D1.1: Framework for measuring the size and development of the bioeconomy

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D1.1:

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Monitoring the Bioeconomy

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
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Summary

This deliverable develops a conceptual analysis framework for quantifying and analysing the development of the EU bioeconomy in the BioMonitor project. This includes defining the scope of the bioeconomy to be considered within the BioMonitor project in terms of sectors and products involved, geographical coverage, time period, as well as the focus topics. The EC's 2018 Bioeconomy Strategy Update recently confirmed that the bioeconomy is high on the political agenda and includes three main action areas, namely 1. Strengthening and scaling-up the bio-based sectors, unlocking investments and markets; 2. Deploying local bioeconomies rapidly across Europe; 3. Understanding the ecological boundaries of the bioeconomy. These action areas constitute an important guidance for how the scope or contents of the monitoring and measuring framework of BioMonitor must look like.

The 'bioeconomy' has several related terms, such as 'bio-based economy', 'green economy' and 'circular economy'. There are clear synergies between especially the bioeconomy and circular economy concepts, such as cascading use of biomass. Factors have been determined to understand what the development of the bioeconomy drives. Knowing these driving forces provides important information for monitoring activities. The sectors covering the bioeconomy have been identified as well as a set of indicators that are going to be quantified and monitored. In our framework measuring developments will in particular focus on the bio-based sectors, because the traditional part of the bioeconomy can already be monitored. The selected indicators commit to the EU Bioeconomy Strategy objectives and are conform with findings from previous studies and stakeholder consultations. Additionally, a several new indicators have been suggested. They are related to measuring the impact of changes in supply, demand drivers, resource availability and policies on sustainability goals.

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1. Introduction

The bioeconomy, which includes those parts of the economy that use renewable biological resources from land and sea – such as crops, trees, fish, animals and micro-organisms – to produce food, materials and energy, is essential for the well-being of humankind. For the longest part of human development, the primary sector has been of utmost important to humans for food, animal fodder and raw materials. Only since the transformation of economies into industrial societies, other sectors have become more relevant in industrialized countries e.g. processing industries, service-oriented sectors. Today, climate change and its related negative impacts pose an additional challenge to develop into a sustainable society. This challenge happens against the background of a rising world population and an increasingly rich middle-class, a rapid increase in urbanization and related pollution problems, and a rise in inequality in income distribution. Sustainable development aims to harmonize economic growth, social inclusion, and environmental protection (United Nations, 2018). The development of the bioeconomy can play an important role in tackling the environmental, social and economic problems that continue to be a challenge not only in post-industrial societies but also in emerging markets (Wesseler and von Braun 2017; Zilberman et al. 2018).

1.1 Bioeconomy strategy

In the last twenty years, EU policymakers 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 stress on the bioeconomy is evident from a multitude of EU policy initiatives and research programmes, including the recent European Bio-Based Industries Joint Undertaking (Wesseler and von Braun, 2017). Many bioeconomy strategies on a regional and national level have been developed (Figure 1); 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, 2018).

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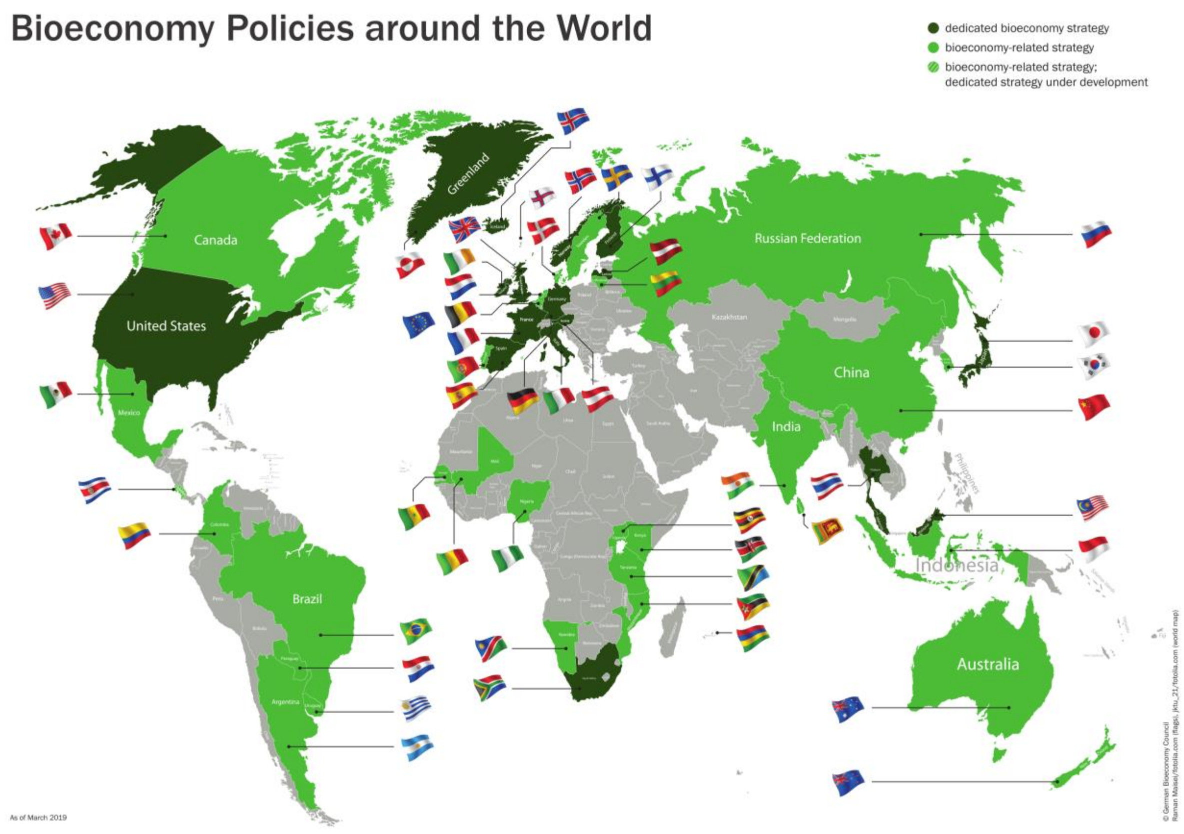

Figure 1: Overview of country bioeconomy strategies (As of March 2019). Source: http://biooekonomierat.de/en/international/ (Accessed: 1 May 2019)

The recent EC Bioeconomy Strategy update (EC, 2018a) confirms that the bioeconomy is high on the political agenda. The update revalidates the five objectives of the 2012 Bioeconomy Strategy that align with five societal challenges:

1. Ensuring food and nutrition security;
2. Managing natural resources sustainably;
3. Reducing dependence on non-renewable, unsustainable resources whether sourced domestically or from abroad;
4. Mitigating and adapting to climate change;
5. Strengthening European competitiveness and creating jobs.

