mobility was stable; only in Poland and Slovakia did mobility increase by 0.03 and 0.07, respectively. Table 3.6 also shows mobility indices for one-year and ten-year transition matrices, that is, short-term and long-term dynamics. According to M1, mobility is higher over ten years than over one year in all countries.

Table 3.6: Mobility Metrics

Short-term mobility in two periods						
Country	One-year 2007–2011		One-year 2012–2016		Change in Mobility	
	M_1	M_2	M_1	M_2	ΔM_1	ΔM_2
Germany	0.83	0.96	0.81	0.98	-0.02	0.02
Finland	0.83	0.98	0.65	0.97	-0.18	0.00
The Netherlands	0.80	0.95	0.63	0.97	-0.18	0.02
France	0.77	0.97	0.73	0.98	-0.04	0.01
Poland	0.68	0.98	0.75	0.99	0.07	0.01
Slovakia	0.78	0.98	0.81	0.99	0.03	0.01
Italy	0.73	0.98	0.73	0.98	0.00	-0.01
Spain	0.69	0.94	0.67	0.96	-0.02	0.02
Portugal	0.72	0.94	0.59	0.96	-0.12	0.02
Latvia	0.80	0.98	0.67	0.92	-0.13	-0.07

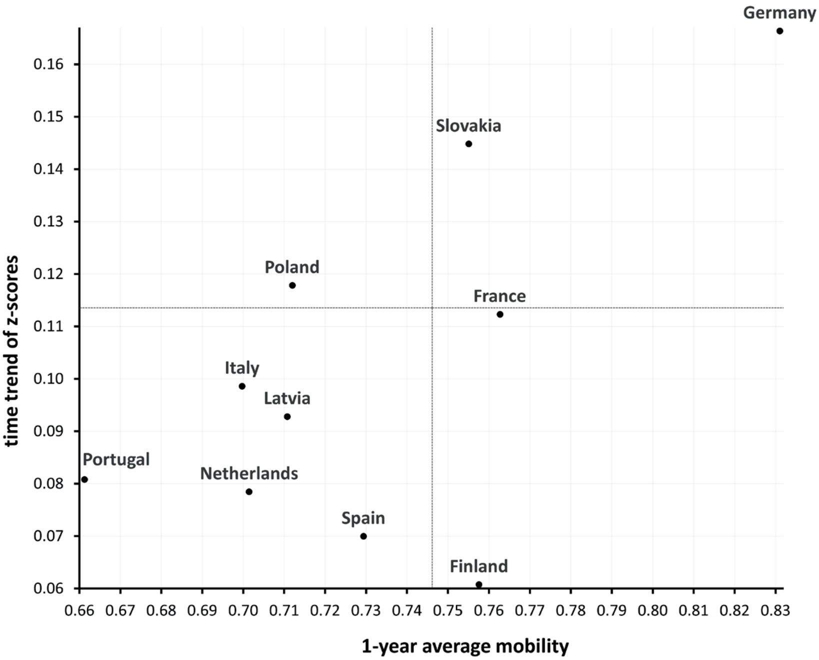
Short-term and long-term mobility						
Country	One-year		Ten-year		Change in Mobility	
	M_1	M_2	M_1	M_2	ΔM_1	ΔM_2
Germany	0.82	0.97	1.13	0.98	0.31	0.01
Finland	0.74	0.98	1.23	0.97	0.49	-0.01
The Netherlands	0.72	0.96	1.10	1.00	0.38	0.03
France	0.75	0.98	1.23	0.98	0.49	0.00
Poland	0.71	0.98	1.11	0.98	0.40	0.00
Slovakia	0.79	0.99	1.24	0.96	0.44	-0.03
Italy	0.73	0.98	1.30	0.99	0.57	0.01
Spain	0.68	0.95	1.20	0.98	0.52	0.03
Portugal	0.65	0.95	1.17	0.97	0.51	0.02
Latvia	0.74	0.95	1.17	0.99	0.43	0.04

Source: Own calculations

To assess the movement of the whole distribution of z-scores over time, we regressed z-scores on a time variable. The result was a significant slope coefficient for all countries. Figure 3.4 depicts the relation between the mobility according to M1, and the z-score slope. We can observe a general pattern of a higher slope with a higher level of mobility. This pattern is unexpected because we previously found an increase in indicators' z-scores and a decrease in mobility over time.

The graph shows that Germany's and Slovakia's bioeconomies improved the fastest while also maintaining the highest short-term mobility. Portugal and Spain experienced relatively slow progress in their bioeconomies while also maintaining low short-term mobility. In contrast to this trend, Finland's bioeconomy had average short-term mobility but improved the slowest. The remaining countries can be found in the middle of the spectrum.

Figure 3.4: Correlation of average one-year mobilities (M1) and time trend of z-scores between countries.



Note: The dotted horizontal and vertical lines depict the averages of the minimum and maximum values.

3.6. CONCLUSIONS

In this quantitative study, we showed the similarities and differences in the dynamic evolution of a wide range of indicators for circular bioeconomies in ten EU Member States. We developed a novel framework in which we normalized indicators with various units and dimensions and then investigated patterns using Markov transition matrices. Our framework allowed us to understand indicators that cover various economic, environmental, and social aspects of a circular bioeconomy.

We found that the evolutions of the EU-10 circular bioeconomies were generally progressive considering all indicators; however, this development was not homogeneous. While most of the EU-10 rapidly progressed in their shares of renewable energy and recycling and circular material use rates, agro-environmental indicators rapidly regressed in Germany, Latvia, and Slovakia. Economic indicators related to circular-economy sectors were among the worst indicators in six countries and among the best in only three countries. The indicators related to R&D generally progressed quickly in the private sector and regressed in the public sector, which suggests that one substituted for the other.

Our results show that the circular bioeconomy is multi-faceted and that, while it generally progressed during the study period, not all indicators moved in the desired direction. This pattern is exemplified in Germany's circular-bioeconomy indicators, which progressed the most on average in comparison to the rest of the EU-10. At the same time, intra-distribution dynamics were also high for Germany: indicators sharply differed in their developments, and their relative rankings strongly varied in consecutive years. Indicators, such as patent applications and ammonia emissions from agriculture, even regressed rapidly. We recommend that policymakers consider all indicators and not only a few because a country with highly dynamic indicators seems to progress differently in economic, environmental, and social aspects. Therefore, examining only a few indicators can bias the picture of a country's circular bioeconomy.

Moreover, our cross-country comparison revealed that circular bioeconomies develop at different paces. Circular bioeconomies in Slovakia, Poland, and Latvia developed quickly in comparison to the rest of the EU-10. Their substantial relative progress from 2006 to 2016 was particularly unexpected because their governments have not implemented any policy actions at national level for the circular bioeconomy during that period. However, D'Adamo et al. (2020b) found that Slovakia, Poland, and Latvia are still lagging behind the rest of the EU in terms of socio-economic performance. Therefore, the rapid development of circular bioeconomies in Slovakia, Poland, and Latvia may be partly explained by a catch-up effect on highly developed circular bioeconomies such as The Netherlands. This finding is consistent with Ronzon and M'Barek (2018), who emphasized the potential of the bioeconomy in Central and Eastern Europe.

In contrast, the circular bioeconomies in Finland, Spain, The Netherlands, and Portugal improved the slowest, even though they have dedicated national bioeconomy strategies. Moreover, Finland and The Netherlands have additional policy and green-growth strategies. Perhaps the impacts of these policy strategies are limited and more concrete policy actions are needed, such as an economy-wide carbon tax or targeted investments in bio-industrial initiatives (Philippidis et al., 2018). It is also possible that more time is needed for these strategies to take effect.

We faced significant challenges in compiling the data needed for our framework. After we had selected our indicators according to their relevance to the circular bioeconomy and data availability, only 41 indicators remained. This number of items is feasible but possibly affects the robustness of the results using Markov transition matrices. As soon as additional indicators become available, this issue could be easily addressed by future studies. Moreover, we analyzed the directions, speeds, and dynamics of circular bioeconomies, but we could not assess their initial states with our framework. In an unlikely but theoretically possible case, a circular bioeconomy could already be at its steady state at the beginning of the study period, so zero progress in its indicators' z-scores would not be problematic. This problem could be solved if quantitative targets for all indicators were determined, which would allow us to assess the distance from realizing those targets.

Another limitation of our study is that we mostly use 'bioeconomy-related' indicators from the SDGs because an established comprehensive indicator framework is absent for the bioeconomy. However, contributing to the SDGs is a major objective of policy strategies targeting the circular bioeconomy, such as the 2018 EU Bioeconomy Strategy (European Commission, 2018). A downside of our results is that not all of these indicators are intended to measure the progress or impact of the circular bioeconomy but more general aspects of sustainable development. For instance, the indicators on the share of renewable energy include types other than bioenergy. Therefore, including more indicators specific to the circular bioeconomy would yield more precise results. As comprehensive indicator frameworks for the circular bioeconomy have already been proposed, we expect more indicators to become available in the future.

With more indicators available in the future, creating, for example, economic, environmental, or social indicator groups to compare their developments and dynamics might produce interesting results. We expect the intra-distribution dynamics to be lower for indicators within groups than for ungrouped indicators. More countries should also be added to the analysis, especially countries with large circular bioeconomies outside the EU, such as the United States and China. We anticipate that more circular bioeconomy indicators for current and additional countries will be collected, the evolution of which our framework can help to analyse.

3.A APPENDIX. DEVELOPMENT OF CIRCULAR BIOECONOMY INDICATORS IN TEN SELECTED EUROPEAN UNION MEMBER STATES FROM 2006 TO 2016 AS BOX PLOTS

Figure 3.A.1: Germany

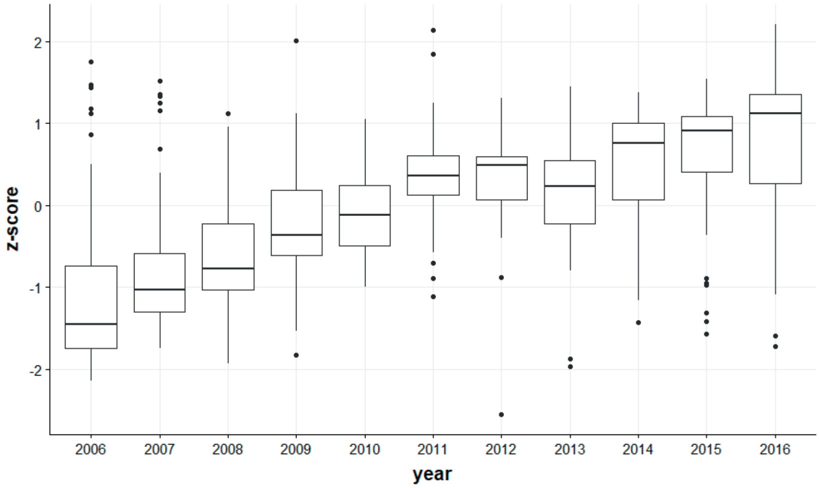


Figure 3.A.2: Finland

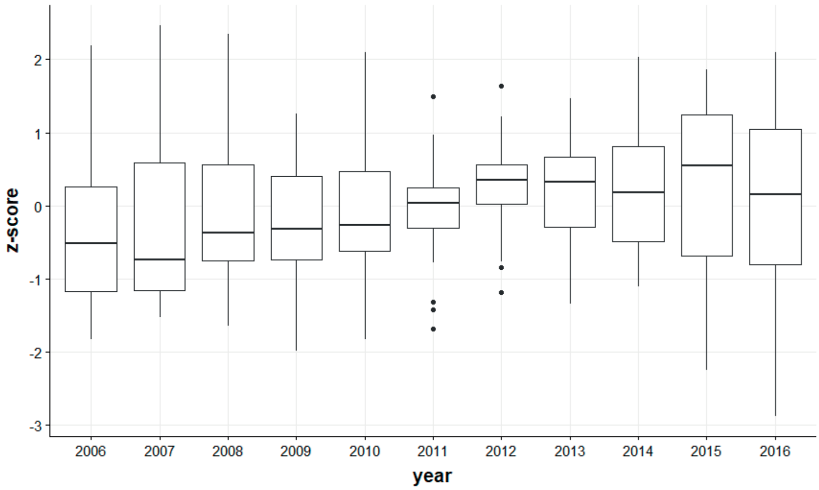


Figure 3.A.3: The Netherlands

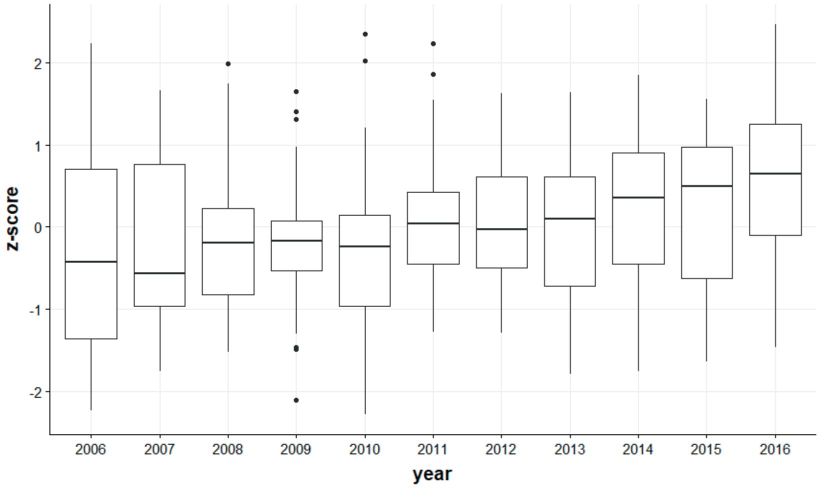


Figure 3.A.4: France

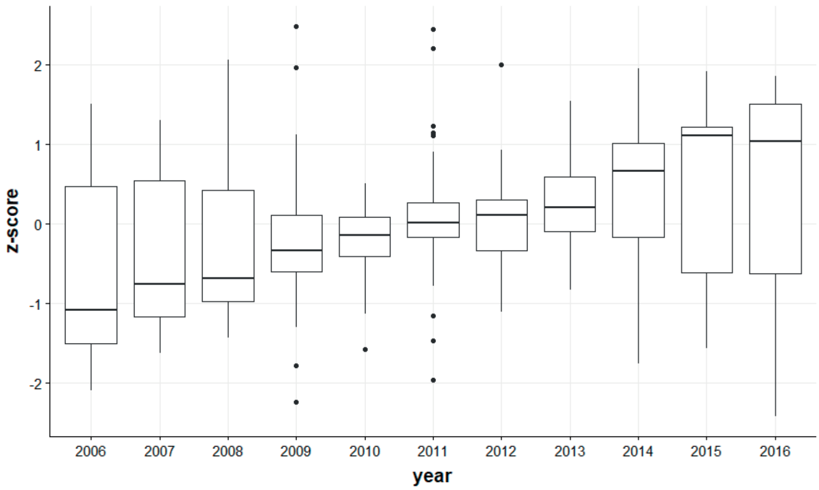


Figure 3.A.6: Slovakia

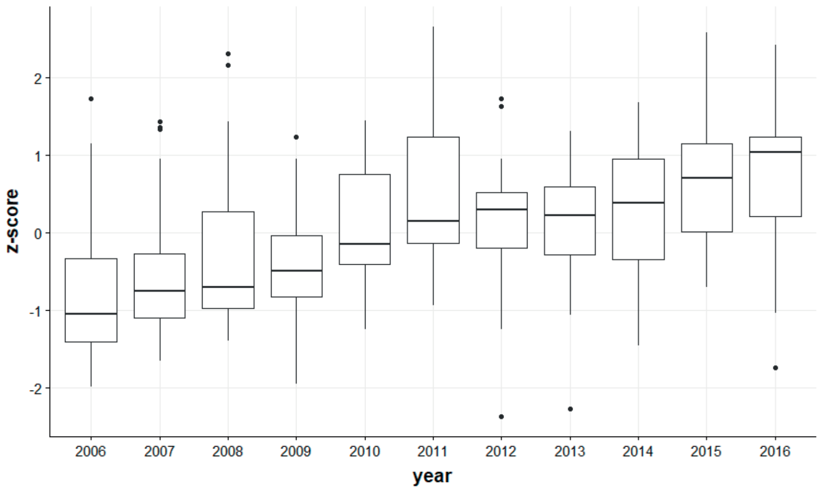


Figure 3.A.7: Italy

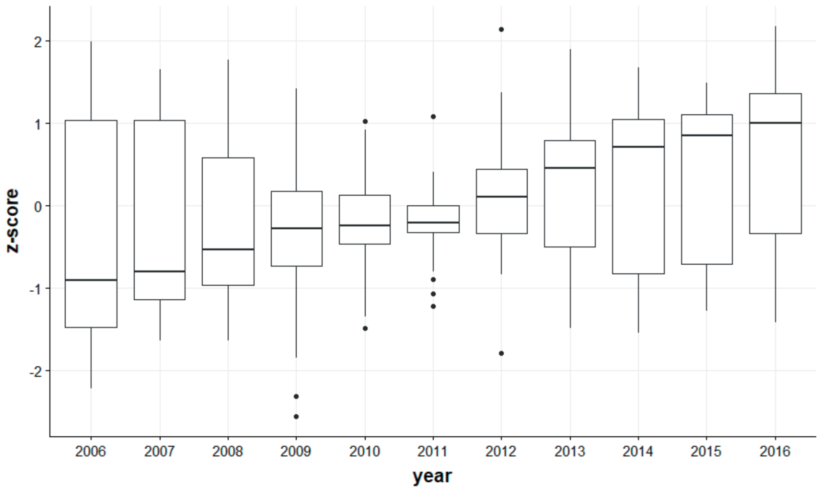


Figure 3.A.8: Spain

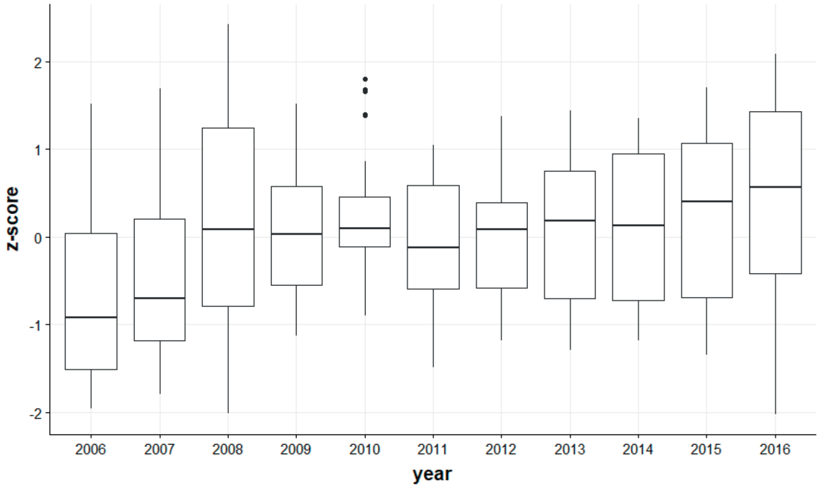


Figure 3.A.9: Portugal

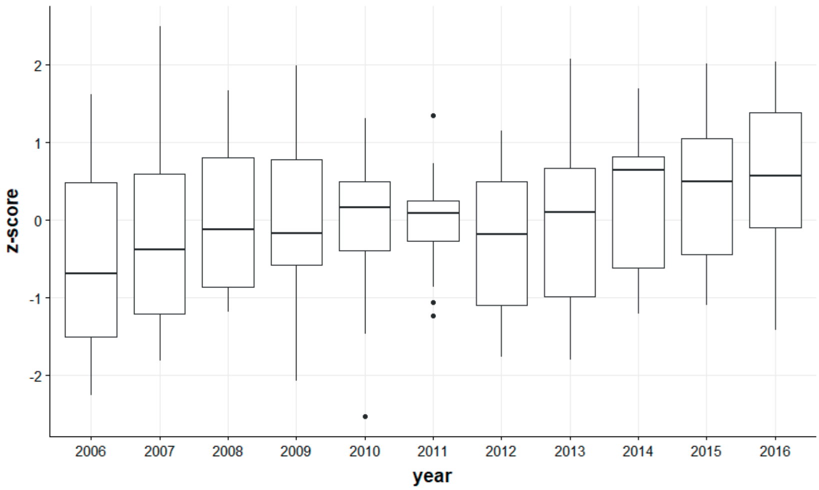
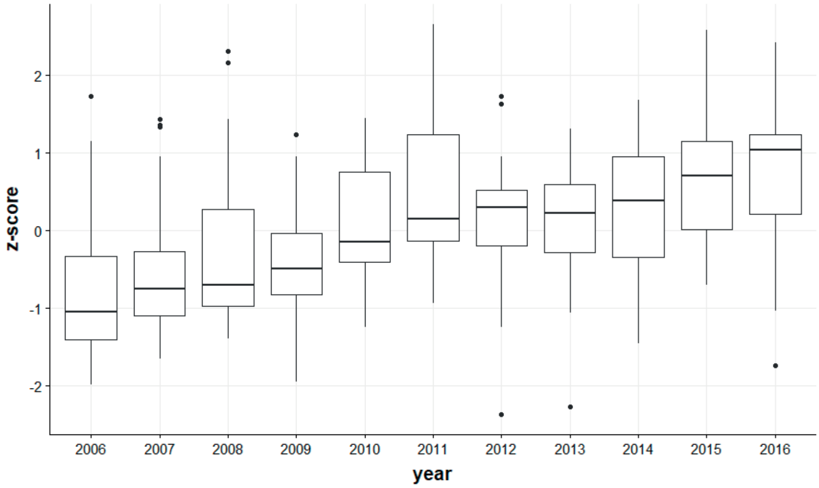


Figure 3.A.10: Latvia



*Note: A box plot illustrates the z-scores for each year. The band inside the box corresponds to the median and the width of the box to the interquartile range. The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to outliers beyond the range of the whiskers.*

CHAPTER 4

Bioeconomy Real Options and Sustainability – Measuring the Contribution of EU Bioeconomies to Sustainable Development[3]

3 This chapter is based on the article: Kardung, M., Cingiz, K & Wesseler, J. H. H. (2022). Bioeconomy Real Options and Sustainability – Measuring the Contribution of EU Bioeconomies to Sustainable Development. To be submitted.

ABSTRACT.

Measuring the sustainability of the bioeconomy is crucial to evaluating its continuous contribution to wellbeing. Previous studies that have addressed sustainability measurement vary in their emphasis on sustainability dimensions and countries' scores. Studies that have addressed the sustainability of the bioeconomy have focused on indicators that measure specific contributions to sustainability. We devise a framework directly linked to the 1987 Brundtland Report's definition of sustainable development. Our framework uses the concepts of intergenerational wellbeing and genuine investment, whereby sustainability is defined as non-declining intergenerational wellbeing over time. Sustainability-related investment projects include uncertainty and irreversibility, which we model explicitly in contrast to previous works. We calculate two related indicators—hurdle rate and maximum incremental social tolerable irreversible costs (MISTICs)—which have a forward-looking approach, investigating whether future investment projects in the bioeconomy are sustainable. We use these two indicators to empirically analyze the sustainability of European Union (EU) Member States' (MSs) bioeconomies and sectors. We found that the hurdle rate in the bioeconomy is lower for the bio-based part than for the non-bio-based part for most countries, indicating a high potential for further sustainable investments in the transition toward an EU bioeconomy. The majority of countries have overall negative MISTICs for their bioeconomy, implying that bioeconomy projects need to provide irreversible benefits. However, all the countries have bioeconomy sectors with positive MISTICs. Our findings are consistent with Ecological Footprint's report indicating ecological deficits for most EU MSs, as they have a greater footprint than biocapacity.

4.1. INTRODUCTION

Assessing a country's societal wellbeing goes beyond standard economic indicators, such as gross domestic product (Stiglitz et al., 2010). The bioeconomy, which entails all economic sectors and systems linked to biological resources and their functions and principles, can contribute meaningfully to societal wellbeing (European Commission, 2018b). Measuring the sustainability of the bioeconomy is crucial to evaluating its continuous contribution to wellbeing.

The updated European Union (EU) Bioeconomy Strategy stresses that "[…] the need to achieve sustainability constitutes a strong incentive to modernize our industries and to reinforce Europe's position in a highly competitive global economy, thus ensuring the prosperity of its citizens" (European Commission, 2018b, p. 4). The overall objective is to ensure the "prosperity" of EU citizens, and measuring this objective is directly linked with sustainable development (European Commission, 2018b; OECD, 2009; von Braun, 2018). Sustainable development was defined in the 1987 Brundtland Report as "meeting the needs and aspirations of the present generation without compromising the ability of future generations to meet their need" (Brundtland, 1987, p. 292). A good understanding of measuring sustainable development is vital for deriving indicators for monitoring the bioeconomy to ensure that such indicators can be directly linked to sustainable development.

Many researchers have addressed sustainability measurement, which is a controversial topic because the ambiguity of the sustainability concept makes it difficult to have agreed-upon measures (Parris & Kates, 2003; Salas-Zapata & Ortiz-Muñoz, 2019). The literature includes several suggestions for measuring sustainability, such as the Ecological Footprint (EF) (Wackernagel & Rees, 1996), the United Nation's (UN) Human Development Index (HDI) (Sagar & Najam, 1998), Bhutan's Gross National Happiness Index (GNH) (Mukherji & Sengupta, 2004). These sustainability indices emphasize different sustainability dimensions: the EF focuses on the environmental dimension, the HDI focuses on the economic and social dimension, and the GNH focuses on the environmental and social dimension (Strezov et al., 2017). The Organization for Economic Co-operation and Development (OECD) has a wide range of work on measuring wellbeing with indicators beyond the gross domestic product (GDP). They assess progress toward the Sustainable Development Goals' targets (OECD, 2019) and measure inclusive growth using a set of economic indicators (OECD, 2018). Lastly, the OECD estimates wellbeing for 362 regions using indicators for nine dimensions, such as income, health status, and environmental quality (OECD, 2014).

Previous sustainability measurement studies vary in their emphasis on sustainability dimensions and in the countries' scores. One striking aspect is that Western countries with high GDPs, which are conventionally considered model countries, do not always rank high. For example, regarding the Happy Planet Index, founded by the New Economics Foundation (2006), countries in Latin America and the Asia Pacific region lead the way with their high life expectancy, wellbeing, and ecological footprints. Another major study is the OECD's Measuring Wellbeing and Progress: Well-being Research, which also supports the idea that macro-statistical indices such as GDP fall short of measuring diverse experiences and living conditions. The study, measuring material conditions, quality of life, sustainability, and their relevant dimensions, and resources for future wellbeing, also aims to bridge the gap between existing metrics and policy interventions[4].

Much discussed is the World Bank's measure of genuine savings and Arrow et al.'s (2003) approach to genuine wealth and investment. Both concepts serve as measures of sustainable economic development over time. The genuine savings rate is computed by subtracting resource depletion and environmental degradation from traditional net savings while adding investment in human capital (Hamilton & Clemens, 1999; Hamilton & Naikal, 2014). The concepts of inclusive wealth and genuine investment are similar: a society's inclusive wealth is determined by measuring the shadow value of the economy's stock of capital assets (including manufactured capital assets, natural capital assets, human capital, etc.). The object of interest is intergenerational wellbeing, the discounted flow of current and future generations' utilities. The main point is that wellbeing is not only the wellbeing of the current generation but also the potential welfare of the generations to follow. Genuine investment is then defined as a measure of changes in the economy's set of capital assets weighted at shadow prices. Accordingly, positive genuine investment is used as an indicator of sustainable development.

Arrow et al. (2012) presented a theoretical framework for analyzing the sustainability of economic development over time using the concepts of intergenerational wellbeing and genuine investment, among others. They define intergenerational wellbeing as the discounted flow of current and future generations' utilities, where utility is derived through consumption of the economy's stock of capital assets, including manufactured goods, services provided by nature, health services, and many more. Barbier (2013) extended Arrow et al.'s (2012) approach with ecosystem services as a special type of natural capital. The author regarded this extension as possible but challenging because many ecosystem goods and services are not traded on the market and have no or only unreliable valuation estimates. Furthermore, the depreciation of natural capital is frequently irreversible (Barbier, 2013), which stresses the need to consider irreversibility in sustainability measurement.

4 https://www.oecd.org/statistics/better-life-initiative.htm

Previous studies on the sustainability of the bioeconomy have focused on indicators that measure its contributions to sustainability. These indicators usually measure a specific aspect of sustainability and do not constitute a comprehensive measure. The EU Bioeconomy Monitoring System has several indicators mapped to the Sustainable Development Goals, but the level at which they are sustainable is unclear[5]. D'Adamo et al. (2020b) presented a framework based on multi-criteria decision analysis that could provide a country's overall sustainability score for the bioeconomy once sufficient data were gathered. A great deal of previous research into sustainability has focused on the land dimension, especially land use change, and its impact on biodiversity greenhouse gas (Bringezu et al., 2021; Liobikiene et al., 2020; O'Brien et al., 2017). The existing literature quantitatively assesses the sustainability of the bioeconomy in the past or develops a framework for its future assessment (Egenolf & Bringezu, 2019; Jander et al., 2020).

Contrary to other studies measuring the bioeconomy's sustainability, we devise a framework that is directly linked to the 1987 Brundtland Report's definition of sustainable development. Our framework is based on Arrow et al. (2012)'s framework, which uses the concepts of intergenerational wellbeing and genuine investment. By including future generations' wellbeing, we directly assess the ability of future generations to meet their own needs. We advance their framework by explicitly including uncertainty and irreversibility. Irreversible is relevant because if we could reverse a decision at zero cost, and the changes implemented today do not turn out to be as desired in the future, we could reverse back, and no harm would have been done. However, this is rarely the case, and the costs of reversing an investment decision are often substantial. Additionally, uncertainty is even more critical if decisions include irreversible costs. We can calculate whether the benefits are larger than the costs if we know exactly what would happen. Uncertainty can be understood as a decision with more than one possible outcome, where no probabilities can be assigned to each outcome. The implications of the future growth of the bioeconomy for sustainability largely depend on irreversibility effects, which are driven by uncertainty about future benefits and costs, including technical change and their degree of irreversibility (Arrow et al., 2012; Dasgupta, 2008; Wesseler, 2009). Irreversibility is important for sustainable development because it ensures that the resources we use today will be available for future generations. When we make decisions that have irreversible consequences, we are essentially depleting resources that cannot be replenished.

This principle, including uncertainty and irreversibility, can be measured with an indicator called the maximum incremental social tolerable irreversible costs (MISTICs) (Wesseler et al., 2007; Wree et al., 2016). These irreversible costs can be tolerated by introducing new technology or other changes to the bioeconomy. The larger the value, the more sustainable an economy will be. We derive the indicator for several sectors and subsectors of the

5 https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en

EU bioeconomy. Our indicators have a forward-looking approach, investigating whether future investment projects are sustainable. We not only assess past development and current state, but we also directly investigate where bioeconomy investment should take place. We apply our framework empirically to the bioeconomy sectors of the EU-28 countries, measuring the sustainability of the transition to a bioeconomy. We estimate reversible and irreversible costs and benefits using bioeconomy value added and greenhouse gas emissions. This estimation allows us to calculate the MISTICs that a sustainable transition to a bioeconomy would entail.

The paper is structured as follows: Section 4.2 provides a detailed description of our conceptual framework, and Section 4.3 outlines the computation of the discount rate. Section 4.4 presents the empirical application of the EU bioeconomy. Section 4.5 discusses the implications of our results and concludes the paper.

4.2. CONCEPTUAL FRAMEWORK

Arrow et al. (2012) presented a theoretical framework for analyzing the sustainability of economic development over time, using the concepts of intergenerational wellbeing V(t) and genuine investment $\Delta V_t = dV/dt$ – among others. The authors defined intergenerational wellbeing as the discounted flow of current and future generations' utilities, where utility is derived through consumption of the economy's stock of capital assets, including manufactured goods, services provided by nature, health services, and many more. Arrow et al. (2012) then defined sustainability as non-declining intergenerational wellbeing over time $\Delta V_t \geq 0$, and genuine investment is defined as a measure of changes in wellbeing ΔVt, that is, as a measure of changes in the economy's set of capital assets weighted at shadow prices. The authors' definition of genuine investment implies that intergenerational wellbeing V(t) is augmented (or deteriorated) via investments solely if the genuine investment's shadow value is positive (or negative). Thus, positive genuine investment is an indicator of sustainable economic development.

Nonetheless, it is important to acknowledge that sustainability-related investment projects (as well as investment projects in general) are additionally, but not to the same degree, characterized by the following features: (1) the investment's expected future rewards are uncertain, as are its expected future losses; (2) the investment's immediate costs are partially or completely irreversible (i.e. sunk costs), as is the investment itself; and (3) the investment's timing is flexible, in that waiting for better future insight is generally possible (e.g. Arrow & Fisher, 2013; Dixit & Pindyck, 1994). As an illustration of uncertainty, sustainability-related investment projects mostly aim at long-term goals, such as the reduction of greenhouse gas emissions, enhanced production and resource use efficiency, and preservation of non-renewable capital assets. These types of projects are inherently uncertain. As an illustration of the irreversibility, the conversion of virgin forests for other uses inevitably entails the loss of biological diversity. Further, the expansion into arable land areas or coastal areas protecting mangrove forests to provide for a growing population causes irreversible and uncertain changes. Lastly, as an illustration of flexibility, the flexible timing of investment projects is generally possible, but a delay entails a cost of foregone benefits. For example, the introduction of a new biorefinery may be postponed due to low current production efficiency and uncertainty about future markets for bio-based products. Technical changes may increase production efficiency, and the markets for bio-based products may develop over time. All three features of investments—uncertainty, irreversibility, and flexibility—need to be considered for the assessment of genuine investment.