While the objectives remain the same as in the 2012 version, the 2018 Bioeconomy Strategy is now accompanied by three main action areas:

1. Strengthening and scaling-up the bio-based sectors, unlocking investments and markets;
2. Deploying local bioeconomies rapidly across Europe;
3. Understanding the ecological boundaries of the bioeconomy

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1.2 Sustainable Development

The concept of sustainable consumption and production gains importance on national, EU and global levels, and the bioeconomy is an important part of that concept (Knudsen et al., 2016). Therefore, sustainability of the bioeconomy is a very important aspect for a monitoring framework. It has three major dimensions: economy, society, and the environment. The sustainability of the bioeconomy is mostly attached to its environmental dimension, especially when it comes to sustainable production and use of biomass. A challenge to measuring the sustainable use of biomass is that there is no consensus on what 'sustainable' means and that current biomass sustainability assessments are a mixture of voluntary standards and regulations (Bosch, van de Pol and Philp, 2015). An indicator for measuring the sustainability of biomass is needed, and it must go beyond just one single factor such as greenhouse gas emissions. A diverse mix of economic, social, and environmental factors need to be considered. Biodiversity is especially relevant in this regard, as there may be a risk that enhanced use of biological raw materials may increase the pressure on ecosystems. Intensive land use practices have caused and are causing losses in biodiversity through loss and degradation of habitats, pollution and overexploitation (Butchart et al. 2010; Pimm et al. 2014).

Sustainability is also directly linked with the Sustainable Development Goals (SDGs). In the 2015 Global Sustainable Development report by the United Nations (2018), the question 'what is to be sustained?' is among other things answered by:

- Goal 12. Ensure sustainable consumption and production patterns.
- Goal 14b. Sustainably use of the oceans and marine resources for sustainable development.
- Goal 15b. Promote sustainable use of terrestrial ecosystems.
- Goal 15c. Sustainably manage forests

These goals are connected with the bioeconomy, and therefore the BioMonitor project will contribute to measuring the progress towards them.

1.3 Problem description

Both the objectives and the action areas of the EC Bioeconomy Strategy constitute important guidance for the BioMonitor and its scope.
The bioeconomy can be split in a traditional part (like agro-food sectors, feed sector, paper and pulp sector) and an emerging part (like the chemical and pharmaceutical sector). Statistics cover traditional sectors and products of the bioeconomy in Europe relatively well, even though there is room for improvement (e.g. Kallio and Solberg, 2018; Buongiorno, 2018). However, there is especially a lack of information and statistics for its emerging innovative industries, such as chemistry and materials sectors that process biomass into bio-based intermediate and end products. This includes (i) a lack of a comprehensive database with statistics for industrial uses of biomass – so far data among different databases are fragmented and non-comparable; (ii) a missing transparent methodology for data collection – so far bio-based data collection mostly relies on

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industry surveys and estimations of experts; and (iii) a lack of value chain integrated data and indicators illustrating flows from raw materials to industrial end products, including bio-waste streams (EC, 2018b). We want to close these data gaps for the emerging bio-based economy. Specific bio-based information has to be integrated thorough the whole statistical framework. Actions are needed at different fronts, from PRODCOM[1] to labour statistics to monetary supply and use tables. In this respect the currently developed Material Flow Monitor (MFM) by CBS Netherlands has potential to capture material flow information across sectors in the economy. However, more detail on bio-based material flows also need to be implemented in this MFM.
The MFM developed by CBS contains information on the supply and use by industry and households of all type of materials including raw materials, end products and waste (Berkel and Delahaye, 2019). The MFM is based on the National Accounts which is an integrated framework of different kind of statistics and based on internatinaly agreed concepts and definitions. In WP3 it is investigated if the MFM is suitable to fill data gaps with regards to bio-based material use and supply across sectors in the economy.

1.4 Objectives

The objective of Work Package 1 and this deliverable D1.1 is to develop a conceptual analysis framework for quantifying and analysing the development of the EU bioeconomy. In order to make the framework operational in the course of the BioMonitor project, a set of indicators for monitoring and measuring the bioeconomy is determined in collaboration with stakeholders, and based on previous studies. While the whole actual process of implementing the monitoring and measuring framework for the bioeconomy will take place in WP2 to WP8, the general scope and the design of the indicator framework to assess the bioeconomy is determined in WP1.

The overall objective of the BioMonitor project is "to establish a statistics and modelling framework for the bioeconomy that is effective (supported by a stakeholders' platform) and robust (compatible with and implementable in existing systems of statistical and customs offices, laboratories and industries). The framework will enable the quantification of the bioeconomy and its economic, environmental, and social impacts in the EU and its Member States via a wide range of indicators."

To achieve the overall objective of the BioMonitor project (see text box above), it is crucial to define the scope of the bioeconomy. There is a need to specify which sectors and products it includes. The geographic level and time period considered for sectors and products should also be defined. These activities will first entail the designing of a conceptual data and modelling framework for monitoring and measuring the bioeconomy, which will then be operationalised within two service tools of the

[1] PRODCOM is a survey, with an at-least-annual frequency, for the collection and dissemination of statistics on the production of industrial (mainly manufactured) goods, both in value and quantity terms, in the European Union

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BioMonitor project, i.e. the BioMonitor Data Platform (WP2 and WP3) and the BioMonitor Model Toolbox (WP4 and WP5).

1.5 Outline of report

To be able to define the scope of the bioeconomy, Chapter 2 presents various definitions. Chapter 3 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 trade-offs. The scope of the bioeconomy will be derived from the bioeconomy definition used in the EU Bioeconomy strategy. Indicators covering all aspects of the bioeconomy are identified as they are relevant for monitoring the development of the bioeconomy (WP2 and WP3) and for analysing the effects of the bioeconomy on sustainability areas by the BioMonitor Model Toolbox (WP4, 5 and 6). In chapter 4 the scope of BioMonitor with respect to sectors, products, space, and time is presented. Chapter 5 presents the set of indicators for monitoring and measuring the bioeconomy. Chapter 6 concludes the deliverable with the implications of the previous chapters for our framework.

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2. Definition of the Bioeconomy

The bioeconomy has an inter-sectoral, (inter)national, and transdisciplinary nature, which allows for varying definitions, depending on the stakeholders: scientists, policymakers, NGOs or private sector. 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 and von Braun, 2017).

A word cloud of 26 different definitions from various sources shows where the stakeholders put their emphasis when defining the bioeconomy (Figure 2). The definitions come from various sources and geographical locations (e.g., the European Commission, EU; the White House, US; the Department of Science and Technology, Republic of South Africa) and organisational background (e.g., A Bioeconomy Strategy for France; Royal Society of Biology; Global Bioeconomy Summit 2018), in order to depict a broad view on the bioeconomy.[2] All definitions define the bioeconomy in one or only a few sentences. The focus is on the ability of the bioeconomy to create economic growth, which is shown by ‘production’ (n=28) and ‘products’ (n=23) being very frequently used words. ‘Resources’ (n=24) and ‘biological’ (n=22) are also repeatedly used words, often in combination. In conclusion, this suggest that the bioeconomy is still a very supply and technology driven system.

Figure 2: Word cloud of the definitions of the bioeconomy

[2] The definitions included in the word cloud are not a complete list of all definitions of the bioeconomy, but only a selection.

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2.1 European Commission's definition

To define the scope of the bioeconomy that will be addressed by the BioMonitor project, our starting point is the European Commission's (2018a) definition:

"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 Comission, 2018, 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" thereby emphasizing sustainability and circularity.

Table 1: Comparison of the bioeconomy definition in the 2012 EU Bioeconomy Strategy with the 2018 EU Bioeconomy Strategy Update

2012 EU Bioeconomy Strategy	2018 EU Bioeconomy Strategy Update
Definition	
"The bioeconomy encompasses the <u>production</u> of renewable <u>biological resources</u> and their <u>conversion</u> into <u>food, feed, bio-based products and bioenergy</u>. It includes <u>agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries.</u> Its sectors have a strong innovation potential due to their use of a wide range of sciences (life sciences, agronomy, ecology, food science and social sciences), enabling and industrial technologies (biotechnology, nanotechnology, information and communication technologies (ICT), and engineering), and local and tacit knowledge"	*"The bioeconomy covers <u>all sectors and systems</u> that <u>rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles</u>. 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"*
Comparison	
• Includes all sectors that produce renewable biological resources or convert them into food, feed, bio-based products and bioenergy by a range of sectors	• Includes all sectors that produce renewable biological resources or convert them into food, feed, bio-based products and bioenergy by a range of sectors • *Additionally,* sectors and systems that rely on biological resources

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2.2 Other definitions

Alongside the definition by the European Commission, there are also definitions from other stakeholders. The Global Bioeconomy Summit has established itself as an important conference, which brings together stakeholders from around the world: ministers and government representatives from Asia, Africa, Europe, South and North America; international policy experts from the United Nations, the Organisation 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*" (Global Bioeconomy Summit 2018, p. 2). Compared to the Commission's definition, this definition explicitly highlights the importance of conserving biological resources as a part of the bioeconomy.

The European Bioeconomy Alliance, a cross-sector overarching alliance of various bioeconomy industries associations (e.g. The European Vegetable Oil and Protein Meal Industry[3]), 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 Alliance, 2016, p. 1).

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

Another perspective comes from organisations representing different sectors, i.e. industrial stakeholders, within the bioeconomy. They emphasise 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)."

[3] A list of all members is available at https://bioeconomyalliance.eu/about-euba-bioeconomyalliance.

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In this definition, the Sustainable Development Goals take a prominent role and reaching them is considered the primary objective.

In summary, these definitions provide 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 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.

2.3 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 3 shows a VENN diagram of 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 low carbon, resource efficient and socially inclusive" (UNEP, 2011, p. 1). The *bioeconomy* is generally considered to be part of the green economy (Figure 3). Generally, the bioeconomy is often more related to global economic growth and technological development (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 (e.g. FAO, 2016) while in others, traditional bio-based products such as bio-based textiles, wood products, pulp and paper are explicitly included as well (e.g. Carus and Dammer, 2018). Figure 3 follows the last mentioned 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 procession of agricultural goods into processed foods and therefore fits into the bio-based economy. Further, many novel developments allow the conversion of and extraction from biological resources to biopolymers that can be used as a building block for wide a range of products including food, feed and other products. One example is the extraction of cyanophycin from biomass that can be used for producing bioplastics but also as an ingredient for food and feed (see e.g. http://www.sustainable-co-production.com).

The *circular economy*, which shares the rise in popularity and can work complementary to the bioeconomy (European Commission, 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 (Bourguignon, 2016). Substitution of non-renewables with sustainable produced biomass is also an important part of circular economy. The concept of circularity is not new and has been the foundation for economy-wide modeling

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dating back at least to the works of François Quesnay and the Physiocratic school of 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 minimised, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy." (European Commission, 2018b).