Investment might generally be defined as "[…] the act of incurring an immediate cost in the expectation of future rewards" (Dixit & Pindyck, 1994, p. 3). The notion of genuine investment is based on Arrows et al.'s (2012) contribution to *sustainability and the measurement of wealth.* For explanatory purposes, the author's formal concepts of wellbeing and genuine investment are illustrated in Appendix A.

Arrow et al.'s (2012) model requires a forecast of the economy's future after time t to well-define the intergenerational wellbeing. The forecast depends on the stock of assets at time t, advancements in technology, consumer preferences, and institutions beyond t. Given that Arrow et al. (2012) captured these time-varying factors as exogenous, we suppose $V(t)$ following a geometric Brownian motion (GBM), which enables us to endogenous future prices and costs without explicitly modeling them.

Moreover, we also analyze the flexibility of investment McDonald and Siegel (1986) and compare the value of an immediate genuine investment decision to the option value of a postponed genuine investment decision. Hence, we implement the real options methodology (Scatasta et al., 2006). For the option value to invest calculations, we follow Dixit and Pindyck (1994). The model is illustrated in Appendix A.

From the methodologies illustrated in Appendix A, we calculate the coefficient:

$$\frac{\beta_1}{\beta_1 - 1}, \qquad (1)$$

which is called the hurdle rate (Demont et al., 2004). The incremental benefit of the new investment costs needs to be at least $\frac{\beta_1}{\beta_1 - 1}$ times the net irreversible costs of the genuine investment project to be considered more beneficial than the best alternative investment available. As the hurdle rate $\frac{\beta_1}{\beta_1 - 1} > 1$, this result has important implications for the measurement of sustainable investments. First, private sector companies taking the irreversibility effects of the investments into account will invest only if the value is larger than $\hat{V}^*$. The values of these investments will be observable, and the related value added will be captured by national accounting statistics. Second, investments with a value below $\hat{V}^*$ will not be observable, but their value is greater than or equal to zero (see equation 14). Not considering these values underestimates the economic value of the bioeconomy. Third, the size of the threshold value $\hat{V}^*$ is larger than one. A lower threshold level, ceteris paribus, increases the incentives for immediate investment, while a higher threshold level decreases them. The size of the threshold level depends not only on market data, such as prices and investment costs but also on policies. Costs for research and development and market approval are outcomes of regulatory policies, and many of these can be considered fixed costs. Policies that reduce these fixed costs can have a positive effect on private sector incentives to invest in and develop the market for bio-based products. Hence, monitoring the regulatory policy environment becomes even more important.

Equation 2 can be rearranged by providing:

$$I < I^* = \hat{V}\frac{\beta_1 - 1}{\beta_1}. \tag{2}$$

Equation (2) is a formula for the threshold level of irreversible costs I to be accepted while staying on a sustainable development path defined as previously defined, $d\hat{Y}/dt \geq 0$. Wesseler (2003), Scatasta et al. (2006), and Wesseler et al. (2007) called this threshold value the MISTICS, that is, the maximum amount of irreversible costs society should be willing to tolerate as compensation for an investment's benefits. Since $\beta_1 > 1$, the MISTICs or I^* have to be lower than $\hat{V}_t$ by the factor $(\beta_1 - 1)/\beta_1$ (the reverse hurdle rate). The hurdle rate $\beta/(\beta - 1)$ reflects the degree of uncertainty and flexibility associated with investment projects. A hurdle rate of 1.5, for example, indicates that the benefits of a genuine investment project have to be at least 1.5 times greater than its irreversible costs to be considered sustainable (Wesseler et al., 2007). Further, since $\hat{V}_t$ is expected to increase over time, the MISTICs will increase as well.

MISTICs can be used as an indicator of the sustainability of a specific investment against irreversible environmental impacts. Possible uncertainties are explicitly considered, and the threshold value is reduced by the size of the hurdle rate, as the benefits $\hat{V}_t$ are divided by the hurdle rate. This adds an additional level of precaution to the assessment. The larger the threshold value, the larger the potential negative irreversible environmental impacts can be, and the more sustainable the specific investment will be, while a lower value indicates the opposite. The MISTICs for investments in the bioeconomy can be estimated for different investments, and changes over time provide an indication of improved or decreased sustainability.

4.3. EMPIRICAL APPLICATION

4.3.1. Sustainable development of the bioeconomy

We used the framework presented in Section 4.2 to empirically analyze the sustainability of EU Member States' (MSs) bioeconomies and sectors. We followed the delimitation of the bioeconomy in terms of bioeconomy sectors from Kardung et al. (2021), which is based on the NACE. Table 4.1 shows the sectors according to the International Standard Industrial Classification of All Economic Activities (ISIC) Rev. 4 codes, as used by the OECD, as well as the corresponding NACE codes.

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Table 4.1: Comparison of the BioMonitor bioeconomy sectors according to the NACE codes with the equivalent ISIC sectors used in the analysis.

BioMonitor sectors (NACE codes)	ISIC sectors
A01: Crop and animal production, hunting and related service activities	01T03: Agriculture, forestry and fishing
A02: Forestry and logging	
A03: Fishing and aquaculture	
C10: Manufacture of food	10T12: Food products, beverages, and tobacco
C11: Manufacture of beverages	
C12: Manufacture of tobacco	
C13: Manufacture of textiles	13T15: Textiles, wearing apparel, leather, and related products
C14: Manufacture of wearing apparel	
C15: Manufacture of leather and related products	
C16: Manufacture of wood and products of wood and cork, except furniture;	16: Wood and of products of wood and cork (except furniture)
C17: Manufacture of articles of straw and plaiting materials	17T18: Paper products and printing
C18: Manufacture of paper and paper products	
C19: Manufacture of coke and refined petroleum products	19: Coke and refined petroleum products
C20: Manufacture of chemicals and chemical products	20T21: Chemicals and pharmaceutical products
C21: Manufacture of basic pharmaceutical products and pharmaceutical preparations	
C22: Manufacture of rubber and plastic products	22: Rubber and plastic products
C31: Manufacture of furniture	31T33: Other manufacturing; repair and installation of machinery and equipment
D35: Electricity, gas, steam, and air conditioning supply	35T39: Electricity, gas, water supply, sewerage, waste, and remediation services
D3511: Production of electricity	
E36: Water collection, treatment, and supply	
E37: Sewerage	
E38: Waste collection, treatment, and disposal activities; materials recovery	
E39: Remediation activities and other waste management services	

Table 4.1: Comparison of the BioMonitor bioeconomy sectors according to the NACE codes with the equivalent ISIC sectors used in the analysis.

BioMonitor sectors (NACE codes)	ISIC sectors
F41: Construction of buildings	41T43: Construction
F42: Civil engineering	
G46: Wholesale trade, except for motor vehicles and motorcycles	45T47: Wholesale and retail trade: repair of motor vehicles
G47: Retail trade, except for motor vehicles and motorcycles	
H: Transportation and storage	49T53: Transportation and storage
I55: Accommodation	55T56: Accommodation and food services
I56: Food and beverage service activities	
M7211: Research and experimental development on biotechnology	TTL_69T82: Other business sector services
R9104: Botanical and zoological gardens and nature reserves activities	90T96: Arts, entertainment, recreation, and other service activities

The value of investments in bioeconomy projects is taken from Cingiz et al. (2021), who calculated the bioeconomy share of value added for 28 EU MS and 36 sectors from 2005 to 2015 using input–output tables. We used a risk-adjusted discount rate of 10.5 percent, as is common in this type of analysis (Demont et al., 2004; Wesseler et al., 2007). Table 4.2 presents the riskless rate of return for the EU-28, calculated by the 10-year average long-term interest rate from the OECD (2021). Following McDonald and Siegel's (1986) approach, we calculated the β_1 coefficient, see Appendix B:

$$\beta_1 = \frac{1}{2} - \frac{r-\gamma_v}{\sigma^2} + \sqrt{\left[\frac{r-\gamma_v}{\sigma^2} - \frac{1}{2}\right]^2 \frac{2r}{\sigma^2}}, \tag{3}$$

where r is the riskless rate of return, γ_v is the difference between the discount rate and the temporal trend of value added, σ^2 is the temporal variance of value added.

The hurdle rate (4) is then calculated for each country and sector:

$$hurdlerate = \frac{\beta_1}{\beta_1 - 1}. \tag{4}$$

We can now calculate the MISTICs, which indicate how much a society should be willing to tolerate to stay on a sustainable path. MISTICs can also have a negative value, implying that the investment would need irreversible benefits to be sustainable.

Table 4.2: Riskless rate of return for EU Member States

Country	Riskless rate	Country	Riskless rate
AUT	0.030	ITA	0.041
BEL	0.032	LTU	0.050
DEU	0.026	LVA	0.054
DNK	0.027	NLD	0.029
ESP	0.040	POL	0.050
FIN	0.029	PRT	0.054
FRA	0.030	SVK	0.037
GBR	0.034	SVN	0.042
GRC	0.087	SWE	0.027
HUN	0.068		
IRL	0.045	Average	0.041

Source: Adapted from OECD (2021)

For example, the impact of the investment could be an increase in biodiversity. MISTICs are calculated as follows:

$$MISTIC = \frac{W}{\frac{\beta_1}{\beta_1 - 1}} + R, \tag{5}$$

where *W is* social incremental reversible benefits, which are weighted by the hurdle rate, and *R* is social incremental irreversible benefits.

4.3.2. Estimating the social incremental reversible benefits

The social incremental reversible and irreversible benefits of investing in the bioeconomy are challenging to quantify because they are manifold and partly intangible. Social benefits are hard to estimate because they cover the full spectrum of costs and benefits, including social and environmental effects. This concept, combined with the bioeconomy, which contributes to sustainable development in multiple ways, makes it challenging to estimate holistic social benefits. First, we must define the social incremental reversible benefits (SIRBs) of investing in the bioeconomy. We calculated the average yearly change in bioeconomy value added over the 2006–2015 period. This average indicates the economic benefit that the bioeconomy provided for a sector over this period.

4.3.3. Estimating the social incremental irreversible benefits

Moving on to the social incremental irreversible benefits (SIIBs), we follow a straightforward and consistent approach to investigating how investing in the bioeconomy affects climate change mitigation, a major policy objective of transitioning to a bioeconomy. We estimated the SIIBs based on greenhouse gases emitted in a sector in relation to the change in bioeconomy value added. The greenhouse gas emissions data are from OECD's

Air Emission Accounts and are provided by ISIC Rev. 4 activities[6]. The greenhouse gas emissions given in tons of CO_2 (carbon dioxide) equivalent include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride. We assumed that the level of greenhouse gas emissions ($GHGe_{ij}$) in year *i* and sector *j* is a linear function of the bioeconomy value added ($BBVA_{ij}$), non-bioeconomy value added ($NBVA_{ij}$), and other factors. We estimated the effect of bioeconomy value added, non-bioeconomy value added if present, and several control variables on greenhouse gas emissions using multiple linear regression, as follows:

$$GHGe_{ij} = \beta_0 + \beta_1 * Year_i + \beta_2 * Country + \beta_3 * BBVA_{ij} + \beta_4 * NBVA_{ij} + \beta_5 * BBVA_{ij} * NBVA_{ij} + \varepsilon_{ij}, \quad (6)$$

where $GHGe_{ij}$ is the level of total greenhouse gases in year *i and sector j*, $Year_i$ is the number of years from 2004, $Country$ is the country of origin, $BBVA_{ij}$ is the bioeconomy value added, $NBVA_{ij}$ is the

non-bioeconomy value added, $BBVA_{ij} * NBVA_{ij}$ is the interaction between the two types of value added components, and ε_{ij} is the error term.

The regression coefficients β_3 and β_4 represent the marginal effect of an additional unit of bioeconomy value added on greenhouse gas emissions. For fully bio-based sectors, we did not have β_4 and thus treated as zero. Then, the difference between β_3 and β_4 provides the complete marginal effect of an additional unit of bioeconomy value added, as we assumed a substitution between bioeconomy and non-bioeconomy. Tables 4.3a and 4.3b present the multiple linear regression results for each sector within the bioeconomy scope. The first model for agriculture, forestry and fishing (01T03) shows a positive coefficient, significant at 0.01 percent, suggesting that an increase in bioeconomy value added correlates with an increase in greenhouse gas emissions.

We can illustrate how we calculate the SIIBs for bioeconomy sectors using textiles, wearing apparel, leather, and related products (13T15) as an example. This partly bio-based sector has statistically significant coefficients for *BE_VA* (-1,814.9) and non_BE_VA (352.0). Thus, we calculate -1,814.9 minus 352.0, which equals 2,166.9. Then, we multiply this value by the carbon price and the average change in the bioeconomy value added in a sector, resulting in the SIIB for a sector for a country. We use Rennert et al.'s (2022) preferred mean social cost of carbon dioxide estimate of €191[7] per ton of CO_2.

6 We downloaded the data from the official website of the OECD, which is freely available at https://stats.oecd.org/Index.aspx?DataSetCode=AEA.

7 Converted from $185, 2020 US dollars via https://www.oanda.com/.

Table 4.3a: Regression results of bioeconomy value added on greenhouse gas emissions per sector.

	Dependent variable					
	GHGe					
	01T03	10T12	13T15	16	17T18	19
Year	-569,453.5**	-97,642.0***	-34,395.4***	-21,533.6***	-45,749.5*	45,993.5
Country	-127,986.6	11,337.1	-80.0	-473.3	-11,794.8	7,013.5
BE_VA	2,321.0***	279.3***	-1,814.9***	197.1***	498.3***	-24,403.0**
Non_BE_VA			352.0***			8,514.5***
BE_Non_ BE_VA			-0.1***			-17.4***
Constant	9,402,511.0***	746,144.9***	212,028.6***	194,912.3**	632,735.6***	172,394.2
Observations	245	245	245	245	245	245
R^2	0.74	0.91	0.85	0.42	0.79	0.74
Adjusted R^2	0.74	0.91	0.85	0.41	0.78	0.73
Residual Std. Error	11,403,827.0 (df = 241)	967,372.9 (df = 241)	255,610.1 (df = 239)	341,896.9 (df = 241)	1,069,230.0 (df = 241)	3,625,068.0 (df = 239)
F Statistic	233.6*** (df = 3; 241)	817.3*** (df = 3; 241)	277.9*** (df = 5; 239)	57.1*** (df = 3; 241)	293.6*** (df = 3; 241)	136.1*** (df = 5; 239)

	Dependent variable					
	GHGe					
	20T21	22	35T39	45T47	49T53	55T56
Year	-384,471.6***	-43,857.3***	-3,094,534.0***	-122,313.1***	-1,046,048.0***	-22,059.9**
Country	36,594.0	8,934.2**	285,747.5	51,004.0***	-156,898.7**	1,272.1
BE_VA	9,347.1***	2,919.9***	-13,678.2*	294.5***	-5,208.1***	182.5***
Non_BE_VA	240.3*	-153.0***	3,531.8***	86.1***	1,440.6***	131.6***
BE_Non_ BE_VA	-0.1***	0.04**	0.5***	-0.001***	-0.1***	-0.01***
Constant	2,919,148.0***	206,634.2*	30,151,178.0***	-110,693.2	10,944,786.0***	-26,540.7
Observations	245	245	245	245	245	245
R^2	0.71	0.72	0.78	0.91	0.88	0.87
Adjusted R^2	0.70	0.71	0.78	0.91	0.87	0.87
Residual Std. Error	4,845,240.0	493,903.9	37,675,915.0	1,726,956.0	8,773,358.0	418,105.9
F Statistic	115.3***	121.0***	173.6***	487.9***	341.7***	329.2***

Note: *p <0.1; **p <0.05; ***p <0.01

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Table 4.3b: Regression results of bioeconomy value added on greenhouse gas emissions per sector.

	Dependent variable:	
	GHGe	
	69T82	90T96
Year	-83,257.8***	-30,604.8***
Country	27,719.8***	9,074.8**
BE_VA	19.6	871.1***
Non_BE_VA	35.7***	-9.8*
BE_Non_BE_VA	-0.000	0.001*
Constant	461,120.7	136,663.5
Observations	245	245
R^2	0.75	0.87
Adjusted R^2	0.74	0.87
Residual Std. Error (df = 239)	1,252,136.0	488,280.0
F Statistic (df = 5; 239)	140.7***	332.9***

Note: *p <0.1; **p <0.05; ***p <0.01

Having estimated the social incremental reversible benefits and reversible benefits, we have all the elements for calculating the $MISTICs_{jk}$ for sector *j* and country *k* as follows:

$$MISTICs_{jk} = \frac{\beta_1 - 1}{\beta_1}_{jk} * \Delta VA_{jk} - \Delta VA_{jk} * (\beta_{3j} - \beta_{4j}) * CO_2 price, \quad (7)$$

where $\frac{\beta_1 - 1}{\beta_1}$ is the reverse hurdle rate for sector *j* and country *k*, ΔVA is the average yearly change in added bioeconomy value added, β_{3j} (β_{4j}) is the marginal effect of an additional unit of (non-) bioeconomy value added on greenhouse gas emissions, and $CO_2 price$ is the social cost of carbon dioxide.

4.3.4. Hurdle rates for bioeconomy sectors

To analyze the potential for sustainable investment in the EU bioeconomy, we examined the hurdle rates for all bioeconomy sectors across all countries. Table 4.4 presents the hurdle rates for all bioeconomies in the EU-28, differentiating between the bio-based and non-bio-based parts of these sectors. The countries with the lowest hurdle rate for their bioeconomy are Italy, the Netherlands, and Portugal, with 1.01, followed closely by Austria, Belgium, Cyprus, Germany, and France, with 1.02. The hurdle rate is lower for the bio-based part for 23 out of 28 countries, with Germany, Finland, France, Ireland, and Romania as exceptions. However, the hurdle rate for the bio and non-bio parts is relatively low for Germany, Finland, and France. Lithuania has the highest hurdle rate (3.91), followed by Latvia (3.16), Ireland (2.95), and Estonia (2.79).

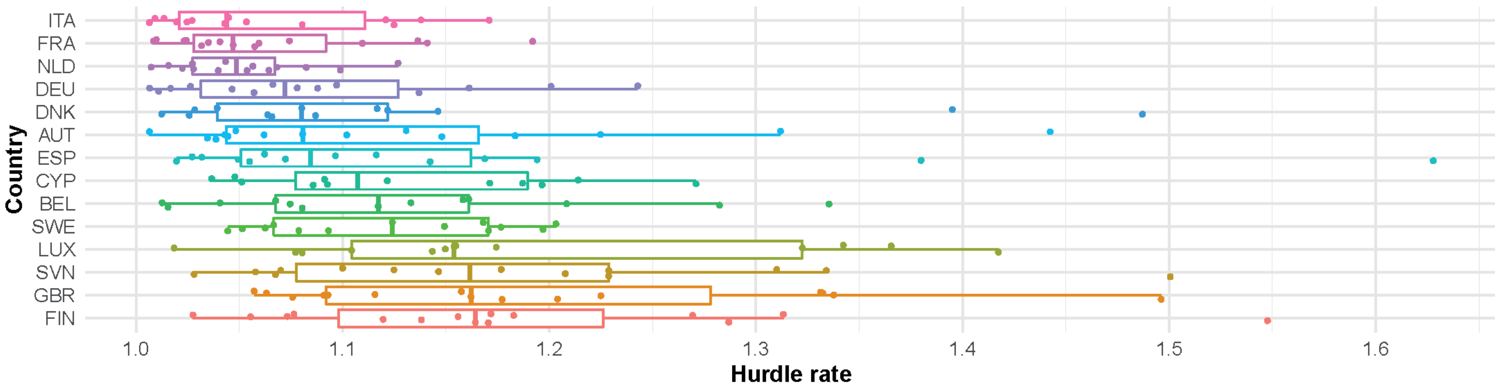
The graphs in Figures 4.1a and 4.1b show high variability in the sectorial hurdle rates within and between the countries[8]. The whiskers of the boxplots in Figure 4.1b extend further than in Figure 4.1a, with Slovakia, Lithuania, Estonia, Bulgaria, Latvia, and Romania as extreme cases, with hurdle rates ranging from -6 to 20. It may be that these extreme values stem from volatile bioeconomy value-added values; these countries are all relatively small, with lower levels of value added, where smaller absolute changes lead to greater relative changes. Figures 4.1a and 4.1b confirm Italy, the Netherlands, Portugal, and France as the countries with the lowest hurdle rates, as their medians (the band inside the box) are the lowest. The highest hurdle rate medians are exhibited by Romania, Latvia, and Bulgaria. These countries also have a high interquartile range (the width of the box), which is generally higher for countries with higher hurdle rate medians.

We ranked all bioeconomy sectors from highest to lowest according to their hurdle rates. Table 4.4 presents the five highest sectors for all countries, which shows where sustainable investment is the most difficult. By contrast, Table 4.5 presents the five sectors with the lowest hurdle rates. Considering all countries, coke and refined petroleum products (19) is the sector that occurs most often among the five highest sectors (16 occurrences) and the sector with the highest hurdle rate (12 occurrences). Other sectors with a frequently high hurdle rate, twelve times, are agriculture, forestry, and fishing (01T03), other manufacturing; repair and installation of machinery and equipment (31T33), and electricity, gas, water supply, sewerage, waste, and remediation services (35T39). Rubber and plastic products (22) stand out as having the highest hurdle rate in the Czech Republic, Greece, Croatia, Hungary, and Romania.

Turning now to the sectors with the lowest hurdle rate, food products, beverages, and tobacco (10T12) lead other sectors, with 21 occurrences. This sector is followed by paper products and printing (17T18), with 17 occurrences. Therefore, these conventional bioeconomy sectors frequently provide the least obstacles to bioeconomy investment. In particular, food products, beverages, and tobacco stand out as the sector with the lowest hurdle rate in eight countries. The third most frequent sector is wholesale and retail trade; repair of motor vehicles (45T47) with 14 occurrences. Transportation and storage (49T53), accommodation, and food services (55T56), other business sector services (69T82), and arts, entertainment, recreation, and other service activities (90T96) also have a frequently low hurdle rate, with nine occurrences among the five lowest sectors each.

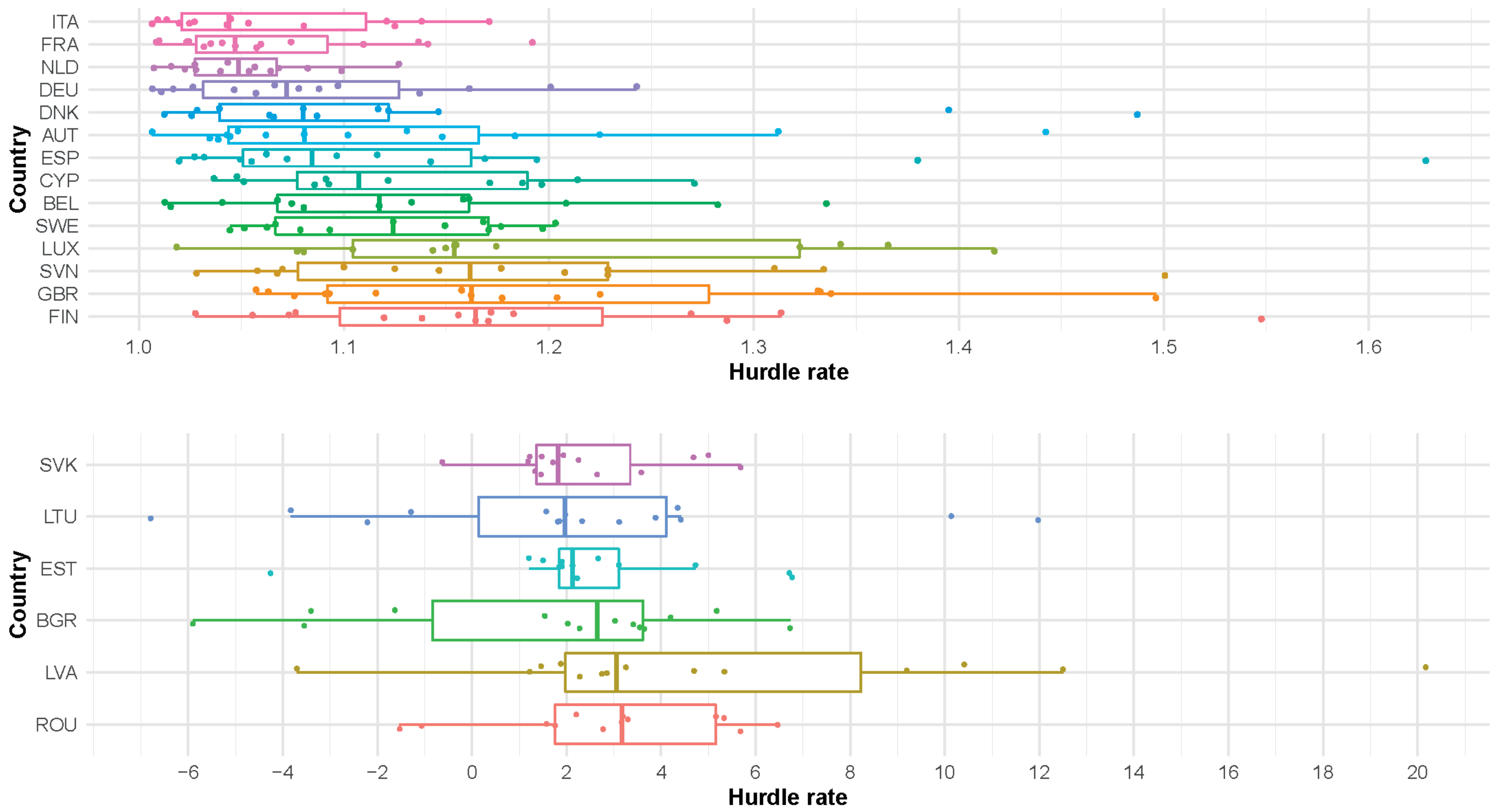
8 The outliers, values greater (less) than the third (first) quartile plus (minus) 1.5 * the IQR, have been removed for these graphs.

Figure 4.1a: Hurdle rates for the bioeconomy per sector for each country as box plots with jittered data points



Note: A box plot illustrates the hurdle rates for each country . The band inside the box corresponds to the median and the width of the box to the inter-quartile range (IQR). The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points c orrespond to the values of each sector The points correspond to the values of each sector The outliers, values greater (less) than the third (first) quartile plus (minus) 1.5 * the IQR , have been removed for these graphs.

Figure 4.1b: Hurdle rates for the bioeconomy per sector for each country as box plots with jittered data points



Note: A box plot illustrates the hurdle r ates for each country . The band inside the box corresponds to the median and the width of the box to the inter-quartile range (IQR). The upper (lower) whisker extends from the hinge to the largest (lowest) value no further than 1.5 * IQR from the hinge. The points correspond to the values of each sector The points correspond to the values of each sector The outliers, values greater (less) than the third (first) quartile plus (minus) 1.5 * the IQR , have been removed.

Table 4.4: Hurdle rates for bioeconomies and the highest bioeconomy sectors for each EU Member State

Country	Hurdle rate Bioeconomy		Five highest sectors									
	Bio	Non-bio	#1	Hurdle rate	#2	Hurdle rate	#3	Hurdle rate	#4	Hurdle rate	#5	Hurdle rate
AUT	1.02	1.02	**19**	9.42	**31T33**	1.44	**20T21**	1.31	**22**	1.22	**35T39**	1.18
BEL	1.02	1.02	**19**	3.39	**31T33**	2.27	**41T43**	1.99	**22**	1.34	**13T15**	1.28
BGR	1.68	12.81	**55T56**	136.18	**10T12**	6.73	**20T21**	5.18	**13T15**	4.2	**49T53**	3.64
CYP	1.02	1.07	**35T39**	4.96	**55T56**	1.64	**69T82**	1.51	**13T15**	1.27	**90T96**	1.21
CZE	1.14	1.27	**22**	5.68	**19**	5.53	**69T82**	3.12	**35T39**	2.48	**01T03**	1.78
DEU	1.02	1.01	**19**	1.53	**13T15**	1.44	**01T03**	1.24	**49T53**	1.2	**31T33**	1.16
DNK	1.03	1.03	**31T33**	2.15	**20T21**	1.88	**01T03**	1.49	**55T56**	1.4	**35T39**	1.15
ESP	1.03	1.03	**19**	2.93	**41T43**	1.68	**69T82**	1.63	**35T39**	1.38	**49T53**	1.19
EST	2.79	2.89	**16**	48.35	**90T96**	34.82	**22**	6.77	**69T82**	6.71	**01T03**	4.73
FIN	1.05	1.03	**19**	1.56	**13T15**	1.55	**35T39**	1.31	**16**	1.29	**20T21**	1.27
FRA	1.02	1.01	**19**	1.29	**31T33**	1.19	**01T03**	1.14	**90T96**	1.14	**13T15**	1.11
GBR	1.09	1.18	**19**	2.74	**35T39**	1.5	**01T03**	1.34	**55T56**	1.33	**13T15**	1.33
GRC	1.04	1.09	**22**	2.27	**19**	2.07	**41T43**	2.01	**16**	2.01	**35T39**	1.72
HRV	1.08	1.09	**22**	5.57	**90T96**	2.36	**41T43**	2.22	**19**	2.16	**69T82**	2.09
HUN	1.33	1.56	**22**	3.04	**20T21**	2.89	**31T33**	2.87	**01T03**	1.89	**45T47**	1.6
IRL	2.95	1.72	**20T21**	5.79	**31T33**	3.46	**13T15**	2.61	**69T82**	2.09	**01T03**	2.01
ITA	1.01	1.01	**19**	1.48	**41T43**	1.45	**69T82**	1.17	**13T15**	1.14	**20T21**	1.12
LTU	3.91	4.60	**10T12**	11.97	**41T43**	10.14	**49T53**	4.42	**90T96**	4.35	**22**	3.88
LUX	1.04	2.12	**90T96**	6.34	**13T15**	1.85	**01T03**	1.42	**35T39**	1.37	**45T47**	1.34
LVA	3.16	4.90	**19**	80.97	**41T43**	20.17	**20T21**	12.5	**31T33**	10.41	**16**	9.19
MLT	1.07	3.37	**49T53**	5.99	**55T56**	3.12	**16**	1.86	**45T47**	1.79	**22**	1.53
NLD	1.01	1.01	**19**	1.54	**35T39**	1.21	**20T21**	1.13	**55T56**	1.1	**01T03**	1.08
POL	1.76	2.52	**69T82**	3.91	**31T33**	3.79	**17T18**	3.09	**20T21**	3.01	**49T53**	2.79
PRT	1.01	1.02	**19**	7.18	**35T39**	6.79	**13T15**	1.73	**49T53**	1.47	**41T43**	1.39
ROU	1.68	-3.20	**22**	14.72	**55T56**	6.46	**31T33**	5.68	**41T43**	5.33	**90T96**	5.16
SVK	1.93	3.70	**01T03**	5.68	**69T82**	5	**90T96**	4.69	**49T53**	3.58	**31T33**	2.64
SVN	1.05	1.13	**41T43**	2.78	**19**	2.25	**22**	1.5	**49T53**	1.33	**20T21**	1.31
SWE	1.08	1.11	**19**	1.81	**01T03**	1.62	**31T33**	1.56	**35T39**	1.2	**16**	1.2

Table 4.5: Hurdle rates for lowest bioeconomy sectors for each EU Member State

Country	Five lowest sectors									
	#1	Hurdle rate	#2	Hurdle rate	#3	Hurdle rate	#4	Hurdle rate	#5	Hurdle rate
AUT	**17T18**	1.01	**45T47**	1.03	**55T56**	1.04	**49T53**	1.04	**10T12**	1.04
BEL	**10T12**	1.01	**17T18**	1.02	**16**	1.04	**90T96**	1.07	**49T53**	1.07
BGR	**90T96**	-254.3	**69T82**	-5.9	**35T39**	-3.55	**17T18**	-3.41	**22**	-1.63
CYP	**19**	-0.38	**10T12**	1.04	**17T18**	1.05	**45T47**	1.05	**41T43**	1.09
CZE	**10T12**	1.06	**49T53**	1.09	**45T47**	1.1	**55T56**	1.15	**16**	1.16
DEU	**10T12**	1.01	**17T18**	1.01	**45T47**	1.02	**35T39**	1.03	**69T82**	1.05
DNK	**19**	-2.36	**90T96**	1.01	**10T12**	1.03	**17T18**	1.03	**69T82**	1.04
ESP	**55T56**	1.02	**17T18**	1.03	**31T33**	1.03	**10T12**	1.05	**01T03**	1.05
EST	**55T56**	-11.47	**19**	-4.26	**13T15**	1.2	**31T33**	1.5	**49T53**	1.85
FIN	**10T12**	1.03	**55T56**	1.06	**45T47**	1.07	**31T33**	1.08	**90T96**	1.12
FRA	**17T18**	1.01	**10T12**	1.01	**20T21**	1.02	**45T47**	1.02	**49T53**	1.03
GBR	**45T47**	1.06	**90T96**	1.06	**10T12**	1.08	**17T18**	1.09	**20T21**	1.09
GRC	**01T03**	1.08	**13T15**	1.08	**17T18**	1.09	**45T47**	1.17	**90T96**	1.19
HRV	**49T53**	1.04	**13T15**	1.05	**10T12**	1.06	**01T03**	1.11	**45T47**	1.17
HUN	**10T12**	1.12	**41T43**	1.16	**19**	1.17	**55T56**	1.19	**13T15**	1.25
IRL	**10T12**	-2.63	**19**	-1.5	**45T47**	1.14	**35T39**	1.25	**49T53**	1.28
ITA	**10T12**	1.01	**45T47**	1.01	**17T18**	1.01	**16**	1.02	**55T56**	1.02
LTU	**31T33**	-13.42	**45T47**	-6.8	**69T82**	-3.83	**17T18**	-2.21	**20T21**	-1.29
LUX	**31T33**	-2.95	**17T18**	1.02	**69T82**	1.08	**10T12**	1.08	**16**	1.1
LVA	**35T39**	-287.74	**69T82**	-3.7	**13T15**	1.22	**49T53**	1.46	**10T12**	1.88
MLT	**90T96**	-17.04	**69T82**	-6.85	**41T43**	1.11	**17T18**	1.14	**01T03**	1.17
NLD	**17T18**	1.01	**31T33**	1.02	**69T82**	1.02	**10T12**	1.03	**49T53**	1.03
POL	**41T43**	-16.15	**22**	-3.35	**13T15**	1.43	**01T03**	1.46	**35T39**	1.58
PRT	**55T56**	1.01	**10T12**	1.02	**01T03**	1.03	**90T96**	1.05	**45T47**	1.07
ROU	**20T21**	-40.99	**19**	-8.61	**69T82**	-1.53	**35T39**	-1.07	**01T03**	1.57
SVK	**22**	-75.25	**16**	-33.29	**41T43**	-0.63	**10T12**	1.19	**13T15**	1.22
SVN	**10T12**	1.03	**45T47**	1.06	**17T18**	1.07	**31T33**	1.07	**55T56**	1.1
SWE	**17T18**	1.04	**10T12**	1.05	**90T96**	1.06	**20T21**	1.07	**22**	1.08

4.3.5. Maximum incremental social tolerable irreversible costs for the bioeconomy

We estimate the MISTICs to analyze the level of irreversible impact that can be considered sustainable for the bioeconomy. MISTICs can be positive or negative, affecting the value's interpretation. A positive value means that society can bear the irreversible costs of investing in the bioeconomy while staying on a sustainable path. For example, an investment project to produce biomass might induce irreversible land use changes that decrease biodiversity and are still sustainable. A negative value means the opposite: a project must increase biodiversity to be sustainable.