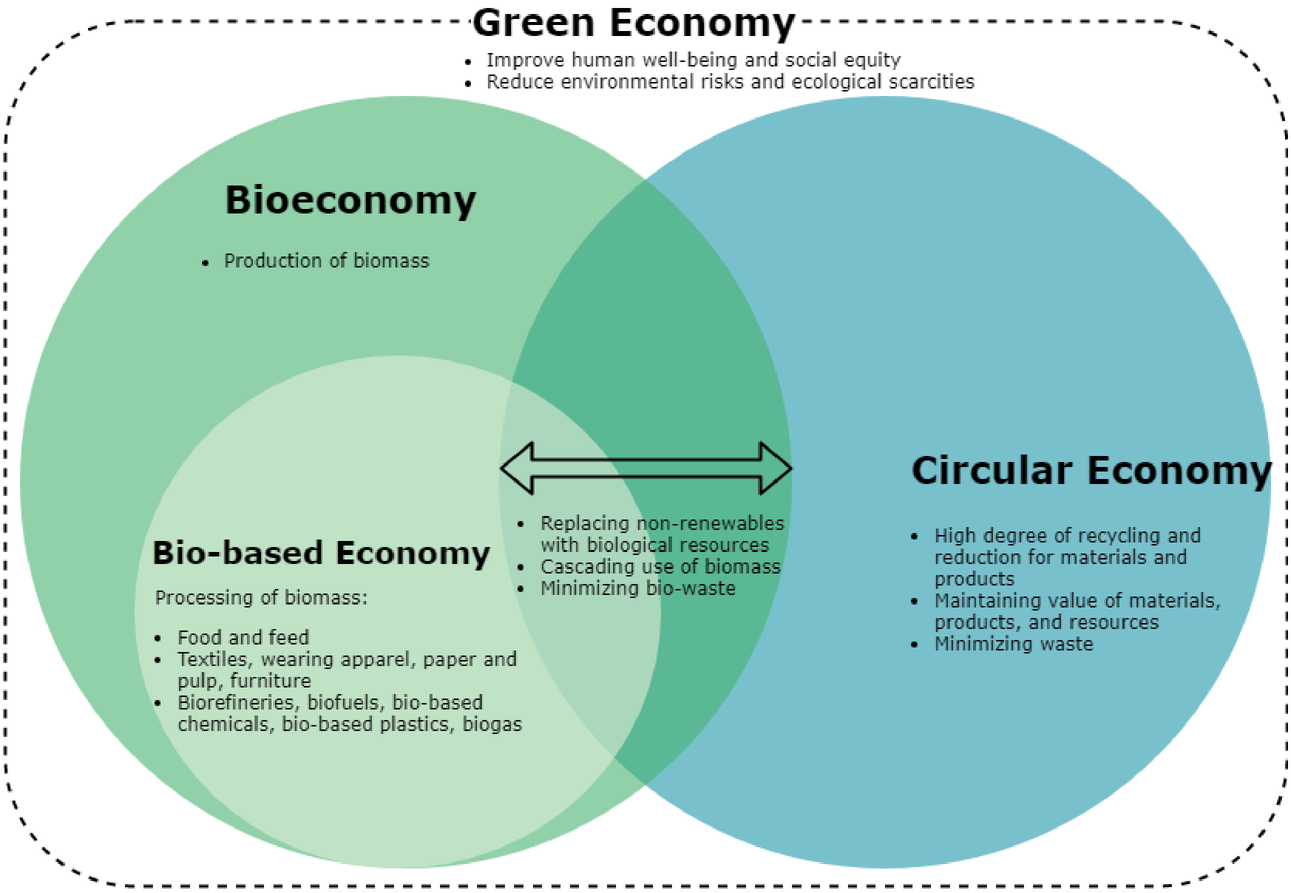

Figure 3: VENN diagram of Bioeconomy, bio-based economy, green economy and circular economy

The synergies between the bioeconomy and circular economy concepts are significant. Several prominent 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 (EuropaBio, 2017; CEPI, 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 (Hetemäki et al., 2017; Carus and Dammer, 2018; European Comission, 2018c). Limitations can occur at the collection, separation and processing of the bio-waste stream, where in some cases this process might cause more GHG emissions than producing another virgin bio-based product.

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Furthermore, toxic and critical substances can accumulate. Moreover, synergies should be regarded with caution. For example, subsidies make it more profitable to burn waste instead of recycling it (Carus and Dammer, 2018).

In conclusion, the Commission's definition of the bioeconomy in its 2018 Bioeconomy Strategy Update is the most relevant for our project and will be used as a guiding principle to develop the scope of the BioMonitor framework. The objective of the BioMonitor project is to develop a statistics and modelling framework to quantify the bioeconomy and its economic, environmental, and social impacts in the EU and its Member States. To achieve this, a generally accepted definition of the bioeconomy must be used to ensure that the results are useful to all stakeholders. The Commission's definition has the largest potential to constitute that.

We follow Carus and Dammer (2018)'s definition of the bio-based economy, but additionally include the food and feed sector. The Green Economy and especially the Circular Economy are concepts that are embedded in the wider policy debates around the bioeconomy, and therefore relevant for our framework.

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3. Driving forces, Resource availability and Policies, strategies and legislation

The bioeconomy is driven by a number of forces. Knowing these driving forces and understanding how they influence the bioeconomy will provide important information for the monitoring and impact assessment activities in the BioMonitor project. Wesseler and von Braun (2017) and other studies (SAT-BBE, 2015b; Sheppard et al. 2011) identified several major forces steering the development of the bioeconomy. They can be grouped under themes, respectively supply drivers (sections 3.1, 3.2 and 3.3) and demand drivers (section 3.4). Subsequently, resource availability (section 3.5) and the measures of governments to influence the development of the bioeconomy are presented (section 3.6).

3.1 Technology and Innovation

Advances in Biological Sciences

Advances in biological sciences are a major supply driver of the bioeconomy. Fermentation of food products was one of the earliest advances whose underlying biological processes have been refined over the past thousands of years (Tramper and Zhu, 2011). The development of recombinant DNA technology in the early 1970s was the start of the modern biotechnology. Today, a wide array of applications of biological sciences are available, including those in the food and feed sectors, biofuels, materials, chemicals, and pharmaceuticals. Genetic engineering is likely to play a key role in further developments of non-food applications (Figure 4). The use of modern biotechnology is not uncontroversial (Wesseler and Kalaitzandonakes, 2011). Policies related to the application of modern biotechnology can have wide ranging implications that need to be considered for assessing impacts (Smart et al., 2015, 2017; Wesseler et al. 2017; Venus et al., 2018).