The first (second) column in Table 4.6 provides the total (per capita) MISTICs for the EU-28 bioeconomies. The major shares of countries have negative MISTICs for their bioeconomies. We used the per capita values to compare the countries. Portugal has the highest value (€7.71), followed by Cyprus (€4.42), Greece (€2.17), and Romania (€2.04). On the contrary, the MISTIC is the lowest for Ireland (€-70.87), followed by Sweden (€-29.71), Denmark (€-20.18), and Finland (€18.44). However, each of these countries has bioeconomy sectors with positive MISTICs.

As before, we ranked all bioeconomy sectors from highest to lowest according to their MISTICs. Table 4.6 presents the five highest sectors for all countries, which indicates the sectors in which bioeconomy investment has the highest benefits. By contrast, Table 4.7 provides the five sectors with the lowest benefits. Considering the EU-28 bioeconomies, electricity, gas, water supply, sewerage, waste, and remediation services (35T39) occur most frequently among the five highest sectors (26 occurrences). In 20 countries, 35T39 has the highest MISTICs. It is followed by other business sector services (69T82; 24 occurrences), transportation, and storage (49T53; 22 occurrences), and textiles, wearing apparel, leather and related products (13T15; 32 occurrences). Transportation and storage (49T53) stands out, with being the first and second highest MISTICs, with 5 and 15 occurrences, respectively. Considering the EU-28 altogether, the five sectors with the highest MISTICs (4 occurrences) are electricity, gas, water supply, sewerage, waste, and remediation services (35T39) in Spain, Great Britain, Italy, and Poland, and transportation and storage (49T53) in Germany.

Agriculture, forestry, and fishing (01T03) have 27 occurrences among the sectors with the lowest MISTICS, making them last place. In 22 countries, this sector has the lowest MISTICs. Second to last is 10T12, with 25 occurrences, and third from last, chemicals, and pharmaceutical products (20T21), with 24 occurrences. Chemicals and pharmaceutical products sector (20T21) has 4 and 19 occurrences as the lowest and second to lowest sectors, respectively. If we consider all countries, the five sectors with the lowest MISTICS are agriculture, forestry, and fishing (01T03) in France and Italy; chemicals and pharmaceutical products (20T21) in Germany; and agriculture, forestry, and fishing (01T03) in Great Britain and Spain, all with two occurrences. This bottom five is closely followed by Ireland's chemicals and pharmaceutical products (20T21).

Table 4.6: MISTICS for bioeconomies and the highest bioeconomy sectors for each EU Member State

Country	MISTICS		MISTICS five highest sectors									
	Mio (€)	€ per capita	#1	Mio (€)	#2	Mio (€)	#3	Mio (€)	#4	Mio (€)	#5	Mio (€)
AUT	-23.8	-2.84	**35T39**	70.89	**49T53**	28.24	**69T82**	0.57	**13T15**	0.06	**55T56**	-1.79
BEL	-61.2	-5.63	**35T39**	47.37	**49T53**	24.46	**19**	12.08	**69T82**	0.58	**13T15**	0.01
BGR	-7	-0.95	**35T39**	30.62	**49T53**	7.82	**13T15**	0.85	**69T82**	0.09	**55T56**	-0.24
CYP	3.6	4.42	**35T39**	3.62	**10T12**	0.43	**90T96**	0.27	**17T18**	0.12	**45T47**	0.11
CZE	-51.1	-4.89	**35T39**	66.52	**19**	2.46	**69T82**	0.34	**55T56**	-0.07	**13T15**	-0.13
DEU	-263.1	-3.23	**49T53**	225.9	**35T39**	179.6	**19**	6.1	**13T15**	5.5	**69T82**	1.59
DNK	-111.8	-20.18	**19**	9.98	**10T12**	5.94	**49T53**	5.25	**22**	2.11	**17T18**	1.1
ESP	-28.2	-0.61	**35T39**	338.04	**49T53**	139.2	**17T18**	3.6	**13T15**	2.08	**16**	2.04
EST	-4.2	-3.16	**35T39**	9.45	**49T53**	4.23	**19**	2.76	**69T82**	0.06	**13T15**	0.05
FIN	-98.9	-18.44	**35T39**	33.11	**69T82**	0.28	**17T18**	0.27	**13T15**	0.1	**55T56**	-0.2
FRA	-388.9	-6.00	**35T39**	116.62	**49T53**	102.66	**22**	6.92	**17T18**	4.59	**69T82**	0.8
GBR	-60.7	-0.97	**35T39**	300.31	**49T53**	112.68	**19**	31.15	**13T15**	6.52	**69T82**	2.24
GRC	23.9	2.17	**01T03**	26.43	**35T39**	21.82	**17T18**	8.09	**90T96**	3.11	**45T47**	1.23
HRV	4.7	1.10	**35T39**	23.97	**49T53**	3.1	**69T82**	0.09	**13T15**	-0.02	**55T56**	-0.33
HUN	-114.2	-11.45	**35T39**	12.61	**49T53**	8.86	**13T15**	0.27	**69T82**	0.15	**55T56**	-0.1
IRL	-318.5	-70.87	**35T39**	40.8	**19**	12.23	**45T47**	0.32	**69T82**	0.28	**90T96**	0.25
ITA	-164	-2.75	**35T39**	271.73	**49T53**	83.01	**13T15**	12.76	**16**	2.42	**69T82**	1.45
LTU	-45	-14.52	**49T53**	11.88	**35T39**	4.32	**13T15**	0.41	**69T82**	0.11	**55T56**	-0.1
LUX	-2.3	-4.49	**49T53**	0.73	**20T21**	0.21	**35T39**	0.19	**17T18**	0.09	**69T82**	0.01
LVA	-12.9	-6.13	**35T39**	14.4	**49T53**	3.8	**19**	0.08	**69T82**	0.07	**13T15**	-0.07
MLT	-1.2	-2.87	**49T53**	0.84	**35T39**	0.32	**69T82**	0.01	**22**	0	**16**	-0.01
NLD	-14.7	-0.89	**35T39**	122.82	**49T53**	50.31	**17T18**	5.77	**13T15**	0.91	**69T82**	0.88
POL	-12.7	-0.33	**35T39**	229.97	**49T53**	97.4	**19**	13.53	**13T15**	3.3	**69T82**	1.16
PRT	70.5	6.71	**35T39**	84.76	**49T53**	19.63	**19**	6.42	**13T15**	4.6	**69T82**	0.17
ROU	41.6	2.04	**35T39**	95.1	**19**	79.31	**49T53**	31.27	**13T15**	0.77	**69T82**	0.36
SVK	-64	-11.83	**49T53**	15.06	**35T39**	13.15	**69T82**	0.14	**13T15**	-0.15	**55T56**	-0.18
SVN	-7.9	-3.87	**35T39**	10.17	**49T53**	4.22	**13T15**	0.1	**69T82**	0.06	**19**	-0.05
SWE	-278.8	-29.71	**19**	5.82	**69T82**	0.44	**13T15**	0.06	**55T56**	-0.76	**16**	-1.22

Table 4.7: MISTICS for lowest bioeconomy sectors for each EU Member State

	MISTICS five lowest sectors									
Country	#1	Mio (€)	#2	Mio (€)	#3	Mio (€)	#4	Mio (€)	#5	Mio (€)
AUT	**01T03**	-52.91	**20T21**	-30.51	**10T12**	-12.09	**19**	-6.59	**22**	-5
BEL	**20T21**	-86.49	**01T03**	-28.63	**10T12**	-14.73	**45T47**	-8.02	**22**	-3.47
BGR	**01T03**	-28.47	**20T21**	-6.7	**10T12**	-3.82	**19**	-2	**17T18**	-1.69
CYP	**49T53**	-0.84	**01T03**	-0.34	**13T15**	-0.05	**69T82**	0	**22**	0
CZE	**01T03**	-78.69	**20T21**	-16.9	**22**	-6.05	**10T12**	-5.59	**49T53**	-4.76
DEU	**20T21**	-311.58	**01T03**	-149.5	**10T12**	-71.69	**90T96**	-44.9	**22**	-39.91
DNK	**20T21**	-61.22	**01T03**	-36.63	**35T39**	-34.96	**45T47**	-1.56	**90T96**	-1.51
ESP	**01T03**	-275.64	**20T21**	-115.5	**10T12**	-54.02	**45T47**	-29.46	**90T96**	-16.3
EST	**01T03**	-15.69	**16**	-1.17	**10T12**	-1.11	**17T18**	-0.69	**45T47**	-0.57
FIN	**01T03**	-66.7	**20T21**	-27.45	**49T53**	-27.26	**10T12**	-3.35	**19**	-2.25
FRA	**01T03**	-415.27	**20T21**	-107.35	**10T12**	-57.25	**45T47**	-25.04	**90T96**	-8.54
GBR	**01T03**	-279.16	**20T21**	-86.35	**10T12**	-56.03	**22**	-24.37	**45T47**	-22.38
GRC	**10T12**	-11.23	**20T21**	-9.31	**19**	-8.11	**49T53**	-6.79	**13T15**	-1.38
HRV	**01T03**	-9.18	**20T21**	-4.52	**10T12**	-2.54	**22**	-1.6	**17T18**	-1.14
HUN	**01T03**	-79.99	**20T21**	-24.88	**19**	-19.13	**22**	-3.8	**10T12**	-3.5
IRL	**20T21**	-261.15	**10T12**	-74.22	**01T03**	-31.87	**49T53**	-1.94	**17T18**	-1.5
ITA	**01T03**	-355.27	**20T21**	-70.17	**10T12**	-36.29	**19**	-23.36	**22**	-18.32
LTU	**01T03**	-28.06	**20T21**	-12.53	**19**	-8.38	**10T12**	-4.9	**45T47**	-2.41
LUX	**01T03**	-1.71	**19**	-0.84	**10T12**	-0.38	**90T96**	-0.28	**22**	-0.13
LVA	**01T03**	-23.76	**20T21**	-2.39	**10T12**	-1.42	**16**	-1.32	**45T47**	-1.11
MLT	**01T03**	-1.1	**90T96**	-0.33	**10T12**	-0.29	**17T18**	-0.23	**45T47**	-0.15
NLD	**01T03**	-122.27	**20T21**	-24.19	**10T12**	-19.91	**45T47**	-14.33	**90T96**	-4.93
POL	**01T03**	-166.34	**20T21**	-70.48	**10T12**	-37.86	**22**	-25.84	**17T18**	-21.62
PRT	**01T03**	-24.99	**20T21**	-6.95	**10T12**	-6	**45T47**	-2.69	**22**	-2.07
ROU	**01T03**	-104.15	**20T21**	-24.01	**10T12**	-22	**17T18**	-3.56	**90T96**	-3.2
SVK	**01T03**	-72.46	**20T21**	-4.4	**22**	-3.29	**17T18**	-2.46	**19**	-2.43
SVN	**01T03**	-10.79	**20T21**	-8.18	**22**	-0.74	**10T12**	-0.67	**17T18**	-0.58
SWE	**01T03**	-118.02	**35T39**	-92.91	**49T53**	-29.15	**20T21**	-22.42	**10T12**	-6.94

4.4. DISCUSSION AND CONCLUSION

In this study, we quantified and compared the sustainability of bioeconomy development in the EU. We conceptualized a theoretical framework building upon Arrow et al.'s (2012) framework for assessing whether economic growth is compatible with sustaining wellbeing over time. We complemented their framework with the characteristics of bioeconomy-related investment projects: uncertainty about future rewards and losses, irreversible impacts, and flexible timing. We linked bioeconomy value added with intergenerational wellbeing and estimated irreversible effects on greenhouse gas emissions, which allowed us to apply our framework empirically to the European Union's bioeconomy. We calculated hurdle rates to describe the degree of uncertainty and flexibility of bioeconomy sectors and the maximum amount of irreversible costs as indicators of the sustainability of bioeconomy investments against irreversible environmental impacts.

We found that the hurdle rate in the bioeconomy is lower for the bio-based part than for the non-bio-based part for most countries, indicating a high potential for further sustainable investments in the transition toward an EU bioeconomy. The countries with the lowest hurdle rates for their bioeconomy are Italy, the Netherlands, and Portugal, followed closely by Austria, Belgium, Cyprus, Germany, and France. The sectorial hurdle rates show high variability within and between countries. Conventional bioeconomy sectors, such as food products, beverages, and tobacco and paper products and printing, have low hurdle rates in many countries. We recommend that policymakers prioritize investment in the bioeconomy in specific sectors, which can vary from country to country. The majority of countries have negative MISTICs for their bioeconomy, implying that bioeconomy projects need to provide irreversible benefits. However, all of the countries have bioeconomy sectors with positive MISTICs. Our findings are consistent with the results reported by the Ecological Footprint, which showed that most EU MSs have an ecological deficit, as they have a greater footprint than biocapacity.

Our results show a high potential for sustainable bioeconomy investments in many European countries, with hurdle rates only slightly above 1. The most potential is frequently in conventional bioeconomy sectors, but unconventional bioeconomy sectors, such as transportation and storage and arts, entertainment, recreation, and other service activities, also show potential. When we look at individual countries, we can see that some surprising sectors have the lowest hurdle rates, such as construction in Poland. Loizou et al. (2019) also identified this as a promising bioeconomy sector with the potential to stimulate knock-on effects in the Polish economy. An expert survey also named construction and building materials a promising bioeconomy sector, along with bio-composites, food and feed additives, pharmaceuticals, and bioplastics (Stegmann et al., 2020). In accordance with this result, we found that the food products, beverages, and tobacco sector has a low hurdle rate in many countries and chemicals and pharmaceutical products in France, Great Britain, Lithuania, Romania, and Sweden.

Moreover, our estimation of the MISTICs revealed that Portugal, Cyprus, Greece, Romania, and Croatia are the only European countries where bioeconomy investments are sustainable without compensating for irreversible impacts. The countries with the lowest MISTICS are Ireland, Sweden, Denmark, and Finland, which performed well in other studies on bioeconomy development (D'Adamo et al., 2020b; Ronzon et al., 2022). These seemingly contradictory results can be explained by the increased difficulty of augmenting investments in an already well-developed bioeconomy. Low-hanging fruits—that is, bioeconomy investment projects that provide high economic and environmental benefits—have already been collected in these countries. However, if we consider the MISTICS on a sectorial level, we find the electricity, gas, water supply, sewerage, waste, and remediation services sector frequently as the highest. This outcome stems from the significant reduction in greenhouse gases in this sector, which is associated with increased bioeconomy value added. Bioenergy can be essential in decarbonizing electricity (IEA, 2016), but it can also cause biodiversity loss, deforestation, increased demand for agricultural land, and water scarcity (GBEP, 2011). The case is similar for transportation and storage, where biofuels are one of the primary ways to decarbonize the sector (IEA, 2021). The MISTICs indicator can be used to evaluate the tradeoff between irreversible benefits and costs of bioenergy investments, where a positive MISTIC value reflects tolerable irreversible costs.

Comparable to this study, the World Bank published several reports with empirical results on "genuine savings" (GS) as an indicator to measure sustainable development. They provide a database that includes the latest estimates of GS for all EU MSs (and most countries in the world) termed "adjusted net savings" (ANS) based on the World Bank (2010) . ANS is calculated by taking net national savings plus education expenditure minus energy depletion, mineral depletion, net forest depletion, carbon dioxide damage, and particulate emissions damage. They do not include other important sources of environmental degradation because of the lack of internationally comparable data. Contrary to our MISTICs, all but one country has positive ANS. The results show Sweden, Denmark, Ireland, and Finland as having high ANS. Greece is the only country with a negative ANS, and Portugal, Romania, and Cyprus have comparatively low values. A possible explanation for these results contradicting ours might be that we estimate the marginal effect of an additional unit of bioeconomy value added on greenhouse gas emissions and then multiply with the change in value added. If this coefficient is negative for a sector estimated uniformly across all countries, it reduces the MISTICs for a country with the most strongly increasing value added.

Agriculture, forestry and fishing, which are the biomass-producing foundation of the bioeconomy, have the lowest MISTICS in most countries and a high hurdle rate in many countries. A combination of these two factors might explain these negative results. First, total factor productivity slightly decreased in the EU between 2004 and 2013 (Baráth & Fertő, 2017), indicating a lower investment potential. Second, the sector is a major contributor to GHG emissions (Kuosmanen et al., 2020), and we found that increases in bioeconomy value added are related to a rise in GHG emissions. According to our results, in most countries, future investment projects in agriculture, forestry and fishing have to compensate for their irreversible costs with an increase in biodiversity or contribute to decarbonizing the sector to be sustainable.

We faced significant challenges in compiling the data needed for the empirical application of our framework. After designing our framework, we aimed to apply it to the EU bioeconomy systematically, which means that we required data available for all EU MSs, sectors, and an extended period. However, data capable of covering all bioeconomy sectors are still lacking (D'Adamo et al., 2020b). Therefore, we could not include a social indicator for the calculation of MISTICs. Further, other indicators measuring important environmental impacts on biodiversity soil quality are not available by economic activity. As soon as additional indicators become available, future studies could quickly address this issue. Similarly, estimating option values is difficult, as they cannot be directly observed; indicators can be derived but are not yet available. These include the number of patent applications over time and public and private sector investments in the bioeconomy.

4.A APPENDIX A.

Arrow et al. (2012) define intergenerational wellbeing $V(t)$ as the discounted flow of current and future generations' utilities U. Utility is derived through consumption $\underline{C}(s)$ at time S and of the economy's stock of capital assets $K(s)$ at time S, including manufactured goods, services provided by nature, health services, and many more.[9] The term $U(\underline{C}(s))$ is interpreted as felicity (utility flow) at date *s*. Accordingly, δ denotes the felicity discount rate. Continuous time is denoted by S and t, $s \geq t$. Consequently, intergenerational wellbeing $V(t)$ is formalized as (Arrow et al., 2012, p. 322):

$$V(t) = \int_t^\infty \left[U(\underline{C}(s)) e^{-\delta(s-t)} \right] ds, \delta \geq 0 \tag{A.1}$$

Arrow et al. (2012) then define sustainability as non-declining intergenerational wellbeing over time $dV/dt \geq 0$. Genuine investment is determined as a measure of changes in wellbeing, where wellbeing is a function of its determinants, namely the economy's stock of capital assets K and time t. Given that $\underline{K}(t), K(s)$ and $\underline{C}(s)$ are determined for all future times $s \geq t$ we can write that $V(t) = V(\underline{K}(t), t)$. This is a standard Ramsey model in which generations make consumption and savings. These savings are capital assets for the next generation. The variable *t* reflects the impact of time-varying factors, which we treat as exogenous. These include changes in terms of trade, technological change, unexplained population growth, and unexplained changes in institutions. Supposing that $V(t)$ is differentiable in $\underline{K}$. If we take the derivative of $V(t)$ with respect to t, and by the definition of sustainability

$$\frac{dV}{dt} = \frac{\partial V}{\partial t}\frac{dt}{dt} + \frac{\partial V}{\partial K}\frac{dK}{dt} = \frac{\partial V}{\partial t} + \sum_i \frac{\partial V(t)}{\partial K_i(t)}\frac{dK_i(t)}{dt} \geq 0$$

To arrive at a measure of comprehensive wealth that accounts for certain exogenous changes (e.g., changes in the total factor of production), we need an additional shadow price. For this purpose, we take *t* as a capital asset. Now, we define $r(t)$ ($= \partial V / \partial t$) as the shadow price of time at t in order to calculate comprehensive wealth, as in Arrow et al. (2012), and $p_i(t)$ ($\equiv \partial V(t) / \partial K_i(t)$, for all i) as the shadow price of the i^{th} capital asset at time t. By letting $I_i(t)$ equal $\Delta K_i(t) / \Delta t$, genuine investment is

$$\Delta V(t) = r(t)\Delta t + \sum p_i(t) I_i(t) \Delta t. \tag{A.2}$$

Equation (A.2) shows that the changes in an economy's set of capital assets weighted at shadow prices, including time, equal the change in wellbeing. Hence, by defining genuine

9 Note that the population size is fixed throughout the model. Moreover, movements in total factor productivity and the changes in international trade are exogenous. The consumption flow at time s include both marketed goods and also leisure, health services, and consumption services supplied by nature.

investment, we establish the relationship between comprehensive wealth and intergenerational wellbeing. Looking at Equation (A.2) in more detail, it shows that positive genuine investment increases wellbeing, while negative genuine investment decreases intergenerational wellbeing. Hence, positive genuine investment facilitates sustainable development.

The costs of irreversible change are implicitly captured in Arrows et al's (2012) genuine investment model by using shadow prices in Equation (A.2). What Equation (A.2) does not explicitly consider is the effect that uncertainty over future benefits and costs has on the number of investments that are partially or completely irreversible. The fact that sustainability is defined as non-declining wellbeing over time ($dV / dt \geq 0$) helps to formally solve the described dilemma. Considering that future benefits and costs of genuine investment will always be uncertain, we determine that $d\hat{V} / dt \geq 0$ needs to be preserved as an important property of the genuine investment model (analogous to the definition of sustainability), where $\hat{V}$ solely considers changes through **reversible investments**. Thus, we assume that genuine investments $\hat{V}(t)$ require among them investments *I* that are irreversible (to keep the model simple, we assume *I* to be time invariant). This is the difference in V and $\hat{V}$: while V includes reversible and irreversible investments, $\hat{V}$ only considers reversible investments. The valuation of $\hat{V}$ comprises uncertainty effects, since $\hat{V}$ follows a GBM. Thus, all three additional features of sustainability-related investment projects are taken into consideration: uncertainty is taken into account by letting $\hat{V}$ follow a GBM, flexibility by making use of the option value concept, and irreversibility by assigning a separate parameter *I* that explicitly reflects the effects of irreversibility.

Arrow et al.'s (2012) model requires a forecast of the economy's future after time t to well-define the intergenerational wellbeing. The forecast depends on the stock of assets at time t, advancements in technology, consumer preferences, and institutions beyond t. Given that Arrow et al. (2012) takes these time-varying factors as exogenous, we suppose $\hat{V}(t)$ following a GBM, which enables us to endogenous future prices and costs to a certain degree without explicitly modeling them.

A stochastic process fulfilling the property of non-negativity through time is GBM. By letting intergenerational wellbeing $\hat{V}$ follow a GBM, uncertainty over future intergenerational wellbeing is introduced to the model (Pindyck, 2000). The GBM features a constant percentage drift (or trend) parameter α, and a constant percentage volatility (or uncertainty) parameter σ. dz shall denote the increment of a Wiener process, which is normally distributed during the time interval Δt with zero mean and variance Δt. Consequently, Equation (A.2) can be reformulated as follows:

$$d\hat{V}(t) = \alpha\left(\hat{V}(t), t\right)dt + \sigma\left(\hat{V}(t), t\right)dz \tag{A.3}$$

$$= \alpha \hat{V}(t)dt + \sigma \hat{V}(t)dz \tag{A.4}$$

The stochastic differential equation in Equation (A.3) can be simplified as Equation (A.4), since we suppose it is a GBM, so that $\alpha(\hat{V}(t),t) = \alpha \hat{V}(t)$ and $\sigma(\hat{V}(t),t) = \sigma \hat{V}(t)$, where α and σ are constants. Percentage changes in $\hat{V}$ ($\Delta \hat{V}/\hat{V}$) are normally distributed in the natural logarithm of $\hat{V}$. Absolute changes in $\hat{V}$ ($\Delta \hat{V}$) are log-normally distributed. Since Equation (4) is continuous over time but not differentiable, we need Ito's Lemma. First, we take the natural log of $\hat{V}(t)$ and by using Ito's lemma,

$$d\left(\ln \hat{V}(t)\right) = \left(\ln \hat{V}(t)\right)' d\hat{V}(t) + \frac{1}{2}\left(\ln \hat{V}(t)\right)'' d\hat{V}(t) d\hat{V}(t) = \frac{d\hat{V}(t)}{\hat{V}(t)} - \frac{1}{2}\frac{1}{\hat{V}(t)^2}\sigma^2 V$$

$$= \frac{d\hat{V}(t)}{\hat{V}(t)} - \frac{1}{2}\frac{1}{\hat{V}(t)^2}\left(\alpha \hat{V}(t)^2 dt^2 + 2\sigma\alpha dtdz + \sigma^2 \hat{V}(t)^2 dz^2\right)$$

$$= \frac{d\hat{V}(t)}{\hat{V}(t)} - \frac{1}{2}\frac{1}{\hat{V}(t)^2}\sigma^2 \hat{V}(t)^2 dt$$

since dt^2, $dtdz$ is equal to 0 and $dz(t)^2 = dt$. Then, we use Equation (A.4).

$$d\left(\ln \hat{V}(t)\right) = \left(\alpha - \frac{\sigma^2}{2}\right)dt + \sigma dz(t)$$

As a next step, we integrate the above equation from 0 to t, and we get

$$\ln \hat{V}(t) = \ln \hat{V}(0) + \left(\alpha - \frac{\sigma^2}{2}\right)t + \sigma z(t) - \sigma z(0)$$

Since the increment of the GBM is normally distributed and is equal to 0 at $t = 0$. Then we get

$$\hat{V}(t) = \hat{V}(0) + exp\left(\left(\alpha - \frac{\sigma^2}{2}\right)t + \sigma z(t)\right) \tag{A.5}$$

Thus far, we have explained how uncertainty about the future level of intergenerational wellbeing $\hat{V}$ is included in our model of genuine investment. In the following paragraphs, we will analyze how the flexibility of investment timing might be taken into account. McDonald and Siegel (1986) developed the basic model of the value of waiting to invest under uncertainty, irreversibility, and flexibility known as the real option model. Scatasta et al. (2006) are among many researchers who suggest making use of the real option model, that is, comparing the value of an immediate genuine investment decision to the option value of a postponed genuine investment decision. Therefore, we will henceforth differentiate between the value $\hat{V}$ and the option value $F(\hat{V})$ of genuine investment projects.

The value to option to invest is a well-known concept. However, for the sake of completion of the model, we will provide the Bellman equation (for a detailed explanation, see Dixit and Pindyck, 1994, Chapters 4 and 5). Since there is no immediate payout before investment, the continuation region, where no investment is made, of the continuous time Bellman equation (Dixit & Pindyck, 1994, p. 140) is:

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$$\delta F = \frac{1}{dt} E\left(dF\right)$$

$$\delta F dt = E\left(dF\right)$$

where $\delta > 0$ is the discount rate. The left-hand side of the equation is the expected return of the investment, and the right-hand side is the expected capital appreciation over an interval dt. Now, by Ito's Lemma, we calculate dF and take the expected value of it $E(dF)$. If we plug into the above equation, we reach the following Bellman equation:

$$\frac{\sigma^2 \hat{V}^2}{2} F''\left(\hat{V}\right) + \alpha \hat{V} F'\left(\hat{V}\right) - \delta F = 0$$

Note that we take $\delta - \alpha > 0$, otherwise growth being larger or equal then discount rate leads the analysis to a trivial case or NPV. Moreover, the above equation satisfies the following boundary conditions (Dixit & Pindyck, 1994, p. 141):

$$F\left(0\right) = 0 \quad \text{(A.6)}$$

$$F\left(\hat{V}^*\right) = \hat{V}^* - I \quad \text{(A.7)}$$

$$F'\left(\hat{V}^*\right) = 1 \quad \text{(A.8)}$$

Following Dixit and Pindyck (1994), who showed that under the assumption $\hat{V}$ follows a GBM, the option value of genuine investments *F(*$\hat{V}$ *)* shall be given by the following equation, where A_1 and A_2 are constants that have yet to be determined, and β_1 and β_2 are the two roots of the fundamental quadratic:

$$\beta_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left[\frac{\alpha}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2\left(\delta - \alpha\right)}{\sigma^2}} > 1, \text{ and } \beta_2 = \frac{1}{2} - \frac{\alpha}{\sigma^2} - \sqrt{\left[\frac{\alpha}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2\left(\delta - \alpha\right)}{\sigma^2}} < 0 \text{ (}$$

δ denotes the exogenous discount rate:

$$F\left(\hat{V}\right) = A_1 \hat{V}^{\beta_1} + A_2 \hat{V}^{\beta_2} \quad \text{(A.9)}$$

Note that Equation (A.9) is subject to the boundary conditions (A.6), (A.7), and (A.8), where I represents the sunk or irreversible costs of a genuine investment project. Boundary condition (A.6) implies that $A_2 = 0$, so that Equation (A.9) can be reduced to:

$$F\left(\hat{V}\right) = A\hat{V}^{\beta_1} \tag{A.10}$$

Boundary conditions two and three concern optimal investment because is a threshold value at or above which it is optimal to invest. The second condition (Equation 7) is the value-matching condition, and the last condition (Equation A.8) is the smooth-pasting condition (Dixit & Pindyck, 1994; Pindyck, 2000, 2002). Boundary conditions two and three concern optimal investment because $\hat{V}^*$ is a threshold value at or above which it is optimal to invest. The second condition (Equation A.7) is the value-matching condition, and the last condition (Equation A.8) is the smooth-pasting condition (Dixit & Pindyck, 1994; Pindyck, 2000, 2002).

Accordingly, the sustainability criterion shall be non-declining intergenerational wellbeing under irreversibility as well as uncertainty and flexibility over time $d\hat{Y}/dt \geq 0$, with:

$$\hat{Y}\left(t\right) = F\left(\hat{V}_t, I\right) \tag{A.11}$$

Since we aim to look at irreversibility effects in more detail, we now pose the question of how much irreversible cost can be accepted (the threshold value of I, I^*) while maintaining a positive genuine investment rate $d\hat{Y}/dt \geq 0$, where I is the stock of irreversible genuine investments. Therefore, we substitute Equation (A.11) into Equations (A.7) and (A.8). By rearranging, we get the following (McDonald & Siegel, 1986):

$$A = \frac{\left(\hat{V}^* - I\right)}{\left(\hat{V}^*\right)^{\beta_1}} = \frac{\left(\beta_1 - 1\right)^{\beta_1 - 1}}{[\left(\beta_1\right)^{\beta_1} I^{\beta_1 - 1}]} \tag{A.12}$$

$$\hat{V}^* = \frac{\beta_1}{\beta_1 - 1} I \tag{A.13}$$

and we have for the value of investment:

$$F\left(V, I\right) = \begin{cases} A\hat{V}^{\beta_1}\hat{V} \leq \hat{V}^* \\ \hat{V} - I > \hat{V}^* \end{cases} \tag{A.14}$$

The result in Equation (A.13) indicates that an investment will be sustainable if the actual value of project *V* is larger than $\hat{V}^*$.

4.B APPENDIX B.

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Thus far, the discount rate has been exogenously introduced into the model. In this section, we discuss how to calculate the equilibrium expected rate of return on investment opportunity following the method introduced by McDonald and Siegel (1986). Note that the main difference between the two models is the cost of investment. In our model, we take the value of investment *V* as a GBM, whereas McDonald and Siegel (1986) take both the cost and the benefit as a GBM. We should also point out that our model aims to measure genuine investment (the change in intergenerational wellbeing). Thus, we define the value of an investment as the discounted flow of current and future generations, and, following Arrow et al. (2012), to measure comprehensive wealth, we show that the changes in an economy's set of capital assets weighted at shadow prices, including time, equals the change in wellbeing (Arrow et al., 2012, p.325). This approach already captures the costs of irreversible change by using shadow prices, so we take the cost of investments as time-invariant. However, to capture the uncertainty and irreversibility of benefits in the model, we take the genuine investment as GBM.

We define the option value to invest by Equations (A.9) and (A.10). Now, we follow McDonald and Siegel's (1986) approach. In the Ito derivative of Equation (A.10), the option value is:

$$\frac{dF}{F} = \beta_1\left(\alpha_v dt + \sigma_v dz_v\right) + \beta_1\left(\beta_1 - 1\right)\frac{1}{2}\sigma_v^2 dt. \tag{B.1}$$

The only risk or unanticipated component of the return on F is the term $\beta_1\sigma_v dz_v$, which is a weighted average of the unanticipated components in the rate of change V. We know from asset pricing models that the risk premium earned on an asset and the riskiness of the asset are proportional. Hence, the discount rate for future payoffs and the equilibrium expected rate of return on the investment opportunity are:

$$\delta = r + \beta_1\left(a_v^* - r\right) \tag{B.2}$$

where α_v^* is the expected rate of return of the assets with an unexpected rate of return $\beta_1\sigma_v dz_v$, r is the risk-free rate. With this, we define risk premium earned, which is the proportional increase in the riskiness of the assets, $\beta_1\left(\acute{a}_v^* - r\right)$. Finally, if we equate the required rate of return on F with the actual expected rate of return on F, then we can arrive at the following equation and solve for β_1:

$$\left[r + \beta_1\left(a_v^* - r\right)\right]dt = E\left(\frac{dF}{F}\right) \tag{B.3}$$

$$\left[r + \beta_1\left(a_v^* - r\right)\right]dt = \beta_1\alpha_v + \beta_1\left(\beta_1 - 1\right)\frac{1}{2}\sigma_v^2\ ]dt \tag{B.4}$$

$$\beta_1 = \frac{1}{2} - \frac{r-\gamma_v}{\sigma^2} + \sqrt{\left[\frac{r-\gamma_v}{\sigma^2} - \frac{1}{2}\right]^2 \frac{2r}{\sigma^2}}$$

where $\gamma_v = a_v^* - a_v$, which defines the difference between the expected rate of return required by investors and actual drift.

4

CHAPTER 5

The Development and Performances of the Novel Food Regulation in The European Union[10]

10 This chapter is based on the article: Kardung, M., Cortesi, B., Soregaroli, C., Varacca, A. & Wesseler, J. H. H. (2022). The Development and Performances of the Novel Food Regulation in The European Union. This is the version that has been initially submitted to *Regulation & Governance*. The article is now under revision.

ABSTRACT.

Evolving consumer demand has led to new food products surging into the market requiring authorization by authorities. The European Union regulates such new food products under its novel food regulation (NFR), which must balance safety and regulatory burden. Contrary to previous studies that statically or qualitatively analyzed the development of the NFR, we aim to assess the performance of the EU NFR over time. We empirically analyze the development of the old and new EU NFR authorization procedure from 1997 to 2020, considering the number of applications, the duration of the authorization procedure, and the determinants of approval. We gather information on novel food applications, resulting in a unique dataset, which we analyze in three stages. We find relatively stable applications across years, with an upsurge at the time the new NFR was introduced. We also show a decreasing trend in the length of the authorization process over the time period covered, although the data are still too limited to effectively quantify the impact of the reformed NFR. Finally, our results suggest that being a private entity rather than a public entity and applying for regulatory approval of a novel food ingredient instead of a product result in higher success rates in authorization decisions.

5.1. INTRODUCTION

Food security, food safety, and environmental sustainability stand out as objectives for food system governance (Belluco et al., 2017; Khajehei et al., 2019). Within the food system, consumer demand is shifting toward new health, functional, and ethnic food as well as different dietary alternatives and environmentally sustainable choices due to demographic changes, globalization, and income and its distribution (Belluco et al., 2017; Hermann, 2009; Marberg et al., 2017). European countries also import many traditional food products from developing countries to meet the consumers' evolving interest in such products (Ververis et al., 2020).

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These changes in consumer demand and the development of new technologies has led to increased innovation in the food sector in recent decades (Willett et al., 2019). New food technologies allow companies to produce food from unconventional sources, such as vitamin K from menaquinone or Antarctic krill oil rich in phospholipids from Euphausia superba (Vapnek, Jessica et al., 2020). Food start-ups such as JUST and MycoTechnology receive large amounts of venture capital for financing their food innovation (Wesseler & Zilberman, 2021).

Innovation is an essential instrument for food companies to face competition in the world market (Bigliardi & Galati, 2013); however, the importance placed on consumer protection and food safety is high in Europe compared to the rest of the world. The advent of new technologies creates concerns of adverse effects to human, environmental, animal, and/or plant health, which trigger the need for standardized regulations (Vapnek, Jessica et al., 2020). Additionally, a series of foodborne disease incidents in the late 1990s drew even more attention to the need to establish general food principles and requirements at the policy level (Hyde et al., 2017; Wesseler & Kalaitzandonakes, 2019).

It is challenging but necessary for policy-makers to keep up with the rapid evolution of the food sector. For this reason, the EU introduced the novel food regulation (NFR) Regulation (EC) 258/97 in 1997. It represents an attempt to define, control, and uniformly regulate the entry of novel food products into the EU market. It was repealed in 2018 by Regulation (EU) 2015/2283—which entered into force in 2018. New food products are considered novel food by the EU, defined as food that had not been consumed to a significant degree by humans in the EU before May 15, 1997, when the first regulation on novel food came into force (European Parliament and Council, 2015).

The European Commission (EC) created its NFR within an extensive general EU food regulation. The actors involved in the regulatory processes are the EC, the European Food Safety Authority (EFSA), Member States (MSs), national and international competent food and safety authorities, and private companies (European Parliament and Council, 2015; European Parliament and Council of the European Union, 1997). Early on, concerns were raised about the regulatory burden and lack of efficiency. The higher the number of actors, the higher the degree of compartmentalization, internally—coordination within the agencies—and externally—with each other (Neuwirth, 2014). A lack of internal and external coordination might increase the time needed to carry out the regulatory process (Grimsby, 2021).

An elaborate authorization procedure for novel food entails costs and benefits for society. A lengthy process might hamper innovation potentials in the food sector, reducing the net benefits for producers and consumers (de-Magistris et al., 2015; Lähteenmäki-Uutela et al., 2021). Companies applying for an authorization face relatively high regulatory compliance costs with the EU NFR and the EU safety requirements (Brookes, 2007; Purnhagen & Wesseler, 2020). Novel food applications are heterogeneous and complex, and thus there can be no uniform authorization procedure for all of them (Ververis et al., 2020). Regulation makes it possible to homogenize the safety and quality requirements asked by the EU, protecting consumers from risks from consuming certain foods (de Magistris et al., 2014; Hyde et al., 2017). Setting standardized risk assessment procedures may also decrease consumer neophobia toward novel food products and increase acceptance (Frewer et al., 2011). Nevertheless, the NFR of 1997 has resulted in several complaints about compliance cost, lack of binding timelines resulting in delays, and discrimination against non-EU food products and food producers (Grimsby, 2021; Holle, 2018; Hyde et al., 2017). The EU reformed the NFR in 2018 to address these criticisms.

Although many studies have analyzed the advantages and shortcomings of the EU NFR, there have been few empirical investigations into the EU NFR's development. Hyde et al. (2017) analyzed applications for approval and substantial equivalence applications[11] submitted under Regulation (EC) 258/97. They found that the mean length for authorized novel food between the receipt of an application by the national body and the approval granted by Commission Decision is 1,194 days, ranging from 267 days to 3,523 days. Grimsby (2020) used quantitative data from 163 applications and 523 notifications to the old NFR and 90 novel food applications from 2018 to July 2019 to the new NFR as background for semi-structured interviews with successful applicants and experts. Their research aimed to study the innovation practices of novel food companies and the NFR's impact on these practices. No systematic differences in the size of companies applying to the two regulations were observed. The study also found an average authorization process length of 3.8 years. The above empirical investigations highlighted the importance

11 Regulation (EC) 258/97 provided a simplified procedure to bring a novel product to the market, which is "substantially equivalent" to an existing counterpart (product) already allowed on the EU market. Substantial equivalence must be demonstrated in an application dossier for notification (Wagenberg, 2014).

of the length of the authorization process as a single performance indicator. However, investigations have been static as no empirical evidence has been provided about the evolution of the authorization length across and within the two NFRs. Whether the reformed NFR resulted in reducing the cost of the authorization process and discrimination against non-EU food products and whether lack of binding timelines resulted in delays has not yet been addressed explicitly. Besides considering dynamic aspects, an assessment of the NFR would benefit from additional indicators that measure the appeal and efficiency of the NFR.

In the present study, we aim to assess the performance of the EU NFR over time, considering the changes between the current Regulation (EU) 2015/2283 and the former Regulation (EC) 258/97. We empirically analyze the development of the old and new EU NFR authorization procedures from 1997 to 2020, introducing a set of simple performance indicators. Specifically, we focus on the following three main research questions (RQs): How many and from where are applications submitted? (RQ1); How is the duration of the novel food authorization procedure developing over time? (RQ2); What is the probability of acceptance and the determinants for a successful novel food application? (RQ3). RQ1 helps investigate the barriers to accessing the authorization procedure and its feasibility for different types of applicants; RQ2 relates to the opportunity cost of the process with the length of the approval decision imposing economic and strategic costs to companies; RQ3 measures the success of applicants and its determinants. We investigate the RQs considering possible trends and whether the more centralized approach of the current NFR has led to a change in any of the above indicators. As the EU novel food catalogue does not include a database with the information we need, we gather the information on the applications under the former and current EU NFRs from each novel food's official EC decision document. This information also allowed us to consider regional differences across countries in submitting novel food applications, resulting in a unique dataset.

The paper is structured as follows: The next section provides background information about regulating novel foods in the EU. In the third section, we describe our data and how we collected them and our empirical strategy to analyze the data. The fourth section presents our results. In the fifth section, we discuss these results. We conclude and provide policy recommendations in the final section.

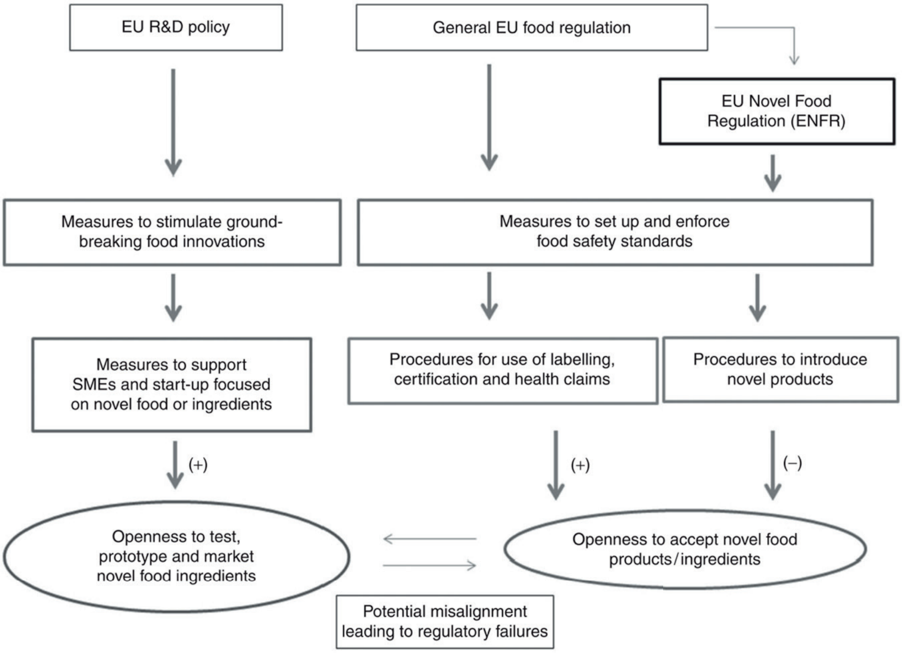
5.2. BACKGROUND

5.2.1. Regulating novel food in the EU

The EU NFR is part of the innovation landscape that includes research and development (R&D) policy and food regulation. The authorization process for novel food is a part of a regulatory environment to promote food safety and quality standards (European Commission, 2000)(Figure 5.1). The EU supports food innovations by giving incentives to research projects, small and medium-sized enterprises (SMEs), and start-ups in the food sector, promoting technological development, innovation, and new opportunities for employment (de Magistris et al., 2015). Implementing regulations causes administration costs (Wesseler & Smart, 2014), and non-justified delays in the authorization process entail costs, especially for innovative companies (Smart et al., 2015).

The EC aims to have transparent and clear policies, starting with a formal definition for novel food. According to Regulation (EU) 2015/2283 (L 327, p. 2-7), the term "novel food" refers to (I) "any food that was not used for human consumption to a significant degree within the Union before May 15 1997" and (II) falls under one of the categories expressed in Article 3 of the NFR (European Parliament and Council, 2015; Pisanello & Caruso, 2018). The categories are food from microorganisms, fungi, and algae; novel foods derived from plants; novel foods from animals, including insects; and food from the novel production processes, including nanofoods. Examples of novel products are foods derived from new production processes such as UV treatment or high-pressure treatment, foods isolated from animals or their parts (e.g., insects, oil from Antarctic krill, peptides from fish)(EFSA, 2012) or isolated from microorganisms, fungi, or algae (e.g., algae oil from Ulkenia sp) (EFSA, 2014). Agricultural products traditionally consumed outside the EU are also considered novel foods, such as noni fruit juice and chia seeds.

Figure 5.1: Regulatory frameworks in the EU NFR innovation landscape.



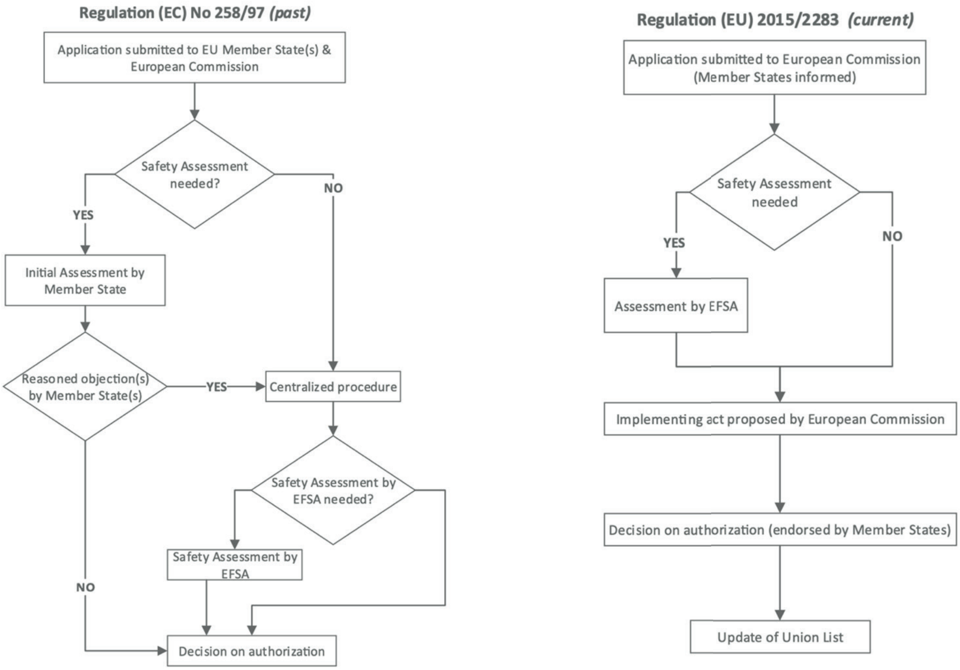
Source: de Magistris et al. (2015)

Novel foods and novel food ingredients need to go through an EU-level assessment before being placed on the EU market (Figure 5.2). Under both regulations, the authorization procedure is performed in two steps of risk assessment (RA) and risk management (RM). The novel food is evaluated during RA based on compliance with the European safety criteria. In RM, the EC decides whether to authorize a product for the EU market (Pisanello & Caruso, 2018).

5.2.2. Comparison of former and current EU NFR

The steps, actors involved, and time limits of the authorization procedure changed from the former NFR to the current one (Tables 5.1 and 5.2). The apparent complexity of the former NFR may have resulted in a potentially longer authorization procedure than that of the current NFR (Pisanello & Caruso, 2018; Scarpa & Dalfrà, 2008). Previous research suggests that the number of authorities involved in the authorization procedure may be a major factor that causes a lengthier procedural period (Hyde et al., 2017). Under the former NFR, three major authorities played a part in the process at the EU level—MSs, the Scientific Committee for Foodstuff (SCFF) or the EFSA, and the EC. The EFSA and the EC lead the process in the current NFR, while MSs only endorse the authorization decision. In the former NFR, the application dossier was initially assessed by the competent authority

Figure 5.2: Main steps of the authorization process of novel food under the past and current EU NFRs.



Source: Ververis et al. (2020)

at the MS level, and the EFSA carried out the additional assessment. In most cases, the application had to be assessed twice (European Parliamentary Research Service, 2015). In the current NFR, the safety evaluation and RA are done entirely by the EFSA. In both NFRs, the RM phase was/is carried out by the EC.

The new NFR improves the synchronization of the legal and technical procedures across all MSs, guaranteeing homogeneity in the process (Ververis et al., 2020). A decentralized and heterogeneous procedure caused by multiple authorities' involvement may result in a long process for the applicant (Millstone & van Zwanenberg, 2002). A long process constitutes a barrier for applicants aiming to place a novel food on the EU market (Hermann, 2009). The new NFR introduces a streamlined notification procedure for traditional foods from third countries to further simplify the authorization. The simplified procedure applies to foods with a "history of safe food use in a third country" for at least 25 years (European Parliament and Council, 2015).

The two regulations also differ in creating the "Union list" of novel foods and their definitions. Under the previous NFR, the definition of novel food and its specifications were general, resulting in different interpretations across MSs (Coppens, 2013). The current NFR updates its definition of novel food, tries to better keep up with scientific and technological progress, and resolves misinterpretations. Additionally, the former NFR also addressed foods and food ingredients containing genetically modified organisms (GMOs). In 2003, a separate regulation was adopted to regulate GMOs exclusively, removing GMOs from the definition in the current NFR. A further change is creating a Union list including all authorized novel foods under Regulation (EC) 258/97, which increases transparency.

In summary, the current Regulation (EU) 2015/2283's authorization procedure has fewer steps than the past NFR, fewer actors involved, and a more centralized approach. Following the regulators' intent, this simplified process should lead to a shorter length of the authorization procedure and an increase in applications.

Table 5.1: Authorization process time - Reg. (EC) No 258/97

Step	Actor	Process time limit
Risk assessment		
Verification of the validity of the dossier	MS	1 month
Initial assessment	MS	3 months
Other MS and EC comment on IA	MS/ EC	2 months (extendible to 4 months when objections are raised)
EFSA safety assessment (if needed)	SCFF/ EFSA	No time limit
Risk management		
Implementation of the draft	EC	No time limit
Final decision deliberation	EC	3 months

Table 5.2: Authorization process time - Reg. (EU) 2015/2283

Step	Actor	Process time limit for novel food or food ingredients	Process time limit for Traditional food from third countries
Risk assessment			
Verification of the validity of the dossier	EC	1 month	1 month
Dossier transmitted to EFSA and MS	EC	1 month	
EFSA safety assessment (if needed)	EFSA	9 months (+ possible clock stops)	4 months
Risk management			
Implementation of the draft and final decision deliberation	EC	7 months	6 months

5.3. MATERIALS AND METHODS

5.3.1. Data and sample collection

We collected our data from the EC's official decision documents on each novel food and the Union list of authorized novel foods, containing all authorized novel foods. Additionally, for each novel food, we collected information from the EFSA Register of Questions and the Scientific Journal of EFSA on the exact dates of its authorization procedure steps, such as the date of application submission and date of final decision. We identified the decision status of each application, which can be authorized, refused, withdrawn, under evaluation, or under consideration. Our dataset includes 294 applications, from which 187 were submitted under Regulation (EC) 258/97 and 107 under Regulation (EU) 2015/2283[12]. We recorded all applications submitted between November 1997 and December 2020 and monitored the approval status until September 2021.

The first observation is "Stevia rebaudiana Bertoni" from November 5, 1997, and the last application is for "6-Siallylactose sodium salt" from September 22, 2020. The EC has authorized 165 out of 294 applications, refused 36, and 80 applications are still ongoing. We measured the length of the authorization process as the number of days between the application submission date and the final decision (either authorization, withdrawal, or refusal) by the EC. We constructed the length of each authorization process by taking the arithmetic sum of the days between submission and decision.

Finally, we deduced information on each applicant at the year of submission from the information previously gathered from the EC's decision documents in terms of whether the applicant is an EU resident, the type of novel food application (novel food as a whole food product or novel food ingredient or both), whether the applicant is a private or public entity, whether they have filed more than one submission throughout the entire 1997–2021 period, and whether the relevant scientific authority is in the same country as the applicant. Table 5.3 presents an overview of the variables derived from our data. Having collected our dataset, we applied an empirical strategy to deal with the lack of information regarding the approval status of the novel foods still under evaluation, as outlined in the following section.

12 Alongside submissions for authorization, we found more than 400 applications for notification under the former NFR and more than 50 under the current regulation. A novel food must be a substantial equivalent of a product already authorized under the NFR for a notification application. In this case, the authorization procedure is shorter and does not entail all the steps that would be required if a novel food product entered the market for the first time. We do not include these submissions in our analysis to ensure comparability.

Table 5.3: Variables derived from the collected data

Variable	Levels
Type of novel product	Novel food Novel food ingredient Novel food and Novel food ingredient GMO Traditional food from a third country
Authorization process length	Date of application submission Date of the final decision (either authorization, withdrawal or refusal)
Type of company	Private Public
Country of origin	Country of applicant
EU/Non-EU country	EU Non-EU
Spatial relation to the competent authority	The same country as the competent authority A different country as the competent authority
Number of NF applications submitted	Single Multiple

5.3.2. Empirical strategy

We assessed the length of the novel food authorization procedure in the EU and analyzed regional differences and the determinants of a successful novel food application. Our empirical strategy consisted of three stages, each addressing the different research questions of this study (Section 5.1).

5.3.2.1. Number of applications and introduction of Regulation (EU) 2015/2283

The first stage addressed RQ1, assessing the yearly number of applications for novel food products and how introducing Regulation (EU) 2015/2283 has affected them. We designed a Bayesian hierarchical model (BHM)(Gelman et al., 2013; McElreath, 2020 and references therein) to decompose the time series of novel food submissions into three additive components. We postulated that the yearly count of novel food applications results from a fixed offset component, α , a time-dependent coeffi linearly depends on the observations in previous years, θ_t , and a dynamic shock following the introduction of the new NFR, β_t . Mathematically, the model can be expressed as follows:

$$
\begin{aligned}
& n_t \sim \text{poisson}\left(\lambda_t\right) \\
& \log\left(\lambda_t\right) = \alpha + \theta_t + \beta_t \times \text{I}\left[t \geq 2018\right] \\
& \alpha \sim \text{normal}\left(\mu_\alpha, \sigma_\alpha\right) \qquad\qquad (1) \\
& \sim \text{normal}\left(\mu_\theta + \rho_\theta \theta_{t-1}, \sigma_\theta\right); \rho_\theta \in \left(-1,\right. \\
& \beta_t \sim \text{normal}\left(\mu_\beta + \rho_\beta \beta_{t-1}, \sigma_\beta\right); \rho_\beta \in \left(-1,1\right),
\end{aligned}
$$

where $\mathbb{I}[\cdot]$ represents an indicator function taking on a value of 1 when its argument is true, μ_α and σ_α express prior hyperparameters for the offset, and μ_θ and μ_β indicate initial mean deviations from the offset. The remaining terms, ρ_θ and ρ_β, serve as the autoregressive coefficients, whereas σ_θ and σ_β represent variance hyperparameters for the corresponding dynamic prior distributions. We provide further details on the model structure and functioning, estimation procedures, inferential calibration, and prior definition for all the latent quantities in Appendix A. In short, β_t represents our parameter set of interest, indicating the additional rate of applications resulting from Regulation (EU) 2015/2283. The fact that β_t depends on its previous values has two uses, one technical and one conceptual. On the technical side, the autoregressive component of β_t helped identify the effect of Regulation (EU) 2015/2283 from the trend component, θ_t. From a conceptual perspective, modeling both θ_t and β_t autoregressively provided a generalization to a simpler model in which the dynamic effects would be independent across periods. This dependence might reflect future expectations about the business of the authorization pipeline: as more products are being submitted for evaluation, capacity constraints might compromise the ability of the competent authority to process applications within a reasonable amount of time, thereby discouraging new candidates from submitting new novel foods. However, since we gave both ρ_θ and ρ_β zero-centered weakly informative prior distributions (see Appendix A), it will depend on the data whether the autoregressive structure actually holds.

5.3.2.2. Proportion of decisions within T years

In the second stage, we investigate RQ2, analyzing how the proportion of applications that received a decision (either approval or rejection) within one, two, three, or four years has changed since the introduction of Regulation 258/97 in January 1997. Specifically, we estimated a linear, quadratic, and flexible (i.e., LOESS regression) model and then plotted fitted line plots to discuss each specification. We calculated each proportion as the sum of applications approved within $k \times 365$ days in year t divided by the total number of applications within the same year, t. Our time series starts at $t = 1997$ and terminates at $T = 2021$ while, as anticipated above, $k \in \{1, 2, 3, 4\}$ years. If at any time $t = 2016$ (i.e., $2021 - max(k) + 1$) or beyond we observed applications with no decision by 2021, we imputed the missing application length using $366 \times (T - t)$. This means that whenever the evaluation was still ongoing, we defined the length of the process as exceeding the considered time window. For each value of k, the most recent year we considered depends on k itself. For example, take $k = 4$. Since we were looking for novel foods that took no more than four years to evaluate, we could not include years beyond 2016 as the data for approval covering a whole year end with the calendar year 2020.

5.3.2.3. Determinants of approval

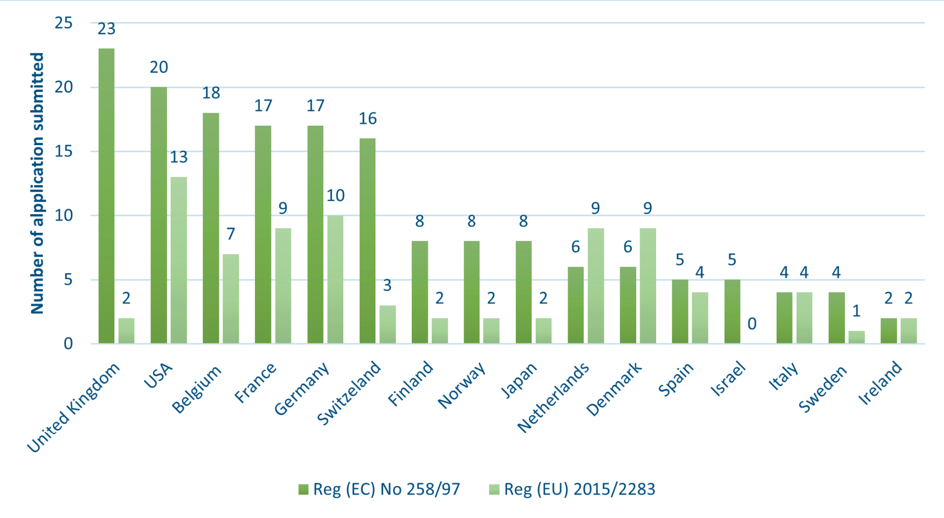
In the third stage, we investigated RQ3, assessing the contribution of different applicants' characteristics to the probability that a novel food is authorized. We defined a Bayesian logit model, where we regressed authorization decisions on a dummy for submissions that occurred under Regulation (EU) 2015/2283 and all indicators presented in Table 5.3. As with the count model introduced in Section 5.3.2., we set up prior distribution for each parameter in the conditional mean function via calibration (see Appendix A). We present the results of applying our empirical strategy to the collected data in the following section.

5.4. RESULTS

5.4.1. Origin and number of yearly applications and the introduction of Regulation (EU) 2015/2283

We looked at applicants' home countries to analyze how the submission of novel food applications varies across regions. Figure 5.3 shows that, before 2017, most applications were submitted from entities in the United Kingdom, followed by Belgium, France, and Germany. EU actors submitted 68.5% of the dossiers under the former NFR, while non-EU actors submitted 31.5%. The non-EU countries with the highest number of applications are the U.S. and Switzerland, with 20 and 16 applications, respectively. The proportion of EU and non-EU entities submitting applications changed slightly with the current NFR, where 70.6% of the applicants were from EU MS, and 29.4% were not from the EU. Since the new NFR was introduced, the most EU actors submitting applications were from Germany, followed by the Netherlands, Denmark, and France.

Figure 5.3: Home countries of novel food applicants under the different NFRs.

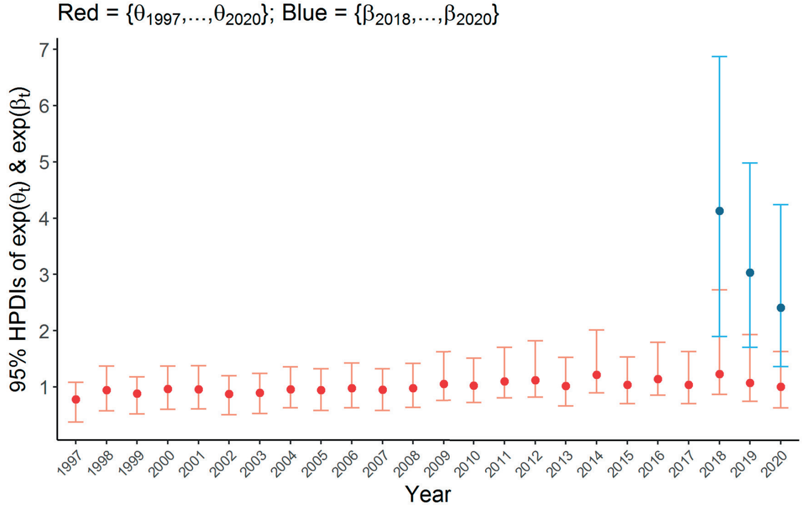


Source: Authors' elaboration.

Novel food applicants can also be different entities such as private companies, public or private research institutes, or non-governmental organizations (NGOs). Most applications were from private companies except for a few cases where the applicants were universities and NGOs. We modeled the yearly number of applications through a BHM (Section 5.3.1.) to evaluate the development of novel food applications and how the new NFR affects this dynamic. Figure 5.4 shows the estimates for all the time-dependent parameters of our reference model, suggesting that the yearly number of applications remained relatively steady between 1997 and 2009, then exhibited slightly higher variability from 2010 to 2020.

However, what stands out is the additional rate of applications following the introduction of Regulation (EU) 2015/2283 in 2018 with the corresponding parameter β_t. However, since β_t decreases in the following two years, our estimates suggest that this upsurge was only temporary.

Figure 5.4: Highest posterior density intervals (HPDI) based on a Bayesian hierarchical model for the time-dependent coefficient of applications (in red) and additional rate of applications from the introduction of Regulation 283/2015 (in blue).



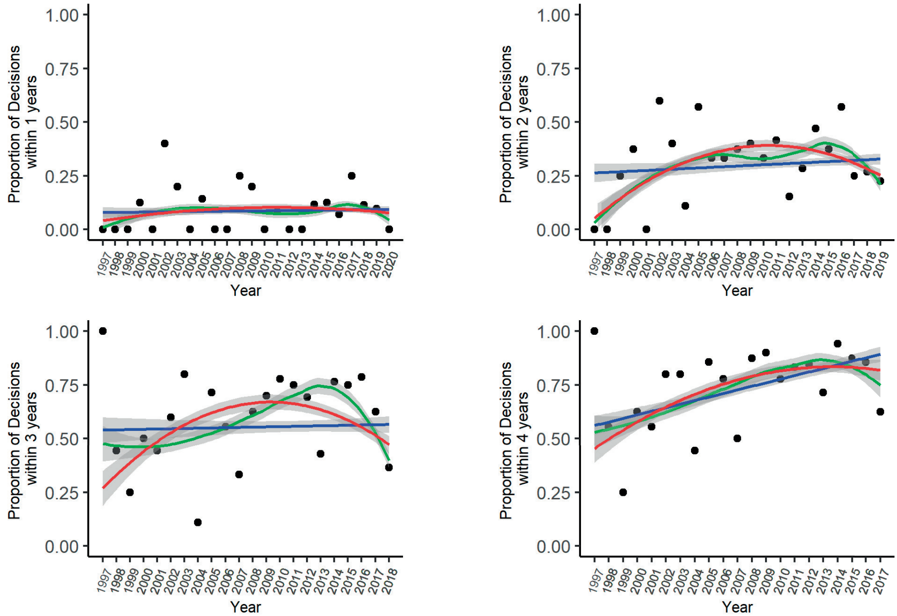
Note: 95% HPDIs represent the interval of the posterior distribution where 95% of the probability lies. The dots indicate the median of the posterior (the maximum a posteiori [MAP] values), which represent our point estimates.

5.4.2. The proportion of decisions within T years and the introduction of Regulation (EU) 2015/2283

Having looked at the number of applications, we next analyzed the length of the authorization procedure for novel food in the EU by assessing the share of applications that received a decision

within a certain period (Section 5.3.2). Figure 5.5 visually represents three differently flexible regression models for the four cut-off periods (one, two, three, and four years). These simple models aimed at eliciting the underlying trend using various degrees of adaptiveness to the data: linear (blue line), quadratic (red line), and LOESS smoothed (green line). The first plot indicates that the EC has not changed the proportion of novel food applications they decided upon within one year from 1997 to 2020 (Figure 5.5). The second and third plots indicate only a very subtle increase in the proportions decided upon within two and three years. The linear lines are sloping slightly upward, while the quadratic and LOESS smoothed lines first increase and then decrease, primarily caused by low proportions in 2018 and 2019. The fourth plot shows a general rise in the proportion of decisions decided upon within four years. However, the non-linear lines show a decline toward the end caused by a lower proportion in 2017. There are also no observations from 2017 onward in this plot.

Figure 5.5: Proportion of applications that received a decision within one, two, three, or four years.



Note: The blue (red, green) line represents the linear (quadratic, flexible) model.