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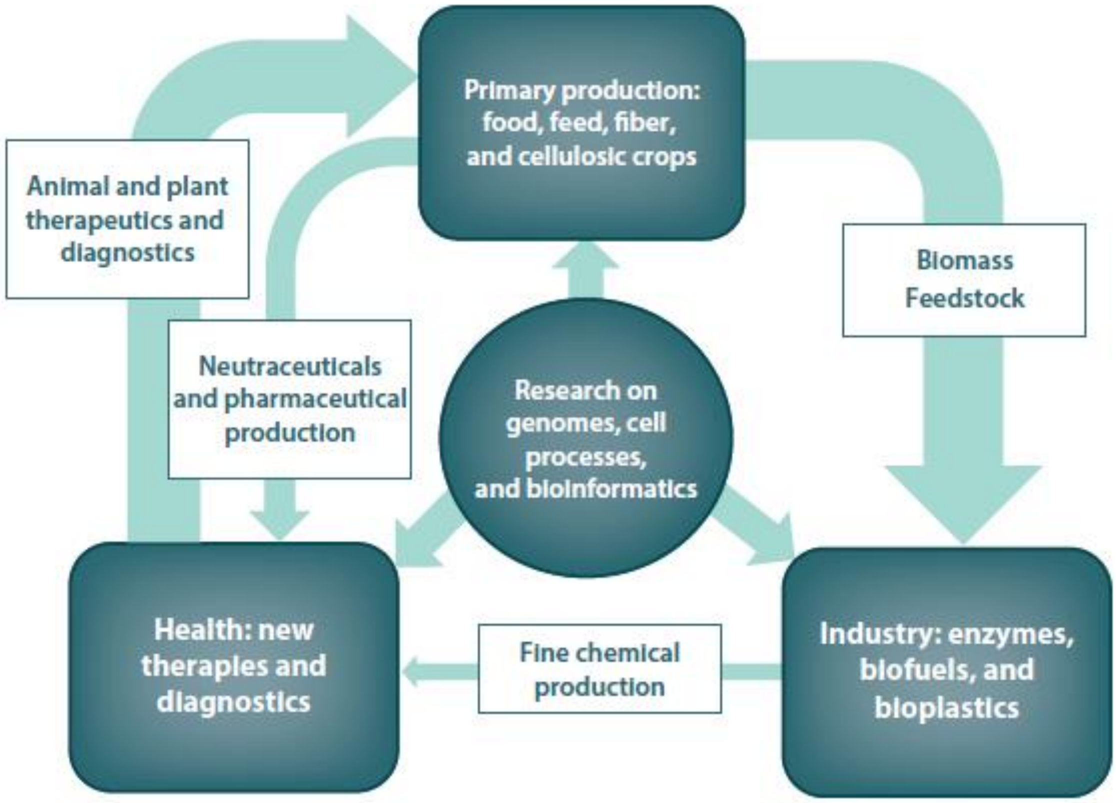

Figure 4: Current and expected integration across biotechnology applications. Source: Wesseler and von Braun (2017)

The technological advances would not have been possible without investments in the bioeconomy. 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, 2018a). But also funding from EC framework programmes (H2020, FP7, etc.) and the BBI-JU initiatives have been supportive to developing the bioeconomy. The BBI-JU is a public-private partnership between the European Union and the Bio-based industries Consortium (BIC). It has formulated a Strategic Innovation and Research Agenda that describes the main technological and innovation challenges to overcome, in order to develop sustainable and competitive bio-based industries in Europe. Research, 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, it makes sense to monitor the impact of technological developments in natural sciences on the performance of the bioeconomy in achieving its objectives. Furthermore, the regulatory environment (e.g. the EU legal framework for the application of genetic modification technology) must be considered as it has a large influence on the technological developments.

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Advances in Information, Communication and Other Technologies

Another important supply driving force related to innovation is the vast and increasing application of information and communication technologies (ICTs). Watanabe et al. (2018) found that in recent years the bioeconomy has taken major steps driven by digital solutions. 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. For example, digitized forest management enables advanced computer-aided growth processes for forest areas (Klitkou et al., 2017).

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.

The developments in digital information and communication technology can also affect market segments of products belonging to the bioeconomy. On the one hand, developments in ICT are linked to a decline in the global markets for graphical paper (Hurmekoski and Hetemäki 2013; Johnston 2016; Latta et al. 2016). On the other hand, online shopping and business led to stable increase in the global consumption of packaging paper and paperboard (Hetemäki and Hurmekoski 2014; Jonsson et al 2018).

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 multi-storey building 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), allow for the increased use of wood in multi-storey buildings (Näyhä et al. 2014; Tollefson 2017). Due to these developments, the market for engineered wood products – especially CLT –and the use of wood in construction are expected to develop rapidly over the next years to decades (UNECE 2018; Hurmekoski et al. 2018). 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 is not a niche product anymore. A similar development can be expected with cultured meat, produced by in vitro cultivation of animal cells.

This implies developments in the ICT sector relevant for the bioeconomy 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 in the standardized classification system and data collecting system.

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3.2 Market organisation

Advances in Horizontal and Vertical Integration

Another supply driver is horizontal and vertical integration of supply chains that related to the bioeconomy can influence the supply and demand side of the bioeconomy market and its impact on the sustainability goals. Therefore, looking at the agricultural sector only and not considering the increase in up- and downstream 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, 2018). Through mergers and acquisitions or voluntary collaboration 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 production (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 are advances in ICTs.

New bioeconomy value chains have emerged based on the increasing use of natural and renewable resources in non-food application. 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). One example is the Äänekoski bioproduct mill in Finland, which combines the production of pulp with a broad range of other bioproducts, such as tall oil, turpentine, bioelectricity, product gas, sulphuric acid and biogas. The bio-refinery is an important part of the value chain of many bio-based products and have the advantage of operating at much lower temperature allowing for smaller units to be built in comparison to fossil fuel-based refineries (Clomburg et al., 2017). The new business models, such as bio-refineries, that are emerging need to be monitored as well.

Globalisation

A further important driving force that influences the markets supply and/or side is the change in globalization. Globalisation 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). Globalisation goes beyond the increase in international trade and vertical and horizontal integration. This process contributes to the harmonisation of value chains and consumer attitudes around the world. Globalisation 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 source of raw material (Jonsson et al. 2018). Furthermore, consumption of packaging paper and paperboard is shifting from the North America and Western Europe to emerging countries such as

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China and these shifts are linked to changes in the location where goods are manufactured (Hetemäki and Hurmekoski, 2014).

The pervasive forces of digitization and globalisation of the socioeconomic system change the framework condition of the bioeconomy. Standards for biorefineries and bio-based products can be expected to be increasingly harmonised and foster positive externalities, which poses a challenge to measuring the bioeconomy. Examples are related to the labelling 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 international level needs to be monitored.

3.3 Climate and environmental change

Increase in Importance of Climate Change and Pressure on Ecosystems

Climate change is a particularly complex driving force in the context of production of biomass for the bioeconomy. On the one hand, it is a major challenge for the agricultural and forestry sectors, because an increase in mean annual temperature as well as more extreme weather events will affect forest and crop growth and wood production (Lindner et al. 2010). Therefore, climate change has a direct effect on biomass production. Climate change also increases uncertainty in these sectors and can potentially cause market disturbances. On the other hand, different climate change mitigation policies may use forests as carbon sink, which might imply a reduction of harvest amounts and less intensive management. However, the forestry and agricultural sector also produce biomass resources that can potentially substitute energy intensive materials or fossil fuels, which would result in intensive management and maximized resource extraction from forests (Böttcher et al., 2012).