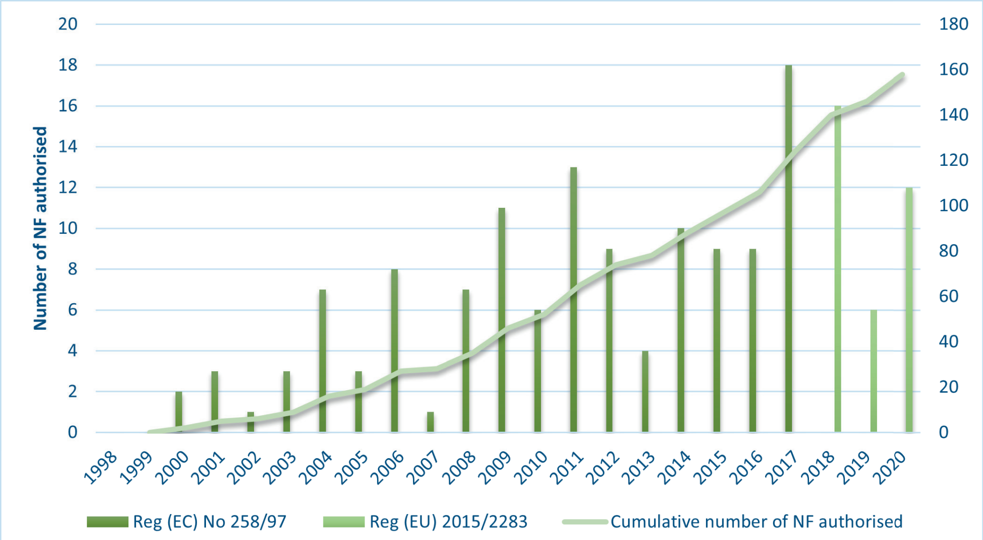
5.4.3. Authorized applications in the EU NFR and determinants of approval

To provide an overview of the development of novel food authorizations in the EU, we looked at the number of authorizations per year, decision status per NFR, and the home countries of successful applicants. Figure 5.6 shows cumulative and yearly authorizations of novel foods from 1998 to 2020. The first novel food ("Phospholipids from Egg Yolk") was authorized in the EU in 2000. The years with the highest number of authorizations are the last year of Regulation (EC) 258/97, 2017, and the first year of Regulation (EU) 2015/2283, 2018.

Table 5.4 shows the number of applications under the different regulations according to their decision status. Although the number of authorized novel foods under the new NFR was lower, many applications are still in process. Only one application got refused after 2018, while the refusals under the former NFR were about 25% of all applications. The former NFR remained in force from 1997 to 2017, with an average of 6.6 successful authorization procedures per year. In comparison, the current NFR has been in force since 2018, with an average of 11 successful applications per year.

To assess the contribution of the new NFR and different applicants' characteristics to the probability that a novel food is authorized, we applied a Bayesian logit model (Section 5.3.2). We regressed the application decision on a dummy for submissions that occurred under Regulation (EU) 2015/2283 and other explanatory variables. Figure 5.7 reports the posterior parameter estimates for the Bayesian logistic regression. First, the 90% HPDIs for the variables "private company" and "novel food (not ingredients)" do not include zero and cover almost entirely negative or positive values, respectively. These results suggest that an application for a novel food (compared to a novel food ingredient) has a lower chance of receiving approval status, while applications from private companies have a higher prospect of receiving an authorization decision.

Figure 5.6: Annual and cumulative numbers of novel foods authorized in the EU.



Source: Authors' elaboration.

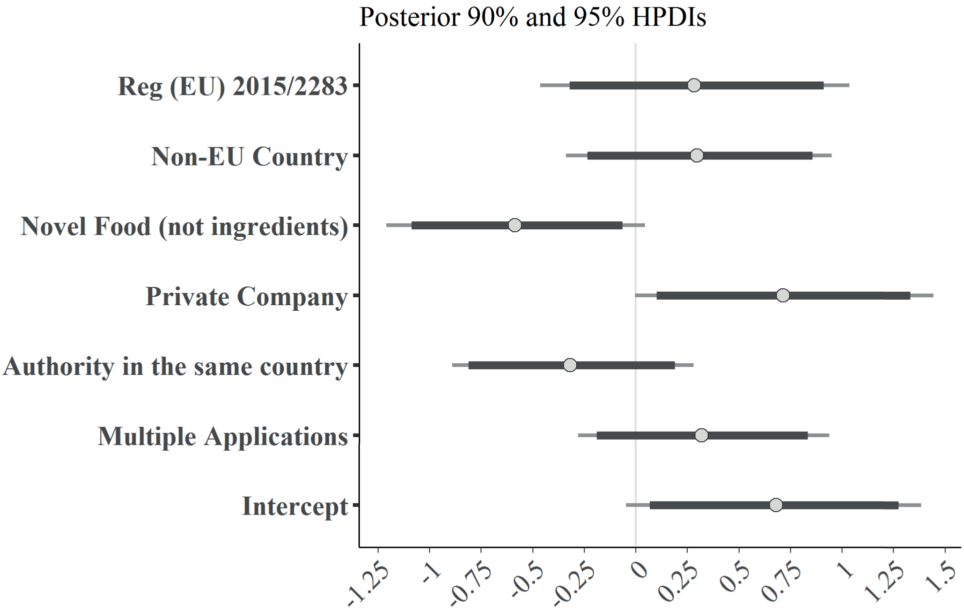
Table 5.4: Number of novel food applications authorized, withdrawn, refused, or in process for Reg. (EC) 258/97, Reg. (EU) 2015/2283, and the transition.

Decision status	Reg. (EC) 258/97	Reg. (EU) 2015/2283 T	Reg. (EU) 2015/2283
Authorized	125	14	26
Withdrawn	9	0	4
Refused	31	4	1
In process	0	4	76
Total	165	22	107

Note: The category Reg. (EU) 2015/2283 T refers to the novel foods authorized during the transition phase of the two EU regulations. Those applications were submitted under the old NFR but approved under the new NFR.

Conversely, our estimates are less clear-cut regarding the remaining covariates. In this respect, the point estimate in Figure 5.7 suggests that applications under Regulation (EU) 2015/2283 are more likely to receive an authorization decision. However, the effect is rather noisy, and the corresponding HPDIs encompass both positive and negative values. Likewise, applicants from non-EU countries and those with multiple applications might be more likely to receive authorization, but the uncertainty in this estimate is too large to deem any conclusion reliable. Similar reasoning applied to applicants from the same country as the competent authority although the sign of the point estimates is negative here. estimate is too large to deem any conclusion reliable.

Figure 5.7: Highest posterior density intervals (HPDI) based on a Bayesian logit model on the probability that a novel food is authorized.



Note: The thick (thin) lines indicate 90% (95%) HPDIs, which represent the interval of the posterior distribution where 90%(95%) of the probability lies. The dots indicate the median of the posterior (the maximum aposteiori [MAP]values), which represent our point estimates.

5

5.5. DISCUSSION

The collected data allowed us to assess RQ1, which addressed the number of yearly novel food submissions to the EU, considering regional differences. Before 2017, the leader in applications was the United Kingdom, followed by Belgium, France, and Germany. While most applications came from EU applicants, the non-EU countries with the highest number of applications were the U.S. and Switzerland. From the entry into force of the new NFR, the European leader in terms of applications was Germany, followed by the Netherlands, Denmark, and France. Considering that the number of novel food applications might be a valuable indicator for innovation in the food sector (Kardung et al., 2020), this finding is consistent with a study by Charlebois (2020), who found the United Kingdom, the U.S., and Germany to be leaders in their global food innovation index.

Concerning the total number of applications, our analysis showed a relatively steady number of novel food applications submitted, with an upsurge in applications in 2018 under the new Regulation (EU) 2015/2283. Even if applications in 2020 are still higher than with the old NFR, we observed a decrease in the additional rate of applications after 2018. The upsurge might be due to a conscious postponement: companies anticipated the introduction of the new NFR and withheld or were compelled to withhold their applications until it was in force. This postponement might explain the unusually high number of applications in 2018 and the lower numbers in the following years. The qualitative study by Grimsby (2020) supports this interpretation, which could explain the decrease in β_t, indicating an only temporary effect. However, the additional rate of applications should be monitored over a few more years to conclude whether or not the NFR led to a structural change in the number of novel foods applications. The number of applications is also an indicator of the appeal of the regulation: does it facilitate access to the procedures or not?

Concerning the length of the authorization procedure (RQ2), we found that the EC increased the share of applications that received a decision within four years from about 50% in 1997 to around 80% in 2017. Differently, decisions within two and three years only show minor improvements. This increase highlights how, over the years, the EC's procedures improved in guaranteeing an upper bound in the application length. Several criticisms have been raised about the long duration of the authorization process (Hermann, 2009; Hyde et al., 2017) and the consequent costs for the system. Even if the process is still quite long in terms of expectations from the industry, we can conclude that at least the uncertainty about its length has consistently been reducing. For the old NFR, we argue that the improvement in the upper-bound length can be explained by the greater experience and efficiency in dealing with novel product applications gained over the years by the actors involved.

Considering the new NFR, improvements in the length of the authorization process were expected. After the regulatory reform in 2018, the EU novel food authorization procedure changed from a decentralized to a centralized scheme. The impact assessment of a novel product is now endorsed by the EFSA rather than the MSs' competent authorities. The main reasons for this change were to simplify the procedure and ensure homogeneous novel food assessments across the EU (European Parliament and Council, 2015). However, considering applications submitted in the first years of implementation, the new NFR did not seem to introduce substantial changes in the observed timings. The proportions of applications receiving a decision within one, two, or three years seem not to be impacted, looking at the linear trend in the length of the authorization process. Moreover, including quadratic and flexible functional forms shows that the applications submitted in the latest years faced poorer performance in regard to length of time until a decision. The new NFR did not impact the proportions of decisions decided within one year, which could be expected, but the proportion of decisions made in two or three years decreased. Therefore, EU policy-makers seem not to have achieved the aspired shortening of the authorization time yet. A possible explanation for this might be the upsurge in applications following the introduction of the new NFR in 2018, which could have created a bottleneck in the authorization pipeline, increasing administrative inefficiencies. This further highlights the importance of RQ1 as the effect on the number of applications per year could be strictly connected to the length of the process, *ceteris paribus* the capacity of the EC administration dedicated to the process. Knowing whether or not the upsurge of applications is temporary as well as the trend in applications is relevant for assessing the effectiveness of the EC administrative bodies in adapting their capacity.

Looking at authorized applications in the EU NFR (RQ3), there seems to be a difference between the rate of authorized novel foods under the old NFR and Regulation (EU) 2015/2283, which show overall successful rates, respectively, of 76% and 97%. However, a careful examination shows corresponding HPDIs with a range that also encompasses negative values. Still, there seems to be evidence that more successful authorizations are obtained under the new NFR. However, the higher probability of acceptance under the new NFR might be biased by the short length of time since its enforcement as several applications made since 2018 are still pending a decision. The more problematic applications will likely undergo a longer authorization process because the EFSA may request additional data from the applicants.

5.6. CONCLUSIONS AND POLICY RECOMMENDATIONS

In this paper, we provide exploratory research assessing the performance of the EU NFR. We empirically analyzed the pre-market authorization procedure using data collected on applications under the former and current EU NFRs. To investigate the appeal and efficiency of the regulations, our empirical strategy focused on a few indicators that could provide proxy measures of the barriers to accessing the authorization procedure, the opportunity costs of the process, and the degree of success of applicants.

Our results showed a relatively stable number of novel food applications over the years, with an upsurge with the introduction of Regulation 283/2015 in 2018. However, it is too early to conclude whether the new NFR facilitated the process and increased the appeal for new applicants. We observed a progressively decreasing number of applications after the first year of introduction. We also showed a decreasing trend in the length of the authorization process, especially for those applications receiving a decision within four years. Until 2020, the new NFR did not seem to impact this trend. The opportunity cost for applicants due to lengthy waiting times is still high even though there appears to be more certainty about the upper bound of the overall duration of the authorization process. Our results suggested that being a private company and applying for a novel food ingredient are predictors of higher success in the authorization decision. Apparently, the new NFR shows a high degree of successful applications. However, this indicator is likely biased upward as it pertains to a subsample of applications that received a decision within a relatively short period of time. Nevertheless, it seems that the policy reform moves into the expected direction.

Our research was limited by publicly available data on novel food. The EC lists novel foods in the so-called “Union list” of novel foods. However, this list only provided the name and specifications of each product without mentioning the date of application or authorization or the applicant. We collected the timing data for each novel food from among different sources (EC website, EFSA Register of Questions, and the literature). However, the dataset has a few gaps as it is not mandatory to publicly release the dates of the various procedural authorization steps. Future policies should include release of these information.

We applied an empirical strategy to deal with the lack of information regarding the decision on applications still under evaluation. However, this lack of data only concerns the new NFR and limits our ability to compare the two regulations. The success of the new NFR should be re-evaluated in a few years when more observations are available. For further research, it would also be interesting to investigate the economic costs of regulatory compliance for novel food producers and to compare the differences before and after the regulatory reform in the EU. Moreover, it might be possible to compare the same or similar products authorized under different legislations, such as Canada or the U.S. or even in the United Kingdom after the Brexit. The impact of the new notification procedure for traditional foods from third countries on the performance of the new NFR should be evaluated as well. This will provide important information for harmonizing food policies and in particular with respect to reducing approval costs without undermining food safety.

5.A APPENDIX.

Priors, Likelihood, and the Full Bayesian Model

In all but the simples modelling exercises involving trivial conjugate probability models, Bayesian computation requires two fundamental ingredients: (i) the joint posterior distribution of the whole parameter set, and (ii) a sampling algorithm that efficiently and efficiently explores the typical set of that distribution (Betancourt & Girolami, 2013; Gelman et al., 2013; Kruschke, 2015; McElreath, 2020). The samples generated this way can be then employed to construct summary statistics, posterior credible intervals, or posterior marginal distributions of the latent quantities of interest.

Setting up a full posterior for our BHM requires both a likelihood function and sensible prior distributions. Although the standard Bayesian literature provides a clear cut between the data model (the likelihood) and prior information, oftentimes in the most complicated setups this dichotomic distinction becomes less clear. To avoid confusion, we hereby drop this taxonomy altogether and adopt a slightly different notation (M. Betancourt, 2020): let $\mathcal{D}\mathcal{D}$ be the full observation set and let $\boldsymbol{\theta\theta}$ be all the latent parameters. Then, the complete Bayesian model is given by the joint distribution:

$$p\left(\mathsf{D},\grave{\boldsymbol{E}}\right)=p\left(\mathsf{D}\,|\,\grave{\boldsymbol{E}}\right)p\left(\grave{\boldsymbol{E}}\right)$$

where $p(\cdot)$ defines a generic probability distribution while, following the standard classification, $p(\grave{\boldsymbol{E}})$ would indicate the prior distribution. Then, using this setup, the full posterior can be specified as:

$$p\left(\grave{\boldsymbol{E}}\,|\,\mathsf{D}\right)=\frac{p\left(\mathsf{D}\,|\,\grave{\boldsymbol{E}}\right)p\left(\grave{\boldsymbol{E}}\right)}{p\left(\mathsf{D}\right)}\propto p\left(\mathsf{D},\grave{\boldsymbol{E}}\right)=p\left(\mathsf{D}\,|\,\grave{\boldsymbol{E}}\right)p\left(\grave{\boldsymbol{E}}\right)$$

Therefore, upon choosing a suitable sampling method to tackle $p(\grave{\boldsymbol{E}}\,|\,\mathsf{D})$, one can explore the posterior of interest only after defining $p(\mathsf{D}\,|\,\grave{\boldsymbol{E}})$ and $p(\grave{\boldsymbol{E}})$.

Modelling the number of applications

Following equation (1), we can make these two expressions explicit by indicating:

$$\begin{aligned}&p\left(\grave{\boldsymbol{E}}\right)=p\left(\alpha,\left\{\theta_t\right\}_{t=1997}^{2020},\sigma_\theta,\rho_\theta,\left\{\beta_t\right\}_{t=2018}^{2020},\sigma_\beta,\rho_\beta\right)\\&p\left(\mathsf{D}\,|\,\grave{\boldsymbol{E}}\right)=\text{poisson}\left(\lambda_t\right),\text{with}:\log\left(\alpha+\theta_t+\beta_t\times\mathsf{I}\left[t\geq 2018\right]\right)\end{aligned}\qquad\text{(A1)}$$

where the first line of equation (A1), $p(\grave{\boldsymbol{E}})$, can be further decomposed using the chain rule of probability and dropping all the resulting uninfluential conditioning:

$$p(\alpha)\left[\prod_{t=1998}^{2020} p(\theta_t \mid \theta_{t-1}, \gamma_\theta, \sigma_\theta)\right] p(\theta_{1997} \mid \gamma_\theta, \sigma_\theta)\, p(\gamma_\theta)\, p(\sigma_\theta)\left[\prod_{t=2019}^{2020} p(\beta_t \mid \beta_{t-1}, \gamma_\beta, \sigma_\beta)\right] p(\beta_{2018} \mid \gamma_\beta, \sigma_\beta)\, p(\gamma_\beta)\, p(\sigma_\beta)$$

where $\rho_\theta = 2\gamma_\theta - 1$ and $\rho_\theta = 2\gamma_\theta - 1$. Consequently, we can expand equation (1) to provide a full representation of the data generating process (DGP):

$$p(\mathcal{D}|\boldsymbol{\Theta}) = \begin{cases} n_t \sim \text{poisson}(\lambda_t) \\ \log(\lambda_t) = \alpha + \theta_t + \beta_t \times \mathbb{I}[t > 2017] \end{cases}$$

$$p(\boldsymbol{\Theta}) = \begin{cases} \alpha \sim \text{normal}(\log(10), 0.25) \\ \theta_t \sim \text{normal}(\log(1) + \rho_\theta \theta_{t-1}, \sigma_\theta);\ \rho_\theta \in (-1{,}1);\ t \in \{1998 \text{ to } 2020\} \\ \beta_t \sim \text{normal}(\log(1.75) + \rho_\beta \beta_{t-1}, \sigma_\beta);\ \rho_\beta \in (-1{,}1);\ t \in \{2019, 2020\} \\ \gamma_\theta \sim \text{beta}(2{,}2);\ \rho_\theta = (2 \times \gamma_\theta) - 1 \\ \gamma_\beta \sim \text{beta}(2{,}2);\ \rho_\beta = (2 \times \gamma_\beta) - 1 \\ \theta_{1997} \sim \text{normal}\left(\log(1), \sigma_\theta / \sqrt{1 - \rho_\theta^2}\right) \\ \beta_{2018} \sim \text{normal}\left(\log(1.75), \sigma_\beta / \sqrt{1 - \rho_\beta^2}\right) \\ \sigma_\theta \sim \text{normal}_+(0{,}0.25) \\ \sigma_\beta \sim \text{normal}_+(0{,}0.25) \end{cases} \qquad \text{(A2)}$$

in which normal_+ indicates a positive half-normal distribution.

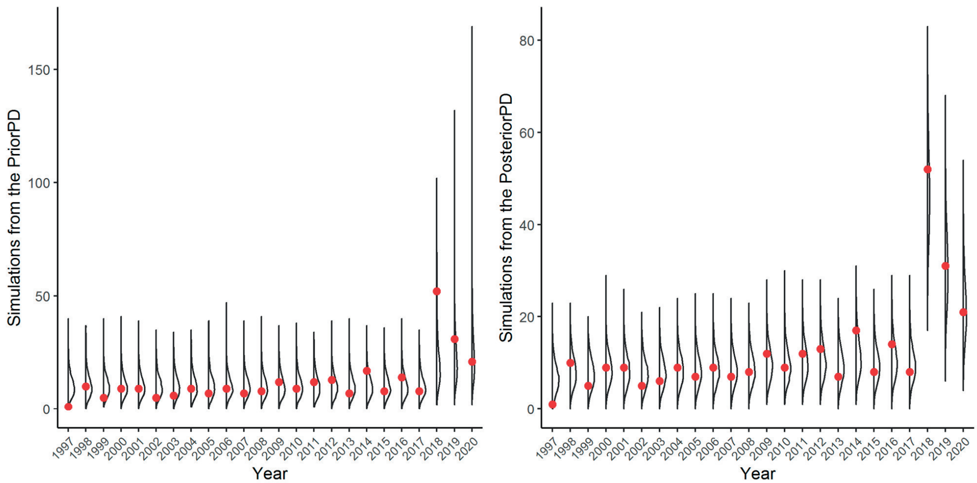
The (marginal) distributions for the base year parameters, θ_{1997} and β_{2018}, are derived algebraically by convoluting all the conditional distributions following the initial period. Given mean and covariance stationarity, one can then show[13] that the variance at time $\min(t)$ is given by the ratio between the standard deviation of the dynamic parameter, divided by the square root of one minus the autoregressive coefficient, squared (as in equation A2). Similarly, the mean at times $t > \min(t)$ is equal to the mean at the beginning of the series, plus the coefficient at $t-1$, scaled by the autoregressive parameter. Finally, we motivate our hyperparameter choices for $\mu_\alpha, \sigma_\alpha, \mu_\theta, \mu_\beta$ (see equation 1) as well as the hyperpriors for σ_θ and σ_β in the next section, where we illustrate simulation-based Prior Predictive Checking (PrPC) to calibrate prior distributions.

13 Details are available upon request.

Prior Distributions

In this section, we present our choice of hyperparameters and hyperpriors for the full BHM in equation (A2). Our strategy consists of calibrating each parameter following the Bayesian workflow methodology proposed in Gabry et al. (2019), Gelman et al. (2020), Betancourt (2020) and Schad et al. (2021). Specifically, we begin with a simple model including only the offset parameter, α , and choose values for μ_α and σ_α by simulating new synthetic observations from the so-called prior predictive distribution (PrPD)(Gabry et al., 2019; McElreath, 2020; Stan Development Team, 2021; Wesner & Pomeranz, 2021). Once this generative model can produce outcomes covering all plausible data configurations, we register its parameters and substitute these values for the priors of our first BHM. Next, we expand the initial configuration by adding the two autoregressive coefficients and follow the same procedure indicated above. We begin by calibrating μ_θ and μ_β, then we complete the model by choosing sensible configurations for σ_θ and σ_β. On the other hand, because we want to encode as little information as possible in ρ_θ and ρ_β, we setup weakly informative beta priors for both γ_θ and γ_β, so that the resulting distribution of the autoregressive coefficients is roughly zero-centred and has decreasing probability away from the mean. This iterative process is sometimes referred to as PrPC (M. Betancourt, 2020; Gelman et al., 2020; Wesner & Pomeranz, 2021). Sampling from $p(\boldsymbol{\grave{E}})$ using the values specified in equation (A2), plugging the resulting simulated parameters into $p(\mathrm{D} \mid \boldsymbol{\grave{E}})$ and then drawing observations from the data model produces the left-hand side panel of Figure A1. The density plots indicate both the range of n_t (vertical axis) and their likelihood had the data been generated according to the process described above. Intuitively, the ensemble should generate counts that are plausible within the domain knowledge of a given problem. In our case, we simply make sure that all the observed number of applications fall within the range of synthetic data simulated through the PrPD, ascertaining that the latter is not too concentrated around the realized counts so that we do not encode too much prior information in the model. Finally, notice that we let the PrPD for the years 2018 and beyond have a longer left tail. Before seeing the data, we cannot say for sure whether n_t has changed after the implementation of Regulation 283/2015, so the most sensible solution is to allow for a wider range of possible outcomes through a proper specification of the prior distribution for β_t.

Figure A1: Prior Predictive Distribution (PrPD – left panel) and Posterior Predictive Distribution (PoPD – right panel) for n_t under the model indicated in equation (A2). The vertical axis indicates the number of applications per year.



Therefore, although the distributions in (A2) might seem at first very informative, they in fact guarantee that our model does not generate unrealistically large or small outcomes, while remaining rather vague on how many applications we should expect each year. This approach to priors is consistent with Gelman et al. (2017), who advocate that 'the priors can only be understood in the context of the likelihood' (hence the name of the paper). Bayesian workflow fully incorporates this principle and provides technical guidelines for applied works.

Modelling the authorization decision

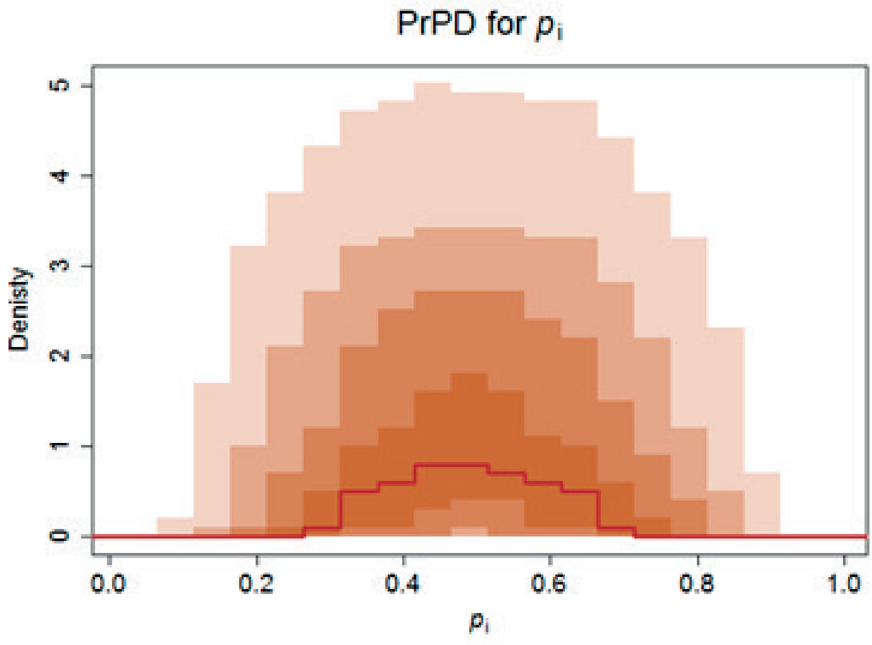
Our simple Bayesian logit model can be generically indicated as:

$$p(\mathrm{D} \mid \grave{\boldsymbol{E}}) = \begin{cases} \text{approved}_i \sim \text{bernoulli}(p_i) \\ \text{logit}(p_i) = \vartheta_0 + \sum_{j=1}^{K} \vartheta_j z_{i,j} \end{cases} \quad \text{(A3)}$$

$$p(\grave{\boldsymbol{E}}) = \{\vartheta_j \sim \text{normal}(0, \sigma_\vartheta); j \in \{1, \ldots, K\}$$

where approved_i is a dichotomic variable taking on value one when application i is authorized, while $z_{i,j}$ indicates one of the K binary indicators introduced in Section 5.3. The parameter ϑ_0 represents the average proportion of approved NF when all other regressors are set to zero, i.e.: $z_{i,j} = 0$ for all

Figure A2: Prior Predictive Distribution (PrPD – left panel) for p_i conditional on $\vartheta_0 = 1.5$ and $\vartheta_j = 0$ for all j. The diffrently shaded areas represent credible intervals between 5% (darker) and 95% (lighter).



j. Because this parameter enters a logit transformation, one can show that any prior distribution on ϑ_0 with support extending beyond 4 to -4 would produce a PrPD for p_i with high probability concentration at either one or zero. Therefore, any prior with large density beyond these thresholds would generate unwarranted very informative bimodal posteriors. To keep the information weak (i.e.: keeping p_i around 0.5), a reasonable work-around to this algebraic issue consists in adopting a 1.5 scaled normal distribution with zero location so that the resulting distribution for p_i resembles Figure A2.

We next calibrate the remaining parameter, σ_ϑ, via PrPC, as discussed in the previous section.

Specifically, setting $\sigma_\vartheta = 0.5$ barely changes the shape of the PrPD for p_i, hence guaranteeing that we do not encode too much information through the priors.

MODEL ESTIMATION VIA MARKOV CHAIN MONTE CARLO

Sampling from the posterior distributions

We sample from the posterior densities implied by equations (A2) and (A3) using Stan (Stan Development Team, 2021). If the target joint distribution does not exhibit poorly identified regions, such as unintended sharp curvatures, or other geometric deficiencies like strong multimodality, Stan can efficiently draw posterior parameters samples from probability functions defined over high dimensional range spaces. Specifically, Stan employs a No-U-Turn Hamiltonian Monte Carlo (NUT-HMC) sampler (M. Betancourt, 2017; M. J. Betancourt & Girolami, 2013; Stan Development Team, 2021) that explores the typical set of any well-behaved twice differentiable distributions through a Markov Chain Monte Carlo (MCMC) algorithm integrated with Hamiltonian dynamics. Moreover, Stan only requires the user to define priors, hyperpriors, and the data model, conveniently removing the need to explicitly derive an expression for either the full Bayesian model or the joint posterior (M. Betancourt, 2017; Neal, 2011). In our work, we run the NUT-HMC algorithm four times, extracting 2000×4 samples from the joint posterior distributions defined through (A2) and (A3). We also apply a 50% burn-in (Geyer, 2011) and no thinning (Link & Eaton, 2012; Maceachern & Berliner, 1994).

Convergence checks for the HMC algorithm

We assess the quality of the estimates obtained through the NUT-HMC sampler using two standard measures of convergence: the split-$\hat{R}$ (Gelman et al., 2013; Stan Development Team, 2021) and the effective sample size (ESS).

The $\hat{R}$ indicator (Figure B1) approaches one whenever the mean variance of the samples extracted by the NUT-HMC in each chain gets close the variance of the samples drawn through all the chains (Stan Development Team, 2021). Therefore, if all the chains did converge to a stationary distribution, the resulting draws would be approximately identical, thereby generating an $\hat{R}$ measure very close to one will converge to one. As displayed in Figure B1, all the models' parameters exhibit $\hat{R}$s of roughly one, indicating that the sample successfully achieved convergence.

Figure A3: Convergence checks for the HMC sampler, R-hat measures for the two models.

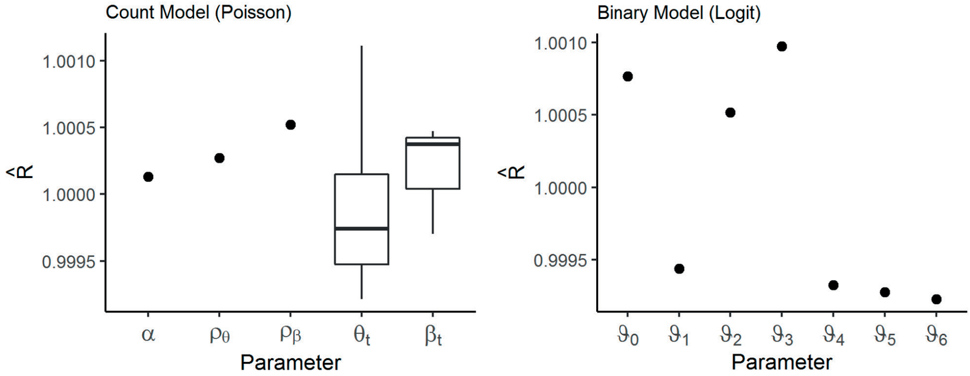
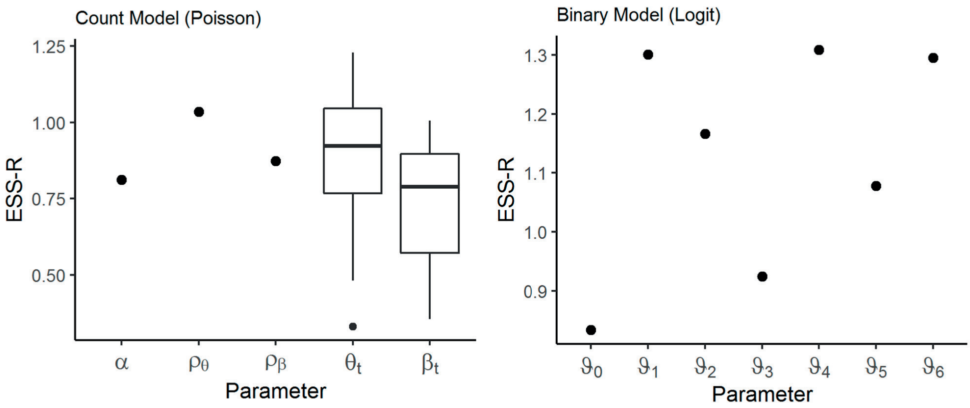


Figure A4: Convergence checks for the HMC sampler, ESS-R measures for the two models.



In general, the samples obtained via MCMC methods will generally be autocorrelated. Therefore, the estimated posterior quantities will usually entail larger variance, thus requiring caution when reporting summaries of the latent quantities of interest (Geyer, 2011). We can however measure to what extent autocorrelation will affect the uncertainty of our estimates by the so-called Effective Sample Size (ESS). In the case of independent samples (i.e.: simple Monte Carlo – MC – samples obtained through the inverse CDF method), the central limit theorem (CLT) provides a lower boundary for the noisiness of an estimator. This threshold is based on the inverse square root of the (MC) sample size. Conversely, when MC samples are correlated, the sample size must be replaced by the ESS, which measures the amount of independent parameter observations drawn from $p(\grave{E} \mid \mathrm{D})$ that would provide the same estimation power as the corresponding autocorrelated sample. For example, for $\mathrm{ESS} = 100$ we would need 100 MCMC samples from the target posterior to achieve the estimation power that we would have obtained, had the draws been independent. Put it differently, the estimation error for the random quantities obtained through NUT-HMC is proportional to $1/\sqrt{\mathrm{ESS}}$, which suggests higher uncertainty with respect to independent MC sampling. Clearly, the closer ESS is to the sample size of the corresponding independent sample, the better. Figure B2 reports the ratio $\mathrm{ESS-R} = \mathrm{ESS}/\mathrm{S}$, where $\mathrm{S} = \sum_{\ell} \mathrm{S}_{\ell}$ and S_{ℓ} indicates the number of NUT-HMC samples drawn each chain ℓ after subtracting the burn-in (Gelman et al., 2013). A widely adopted heuristic recommends regarding $\mathrm{ESS-R}$ smaller than 0.1 unreliable, as the corresponding posterior summaries would be too noisy. In this respect, the Hamiltonian Dynamics exploited in Stan's algorithm could instead produce superefficient estimates through anticorrelated samples. In such cases, we would observe $\mathrm{ESS-R} > 1$, which would imply higher precision than independent sampling. Figure B2 reports the $\mathrm{ESS-R}$ for all the latent parameters in equation (A2) and (A3), indicating that all these quantities have been estimated with a reasonable number of posterior samples (with several showing anticorrelation).

Checking model fit

In this section, we assess the consistency of the dynamic Poisson model defined in equation (A2) with our observed annual application counts. Specifically, we compare our outcome data to 4000 NUT-HMC draws (i.e.: $2000 \times 4 \times 0.5$) from the Posterior Predictive Distribution (PoPD), which we define as the marginalisation (Bayarri & Castellanos, 2007; Gelman et al., 2013; Kruschke, 2015):

$$p\left(\tilde{n}_t | n_t\right) = \int p\left(\tilde{n}_t, \boldsymbol{\grave{E}} | n_t\right) d\boldsymbol{\grave{E}} = \int p\left(\tilde{n}_t | \boldsymbol{\grave{E}}, n_t\right) p\left(\boldsymbol{\grave{E}} \mid n_t\right) d\boldsymbol{\grave{E}} = \int p\left(\tilde{n}_t | \boldsymbol{\grave{E}}\right) p\left(\boldsymbol{\grave{E}} \mid n_t\right) d\boldsymbol{\grave{E}} \qquad \text{(B1)}$$

where $\mathrm{p}(\boldsymbol{\grave{E}} \mid n_t)$ indicates the joint posterior distribution of $\boldsymbol{\grave{E}}$. Since the integral in equation B1 is algebraically intractable, we perform Monte Carlo integration to obtain the distribution of interest through simulation. Given a collection of S samples from the posterior distribution, $\{\boldsymbol{\grave{E}}^{(\mathrm{s})}\}_{1:\mathrm{S}}$, we draw one $\tilde{n}^{(\mathrm{s})}$ from $\tilde{n}\ \boldsymbol{\grave{E}}^{(\ )}$, for each $\mathrm{s} \in \mathrm{S}$. The resulting density plots in right-hand side plot of Figure A1 helps us assess visually whether the n_t sequence (red dots) is consistent with $\{\tilde{n}_t^{(\mathrm{s})}\}_{1:\mathrm{S}}$ (density plots – Gelman et al., 2020; Betancourt, 2020; Schad et al., 2020). Specifically, the reported simulations from the PoPD (density plots) show that our model fits the observed data remarkably well, although the rather vague information encoded in the prior for β_t produces rather noisy posterior estimates. This higher uncertainty results from the limited number of observations beyond the implementation date of Reg. 283/2015, where prior information dominates on the likelihood.

5

CHAPTER 6

General Discussion and Conclusions

6.1. GENERAL DISCUSSION

This thesis addressed the overall research question:

How is the EU bioeconomy developing and affecting the economy, society, and the environment?

The approach to measuring the EU bioeconomy can be represented by a reversed pyramid, reflecting narrowing of the perspective from the second through the fifth chapter. First, the thesis presented a conceptual framework. Then, it empirically investigated how the bioeconomy is developing and affecting the economy, society, and the environment, assessed the sustainability of bioeconomy sectors, and finally analyzed the relationship between regulation and innovation in the food sector.

The change in perspective allowed investigation of the development of the EU bioeconomy from various angles, revealing patterns that might stay hidden when viewed from a single angle. So far, relatively few studies have monitored and measured the bioeconomy across EU states (D'Adamo et al., 2020b; Ronzon et al., 2022; Ronzon & M'Barek, 2018), and additional, comparable measurement and monitoring methodologies for the trends in the bioeconomy are needed (Bracco et al., 2018). Chapters 3 and 4 of the thesis provided cross-country analyses for 10 and 28, respectively, (former) EU MSs. The conceptual framework in Chapter 2 helped in interpreting the empirical results in Chapters 3 to 5. The bioeconomy cuts across economic sectors, and researchers have suggested that measurement should inform its ongoing evolution across different sectors (Wesseler & von Braun, 2017). Several studies have followed the NACE – to have clear and consistent sectoral boundaries for measuring the bioeconomy (Efken et al., 2016; Fumagalli & Trenti, 2014; Lier et al., 2018; Piotrowski et al., 2018; Ronzon et al., 2017; SAT-BBE, 2015a). Chapter 2 built upon the existing literature and provided a wide-ranging list of NACE sectors delimiting the bioeconomy. Chapter 4 used this sectoral delimitation and bioeconomy value-added by sector, including up- and downstream linkages, using Input-Output tables from Cingiz et al. (2021) to provide a unique, extensive analysis of bioeconomy sectors comparable among all EU MSs.

Prior studies have noted the importance of measurement tools that track the contribution of the bioeconomy and other developments towards sustainable development, including reproducible capital (e.g., buildings), human capital (e.g., education), and natural capital (e.g., land) (Calicioglu & Bogdanski, 2021; Dasgupta et al., 2015). GDP has been the policy and discourse-dominating indicator for economic and general welfare, but it does not include the depreciation of capital assets nor other environmental and social aspects (Dasgupta et al., 2015; Stiglitz et al., 2018). Instead, a broad range of indicators measuring the bioeconomy's contribution to reaching the SDGs is crucial to assess its success (Calicioglu & Bogdanski, 2021; O'Brien et al., 2017; Wesseler & von Braun, 2017). This thesis has made four contributions to the literature on measuring the sustainability of the bioeconomy: First, a conceptual framework to understand this contribution (Chapter 2). Second, a framework for assessing the development of the bioeconomy using any number of indicators and finding its speed and patterns (Chapter 3). Third, a framework measuring the bioeconomy's sustainability framework that is directly linked to the 1987 Brundtland Report's definition of sustainable development (Chapter 4). Fourth, an analysis of the sustainability of the EU food sector.

The bioeconomy is a complex system; its measurement therefore benefits from a comprehensive systems analysis (van Leeuwen et al., 2015). Using Chapter 2 as an interpretive framework is useful to reflect on the development of the many indicators covering various elements of the bioeconomy in Chapter 3. The same applies to the two indicators measuring the sustainability of all bioeconomy sectors in Chapter 4. Chapters 3 and 4 complement each other, as they cover many indicators measuring specific aspects for the whole bioeconomy, on the one hand, and two comprehensive indicators measuring sustainable development for individual bioeconomy sectors on the other. Chapter 5 helps validate Chapters 3 and 4, as it provides indicators for more specific elements of a particular industry. Looking at the results from Chapters 2 through 5, one can draw additional conclusions addressing the overall research question. Combining the approaches from Chapters 2 to 5 allows analysis and comparison of the bioeconomies of EU MSs. Chapter 2 found resource availability as a driving force of the bioeconomy, as land, water, and skilled labor are its important inputs. The development of the bioeconomy heavily depends on biomass production, which again depends on the land available for biomass production, available water, and people who can work in the bioeconomy. The type and quality of available biomass are affecting the bioeconomy as well. Biomass can originate from agriculture, forestry, marine environment, or waste. France and Germany are European countries with a lot of potential for biomass production (Hamelin et al., 2019; Verkerk et al., 2019) and large workforces (OECD, 2022). These conditions make the two countries a good example to illustrate how the collection of chapters of this thesis can provide additional insights. Chapter 3 showed that France and Germany have a high number of bioeconomy-related policy actions and that their bioeconomies are progressing quickly. Germany's circular-bioeconomy indicators have advanced the most (on average) compared to the rest of the EU-10, while France is also among the more advancing countries. At the same time, intra-distribution dynamics were high for Germany, which means that indicators sharply differed in their developments and that their relative rankings varied in consecutive years.

Going into more in-depth analysis, ammonia emissions from agriculture increased in Germany, and while this is undesirable considering the environmental impact, it also indicates high biomass production. In France, R&D personnel and gross domestic expenditure on R&D by the government have regressed, which could negatively impact innovation and the development of new technologies there. However, Chapter 4 showed that both countries have high potential for further investments in their bioeconomies. Germany and France generally have low hurdle rates for their bioeconomy sectors. Contrarily, agriculture, forestry, and fishing are among the five sectors with the highest hurdle rates in both countries, indicating that the potential for further sustainable investments in the biomass-producing sectors is limited compared to other sectors. But there are sufficient bioeconomy sectors with lower hurdle rates. For example, in Germany and France, food products, beverages and tobacco, paper products and printing, wholesale and retail trade, and repair of motor vehicles are among the sectors with the lowest hurdle rates. While these sectors are not considered to have the highest level of innovation compared, for example, to the information technology sector, this might change (Friedman, 2015). Chapter 5 provided several indicators for innovation in the food sector and found that it is increasing. The number of applications for the authorization of NF products has upsurged recently, even though the procedure takes a considerable time. Germany and France are the home countries of many applications, indicating that they are leading innovators in the food sector.

Looking back at the insights from all chapters allowed a nuanced view of Germany's and France's bioeconomies and explained their good position in the EU going beyond their biomass potential (D'Adamo et al., 2020b; Morone et al., 2022). It also showed that the bioeconomy is a complex system with many interactions that should be analyzed comprehensively. This insight supports using a complex systems perspective in economic research (Foster, 2005). Foster (2006) argued that developing a complex economic systems approach is necessary to study the microeconomic and macroeconomic implications of economic behavior. Studying the whole range of potential actions, from legislative and regulatory acts to changing individual behaviours, requires the economy and society to be analyzed in their full complexity (Foxon et al., 2013).

Innovation as an important driver of long-term economic growth has been well-established in the economic literature (Aghion & Howitt, 1992; Grossman & Helpman, 1993; Romer, 1990). Innovation is broadly defined as developing new technologies, including creating new processes or products, commercializing them, and bringing them to market (Sachs & McArthur, 2002). Chapter 2 confirmed a similar relationship between innovation and bioeconomy development. Advances in biological sciences and in information and communication technologies, and other technological advances are needed to reach the societal objectives of the bioeconomy. Bringing new bio-based products is especially challenging because there are already similar fossil-based products on the market. For the production process of an existing product, costs are minimized over time, and social costs like carbon emissions are not priced into the market. These challenges make private investments in developing new products less attractive and public investments indispensable (Zilberman et al., 2013). Therefore, measuring innovation in the bioeconomy is central for policymakers.

Keeping track of innovation in the bioeconomy is challenging because there has been no proper, broader measurement of ongoing innovation activities and their outcomes (Wydra, 2020). Patents have long been used as an indicator of innovation in a country's economy (Archibugi, 1992). Patents represent the outcome of the inventive process and, more specifically, those inventions expected to have a business impact. However, using patents as an indicator has the problem that companies sometimes protect their innovations with industrial secrecy, and the propensity to patent varies by sector and country (Shepherd & Shepherd, 2003). Sirilli (1987) also argued that many patents are worthless and never used and that the economic impact of patents is highly skewed. Chapter 2 proposed, new spatially differentiated indicators for revealing these effects, measuring, among other things, innovation via the number of patents submitted by field and sub-field. However, Chapter 5 provided another measure of innovation for the food sector: the number of NF applications. Compared to patents, companies are less likely to apply without using them afterward because of the high costs of the authorization procedure. Also, NF applications involve a product or ingredient ready for the market, while patents often have no direct economic benefit. Considering the empirical results, Chapter 3 showed that patent applications are among the worst in Germany, Italy, and France, while they are among the best in Poland. But as mentioned before, Germany and France are the home countries of many applications, indicating that they are leading innovators in the food sector.

6.2. SYNTHESIS OF ANSWERS TO THE RESEARCH QUESTIONS

Each of the research questions (1 to 4) described in Chapter 1.3 was addressed in a chapter (2 to 5) of this thesis. Hereafter, a synthesis of the answers to these research questions is provided.

Research Question 1: What is driving the development of the EU bioeconomy, and how can it be measured?

Chapter 2 developed a conceptual analysis framework for quantifying and analyzing the development of the bioeconomy, determined the general scope for the framework, and derived a set of indicators for answering this research question. The chapter reviewed the literature to identify several major forces steering the development of the bioeconomy. They are grouped as supply drivers, including technology and innovation, market organization, an increase in the importance of climate change and pressure on ecosystems demand, and demand drivers, including demographics, economic development, and consumer preferences. Other driver groups are resource availability and the measures of governments to influence the development of the bioeconomy, which include global, EU, and national policies, regional policies, and legislation. A wide range of bioeconomy sectors was derived from the EC's definition, including biomass-producing activities, conventional biomass processing activities, novel biomass processing activities, and service-related activities that use biomass (European Commission, 2018b). A major issue in monitoring the bioeconomy is that national statistical agencies seldom distinguish between bio-based and non-bio-based products (Jander et al., 2020), which limits monitoring efforts. The chapter found few indicators addressing innovation, policies, strategies, and legislation within a monitoring and measuring framework (Lier et al., 2018; SAT-BBE, 2015b), but these factors heavily influence the development of the bioeconomy (Nițescu & Murgu, 2020; Tsiropoulos et al., 2017; Wesseler & Zilberman, 2021). New indicators measuring changes over time have been suggested for monitoring innovation, policies, strategies, and legislation. The indicators can be combined into time-series datasets and put onto a standardized scale that allows further transformation to compare developments among EU MSs or even beyond, as commonly done in the literature on economic growth (Quah, 1996) or trade (Zaghini, 2005). Researchers have considered it crucial for society to achieve sustainable development at national, EU, and global levels, and the bioeconomy can contribute to that achievement (Knudsen et al., 2015; O'Brien et al., 2017). The sustainability of the bioeconomy is mainly attached to its environmental dimension, especially regarding sustainable production and use of biomass (Capasso & Klitkou, 2020; D'Adamo et al., 2020a). Biomass can be produced and used more sustainably by including principles from the circular economy (Carus & Dammer, 2018; Hetemäki et al., 2017). Therefore, the chapter proposed indicator measures; among others, 'Material use efficiency' and 'Sustainable resource use' for the degree of circularity of the bioeconomy and various indicators for measuring its contribution to the UN SDGs, respectively.

Research Question 2: What patterns can be found in the evolution of the bioeconomies of ten selected EU Member States?

Chapter 3 showed similarities and differences in the dynamic evolution of a wide range of indicators for circular bioeconomies in ten EU MSs. The chapter developed a novel framework in which indicators with various units and dimensions were normalized and then investigated patterns by using Markov transition matrices. The framework helped in understanding indicators that cover various economic, environmental, and social aspects of a circular bioeconomy. Bracco et al. (2019) reviewed existing monitoring approaches to the bioeconomy and collected 269 distinct indicators from 19 sources that measured a wide range of impact categories, and Lier et al. (2018) proposed 161 indicators for a bioeconomy monitoring framework. This chapter addressed several issues associated with frameworks using a high number of indicators, such as normalization and information overflow (Berg et al., 2019; Lyytimäki et al., 2020; Miola & Schiltz, 2019). A normalization method was used that allows for country comparison and is insensitive to outliers. The chapter used the slope parameter of a linear regression as a novel manner to rank the normalized indicators and Markov transition matrices to analyze the distribution of many indicators, compared to one indicator in previous studies (Alessandrini et al., 2007; Chiappini, 2014; Fertö & Soós, 2008; Zaghini, 2005). The chapter found that the evolutions of the EU-10 circular bioeconomies were generally progressive, considering all indicators; however, this development was not homogeneous. Circular bioeconomies in Slovakia, Poland, and Latvia developed quickly compared to the rest of the EU-10. Their substantial relative progress from 2006 to 2016 was particularly unexpected because their governments had not implemented any policy actions at the national level for the circular bioeconomy during that period. However, D'Adamo et al. (2020b) found that Slovakia, Poland, and Latvia are still lagging behind the rest of the EU regarding socioeconomic performance. Therefore, the rapid development of circular bioeconomies in these countries may partly be explained by a catch-up effect on highly developed circular bioeconomies such as the Netherlands. This finding is consistent with that of Ronzon and M'Barek (2018), who emphasized the potential of the bioeconomy in Central and Eastern Europe. The indicators related to R&D generally progressed quickly in the private sector and regressed in the public sector, which suggests that one substituted for the other.

Research Question 3: How sustainable is the transition to a bioeconomy in the economic sectors of EU Member States?

Chapter 4 quantified and compared the sustainability of bioeconomy development in the EU. A theoretical framework was conceptualized, building upon Arrow et al.'s (2012) framework for assessing whether economic growth is compatible with sustaining well-being over time. The chapter complemented their framework with the characteristics of bioeconomy-related investment projects: uncertainty of future rewards and losses, irreversible impacts, and flexible timing. Not considering these characteristics could compromise sustainability measurement because benefits of genuine investment projects would be overestimated. The chapter devised a framework that is directly linked to the 1987 Brundtland Report's definition of sustainable development using the concept of intergenerational wellbeing. Bioeconomy value-added was linked with intergenerational wellbeing, and irreversible effects on greenhouse gas emissions were estimated, which allowed applying the framework empirically to the EU's bioeconomy. The chapter calculated hurdle rates to describe the degree of uncertainty and flexibility of bioeconomy sectors and the maximum amount of irreversible costs as an indicator for the sustainability of bioeconomy investments against irreversible environmental impacts. It was found that the hurdle rate in the bioeconomy is lower for the bio-based part than for the non-bio-based part for most countries, indicating high potential for further sustainable investments in the transition towards an EU bioeconomy. The sectoral hurdle rates showed high variability within and between countries. Conventional bioeconomy sectors such as food products, beverages and tobacco, and paper products and printing have low hurdle rates in many countries. The major share of countries have negative maximum incremental social tolerable irreversible costs (MISTICs) for their bioeconomy, implying that bioeconomy projects need to provide irreversible benefits. However, every country has bioeconomy sectors with positive MISTICs. The findings are consistent with results from the Ecological Footprint, where most EU MSs have an ecological deficit as they have a greater footprint than biocapacity.

Research Question 4: How is the EU's novel food regulation developing and impacting innovation in the food sector?

Chapter 5 provided exploratory research assessing the performances of the EU NFR. The chapter empirically analyzed the pre-market authorization procedure by using data collected on applications under the former and current EU NFR. To investigate the appeal and efficiency of the Regulation, the empirical strategy focused on a few new indicators that could provide proxy measures of barriers to accessing the authorization procedure, the opportunity costs of the process, and the degree of success of applicants. Several criticisms have been raised about the long duration of the authorization process (Hermann, 2009; Hyde et al., 2017) and the consequent costs for the system. Hermann (2009, p. 505) highlighted that "costs, complexity, length and uncertain outcomes of NFR procedures have led to uncertainties about the likelihood of successful applications and discouraged firms of the sector to file applications." The empirical findings suggest that expectations impact firm investment decisions, as the EU has had a relatively stable number of NF applications over the years, with an upsurge with the introduction of the new NFR in 2018. However, it is too early to conclude whether the new NFR facilitated the process and increased the appeal for new applicants. A progressively decreasing number of applications after the first year of introduction was observed. A decreasing trend in the length of the authorization process was shown, especially for those applications receiving a decision within four years. Until now, the new NFR has not seemed to impact this trend. The opportunity cost for applicants due to lengthy waiting times is still high, even if there appears to be more certainty about the upper bound of the overall duration of the authorization process. Innovation in the food industry is growing in importance (Grunert et al., 1997) and impacting the whole supply chain (Zilberman et al., 2022). Therefore, it is becoming more important to measure the level of innovation and the factors affecting it. The chapter provided a new indicator for innovation in the food sector: the number of NF applications. The results suggest that being a private company and applying for an NF ingredient are predictors of higher success in the authorization decision. Apparently, the new NFR shows a high degree of successful applications. However, this indicator is likely biased upward as it pertains to a subsample of applications that received a relatively quick decision.

6.3. OVERARCHING POLICY RECOMMENDATIONS

In the 2018 Bioeconomy Strategy Action Plan, EU policymakers stated that they aim to increase observation, measurement, monitoring, and reporting capabilities and develop the Bioeconomy Monitoring System. This monitoring system covers environmental, social, and economic dimensions of sustainability and relates to the overarching SDGs (Kilsedar et al., 2021). The common approach is to use indicators that measure different sustainability aspects and have targets for them that are considered sustainable (Bracco et al., 2019). It is recommended to use indicators designed specifically for measuring sustainable development as well, that is, indicators that explicitly consider the wellbeing of future generations and how they will be affected by irreversibility and uncertainty.

The EU Bioeconomy Monitoring System uses a hierarchical structure, where broad objectives are broken down into normative criteria, which are further broken down into key components (European Commission, 2022a). The full list of indicators planned to be implemented in the system amounts to 168 indicators. The EU Bioeconomy Progress Report states that the nested structure allows for aggregation of the indicators to the different levels of the hierarchy and considers the 'key components' level the most appropriate level of aggregation (European Commission, 2022a). However, while this type of aggregation improves user-friendliness, it also bears the risk of ignoring more nuanced trends at the lower level of aggregation. EU policymakers should consider as many indicators as are available in a given period, assessing their speed and direction.

Monitoring frameworks such as the one presented in this thesis should be used with caution. As with any framework, this work on indicators simplifies the intricate complexity of the bioeconomy. No indicator or set of indicators can perfectly capture different aspects of reality (Maggino, 2017). It also represents a compromise regarding what can be quantified, the type of data collected, and its quality. The ramifications are that indicators and related methodology should be viewed as value-neutral and only measure what they point to. A link to specific policy objectives should only be made if they explicitly refer to one or more indicator(s) and associated methodology. It would be unsound to assume that increases in all the indicators that mark the transition towards bioeconomy mean that all possible aspects of this transition have been accomplished. This caution is especially true for environmental indicators, where environmental aspects of sustainability transition to bioeconomy are much less abundant than economic indicators.

Developing new bio-based products requires substantive investments from companies, and they have problems with cost-effectiveness (Lange et al., 2021; Mujtaba et al., 2022). Chapter 4 showed that many bioeconomy sectors still have high hurdle rates, making future returns more risky and uncertain (Wree et al., 2016). A higher hurdle rate indicates that companies need to expect higher benefits for an investment in developing a bio-based product to be sustainable. Policymakers can increase private investment in bio-economy sectors by reducing the uncertainty of future benefits in a sector, for example, by introducing a public procurement program of bio-based products for the EU similar to the United States Department of Agriculture BioPreferred Program. Chapter 3 showed that research and development progressed in the private sector but regressed in the public sector in selected countries in the EU. Providing incentives for private investments is even more critical if this trend continues and would complement existing public-private partnerships[14].

Chapter 5 found that regulators could offset the sluggishness of the authorization procedure for NFs in the EU by reducing the degree of uncertainty regarding the maximum expected length. As was presented in the framework in Chapter 4, uncertainty creates the need for additional benefits for an investment to be sustainable. Therefore, policymakers could unlock investments, as described in the 2022 EU Bioeconomy Strategy Progress Report, by ensuring a maximum time the authorization would take. This action could also be applied with authorization procedures in other bioeconomy sectors, such as microbial biological control agents (Frederiks & Wesseler, 2019), biopharmaceuticals (Tsuji, 2008), or genetically engineered crops (Smart et al., 2017). Policymakers can foster investment opportunities by lowering the expected irreversible approval costs and by decreasing the approval process's expected length and uncertainty about this length.

6.4. LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The availability and quality of data for measuring and analyzing the bioeconomy were limitations that kept coming back during the research. Compared to other economic research, splitting out the bio-based portion of the bioeconomy is an added issue. The data situation is challenging when observing the bio-based sectors, and it becomes even more challenging when considering export and import data and flows. In addition, bio-based

14 The most prominent example of a public-private partnership for the EU bioeconomy is the Circular Bio-based Europe Joint Undertaking.

and fossil-based economies are intimately interlinked, and in assessing the bioeconomy, one must not lose sight of the rest of the economy. Changes or trends in the fossil-based economy might have a profound impact on the bioeconomy.

The research was limited mainly to the EU and did not view interactions with other regions to the full extent. The conceptual framework in Chapter 2 considered globalization and global policies a driving force, emphasizing the importance of international trade. Also, some indicators, such as 'Comparative advantage', capture the relationship of the EU bioeconomy with the rest of the world. But the framework's scope is based on the EC's bioeconomy definition. The existing indicators mainly came from a European source (Lier et al., 2018) and were discussed with stakeholders from the EU. Chapters 3 and 4 empirically assessed EU bioeconomies and only considered global effects to a limited extent via indicators such as greenhouse gas emissions. However, the frameworks behind the empirical analysis could also be used for other world regions. Chapter 5 analyzed the EU's NFR, for which applicants from outside the EU can apply. Most applications come from applicants from the United States. However, the results of this chapter cannot be generalized to other world regions and must be validated first.

European policymakers struggle to counteract the rural exodus by implementing policies that effectively promote rural development and provide more job opportunities in sparsely populated regions. Rural areas are most affected by bioeconomy policies, so by supporting the bioeconomy, policymakers intend to promote the economic development of these areas, among other goals. Rural areas depend on the bioeconomy for their economic development more so than urban areas, and in many European countries, they are left behind. Rural regions of the EU have a higher risk of poverty or social exclusion, fewer highly educated people, and worse infrastructure than non-rural regions (Abreu et al., 2019). Future research should address whether bioeconomy policies succeed in promoting rural development by offering more economic opportunities.

While development of the bioeconomy is driven ambitiously by the EU and by EU MSs, concrete bioeconomy-related policies are scarce. Countries are also willing to intensively promote the development of their bioeconomies politically, using enabling policy means (Dietz et al., 2018). In recent years, researchers have analyzed bioeconomy strategies qualitatively, and the approaches and objectives of these strategies have been scrutinized (De Besi et al., 2015; Dietz et al., 2018; Meyer, 2017). The EU's efforts are the most advanced compared to other world regions but still appear to be a somewhat fragmented, inconsistent, and heterogenous policy field (Vogelpohl et al., 2022). Existing bioeconomy-related strategies often aim for mid- and long-term impacts, which are difficult to evaluate. The use of indicators to measure the development and various intended outcomes of the bioeconomy has recently been widespread, with data gaps often being the biggest challenge to overcome (Ronzon et al., 2022). However, future research should address the uncertainty about the causation between bioeconomy policy strategies and their objectives.

A large group of scientists worldwide has recently declared that climate change could "cause significant disruptions to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable" (Ripple et al., 2020, p. 10). The EU vowed to become the world's first "climate-neutral bloc" by 2050 in the European Green Deal (European Commission, 2019b) and highlighted the vital role of the bioeconomy in achieving this climate neutrality and environmental, economic, and social sustainability (European Commission, 2022a). Tracking the path towards a bioeconomy is challenging because it affects many economic sectors, societal aspects, and environmental systems. This thesis provided sophisticated and novel approaches and indicators for measuring the bioeconomy and found varying but generally positive trends. A focus was on providing methods to analyze the many aspects of the bioeconomy and its contribution to sustainability. Additional research is needed to measure whether the bioeconomy's contribution towards sustainable development, which is most threatened by climate change, is sufficient and fast enough.

REFERENCES

Acemoglu, D., & Azar, P. D. (2020). Endogenous Production Networks. *Econometrica*, *88*(1), 33–82. https://doi.org/10.3982/ecta15899

Aghion, P., & Howitt, P. (1992). A Model of Growth Through Creative Destruction. *Econometrica*, *60*(2), 323. https://doi.org/10.2307/2951599

Alessandrini, M., Fattouh, B., & Scaramozzino, P. (2007). The changing pattern of foreign trade specialization in Indian manufacturing. *Oxford Review of Economic Policy*, *23*(2), 270–291. https://doi.org/10.1093/oxrep/grm013

Antonucci, F., Figorilli, S., Costa, C., Pallottino, F., Raso, L., & Menesatti, P. (2019). A review on blockchain applications in the agri-food sector. *Journal of the Science of Food and Agriculture*, *99*(14), 6129–6138. https://doi.org/10.1002/jsfa.9912

Archibugi, D. (1992). Patenting as an indicator of technological innovation: A review. *Science and Public Policy*. https://doi.org/10.1093/spp/19.6.357

Arrow, K., Dasgupta, P., Goulder, L., Daily, G., Ehrlich, P., Heal, G., Levin, S., Mäler, K.-G., Schneider, S., Starrett, D., & others. (2004). Are we consuming too much? *Journal of Economic Perspectives*, *18*(3), 147–172.

Arrow, K., Dasgupta, P., & Mäler, K.-G. (2003). Evaluating Projects and Assessing Sustainable Development in Imperfect Economies. *Environmental and Resource Economics*, *26*(4), 647–685. https://doi.org/10.1023/B:EARE.0000007353.78828.98

Arrow, K. J., Dasgupta, P., Goulder, L. H., Mumford, K. J., & Oleson, K. (2012). Sustainability and the measurement of wealth. *Environment and Development Economics*, *17*(3), 317–353. https://doi.org/10.1017/S1355770X12000137

Arrow, K. J., & Fisher, A. C. (2013). Environmental preservation, uncertainty, and irreversibility. In *Economics of Natural & Environmental Resources* (pp. 479–488). Taylor and Francis. https://doi.org/10.2307/1883074

Baráth, L., & Fertő, I. (2017). Productivity and Convergence in European Agriculture. *Journal of Agricultural Economics*, *68*(1), 228–248. https://doi.org/10.1111/1477-9552.12157

Barbier, E. B. (2013). Wealth accounting, ecological capital and ecosystem services. *Environment and Development Economics*, *18*(2), 133–161. https://doi.org/10.1017/S1355770X12000551

Bartolini, F., Gava, O., & Brunori, G. (2017). Biogas and EU's 2020 targets: Evidence from a regional case study in Italy. *Energy Policy*, *109*, 510–519. https://doi.org/10.1016/j.enpol.2017.07.039

Bayarri, M. J., & Castellanos, M. E. (2007). Bayesian Checking of the Second Levels of Hierarchical Models. *Statistical Science*, *22*(3). https://doi.org/10.1214/07-STS235

Bell, J., Paula, L., Dodd, T., Németh, S., Nanou, C., Mega, V., & Campos, P. (2018). EU ambition to build the world's leading bioeconomy—Uncertain times demand innovative and sustainable solutions. *New Biotechnology*, *40*, 25–30. https://doi.org/10.1016/j.nbt.2017.06.010

Belluco, S., Halloran, A., & Ricci, A. (2017). New protein sources and food legislation: The case of edible insects and EU law. *Food Security*, *9*(4), 803–814. https://doi.org/10.1007/s12571-017-0704-0

Berg, A., Lähteenoja, S., Ylönen, M., Korhonen-Kurki, K., Linko, T., Lonkila, K.-M., Lyytimäki, J., Salmivaara, A., Salo, H., Schönach, P., & Suutarinen, I. (2019). *PATH2030 – An Evaluation of Finland's Sustainable Development Policy* [Serial publication]. Prime Minister's Office. https://julkaisut.valtioneuvosto.fi/handle/10024/161601

BERST. (2014). *Criteria and Indicators describing the regional bioeconomy*. https://www.wecr.wur.nl/BerstPublications/D1.1 Criteria and Indicators describing Regional Bioeconomy (Oct 2014).pdf

Betancourt, M. (2017). *A Conceptual Introduction to Hamiltonian Monte Carlo*. https://doi.org/10.48550/ARXIV.1701.02434

Betancourt, M. (2020). *Towards A Principled Bayesian Workflow (RStan)*. https://github.com/betanalpha/knitr_case_studies/tree/master/principled_bayesian_workflow

Betancourt, M. J., & Girolami, M. (2013). *Hamiltonian Monte Carlo for Hierarchical Models*. https://doi.org/10.48550/ARXIV.1312.0906

Biermann, F., Hickmann, T., Sénit, C.-A., Beisheim, M., Bernstein, S., Chasek, P., Grob, L., Kim, R. E., Kotzé, L. J., Nilsson, M., Ordóñez Llanos, A., Okereke, C., Pradhan, P., Raven, R., Sun, Y., Vijge, M. J., van Vuuren, D., & Wicke, B. (2022). Scientific evidence on the political impact of the Sustainable Development Goals. *Nature Sustainability*, *5*(9), Article 9. https://doi.org/10.1038/s41893-022-00909-5

Bigliardi, B., & Galati, F. (2013). Models of adoption of open innovation within the food industry. *Trends in Food Science & Technology*, *30*(1), 16–26. https://doi.org/10.1016/J.TIFS.2012.11.001

BIOÖKONOMIERAT. (2018). *Global Bioeconomy Summit Communiqué Global Bioeconomy Summit 2018 Innovation in the Global Bioeconomy for Sustainable and Inclusive Transformation and Wellbeing*.

BNetzA Marktstammdatenregister. (n.d.). *Auswertung des Registers durch das ZSW Baden-Württemberg*. Retrieved September 15, 2019, from https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/EEG_Registerdaten_node.html;jsessionid=F68354DE8042158224AE13C9BC04E00C

Booysen, F. (2002). An overview and evaluation of composite indices of development. *Social Indicators Research*, *59*(2), 115–151. https://doi.org/10.1023/A:1016275505152

Bórawski, P., Be\ldycka-Bórawska, A., Szymańska, E. zbieta J., Jankowski, K. J., Dubis, B., & Dunn, J. W. (2019). Development of renewable energy sources market and biofuels in The European Union. *Journal of Cleaner Production*, *228*, 467–484. https://doi.org/10.1016/j.jclepro.2019.04.242

Bracco, S., Calicioglu, O., Juan, M. G. S., Flammini, A., Gomez San Juan, M., & Flammini, A. (2018). Assessing the contribution of bioeconomy to the total economy: A review of national frameworks. *Sustainability (Switzerland)*, *10*(6), 1698. https://doi.org/10.3390/su10061698

Bracco, S., Tani, A., Çalıcıoğlu, Ö., Gomez San Juan, M., & Bogdanski, A. (2019). *Indicators to Monitor and Evaluate the Sustainability of Bioeconomy. Overview and A Proposed Way Forward*.