The bioeconomy is thought to offer opportunities 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. The bioeconomy may also contribute to climate change adaptation by creating new value chains, which may activate land management (Verkerk et al. 2018)[4]. The use of new breeding technologies provides 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 than comparable fossil-based or fossil-intensive products (e.g. Leskinen et al. 2018). However, they may have greater water, eutrophication, and land-use footprints (van den Oever, 2017). As a consequence, bio-based products are not per se more environmentally friendly or more sustainable than fossil-based products. To determine if this happens, the quantities in biological resources provided and needed and the contribution to greenhouse gas emission often require complex monitoring of material flows.

[4] LUC and ILUC caused by the development of bio-based value chains can either have positive or negative CC impacts. It is a case-by-case assessment but the goal foreseen by bioeconomy policies/strategies is certainly to support those that contribute to CC adaptation.

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3.4 Demographics, economic development and consumer preferences

The previous section addressed the supply side drivers of the bioeconomy. This section explains the factors that drive the demand for bioeconomy products. These include, among others, demographics (population growth, human capital, and education), economic development (income growth) and consumer preferences (taste, behaviour). Economic development or income growth directly influences the budgets available for buying food and non-food products. If income levels per capita are low, then a large part of income is spent on food consumption whereas richer people spend relatively less on food.

The strong world population growth is another important determinant on the demand-side. Naturally, a growing population leads to an increase in demand for all kinds of products. For example, the pressure on cropland use is further expanding 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 biodiversity 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 (European Commission, 2007). For example, a rising awareness 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 health and environmental attributes of novel food products (Dolgopolova 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.

Monitoring the development of labels and related requirements in relation to the demand for novel bio-based products will be part of the BioMonitor project.

3.5 Resource availability

A variety of resources is needed to fuel the economy such as for example water, air or skilled labour. The most important resource for the bioeconomy is biomass, either domestically produced or imported. If there is no biomass available, then there is no base for developing the bioeconomy. Besides the quantity, also the type and quality of available biomass is 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 for optimal utilization. A constraint for the production of biomass is that it must be ecologically sustainable to avoid negative environmental impacts. Furthermore, biomass production for non-food use should not compete with food production. A large future potential lies in waste biomass, especially agricultural residues and food waste (van der Hoeven, 2014).

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3.6 Policies, strategies and legislation

Global, EU and national policies

Agricultural, fisheries, and forestry policies are important drivers for the bioeconomy. They 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 of bioenergy production. The focus on bioenergy could also affect other parts of the bioeconomy, lead to distortions within the bioeconomy (such as an overly cultivation of energy crops) and hinder environmental benefits and cascading use of biomass. For the further development, bioeconomy strategies take a big role as they outline visions and intentions of countries and regions. The market mechanisms of the bioeconomy are of high complexity and policy measures targeted towards single effects involve trade-offs, leakage, and rebound effects (SAT-BBE, 2015a). This means that also policies not directly targeted at the bioeconomy can have a considerable effect (see also Section 2.3). For example, policies on fossil fuel use could have an immense effect on the bioeconomy, because fossil fuel-based products can be substituted with bio-based products. Tsiropoulos et al. (2017) find that fossil fuel prices are a key determinant of bioeconomy development.

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 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 Bioeconomy Strategy for Europe (EC, 2018), 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. By leveraging their unique regional advantages, regions can pool their resources and achieve critical mass around shared priorities. To carry out the RIS3 strategies, regions will have to evolve along a development path, which goes from strategy to implementation of business innovation. The EU supports this trajectory by offering H2020 funding for exploring innovations and ERDF for piloting and implementing regional initiatives. As an additional stimulus, the EC introduced the Juncker Investment Plan (2014)[5], which has the aim to mobilise finance for investments by the European Fund for Strategic Investments (EFSI) and to support investments in bio-based business and industries. Further, other instruments like specific networks (ERRIN, COSME, ERIAFF, BBI-JU, S3, Bioeconomy Panel), data intelligence (S3 database, Bioeconomy Observatory, Cluster Observatory) and events (BioEconomy Stakeholder meeting, TCI Network Conferences in the field of clusters, Week of the Regions and the Cities) are in place.

Although many European regions have expressed ambitions to valorise agricultural, forest, marine or urban biomass and waste into new bio-based products (i.e. 100-170 regions have a bioeconomy

[5] An Investment Plan for Europe, COM (2014).

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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, Bioased 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.

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 agricultural commodities. The Common Fisheries Policy regulates fisheries management, international policy, market organisation, and the European Maritime and Fisheries Fund, and therefore has a high relevance for biomass from the maritime environment. The EU foods 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, because they steer the handling of bio-waste streams.

Policies, strategies and legislation are in place at EU, Member State and regional levels. The BioMonitor project will follow the impact of these bioeconomy related policies on the performance of the bioeconomy EU in terms of sustainability objectives of regions and countries.

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4. Bioeconomy scope in the BioMonitor project

4.1 Rationale

In BioMonitor, we need to define a clear scope for the bioeconomy as a basis for monitoring. The scope is first and foremost based on the European Commission's (2018b) definition of the bioeconomy and the 2018 Bioeconomy Strategy Update. Subsequently, we define the system boundaries of the bioeconomy in BioMonitor with regard to its sectoral, product-level, spatial, and time boundaries.

Figure 5 summarizes the issues discussed in previous chapters in a conceptual framework for the BioMonitor project. This should be seen as a dynamic and not as a static process. The Drivers-Impact-Results (DIR) framework[6] has been adapted from the SAT-BBE project (Van Leeuwen et al, 2013). 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 labour, which influences the biomass market in the centre. In the centre of the framework are the different supplies and uses of biomass, which are endogenously determined through the aforementioned three boxes of driver types. Also, waste/by-products, which usage is the key to a sustainable and circular bioeconomy, has been taken into account. In combination, the drivers, policies and resources have an impact on the demand and supply of the bioeconomy which on its turn determines to what extend 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 'adapting to climate change' could be reflected in the criteria 'reduce greenhouse gas (GHG) with 40% from 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 policy makers (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). On 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 to the affected sustainable objectives caused by status of drivers and resource availabilities so far. On their turn, adapted policy targets in conjunction with the drivers will again influence the sustainable

[6] The DIR concept is based on the Driver-Pressure-State-Impact-Response (DPSIR) model (EEA, 2007[6]), which is a causal framework for describing the interactions between society and the environment. On its turn the DPSIR framework is based on the Pressure-State-Response model, developed by the OECD.

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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 it's monitoring requires a comprehensive systems analysis. Both dynamics within the bioeconomy and interactions and pressures from 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 sustainbility and circularity of the bioeconomy. Furthermore, the monitoring has to be spatially explicit to analyse the development of local bioeconomies. As the advances in technology consitute a important driving force of the bioeconomy, monitoring must include private and public efforts to advance these technologic developments.

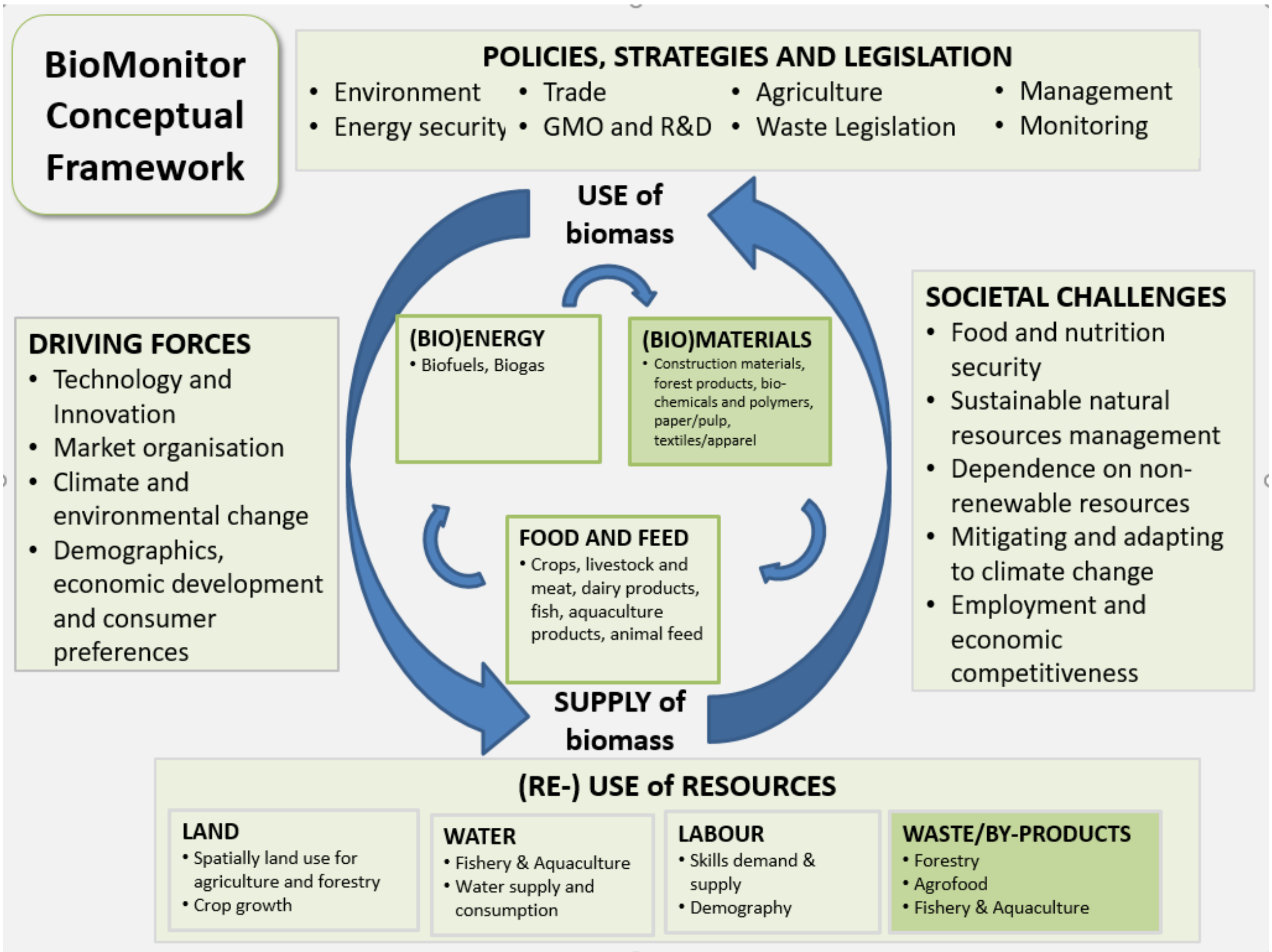

Figure 5: Overview of the relations within the bioeconomy. Source: Adapted from SAT-BBE (2015b)

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4.2 Sectors

4.2.1 Sectors in Bioeconomy

The broad definition of the bioeconomy by the European Commission asks for a list of sectors that makes up the entirety of the bioeconomy. The sectors considered are directly linked with the System of National Accounts and follows the Statistical Classification of Economic Activities in the European Community – From the French, Nomenclature Statistique des activités économiques dans la Communauté européenne (NACE).

In order to have clear and consistent sectoral boundaries for BioMonitor, we use the NACE statistical classification of economic activities, used in the European Communities. NACE provides a four-digit classification with a hierarchical structure:

- a first level consisting of headings identified by an alphabetical code (Sections),
- a second level consisting of headings identified by a two-digit numerical code (Divisions),
- a third level consisting of headings identified by a three-digit numerical code (Groups),
- a fourth level consisting of headings identified by a four-digit numerical code (Classes).

Bioeconomy industries can be broadly assigned to three different kinds of economic activities to be linked with NACE:

1. Natural-resource based activities that directly exploit a biological resource (agriculture, forestry, fisheries) and provide biomass as input for other industries
2. Conventional activities to further process the biomass from 1. (food, feed, tobacco, beverages, wood and wood products, textiles, wearing apparel, leather, paper and pulp, furniture)
3. Novel activities to further process the biomass and/or biomass residues from 1 or use processing residues from 2. (biorefineries, biofuels, bio-based chemicals, bio-based plastics, biogas)

The first type of sectors can be attributed to the bioeconomy completely and therefore is straightforward to be included in the BioMonitor monitoring framework (see also Table 2). Also, from the second type of sectors, food, tobacco, beverages, wood and wood products and paper and pulp are fully bio-based.