Bringezu, S., Distelkamp, M., Lutz, C., Wimmer, F., Schaldach, R., Hennenberg, K. J., Böttcher, H., & Egenolf, V. (2021). Environmental and socioeconomic footprints of the German bioeconomy. *Nature Sustainability*, *4*(9), Article 9. https://doi.org/10.1038/s41893-021-00725-3

Bringezu, S., Schütz, H., Arnold, K., Merten, F., Kabasci, S., Borelbach, P., Michels, C., Reinhardt, G. A., & Rettenmaier, N. (2009). Global implications of biomass and biofuel use in Germany – Recent trends and future scenarios for domestic and foreign agricultural land use and resulting GHG emissions. *Journal of Cleaner Production*, *17*. https://doi.org/10.1016/j.jclepro.2009.03.007

Brookes, G. (2007). Economic impact assessment of the way in which the EU novel foods regulatory approval procedures affect the EU food sector. *Pgeconomics.Co.Uk*. http://pgeconomics.co.uk/pdf/novelfoods.pdf

Brundtland, G. H. (1987). Our common future—Call for action. *Environmental Conservation*, *14*(4), 291–294.

Bugge, M. M., Hansen, T., & Klitkou, A. (2016). What is the bioeconomy? A review of the literature. *Sustainability (Switzerland)*, *8*(7), 691. https://doi.org/10.3390/su8070691

Buongiorno, J. (2018). On the accuracy of international forest product statistics. *Forestry: An International Journal of Forest Research*, *91*(5), 541–551. https://doi.org/10.1093/forestry/cpy025

Calicioglu, Ö., & Bogdanski, A. (2021). Linking the bioeconomy to the 2030 sustainable development agenda: Can SDG indicators be used to monitor progress towards a sustainable bioeconomy? *New Biotechnology*, *61*, 40–49. https://doi.org/10.1016/j.nbt.2020.10.010

Capasso, M., & Klitkou, A. (2020). Socioeconomic indicators to monitor Norway's bioeconomy in transition. *Sustainability (Switzerland)*, *12*(8), 3173. https://doi.org/10.3390/SU12083173

Carrez, D., Carus, M., Griffon, M., Jilkova, J., Juhász, A., Lange, L., Mavsar, R., Pursula, T., & Consuelo Varela, O. (2017). *Expert Group Report-Review of the EU Bioeconomy Strategy and its Action Plan*.

Carus, M., & Dammer, L. (2018). The Circular Bioeconomy—Concepts, Opportunities, and Limitations. *Industrial Biotechnology*, *14*(2), 83–91. https://doi.org/10.1089/ind.2018.29121.mca

Challinor, A., Adger, W., & Benton, T. (2017). Climate risks across borders and scales. *Nat. Clim. Chang*, *7*, 621–623.

Charlebois, S. (2020). Which countries are true food innovators? *New Food Magazine.* https://www.newfoodmagazine.com/article/128292/global-food-innovation/

Cherubini, F. (2010). The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Conversion and Management*, *51*(7), 1412–1421. https://doi.org/10.1016/j.enconman.2010.01.015

Chiappini, R. (2014). Persistence vs. Mobility in industrial and technological specialisations: Evidence from 11 Euro area countries. *J Evol Econ*, *24*, 159–187. https://doi.org/10.1007/s00191-013-0331-7

Choi, H. S., Grethe, H., Entenmann, S. K., Wiesmeth, M., Blesl, M., & Wagner, M. (2019). Potential trade-offs of employing perennial biomass crops for the bioeconomy in the EU by 2050: Impacts on agricultural markets in the EU and the world. *GCB Bioenergy*, *11*(3), 483–504. https://doi.org/10.1111/gcbb.12596

Cingiz, K., Gonzalez-Hermoso, H., Heijman, W., & Wesseler, J. H. H. (2021). A Cross-Country Measurement of the EU Bioeconomy: An Input–Output Approach. *Sustainability*, *13*(6), 3033. https://doi.org/10.3390/su13063033

Clomburg, J. M., Crumbley, A. M., & Gonzalez, R. (2017). Industrial biomanufacturing: The future of chemical production. *Science*, *355*(6320), aag0804.

Confederation of European Forest Owners. (2017). *Private Forest Owners Call for An Ambitious Update of the EU Bioeconomy Strategy*.

Coppens, P. (2013). The revision of the novel foods regulation: Forget about cloning and nanotechnology, let's focus on the scope. *European Food and Feed Law Review*, *8*(4), 238–246.

D'Adamo, I., Falcone, P. M., Imbert, E., & Morone, P. (2020a). Exploring regional transitions to the bioeconomy using a socio-economic indicator: The case of Italy. *Economia Politica*, 1–33. https://doi.org/10.1007/s40888-020-00206-4

D'Adamo, I., Falcone, P. M., & Morone, P. (2020b). A New Socio-economic Indicator to Measure the Performance of Bioeconomy Sectors in Europe. *Ecological Economics*, *176*, 106724. https://doi.org/10.1016/j.ecolecon.2020.106724

D'Amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B. D., & Toppinen, A. (2017). Green, circular, bio economy: A comparative analysis of sustainability avenues. *Journal of Cleaner Production*, *168*, 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053

Dasgupta, P. (2008). Nature in Economics. *Environmental and Resource Economics*, *39*(1), 1–7. https://doi.org/10.1007/s10640-007-9178-4

Dasgupta, P. (2021). The Economics of Biodiversity: The Dasgupta Review—Full Report. *London: HM Treasury*.

Dasgupta, P., Duraiappah, A., Managi, S., Barbier, E., Collins, R., Fraumeni, B., Gundimeda, H., Liu, G., & Mumford, K. J. (2015). How to measure sustainable progress. *Science*, *350*(6262), 748–748. https://doi.org/10.1126/science.350.6262.748

de-Magistris, T., Pascucci, S., & Mitsopoulos, D. (2015). Paying to see a bug on my food: How regulations and information can hamper radical innovations in the European Union. *British Food Journal*, *117*(6), 1777–1792. https://doi.org/10.1108/BFJ-06-2014-0222

Demont, M., Wesseler, J., & Tollens, E. (2004). Biodiversity versus transgenic sugar beet: The one euro question. *European Review of Agricultural Economics*, *31*(1), 1–18. https://doi.org/10.1093/erae/31.1.1

Dietz, T., Börner, J., Förster, J., & Von Braun, J. (2018). Governance of the bioeconomy: A global comparative study of national bioeconomy strategies. *Sustainablility*, *10*(27). https://doi.org/10.3390/su10093190

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under Uncertainty Investment under Uncertainty. Princeton University Press. United States of America.*

Dolgopolova, I., & Teuber, R. (2016). *Consumers' Willingness-to-pay for Health-enhancing Attributes in Food Products: A Meta-analysis*. https://doi.org/10.22004/AG.ECON.235390

Dongo, D. (2018). *Blockchain nella filiera alimentare, il prototipo di Bari | GIFT*. https://www.greatitalianfoodtrade.it/consum-attori/blockchain-nella-filiera-alimentare-il-prototipo-di-bari

Dubois, O., & Gomez San Juan, M. (2016). *How Sustainability is Addressed in Official Bioeconomy Strategies at International, National and Regional Levels*.

Efken, J., Dirksmeyer, W., Kreins, P., & Knecht, M. (2016). Measuring the importance of the bioeconomy in Germany: Concept and illustration. *NJAS - Wageningen Journal of Life Sciences*, *77*, 9–17. https://doi.org/10.1016/j.njas.2016.03.008

EFSA. (2012). Scientific Opinion on the substantiation of a health claim related to krill oil and maintenance of joint comfort pursuant to Article 13(5) of Regulation (EC) No 1924/2006. *EFSA Journal*, *10*(12). https://doi.org/10.2903/j.efsa.2012.3003

EFSA. (2014). Scientific Opinion on the extension of use for DHA and EPA-rich algal oil from Schizochytrium sp. As a Novel Food ingredient. *EFSA Journal*, *12*(10), 3843–3843. https://doi.org/10.2903/J.EFSA.2014.3843

Egenolf, V., & Bringezu, S. (2019). Conceptualization of an Indicator System for Assessing the Sustainability of the Bioeconomy. *Sustainability*, *11*(2), 443. https://doi.org/10.3390/su11020443

Ellen MacArthur Foundation. (2013). *Towards the Circular Economy—Economic and business rationale for an accelerated transition*.

Eriksson, D., Kershen, D., Nepomuceno, A., Pogson, B. J., Prieto, H., Purnhagen, K., Smyth, S., Wesseler, J., & Whelan, A. (2019). A comparison of the EU regulatory approach to directed mutagenesis with that of other jurisdictions, consequences for international trade and potential steps forward. *New Phytologist*, *222*(4), 1673–1684. https://doi.org/10.1111/NPH.15627

EuropaBio. (2017). *Strengthening Biotechnology and the Eu Project*. http://www.europabio.org/sites/default/files/Printed version lowres.pdf

European Bioeconomy. (2016). *Alliance Bioeconomy-A Motor for the Circular Economy*.

European Commission. (n.d.). The European Green Deal Investment Plan and JTM Explained. *Available Online: Https://Ec.Europa.Eu/Commission/Presscorner/Detail/En/Qanda_20_24*.

European Commission. (2000). *White Paper on food safety—COM (1999)*. 719–719.

6

European Commission. (2015). *Closing the Loop-An EU Action Plan for the Circular Economy; Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*.

European Commission. (2018a). A Clean Planet for all—A European long-term strategic vision for a prosperous , modern , competitive and climate neutral economy. *Com(2018) 773.*, 114.

European Commission. (2018b). A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment. Updated Bioeconomy Strategy. *Available Online: Https://Eur-Lex.Europa.Eu/Legal-Content/EN/TXT/?Uri=CELEX%3A52018DC0673*.

European Commission. (2019a). *Agri-environmental indicator—Intensification—Extensification—Statistics Explained*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Agri-environmental_indicator_-_intensification_-_extensification

European Commission. (2019b). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM/2019/640 final*.

European Commission. (2020). Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions A new Circular Economy Action Plan For a cleaner and more competitive Europe. In *COM/2020/98 final*.

European Commission. (2021). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review* (COM(2021) 554 final 2021/0201(COD)). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0554

European Commission. (2022a). *European bioeconomy policy: Stocktaking and future developments : report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. Publications Office of the European Union. https://data.europa.eu/doi/10.2777/997651

European Commission. (2022b). *What is the current Novel Food legislation?* https://food.ec.europa.eu/safety/novel-food/legislation_en

European Commission. Directorate General for Research and Innovation. (2021). *Everyone at the table: Co creating knowledge for food systems transformation.* Publications Office. https://data.europa.eu/doi/10.2760/21968

European Council. (2020). *European Council conclusions, 10-11 December 2020*. EUCO 22/20 CO EUR 17 CONCL 8. https://www.consilium.europa.eu/media/47296/1011-12-20-euco-conclusions-en.pdf

European Environment Agency. (2021). *Trends and projections in Europe 2021.* Publications Office. https://data.europa.eu/doi/10.2800/80374

European Environment Agency & Federal Office for the Environment FOEN. (2020). *Is Europe living within the limits of our planet?: An assessment of Europe's environmental footprints in relation to planetary boundaries.* Publications Office. https://data.europa.eu/doi/10.2800/890673

European Parliament and Council. (2015). Regulation (EU) 2015/ 2283 of the European Parliament and of the Council of 25 November 2015 on novel foods, amending Regulation (EU) No 1169/ 2011 of the European Parliament and of the Council and repealing Regulation (EC) No 258/ 97 of the European Parliament and of the Council and

Commission Regulation (EC) No 1852/ 2001. *Official Journal of the European Union*, *L327*, 1–222.
European Parliament and Council of the European Union. (1997). Regulation (EC) No 258/97 of the European Parliament and of the Council of 27 January 1997 concerning novel foods and novel food ingredients. *Official Journal of the European Communities*, *L43*(40), 1–6.
European Parliamentary Research Service. (2015). Updating rules on novel foods to keep up with scientific advances. *Briefing June 2015 Members' Research Service PE 564.383*.
Eurostat. (2019). Sustainable development in the European Union—Monitoring report on progress towards the SDGs in an EU context—2019 edition. In *Statistical books*. https://doi.org/10.2785/44964
FAO. (2009). *Declaration of the World Summit on Food Security*.
Fertö, I., & Soós, K. A. (2008). Trade specialization in the European Union and in postcommunist European countries. In *Eastern European Economics* (Vol. 46, Issue 3, pp. 5–28). Taylor & Francis, Ltd. https://doi.org/10.2753/EEE0012-8775460301
Foster, J. (2005). From simplistic to complex systems in economics. *Cambridge Journal of Economics*, *29*(6), 873–892. https://doi.org/10.1093/cje/bei083
Foster, J. (2006). Why Is Economics Not a Complex Systems Science? *Journal of Economic Issues*, *40*(4), 1069–1091. https://doi.org/10.1080/00213624.2006.11506975
Foxon, T. J., Kohler, J., Michie, J., & Oughton, C. (2013). Towards a new complexity economics for sustainability. *Cambridge Journal of Economics*, *37*(1), 187–208. https://doi.org/10.1093/cje/bes057
Frederiks, C., & Wesseler, J. H. (2019). A comparison of the EU and US regulatory frameworks for the active substance registration of microbial biological control agents. *Pest Management Science*, *75*(1), 87–103. https://doi.org/10.1002/ps.5133
Frewer, L. J., Bergmann, K., Brennan, M., Lion, R., Meertens, R., Rowe, G., Siegrist, M., & Vereijken, C. (2011). Consumer response to novel agri-food technologies: Implications for predicting consumer acceptance of emerging food technologies. *Trends in Food Science & Technology*, *22*(8), 442–456. https://doi.org/10.1016/J.TIFS.2011.05.005
Friedman, L. F. (2015). *The IT industry is out-innovating all others by a longshot*. Business Insider. https://www.businessinsider.com/most-innovative-industries-2015-5
Fumagalli, S., & Trenti, S. (2014). *A first attempt to measure the bio-based economy*. https://www.group.intesasanpaolo.com/scriptIsir0/si09/contentData/view/Bioeconomy_Ottobre 2014.pdf?id=CNT-05-000000023F746&ct=application/pdf
Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2019). Visualization in Bayesian workflow. *Journal of the Royal Statistical Society: Series A (Statistics in Society)*, *182*(2), 389–402. https://doi.org/10.1111/rssa.12378
GBEP. (2011). *The global bioenergy partnership sustainability indicators for bioenergy*. https://www.fao.org/3/ap506e/ap506e.pdf
Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). *Bayesian Data Analysis* (0 ed.). Chapman and Hall/CRC. https://doi.org/10.1201/b16018
Gelman, A., Simpson, D., & Betancourt, M. (2017). The Prior Can Often Only Be Understood in the Context of the Likelihood. *Entropy*, *19*(10), 555. https://doi.org/10.3390/e19100555
Gelman, A., Vehtari, A., Simpson, D., Margossian, C. C., Carpenter, B., Yao, Y., Kennedy, L., Gabry, J., Bürkner, P.-C., & Modrák, M. (2020). *Bayesian Workflow*. https://doi.org/10.48550/ARXIV.2011.01808

German Bioeconomy Council. (2018). *Bioeconomy Policy (Part II) Synopsis of National Strategies around the World*. Office of the Bioeconomy Council. http://biooekonomierat.de/fileadmin/Publikationen/berichte/Bioeconomy-Policy_Part-II.pdf

Geyer, C. (2011). *Introduction to Markov Chain Monte Carlo*. https://www.semanticscholar.org/paper/1-Introduction-to-Markov-Chain-Monte-Carlo-Geyer/21a92825dcec23c743e77451ff5b5ee6b1091651

Griggs, D. (2018). The Sustainable Development Goals. In *Companion to Environmental Studies* (pp. 725–731). Routledge.

Grimsby, S. (2021). New novel food regulation and collaboration for innovation. *British Food Journal*, *123*(1), 245–259. https://doi.org/10.1108/BFJ-02-2020-0154

Grossman, G. M., & Helpman, E. (1993). *Innovation and Growth in the Global Economy*. MIT Press.

Grunert, K. G., Harmsen, H., Meulenberg, M., Kuiper, E., Ottowitz, T., Declerck, F., Traill, B., & Göransson, G. (1997). A framework for analysing innovation in the food sector. In B. Traill & K. G. Grunert (Eds.), *Products and Process Innovation in the Food Industry* (pp. 1–37). Springer US. https://doi.org/10.1007/978-1-4613-1133-1_1

Hamelin, L., Borzęcka, M., Kozak, M., & Pudełko, R. (2019). A spatial approach to bioeconomy: Quantifying the residual biomass potential in the EU-27. *Renewable and Sustainable Energy Reviews*, *100*, 127–142. https://doi.org/10.1016/j.rser.2018.10.017

Hamilton, K., & Clemens, M. (1999). Genuine savings rates in developing countries. In *World Bank Economic Review* (Vol. 13, Issue 2, pp. 333–356). Oxford University Press. https://doi.org/10.1093/wber/13.2.333

Hamilton, K., & Naikal, E. (2014). Genuine saving as an indicator of sustainability. In *Handbook of Sustainable Development: Second Edition* (pp. 336–347). https://doi.org/10.4337/9781782544708.00034

Häyhä, T., Cornell, S., Hoff, H., Lucas, P., & Van Vuuren, D. (2018). Operationalizing the concept of a safe operating space at the EU level–first steps and explorations. *Stockholm Resilience Centre Technical Report, Prepared in Collaboration with Stockholm Environment Institute (SEI) and PBL Netherlands Environmental Assessment Agency. Stockholm Resilience Centre, Stockholm University, Sweden*.

Heijman, W. (2016). How big is the bio-business? Notes on measuring the size of the Dutch bioeconomy. *NJAS - Wageningen Journal of Life Sciences*, *77*, 5–8. https://doi.org/10.1016/j.njas.2016.03.004

Hermann, M. (2009). The impact of the European Novel Food Regulation on trade and food innovation based on traditional plant foods from developing countries. *Food Policy*, *34*(6), 499–507. https://doi.org/10.1016/j.foodpol.2009.08.005

Hetemäki, L., Hanewinkel, M., Muys, B., Ollikainen, M., Palahí, M., & Trasobares, A. (2017). Leading the way to a European circular bioeconomy strategy. *Volume 5*, 52–52.

Hetemäki, L., & Hurmekoski, E. (2014). Forest products market outlook. In *Future of the European forest-based sector: Structural changes towards bioeconomy. What Science Can Tell Us* (pp. 15–32).

Holle, M. (2018). Pre-Market Approval and Its Impact on Food Innovation: The Novel Foods Example. *Regulating and Managing Food Safety in the EU*, 291–330. https://doi.org/10.1007/978-3-319-77045-1_14

Hurmekoski, E., Jonsson, R., Korhonen, J., Jänis, J., Mäkinen, M., Leskinen, P., & Hetemäki, L. (2018). Diversification of the forest industries: Role of new wood-based products. In *Canadian Journal of Forest Research* (Vol. 48, Issue 12, pp. 1417–1432). Canadian Science Publishing. https://doi.org/10.1139/cjfr-2018-0116

Hyde, R., Hartley, S., & Millar, K. (2017). European Novel Foods Policy at a Critical Juncture : *Food and Drug Law Journal*, *72*(2), 472–505.

IEA. (2016). *IEA Bioenergy Annual Report 2016*. https://www.ieabioenergy.com/wp-content/uploads/2017/04/IEA-Bioenergy-Annual-Report-2016.pdf

IEA. (2021). *Transport Biofuels*. IEA. https://www.iea.org/reports/transport-biofuels

Investopedia. (n.d.). Horizontal Integration. *Available Online: Https://Www.Investopedia.Com/Terms/h/Horizontalintegration.Asp*.

Iost, S., Labonte, N., Banse, M., Geng, N., Jochem, D., & Schweinle, J. (2019). *German Bioeconomy: Economic Importance and Concept of Measurement*. *68*(4), 275–288.

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In *Zenodo*. https://doi.org/10.5281/ZENODO.3832099

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*.

Issa, I., Delbrück, S., & Hamm, U. (2019). Bioeconomy from experts' perspectives – Results of a global expert survey. *PLOS ONE*, *14*(5), e0215917. https://doi.org/10.1371/journal.pone.0215917

Italian Presidency of Council of Ministers. (2017). *Bioeconomy in Italy—A unique opportunity to reconnect the ECONOMY, SOCIETY and the ENVIRONMENT*. 64.

Jander, W., & Grundmann, P. (2019). Monitoring the transition towards a bioeconomy: A general framework and a specific indicator. *Journal of Cleaner Production*, *236*, 117564. https://doi.org/10.1016/j.jclepro.2019.07.039

Jander, W., Wydra, S., Wackerbauer, J., Grundmann, P., & Piotrowski, S. (2020). Monitoring Bioeconomy Transitions with Economic–Environmental and Innovation Indicators: Addressing Data Gaps in the Short Term. *Sustainability*, *12*(11), Article 11. https://doi.org/10.3390/su12114683

Jin, Y., Drabik, D., Heerink, N., & Wesseler, J. (2019). Getting an Imported GM Crop Approved in China. *Trends Biotechnol.*, *37*, 566–569.

Joint Research Centre. (2019). *Bioeconomy Policy | Knowledge for policy*. https://knowledge4policy.ec.europa.eu/bioeconomy/bioeconomy-policy_en

Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., van Leeuwen, M., M'barek, R., van Meijl, H., Piotrowski, S., Ronzon, T., Sauer, J., Verhoog, D., Verkerk, P. J., Vrachioli, M., Wesseler, J. H. H., & Zhu, B. X. (2021). Development of the circular bioeconomy: Drivers and indicators. *Sustainability*, *13*(1), 1–24. https://doi.org/10.3390/su13010413

Kardung, M., Costenoble, O., Dammer, L., Delahaye, R., Lovric´, M., Leeuwen, M., van, M., R., Meijl, H., van, P., S., Ronzon, T., Verhoog, D., Verkerk, H., Vrachioli, M., Wesseler, J., & Zhu, B. X. (2020). *D1. 1: Framework for measuring the size and development of the bioeconomy. Biomonitor: Horizon, European Commission*. http://biomonitor.eu/news/d1-1-framework-for-measuring-the-size-and-development-of-the-bioeconomy/

Keegan, D., Kretschmer, B., Elbersen, B., & Panoutsou, C. (2013). Cascading use: A systematic approach to biomass beyond the energy sector. *Biofuels Bioprod. Biorefining*, *7*(2), 193–206. https://doi.org/10.1002/bbb.1351

Khajehei, F., Piatti, C., & Graeff-Hönninger, S. (2019). Novel food technologies and their acceptance. *Food Tech Transitions: Reconnecting Agri-Food, Technology and Society*, 3–22. https://doi.org/10.1007/978-3-030-21059-5_1/COVER

Kilsedar, C., Wertz, S., Robert, N., & Mubareka, S. (2021). *Implementation of the EU Bioeconomy Monitoring System dashboards*. *KJ-03-21-025-EN-N (online)*. https://doi.org/10.2760/577115 (online)

Knudsen, M. T., Hermansen, J. E., & Thostrup, L. B. (2015). *Mapping Sustainability Criteria for the Bioeconomy*. *October*.

Kristinsson, H. G., & Jörundsdóttir, H. Ó. (2019). Food in the bioeconomy. *Trends in Food Science & Technology*, *84*, 4–6. https://doi.org/10.1016/j.tifs.2018.10.011

Kruschke, J. K. (2015). *Doing Bayesian data analysis: A tutorial with R, JAGS, and Stan* (Edition 2). Academic Press.

Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., & Aylmer, C. (2013). Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics*, *93*, 57–68. https://doi.org/10.1016/j.ecolecon.2013.04.019

Kuosmanen, T., Kuosmanen, N., El-Meligli, A., Ronzon, T., Gurria, P., Iost, S., & M'Barek, R. (2020). *How big is the bioeconomy? Reflections from an economic perspective*. https://doi.org/10.2760/144526

Lafortune, G., Fuller, G., Moreno, J., Schmidt-Traub, G., & Kroll, C. (2018). SDG Index and Dashboards—Detailed Methodological paper. In *Global Responsabilities. Implementing the Goals* (Issue September). https://raw.githubusercontent.com/sdsna/2018GlobalIndex/master/2018GlobalIndexMethodology.pdf

Lahteenmaki-Uutela, A. (2007). *European novel food legislation as a restriction to trade*. https://doi.org/10.22004/AG.ECON.7909

Lähteenmäki-Uutela, A., Rahikainen, M., Lonkila, A., & Yang, B. (2021). Alternative proteins and EU food law. *Food Control*, *130*(June), 108336. https://doi.org/10.1016/j.foodcont.2021.108336

Lange, L., Connor, K. O., Arason, S., Bundgård-Jørgensen, U., Canalis, A., Carrez, D., Gallagher, J., Gøtke, N., Huyghe, C., Jarry, B., Llorente, P., Marinova, M., Martins, L. O., Mengal, P., Paiano, P., Panoutsou, C., Rodrigues, L., Stengel, D. B., van der Meer, Y., & Vieira, H. (2021). Developing a Sustainable and Circular Bio-Based Economy in EU: By Partnering Across Sectors, Upscaling and Using New Knowledge Faster, and For the Benefit of Climate, Environment & Biodiversity, and People & Business. *Frontiers in Bioengineering and Biotechnology*, *8*. https://www.frontiersin.org/articles/10.3389/fbioe.2020.619066

Latvian Ministry of Agriculture. (2018). *Latvian Bioeconomy Strategy 2030*.

Leclère, D., Obersteiner, M., Barrett, M., Butchart, S. H. M., Chaudhary, A., De Palma, A., DeClerck, F. A. J., Di Marco, M., Doelman, J. C., Dürauer, M., Freeman, R., Harfoot, M., Hasegawa, T., Hellweg, S., Hilbers, J. P., Hill, S. L. L., Humpenöder, F., Jennings, N., Krisztin, T., … Young, L. (2020). Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature*, *585*(7826), Article 7826. https://doi.org/10.1038/s41586-020-2705-y

Leskinen, P., Cardellini, G., González-García, S., Hurmekoski, E., Sathre, R., Seppälä, J., Smyth, C., Stern, T., Verkerk, P. J., & Johannes, P. (2018). Substitution effects of wood-based products in climate change mitigation. *From Science to Policy 7*. https://doi.org/10.36333/fs07

Levin Institute. (n.d.). *What Is Globalization?|Globalization101*. Retrieved June 12, 2019, from https://www.globalization101.org/what-is-globalization

Lier, M., Aarne, M., Kärkkäinen, L., Korhonen, K. T., Yli-Viikari, A., & Packalen, T. (2018). *Synthesis on bioeconomy monitoring systems in the EU Member States-indicators for monitoring the progress of bioeconomy*. http://urn.fi/URN:ISBN:978-952-326-607-0

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M. J., & Marchetti, M. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, *259*(4), 698–709. https://doi.org/10.1016/j.foreco.2009.09.023

Link, W. A., & Eaton, M. J. (2012). On thinning of chains in MCMC: *Thinning of MCMC chains*. *Methods in Ecology and Evolution*, *3*(1), 112–115. https://doi.org/10.1111/j.2041-210X.2011.00131.x

Linser, S., & Lier, M. (2020). The contribution of sustainable development goals and forest-related indicators to national bioeconomy progress monitoring. *Sustainability (Switzerland)*, *12*(7). https://doi.org/10.3390/su12072898

Liobikiene, G., Chen, X., Streimikiene, D., & Balezentis, T. (2020). The trends in bioeconomy development in the European Union: Exploiting capacity and productivity measures based on the land footprint approach. *Land Use Policy*, *91*, 104375. https://doi.org/10.1016/j.landusepol.2019.104375

Loizou, E., Jurga, P., Rozakis, S., & Faber, A. (2019). Assessing the potentials of bioeconomy sectors in Poland employing input-output modeling. *Sustainability (Switzerland)*, *11*(3), 1–12. https://doi.org/10.3390/su11030594

Lyytimäki, J., Salo, H., Lepenies, R., Büttner, L., & Mustajoki, J. (2020). Risks of producing and using indicators of sustainable development goals. *Sustainable Development*, *28*(6), 1528–1538. https://doi.org/10.1002/sd.2102

Maceachern, S. N., & Berliner, L. M. (1994). Subsampling the Gibbs Sampler. *The American Statistician*, *48*(3), 188–190. https://doi.org/10.1080/00031305.1994.10476054

Maggino, F. (2017). Developing Indicators and Managing the Complexity. In F. Maggino (Ed.), *Complexity in Society: From Indicators Construction to their Synthesis* (Vol. 70, pp. 87–114). Springer International Publishing. https://doi.org/10.1007/978-3-319-60595-1_4

Marberg, A., van Kranenburg, H., & Korzilius, H. (2017). The big bug: The legitimation of the edible insect sector in the Netherlands. *Food Policy*, *71*, 111–123. https://doi.org/10.1016/j.foodpol.2017.07.008

Martin-Laffon, J., Kuntz, M., & Ricroch, A. E. (2019). Worldwide CRISPR patent landscape shows strong geographical biases. *Nature Biotechnology*, *37*(6), 613–620. https://doi.org/10.1038/s41587-019-0138-7

Mazac, R., Meinilä, J., Korkalo, L., Järviö, N., Jalava, M., & Tuomisto, H. L. (2022). Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80%. *Nature Food*, *3*(4), 286–293. https://doi.org/10.1038/s43016-022-00489-9

McDonald, R., & Siegel, D. (1986). The Value of Waiting to Invest. *The Quarterly Journal of Economics*, *101*(4), 707. https://doi.org/10.2307/1884175

McElreath, R. (2020). *Statistical rethinking: A Bayesian course with examples in R and Stan* (2nd ed.). Taylor and Francis, CRC Press.

Meesters, K. P. H., van Dam, J. E. G., & Bos, H. L. (2013). *Protocol monitoring materiaalstromen biobased economie*.

Millstone, E., & van Zwanenberg, P. (2002). The Evolution of Food Safety Policy–making Institutions in the UK, EU and Codex Alimentarius. *Social Policy & Administration*, *36*(6), 593–609. https://doi.org/10.1111/1467-9515.T01-1-00306

Ministerie van EZ. (2013). *Groene economische groei in Nederland (Green Deal)* (pp. 1–7). https://zoek.officielebekendmakingen.nl/kst-33043-14.html

Ministry of Economic Affairs and Climate Policy. (2018). *The Position of the Bioeconomy in the Netherlands* (pp. 1–8).

Ministry of Employment and the Economy. (2014). *The Finnish Bioeconomy Strategy*. 31.

Miola, A., & Schiltz, F. (2019). Measuring sustainable development goals performance: How to monitor policy action in the 2030 Agenda implementation? *Ecological Economics*, *164*(May), 106373. https://doi.org/10.1016/j.ecolecon.2019.106373

Morone, P., D'Adamo, I., & Cianfroni, M. (2022). Inter-connected challenges: An overview of bioeconomy in Europe. *Environmental Research Letters*, *17*(11), 114031. https://doi.org/10.1088/1748-9326/ac9dac

Mujtaba, M., Lipponen, J., Ojanen, M., Puttonen, S., & Vaittinen, H. (2022). Trends and challenges in the development of bio-based barrier coating materials for paper/cardboard food packaging; a review. *Science of The Total Environment*, *851*, 158328. https://doi.org/10.1016/j.scitotenv.2022.158328

Mukherji, P. Nath., & Sengupta, Chandan. (2004). *Indigneity and Universality in Social Science: A South Asian Response.* (p. 406).

Nationale Akademie der Wissenschaften Leopoldina, D. F. und U. der deutschen A. der W. (2019). *Towards a scientifically justified, differentiated regulation of genome edited plants in the EU*.

Näyhä, A., Hetemäki, L., & Stern, T. (2014). New products outlook. In *Future of the European forest-based sector: Structural changes towards bioeconomy. What Science Can Tell Us* (pp. 43–52).

Neal, R. M. (2011). MCMC Using Hamiltonian Dynamics. In *Handbook of Markov Chain Monte Carlo* (pp. 139–188). Chapman and Hall/CRC. https://doi.org/10.1201/b10905-10

Neuwirth, R. J. (2014). "'Novel food' for thought" on law and policymaking in the global creative economy. *European Journal of Law and Economics*, *37*(1), 13–50. https://doi.org/10.1007/s10657-013-9415-y

Nițescu, D. C., & Murgu, V. (2020). The Bioeconomy and Foreign Trade in Food Products—A Sustainable Partnership at the European Level? *Sustainability*, *12*(6), 2460. https://doi.org/10.3390/su12062460

O'Brien, M., Wechsler, D., Bringezu, S., & Schaldach, R. (2017). Toward a systemic monitoring of the European bioeconomy: Gaps, needs and the integration of sustainability indicators and targets for global land use. *Land Use Policy*, *66*(May), 162–171. https://doi.org/10.1016/j.landusepol.2017.04.047

OECD. (2009). *The Bioeconomy to 2030: Designing a Policy Agenda*. OECD. https://doi.org/10.1787/9789264056886-en

OECD. (2014). How's Life in Your Region? In *How's Life in Your Region?* (p. 295). OECD Publishing. https://doi.org/10.1787/9789264217416-en

OECD. (2016). Measuring Distance to the SDG Targets: An assessment of where OECD countries stand. In *The Organisation for Economic Co-operation and Development: Paris, France, 2018* (pp. 56–57). https://doi.org/10.1787/d20adaa6-en

OECD. (2018). *The Framework for Policy Action on Inclusive Growth*. *May*, 30–31.

OECD. (2019). Measuring Distance to the SDG Targets 2019. In *Measuring Distance to the SDG Targets 2019*. OECD. https://doi.org/10.1787/a8caf3fa-en

OECD. (2021). *Long-term interest rates (indicator)*. https://doi.org/10.1787/662d712c-en

OECD. (2022). *ALFS Summary tables: Annual labour force* [Data set]. https://stats.oecd.org/Index.aspx?DataSetCode=ALFS_POP_LABOUR

Paarlberg, R. (2014). A dubious success: The NGO campaign against GMOs. *GM Crops & Food*, *5*(3), 223–228. https://doi.org/10.4161/21645698.2014.952204

Palahí, M., Hetemäki, L., & Potočnik, J. (2020, March 20). Bioeconomy: The missing link to connect the dots in the EU Green Deal. *EFI Blog*. https://blog.efi.int/bioeconomy-the-missing-link-to-connect-the-dots-in-the-eu-green-deal/

Parris, T. M., & Kates, R. W. (2003). Characterizing and measuring sustainable development. *Annual Review of Environment and Resources*, *28*(1), 559–586.

Philippidis, G., Bartelings, H., & Smeets, E. (2018). Sailing into Unchartered Waters: Plotting a Course for EU Bio-Based Sectors. *Ecological Economics*, *147*, 410–421. https://doi.org/10.1016/j.ecolecon.2018.01.026

Pindyck, R. S. (2000). Irreversibilities and the timing of environmental policy. *Resource and Energy Economics*, *22*(3), 233–259. https://doi.org/10.1016/S0928-7655(00)00033-6

Pindyck, R. S. (2002). Optimal timing problems in environmental economics. *Journal of Economic Dynamics and Control*, *26*(9–10), 1677–1697. https://doi.org/10.1016/S0165-1889(01)00090-2

Piotrowski, S., Carus, M., & Carrez, D. (2016). *European Bioeconomy in Figures 2008 – 2016* (p. 24). www.biconsortium.eu

Piotrowski, S., Carus, M., & Carrez, D. (2018). *European Bioeconomy in Figures*. www.biconsortium.eu

Piotrowski, S., Wesseler, J., Kardung, M., Leeuwen, M. V., Meijl, H. V., Costenoble, O., Vrins, M., Groot, T. D., & Jansen, K. (2019). *First Stakeholder Workshop—D7.2*. *BioMonitor*.

Pisanello, D., & Caruso, G. (2018). Novel Foods in the European Union. *Novel Foods in the European Union*, 1–29. https://doi.org/10.1007/978-3-319-93620-8

Plieninger, T., Torralba, M., Hartel, T., & Fagerholm, N. (2019). Perceived ecosystem services synergies, trade-offs, and bundles in European high nature value farming landscapes. *Landscape Ecology*, *34*(7), 1565–1581. https://doi.org/10.1007/s10980-019-00775-1

Provenance. (2016). *From shore to plate: Tracking tuna on the blockchain | Provenance*. https://www.provenance.org/tracking-tuna-on-the-blockchain#overview

Pülzl, H., Kleinschmit, D., & Arts, B. (2014). Bioeconomy—An emerging meta-discourse affecting forest discourses? *Scandinavian Journal of Forest Research*, *29*(4), 386–393. https://doi.org/10.1080/02827581.2014.920044

Purkus, A., Hagemann, N., Bedtke, N., & Gawel, E. (2018). Towards a sustainable innovation system for the German wood-based bioeconomy: Implications for policy design. *Journal of Cleaner Production*, *172*, 3955–3968. https://doi.org/10.1016/j.jclepro.2017.04.146

Purnhagen, K. P., & Wesseler, J. (2020). *The SAMs Report 'Towards a Sustainable Food System' Bites the Hand That Feeds Us!* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3621330

Purnhagen, K. P., & Wesseler, J. H. (2019). Maximum vs minimum harmonization: What to expect from the institutional and legal battles in the EU on gene editing technologies. *Pest Management Science*, *75*(9), 2310–2315. https://doi.org/10.1002/ps.5367

Purnhagen, K., & Wesseler, J. (2021). EU Regulation of New Plant Breeding Technologies and Their Possible Economic Implications for the EU and Beyond. *Applied Economic Perspectives and Policy*, *43*(4), 1621–1637. https://doi.org/10.1002/aepp.13084

Quah, D. (1993). Empirical cross-section dynamics in economic growth. *European Economic Review*, *37*(2–3), 426–434. https://doi.org/10.1016/0014-2921(93)90031-5

Quah, D. T. (1996). Empirics for economic growth and convergence. *European Economic Review*, *40*(6), 1353–1375. https://doi.org/10.1016/0014-2921(95)00051-8

Reinders, M. J., Onwezen, M. C., & Meeusen, M. J. G. (2017). Can bio-based attributes upgrade a brand? How partial and full use of bio-based materials affects the purchase intention of brands. *Journal of Cleaner Production*, *162*, 1169–1179. https://doi.org/10.1016/j.jclepro.2017.06.126

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F. C., Müller, U. K., Plevin, R. J., Raftery, A. E., Ševčíková, H., Sheets, H., … Anthoff, D. (2022). Comprehensive evidence implies a higher social cost of CO2. *Nature*, *610*(7933), 687–692. https://doi.org/10.1038/s41586-022-05224-9

Rinne, J., Lyytimäki, J., & Kautto, P. (2013). From sustainability to well-being: Lessons learned from the use of sustainable development indicators at national and EU level. *Ecological Indicators*, *35*, 35–42. https://doi.org/10.1016/j.ecolind.2012.09.023

Ripple, W. J., Wolf, C., Newsome, T. M., Barnard, P., & Moomaw, W. R. (2020). World Scientists' Warning of a Climate Emergency. *BioScience*, *70*(1), 8–12. https://doi.org/10.1093/biosci/biz088

RIS3 SK. (2013). *Through knowledge towards prosperity—Research and Innovation Strategy for Smart Specialisation of the Slovak Republic*.

Robert, N., Giuntoli, J., Araujo, R., Avraamides, M., Balzi, E., Barredo, J. I., Baruth, B., Becker, W., Borzacchiello, M. T., Bulgheroni, C., Camia, A., Fiore, G., Follador, M., Gurria, P., la Notte, A., Lusser, M., Marelli, L., M'Barek, R., Parisi, C., … Mubareka, S. (2020). Development of a bioeconomy monitoring framework for the European Union: An integrative and collaborative approach. *New Biotechnology*, *59*, 10–19. https://doi.org/10.1016/j.nbt.2020.06.001

Romer, P. M. (1990). Endogenous Technological Change. *Journal of Political Economy*, *98*(5, Part 2), S71–S102. https://doi.org/10.1086/261725

Ronzon, T., Iost, S., & Philippidis, G. (2022). Has the European Union entered a bioeconomy transition? Combining an output-based approach with a shift-share analysis. *Environment, Development and Sustainability*, *24*(6), 8195–8217. https://doi.org/10.1007/s10668-021-01780-8

Ronzon, T., Lusser, M., Landa, L., M'Barek, R., Belward A., Giuntoli, J., & Cristobal, J. (2016). *Joint Research Centre Science for Policy Report: Bioeconomy Report 2016*.

Ronzon, T., & M'Barek, R. (2018). Socioeconomic Indicators to Monitor the EU's Bioeconomy in Transition. *Sustainability*, *10*(6), 1745. https://doi.org/10.3390/su10061745

Ronzon, T., Piotrowski, S., M'Barek, R., & Carus, M. (2017). A systematic approach to understanding and quantifying the EU's bioeconomy. *Bio-Based and Applied Economics*, *6*(1), 1–17. https://doi.org/10.13128/BAE-20567

Ronzon, T., Piotrowski, S., M'barek, R., Carus, M., & Tamošiūnas, S. (n.d.). *Job and Wealth in the EU Bioeconomy*. Retrieved April 1, 2021, from http://data.europa.eu/89h/7d7d5481-2d02-4b36-8e79-697b04fa4278

Ronzon, T., & Sanjuán, A. I. (2020). Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. *Journal of Cleaner Production*, *254*, 119832. https://doi.org/10.1016/j.jclepro.2019.119832

Sachs, J. D., & McArthur, J. W. (2002). Technological advancement and long-term economic growth in Asia. In *Technology and the new economy* (pp. 157–185). MIT Press.

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., & Fuller, G. (2018). SDG Index and Dashboards Report 2018: Global Responsibilities. *Global Responsabilities. Implementing the Goals*, *September*, 1–476.

Sagar, A. D., & Najam, A. (1998). The human development index: A critical review. *Ecological Economics*, *25*(3), 249–264. https://doi.org/10.1016/S0921-8009(97)00168-7

Salas-Zapata, W. A., & Ortiz-Muñoz, S. M. (2019). Analysis of meanings of the concept of sustainability. *Sustainable Development*, *27*(1), 153–161. https://doi.org/10.1002/sd.1885

Salerno, A. (2018). *Dalla piantagione alla tazzina: La blockchain entra nel caffè—Blockchain 4innovation*. https://www.blockchain4innovation.it/mercati/agrifood/dalla-piantagione-alla-tazzina-la-blockchain-entra-nel-caffe/

SAT-BBE. (2015a). *Evaluation of expected impacts and monitoring the trajectory of the bioeconomy*. *March*, 1–51.

SAT-BBE. (2015b). *Systems analysis description of the bioeconomy*. *March*, 1–40.

Scarpa, B., & Dalfrà, S. (2008). Regulating the Novel Foods Sector: Moving forward. *European Food and Feed Law Review*, *3*(5), 8–8.

Scatasta, S., Wesseler, J., & Demont, M. (2006). Irreversibility, Uncertainty, and the Adoption of Transgenic Crops: Experiences from Applications to HT Sugar Beets, HT Corn, and Bt Corn.

In *Regulating Agricultural Biotechnology: Economics and Policy* (pp. 327–352). Springer US. https://doi.org/10.1007/978-0-387-36953-2_16
Schad, D. J., Betancourt, M., & Vasishth, S. (2021). Toward a principled Bayesian workflow in cognitive science. *Psychological Methods*, *26*(1), 103–126. https://doi.org/10.1037/met0000275
Sébastien, L., Bauler, T., & Lehtonen, M. (2014). Can Indicators Bridge the Gap between Science and Policy? An Exploration into the (Non)Use and (Non)Influence of Indicators in EU and UK Policy Making. *Nature and Culture*, *9*(3), 316–343. https://doi.org/10.3167/nc.2014.090305
Shepherd, W. G., & Shepherd, J. M. (2003). *The Economics of Industrial Organization: Fifth Edition*. Waveland Press.
Sheppard, A. W., Gillespie, I., Hirsch, M., & Begley, C. (2011). Biosecurity and sustainability within the growing global bioeconomy. *Current Opinion in Environmental Sustainability*, *3*(1–2), 4–10. https://doi.org/10.1016/j.cosust.2010.12.011
Shorrocks, A. F. (1978). The Measurement of Mobility. *The Econometric Society*, *46*(5), 1013–1024.
Sijtsema, S. J., Onwezen, M. C., Reinders, M. J., Dagevos, H., Partanen, A., & Meeusen, M. (2016). Consumer perception of bio-based products—An exploratory study in 5 European countries. *NJAS: Wageningen Journal of Life Sciences*, *77*(1), 61–69. https://doi.org/10.1016/j.njas.2016.03.007
Sirilli, G. (1987). Patents and inventors: An empirical study. *Research Policy*, *16*(2), 157–174. https://doi.org/10.1016/0048-7333(87)90029-1
Smart, R. D., Blum, M., & Wesseler, J. (2015). EU member states' voting for authorizing genetically engineered crops: A regulatory gridlock: *German Journal of Agricultural Economics*, *64*(4), 244–262.
Smart, R. D., Blum, M., & Wesseler, J. (2017). Trends in Approval Times for Genetically Engineered Crops in the United States and the European Union. *Journal of Agricultural Economics*, *68*(1), 182–198. https://doi.org/10.1111/1477-9552.12171
Sosnowski, S., Hetman, K., Grabczuk, K., Cholewa, M., Sobczak, J., P\c ekalski, T., Walasek, A., Mocior, E. zbieta, Habza, A., Janczarek, P., Bartuzi, K., Bo\.zeński, E., Bryda, K., Byzdra, I., Donica, D., Franaszek, P., Kawa\lko, B., Nakielska, I., Orze\l, Z., … Rycaj, E. (2014). *Regional Innovation Strategy for the Lubelskie Voivodeship 2020- Regional Innovation Strategy for Smart Specialisation (RIS3)*.
Spencer, W. F., Cliath, M. M., van den Oever, M., Molenveld, K., Van Der Zee, M., & Bos, H. (2017). Bio-based and biodegradable plastics—Facts and Figures Focus on food packaging in the Netherlands. *Wageningen Food & Biobased Research*.
Spierling, S., Knüpffer, E., Behnsen, H., Mudersbach, M., Krieg, H., Springer, S., Albrecht, S., Herrmann, C., & Endres, H. J. (2018). Bio-based plastics—A review of environmental, social and economic impact assessments. *Journal of Cleaner Production*, *185*, 476–491. https://doi.org/10.1016/j.jclepro.2018.03.014
Stan Development Team. (2021). *Stan Modeling Language Users Guide and Reference Manual* (Version 2.27). http://mc-stan.org
Stegmann, P., Londo, M., & Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation & Recycling: X*, *6*, 100029. https://doi.org/10.1016/j.rcrx.2019.100029
Stiglitz, J. E., Fitoussi, J.-P., & Durand, M. (2018). *Beyond GDP Measuring What Counts for Economic and Social Performance and For Good Measure Advancing Research on Well-being Metrics Beyond GDP High-Level Expert Group on the Measurement of Economic Performance and Social Progress (HLEG)*. OECD. https://doi.org/10.1787/9789264307292-en

Stiglitz, J. E., Sen, A., & Fitoussi, J.-P. (Eds.). (2010). *Mismeasuring our lives: Why GDP doesn't add up*. New Press.

Strezov, V., Evans, A., & Evans, T. J. (2017). Assessment of the Economic, Social and Environmental Dimensions of the Indicators for Sustainable Development. *Sustainable Development*, *25*(3), 242–253. https://doi.org/10.1002/sd.1649

Strohbach, M. W., Kohler, M. L., Dauber, J., & Klimek, S. (2015). High Nature Value farming: From indication to conservation. *Ecological Indicators*, *57*, 557–563. https://doi.org/10.1016/j.ecolind.2015.05.021

Tollefson, J. (2017). The wooden skyscrapers that could help to cool the planet. *Nature*, *545*(7654), 280–282. https://doi.org/10.1038/545280a

Tramper, J., & Zhu, Y. (2012). *Modern Biotechnology: Panacea or New Pandora's Box?* (Vol. 49). Wageningen Academic Pubishers.

Tsiropoulos, I., Hoefnagels, R., van den Broek, M., Patel, M. K., & Faaij, A. P. C. (2017). The role of bioenergy and biochemicals in CO2 mitigation through the energy system – a scenario analysis for the Netherlands. *GCB Bioenergy*, *9*(9), 1489–1509. https://doi.org/10.1111/gcbb.12447

Tsuji, K. (2008). Approval of new biopharmaceuticals 1999–2006: Comparison of the US, EU and Japan situations. *European Journal of Pharmaceutics and Biopharmaceutics*, *68*(3), 496–502. https://doi.org/10.1016/j.ejpb.2007.07.013

UN. (2019). *Forest Products Annual Market. Review 2017–2018*.

Unep, ILO, UNIDO, UNDP, & Unitar. (2012). *Advancing an Inclusive Green Economy: Rationale and Context—Definitions for Green Economy*.

United Nations. (2017). Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development. A/RES/71/313 E/CN.3/2018/2. *Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development*, 1–21.

United Nations. (2022). *Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development*. https://unstats.un.org/sdgs/indicators/Global%20Indicator%20Framework%20after%202022%20refinement_Eng.pdf

Urmetzer, S., Lask, J., Vargas-Carpintero, R., & Pyka, A. (2020). Learning to change: Transformative knowledge for building a sustainable bioeconomy. *Ecological Economics*, *167*, 106435. https://doi.org/10.1016/j.ecolecon.2019.106435

Van Berkel, J., & Delahaye, R. (2019). Material Flow Monitor 2016–technical report. *CBS Den Haag*. https://www.cbs.nl/-/media/_pdf/2019/10/material%20flow%20monitor%202016%20cbs%20-%20technical%20report.pdf

Van Leeuwen, M. (2016). *Final report of BERST project*. https://cordis.europa.eu/docs/results/613/613671/final1-finalreport-rev-berst-may-2016-.pdf

van Leeuwen, M., Smeets, E., van Meijl, H., Tsiropoulos, I., Linder, M., Moiseyev, A., O'Brien, M., Wechsler, D., Valin, H., Verburg, P., van Teeffelen, A., Schulp, N., Derkzen, M., Reinhard, P., Junker, F., Döring, R., & Msangi, S. (2015). *Design of a systems analysis tools framework for a EU bioeconomy strategy*. 57.

Vapnek, Jessica, Purnhagen, Kai, & Hillel, Ben. (2020). *Regulatory and Legislative Framework for Novel Foods* [Application/pdf]. 29 pages. https://doi.org/10.15495/EPUB_UBT_00005178

Venus, T. J., Drabik, D., & Wesseler, J. (2018). The role of a German multi-stakeholder standard for livestock products derived from non-GMO feed. *Food Policy*, *78*, 58–67. https://doi.org/10.1016/j.foodpol.2018.02.009

Verkerk, P. J., Fitzgerald, J. B., Datta, P., Dees, M., Hengeveld, G. M., Lindner, M., & Zudin, S. (2019). Spatial distribution of the potential forest biomass availability in Europe. *Forest Ecosystems*, *6*(1), 5. https://doi.org/10.1186/s40663-019-0163-5

Verkerk, P., Martinez de Arano, I., & Palahí M. (2018). The bio-economy as an opportunity to tackle wildfires in Mediterranean forest ecosystems. *For. Policy Econ*, *86*, 1–3.

Ververis, E., Ackerl, R., Azzollini, D., Colombo, P. A., de Sesmaisons, A., Dumas, C., Fernandez-Dumont, A., Ferreira da Costa, L., Germini, A., Goumperis, T., Kouloura, E., Matijevic, L., Precup, G., Roldan-Torres, R., Rossi, A., Svejstil, R., Turla, E., & Gelbmann, W. (2020). Novel foods in the European Union: Scientific requirements and challenges of the risk assessment process by the European Food Safety Authority. *Food Research International*, *137*, 109515. https://doi.org/10.1016/j.foodres.2020.109515

Vivien, F. D., Nieddu, M., Befort, N., Debref, R., & Giampietro, M. (2019). The Hijacking of the Bioeconomy. *Ecological Economics*, *159*, 189–197. https://doi.org/10.1016/j.ecolecon.2019.01.027

von Braun, J. (2018). Bioeconomy – The global trend and its implications for sustainability and food security. *Global Food Security*, *19*(October), 81–83. https://doi.org/10.1016/j.gfs.2018.10.003

Wackernagel, M., & Rees, W. E. (1996). *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers.

Walter, A., Finger, R., Huber, R., & Buchmann, N. (2017). Smart farming is key to developing sustainable agriculture. *Proceedings of the National Academy of Sciences*, *114*(24), 6148–6150. https://doi.org/10.1073/pnas.1707462114

Watanabe, C., Naveed, N., & Neittaanmäki, P. (2019). Digitalized bioeconomy: Planned obsolescence-driven circular economy enabled by Co-Evolutionary coupling. *Technology in Society*, *56*(May), 8–30. https://doi.org/10.1016/j.techsoc.2018.09.002

Weikard, H.-P., Punt, M., & Wesseler, J. (2006). Diversity measurement combining relative abundances and taxonomic distinctiveness of species. *Diversity and Distributions*, *12*(2), 215–217. https://doi.org/10.1111/j.1366-9516.2006.00234.x

Wesner, J. S., & Pomeranz, J. P. F. (2021). Choosing priors in Bayesian ecological models by simulating from the prior predictive distribution. *Ecosphere*, *12*(9). https://doi.org/10.1002/ecs2.3739

Wesseler, J. (2003). Resistance economics of transgenic crops under uncertainty—A real option approach. In *Battling Resistance to Antibiotics and Pesticides: An Economic Approach* (Issue May, pp. 214–237).

Wesseler, J. (2009). The Santaniello Theorem of Irreversible Benefits. *AgBioForum*, *12*(1), 8–13.

Wesseler, J., & Kalaitzandonakes, N. (2019). Present and Future EU GMO Policy. In H. W. Dries L. Jongeneel R. ,. Purnhagen K. ,. Wesseler J. (Ed.), *EU Bioeconomy Economics and Policies: Volume II.* (pp. 245–256). Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-28642-2_13

Wesseler, J., Politiek, H., & Zilberman, D. (2019). The Economics of Regulating New Plant Breeding Technologies—Implications for the Bioeconomy Illustrated by a Survey Among Dutch Plant Breeders. *Frontiers in Plant Science*, *10*, 1597–1597. https://doi.org/10.3389/fpls.2019.01597

Wesseler, J., Scatasta, S., & Nillesen, E. (2007). The Maximum Incremental Social Tolerable Irreversible Costs (MISTICs) and other benefits and costs of introducing transgenic maize in the EU-15. *Pedobiologia*, *51*(3), 261–269. https://doi.org/10.1016/j.pedobi.2007.04.004

Wesseler, J., & Smart, R. (2014). Environmental impacts. *Socio-Economic Considerations in Biotechnology Regulation*, 81–95. https://doi.org/10.1007/978-1-4614-9440-9_6/COVER

Wesseler, J., Smart, R. D., Thomson, J., & Zilberman, D. (2017). Foregone benefits of important food crop improvements in Sub-Saharan Africa. *PLoS ONE*, *12*(7), 1–12. https://doi.org/10.1371/journal.pone.0181353

Wesseler, J., & von Braun, J. (2017). Measuring the Bioeconomy: Economics and Policies. *Annual Review of Resource Economics*, *9*(1), 275–298. https://doi.org/10.1146/annurev-resource-100516-053701

Wesseler, J., & Zhao, J. (2019). Real Options and Environmental Policies: The Good, the Bad, and the Ugly. *Annual Review of Resource Economics*, *11*(1), 43–58. https://doi.org/10.1146/annurev-resource-100518-094140

Wesseler, J., & Zilberman, D. (2021). Biotechnology, bioeconomy, and sustainable life on land. In V. Beckmann (Ed.), *Transitioning to Sustainable Life on Land*. MDPI.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., … Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, *393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

World Bank. (2010). *The Changing Wealth of Nations: Measuring Sustainable Development in the New Millennium*. The World Bank. https://doi.org/10.1596/978-0-8213-8488-6

Wree, P., Sauer, J., Wree, P., & Sauer, J. (2016). *Genetically Modified Herbicide Resistant Rapeseed in Germany: A Socio-Economic Assessment*. https://doi.org/10.22004/AG.ECON.284981

Wydra, S. (2020). Measuring innovation in the bioeconomy – Conceptual discussion and empirical experiences. *Technology in Society*, *61*, 101242. https://doi.org/10.1016/j.techsoc.2020.101242

Yoshida, T. (2017). *Applied bioengineering: Innovations and future directions* (T. Yoshida, Ed.). Wiley-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/9783527800599

Zaghini, A. (2005). Evolution of trade patterns in the new EU member states. *Economics of Transition*, *13*(4), 629–658. https://doi.org/10.1111/j.0967-0750.2005.00235.x

Zarbà, C., Chinnici, G., & D'Amico, M. (2020). Novel Food: The Impact of Innovation on the Paths of the Traditional Food Chain. *Sustainability*, *12*(2), 555. https://doi.org/10.3390/su12020555

Zhang, R., Sun, C., Zhu, J., Zhang, R., & Li, W. (2020). Increased European heat waves in recent decades in response to shrinking Arctic sea ice and Eurasian snow cover. *Npj Climate and Atmospheric Science*, *3*(1), 1–9. https://doi.org/10.1038/s41612-020-0110-8

Zilberman, D., Gordon, B., Hochman, G., & Wesseler, J. (2018). Economics of sustainable development and the bioeconomy. *Applied Economic Perspectives and Policy*, *40*(1), 22–37. https://doi.org/10.1093/aepp/ppx051

Zilberman, D., Kim, E., Kirschner, S., Kaplan, S., & Reeves, J. (2013). Technology and the future bioeconomy. *Agricultural Economics*, *44*(s1), 95–102. https://doi.org/10.1111/agec.12054

Zilberman, D., Reardon, T., Silver, J., Lu, L., & Heiman, A. (2022). From the laboratory to the consumer: Innovation, supply chain, and adoption with applications to natural resources. *Proceedings of the National Academy of Sciences*, *119*(23), e2115880119. https://doi.org/10.1073/pnas.2115880119

Summary

EU policymakers strive to transform their fossil-based economies and steer them onto a sustainable path by using their natural resources differently. Tracking this path is challenging because it affects many economic sectors, societal aspects, and environmental systems and requires sophisticated and novel approaches and indicators.

One opportunity for a society is to transition towards a bioeconomy, which entails all economic sectors and systems being linked to biological resources and their functions and principles. A bioeconomy in the EU could tackle economic, environmental, and social problems if the transition from a fossil-based economy is adequately realized. The bioeconomy is a broad strategy tackling many economic, social, and environmental challenges simultaneously. There are tradeoffs with other policies as links between policies increase, which makes objectives and elements more complicated. The EU aims to promote the bioeconomy and reach the UN SDGs by establishing an extensive policy framework, and tracking this process and its dynamics is crucial to ensure that resources are efficiently spent.

Chapter 2 developed a conceptual analysis framework for quantifying and analyzing the development of the bioeconomy, determined the general scope for the framework, and derived a set of indicators. The chapter reviewed the literature to identify several primary forces steering the development of the bioeconomy. They were grouped as supply drivers, demand drivers, resource availability, and government measures. A broad range of bioeconomy sectors was derived from the EC's bioeconomy definition. New indicators have been suggested for monitoring innovation, policies, strategies, and legislation, which were sparse in previous works. The chapter proposed indicator measures, among others, 'Material use efficiency' and 'Sustainable resource use', for the degree of circularity of the bioeconomy and various indicators for measuring its contribution to the SDGs.

Chapter 3 showed the similarities and differences in the dynamic evolution of a wide range of indicators for circular bioeconomies in ten EU MSs. The chapter developed a novel framework in which indicators covering economic, environmental, and social aspects of the circular bioeconomy were normalized and then investigated patterns by using Markov transition matrices. The normalization method allows for country comparison and is insensitive to outliers. The chapter used a novel manner to rank the normalized indicators and Markov transition matrices to analyze the distribution of many indicators, compared to one indicator in previous studies. The chapter found that the EU-10 circular bioeconomies were generally developing well considering all indicators; however, this development was not homogeneous. The indicators related to R&D generally progressed

quickly in the private sector and regressed in the public sector, which suggests that one substituted for the other.

Chapter 4 quantified and compared the sustainability of bioeconomy sectors in the EU. A theoretical framework was conceptualized for assessing whether bioeconomy development is compatible with sustaining wellbeing over time. The framework included the characteristics of bioeconomy-related investment projects: uncertainty of future rewards and losses, irreversible impacts, and flexible timing. Not considering these characteristics could compromise sustainability measurement because the benefits of genuine investment projects would be overestimated. The chapter linked bioeconomy value-added with intergenerational wellbeing and estimated irreversible effects on greenhouse gas emissions, which allowed applying the framework empirically to the EU's bioeconomy. It was found that the hurdle rate in the bioeconomy is lower for the bio-based part than for the non-bio-based part for most countries, indicating high potential for further sustainable investments in the transition towards an EU bioeconomy. The findings are consistent with results from the Ecological Footprint, where most EU MSs have an ecological deficit as they have a larger footprint than biocapacity.

Chapter 5 contributed exploratory research assessing the performance of the EU NFR. The chapter empirically analyzed the pre-market authorization procedure of the NFR. The empirical strategy focused on a few new indicators to investigate the appeal and efficiency of the Regulation. These new indicators provided proxy measures of the barriers to accessing the authorization procedure, the process's opportunity costs, and the applicants' degree of success. The empirical findings suggest that expectations impact firm investment decisions as the number of NF applications has been relatively stable over the years, with an upsurge with the introduction of the new NFR in 2018. A decreasing trend in the length of the authorization process was shown, especially for those applications receiving a decision within four years. The chapter provided a new indicator for innovation in the food sector, which is growing in importance for the whole supply chain.

Finally, Chapter 6 provided a general discussion of the results, drawing additional conclusions by looking at all chapters together and relating them to societal and scientific debates on bioeconomy monitoring, sustainability, and innovation. Furthermore, the chapter synthesized the results from the previous chapters. Overarching policy recommendations, especially concerning the EU Bioeconomy Strategy, were presented. The last section discussed limitations and suggestions for further research. Additional research is particularly needed to measure whether the bioeconomy's contribution towards sustainable development, which is most threatened by climate change, is sufficient and timely.

Authorship Statements

Chapter 1 *General Introduction* The general research question and its general scientific and social perspective were proposed by my promotor. I delineated the research question, described how it fits in the current scientific literature and described its potential social impact. I revised the text two times, after comments of my co-promotor and promotor.

Chapter 2 *Development of the Circular Bioeconomy: Drivers and Indicators*. Conceptualization of the chapter was done by my promotor, two co-authors, and myself. I did the formal analysis of the chapter. My promotor, two co-authors, and myself wrote the original draft of the chapter. I revised the text several times, after comments of my promotor and several co-authors.

Chapter 3 *Full Speed Ahead or Floating Around? Dynamics of Selected Circular Bioeconomies in Europe*. Conceptualization of the chapter was done by my co-promotor and myself. Methodology was done by my co-promotor and myself. I did the data and formal analysis of the chapter. I wrote the original draft of the chapter. I revised the text several times, after comments of my co-promotor.

Chapter 4 *Bioeconomy Real Options and Sustainability - Measuring the Contribution of EU Bioeconomy Sectors to Sustainable Development*. Conceptualization of the chapter was done by my promotor, one co-author, and myself. Methodology was done by my promotor, one co-author, and myself. I did the data and formal analysis. I wrote the introduction, empirical application, and discussion and conclusion of the chapter. I revised the text several times, after comments of my promotor and co-author.

Chapter 5 *The Development and Performances of the Novel Food Regulation in The European Union*. Conceptualization of the chapter was done by my promotor, one co-author, and myself. Data collection and was done by a co-author, which I supervised. Data analysis was done by a co-author. I wrote introduction, results, discussion, and conclusion of the chapter. I revised the text several times, after comments of my promotor and co-authors.

Chapter 6 *General discussion*. I wrote the first draft of the text. I revised the text once, after comments of my promotor and co-promotor.

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The journey of my Ph.D. research has been divided into two parts: the pre-pandemic period and the pandemic period. And while both were very different in my research and personal life, important people in both periods made them special. In the first part of my Ph.D., I experienced the collaborative and sociable part of the research and never understood the stereotype of a "lonely Ph.D". However, in the second part, I did experience the more solitary and independent part of the research. But in both periods, important people supported me and ensured that I would succeed.

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About the author

Maximilian Kardung grew up in Witten, Germany and moved to the Netherlands for his studies in 2010. He completed his bachelor's degree in Economics and Governance in 2015 and his MSc degree in Urban Environmental Management with a specialization in Environmental Economics in 2017, both at Wageningen University. For his MSc thesis, he worked with Wageningen Economic Research on the governance of natural areas in the Netherlands and he spent his academic internship at the Institute for Ecological Economy Research. This internship and the work on his MSc thesis encouraged him to pursue a career in research.

He started his Ph.D. studies in 2018 under the supervision of Prof. Justus Wesseler and Dr. Dusan Drabik at the Agricultural Economics and Rural Policy group. His research focuses on measuring and monitoring the bioeconomy. The research uses quantitative and qualitative methods to assess the economic, social, and environmental impacts of transitioning from a fossil-based economy to a bio-based economy. He worked on the EU Horizon 2020 project "BioMonitor", which aimed to establish a sustainable statistics and modeling framework for the bioeconomy.

Currently, he is employed as a postdoctoral researcher at the Agricultural Economics and Rural Policy group and works in the EU Horizon 2020 project "GeneBEcon".

Maximilian Kardung
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Name of the learning activity	Department/Institute	Year	ECTS*
Project related competences			
A1 Managing a research project			
Writing the Research Proposal	WUR	2018/2019	6
WASS Introduction Course	WASS	2019	1
'Measuring and Monitoring the Bioeconomy - A Framework to Measure and Monitor the Development of the EU Bioeconomy'	ICABR 2019, Ravello - Italy	2019	1
'Full Speed Ahead or Floating Around? Exploring the Dynamics of European Bioeconomies'	WASS PhD Day, Wageningen, The Netherlands	2019	0.5
Scientific Writing	WGS	2019/2020	1.8
'Full Speed Ahead or Floating Around? Dynamics of Selected European Circular Bioeconomies'	EAAE Seminar 175, Online	2021	1
'The Development of the Novel Food Regulation and its Impact in the European Union'	ICABR 2021, Ravello - Italy	2021	1
'Measuring the Sustainable Development of the EU Bioeconomy'	XVI EAAE Virtual Congress, Online	2021	1
BioMonitor Consortium meetings	WUR	2019 - 2022	1
Reviewing scientific papers	Austrian Journal of Forest Science, Research Evaluation	2021/2022	1
A2 Integrating research in the corresponding discipline			
Advanced Microeconomics, UEC-51806	WUR	2018	6
Assessing Economics and Policies Using the Real Options Methodology	WASS	2019	3
Economic Modelling in the Bioeconomy	WASS	2019	3
Global Change and Challenge of Sustainable Feeding a Growing Planet	WASS	2022	1.5
General research related competences			
B1 Placing research in a broader scientific context			
Advanced Econometrics, YSS-34306	WUR	2018	6
Advanced Course on Economic Regulation	WASS	2019	2

Panel discussant at opening of the Academic Year 2021 - 2022	WUR	2021	0.5
B2 Placing research in a societal context			
Popular Science Writing	WASS	2021	1.5
There will be blood: CineScience in the Park	WUR	2021	0.5
Career related competences/personal development			
C1 Employing transferable skills in different domains/careers			
Teaching Assistant: Economics of Agribusiness	WUR	2019	1
Supervision of M.Sc. Thesis	WUR	2020/2021	1
Total			**41.3**

*One credit according to ECTS is on average equivalent to 28 hours of study load

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