Based on the NACE classification, the inclusion of Divisions A01 – A03 (i.e. agriculture, forestry and fishery) is 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[7]) and C31 (furniture) are traditional sectors that to some extent use bio-based input. Like in most other studies, they are part of the bioeconomy in BioMonitor, but only for their share of bio-based production. C20 (chemical products), C21 (pharmaceutical products, C22 (rubber and plastic products), and C2365 (fibre cement) are sectors, which include novel activities that further process

[7] This division includes blending of biofuels in the manufacture of refined petroleum products.

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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 BioMonitor. In order to measure the development of new, innovative industries that make novel uses of biomass, biorefineries and cascading use of biomass are two essential concepts that should be captured in the BioMonitor project.

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 (accomodation) and I56 (food and beverage service activities). To capture the whole bioeconomy these sectors are also included in the BioMonitor scope to the extent that their bioeconomy share can be determined. To achieve this, BioMonitor builds on existing literature on this topic (e.g. Efken et al. 2016).

Table 2 and Table A.3 in Appendix 2 summarize which sectors have been considered by previous efforts that have been proposed for monitoring the bioeconomy (SAT-BBE, 2015a; Ronzon *et al.*, 2017; European Commission 2018; Fumagalli and Trenti 2014; Efken et al. 2016; Piotrowski et al. 2018; Lier et al. 2018). For example, the European Commission in its report uses ten sectors and the major indicators applied include turnover, value-added, and jobs. Table 3 and Tables A.2 in Appendix 2 show the numbers reported for 2008 to 2015.

Table 2 also indicates which sectors are considered as part of the bioeconomy in BioMonitor. However, the project focuses in detail on bio-based production. For that reason, two groups of sectors are distinguished: On the one side the sectors that BioMonitor will focus its improvements (data, methods, and models) on, which are the manufacturing sectors (C10 – 17, C19 – 22, C31, and D35); On the other side the sectors (e.g. A01 – 03, F41 & 42, G46) for which exisiting databases and methods will be reviewed and used with less focus on improving data, methods, and models.

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Table 2: Sectors of the bioeconomy included in previous studies and in the BioMonitor project

NACE		Fumagalli and Trenti(2014)	SAT-BBE (2015)	Efken et al. (2016)	European Commission (2018a)	Piotrowski et al. (2018)	Ronzon et al. (2017)	BioMonitor project
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 of 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	✓	✓	✓	✓	✓✓
C22	Manufacture of rubber and plastic products	X	✓	X	✓	✓	✓	✓✓
C2365	Manufacture of fibre cement	X	X	X	X	X	X	✓✓
C31	Manufacture of furniture	X	✓	X	✓	✓	✓	✓✓
C7211	Research and experimental development on biotechnology	X	X	X	X	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 of motor vehicles and motorcycles	X	X	✓	X	X	X	✓
G47	Retail trade, except of 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	✓
R9104	Botanical and zoological gardens and nature reserves activities	X	X	X	X	X	X	✓
	✓ = Included, ✓✓ = Focus							

Statistics and methods measuring the contribution of the bioeconomy to reaching the global societal objectives are relatively well developed for its traditional sectors and products like food,

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feed, pulp & paper, and bioenergy chains (Lier et al., 2018). For example, according to Ronzon and M'Barek (2018), the EU-28 bioeconomy was responsible for 18 million full-time jobs, generated €2.3 trillion of turnover, and contributed to a value added of €620 billion in 2015. In relation to the whole EU economy, the bioeconomy made up 8.2% of the labour force and 4.2% of GDP (Ronzon and M'Barek, 2018). Over the period 2008 to 2015 most sectors of the EU bioeconomy had a positive average annual growth rate with bio-based electricity at 7.5% being the frontrunner (Table 3). Bio-based textiles (-0.59%) and Forestry (-0.08%) are the only sectors with a slightly negative average annual growth rate.

Total private investment in potential bio-based industries like chemicals and plastics, pharmaceuticals, paper and paper products, forest-based products, textile, biofuels and bioenergy amounted to €1.1 billion during 2014 and 2015 (Piotrowski et al., 2016). This is spread among 56 projects, of which 11 are related to lignocellulosic based, 38 to forestry based, 3 to agricultural crops based, and 4 to organic waste-based value chains.

Table 3: Value added in the bioeconomy by sectors in EU-28. Source: European Commission (2018)

NACE	**Value added (in million €)**								
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Average Annual growth rate**
Agriculture	206292	203191	211774	213281	213792	217469	224345	233408	1.80%
Food, beverage and tobacco	168160	144496	160257	169384	171212	180041	173826	173597	0.74%
Wood products and furniture	50591	48091	52470	52960	50864	50032	52772	56314	1.67%
Bio-based textiles	50467	41223	44288	44685	42742	42161	44029	47165	-0.59%
Paper	40651	36983	41245	42231	41877	41246	43412	45590	1.83%
Forestry	29327	23815	26426	27508	26554	27155	28467	28341	-0.08%
Bio-based chemicals, pharmaceuticals, plastics and rubber (excl. biofuels)	20365	17275	19290	22704	21489	22563	24340	23834	2.80%
Fishing and Aquaculture	5954	6026	6512	6638	6313	6113	6655	6957	2.36%
Liquid biofuels	2449	2286	2808	3310	2529	2682	2796	3138	4.72%
Bio-based electricity	1598	1773	2111	2347	2105	2341	2725	2560	7.50%

4.2.2 Service sector

The service sectors (G46 and G47) are seen as subsectors of the bioeconomy (table 2). A major problem of monitoring these service sectors is the status of the data base, which have more data gaps than those for primary production and manufacturing (Efken et al. 2016). For services 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. Efken et al. 2016 use estimates from different market research companies to calculate the share of turnover for G46 (wholesale trade), G47 (retail trade),

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I55 (accommodation) and I56 (food and beverage service activities) for Germany. 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.

BioMonitor efforts will consider the approach for the service sector by Efken et al. 2016 for the whole EU, where it is feasible for monitoring the development, but it will not develop or improve methodologies and indicators for this sector. In WP3 we consider if the data from the MFM is suitable enough to be used for monitoring.

4.2.3 Circular economy

Similar to the bioeconomy, the circular economy is a cross-sectoral concept covering a broader spectrum of subjects. This leads to comparable issues with respect to monitoring. Arguably, it is an even bigger challenge to find a broadly accepted and precise definition for the circular economy than for the bioeconomy. It is applied in various ways, depending on the specific interests of the stakeholders (Mayer et al., 2019).

The circular economy considers biotic (renewable) and abiotic (non-renewable) natural resources (PBL, 2018). The aim is to reduce the use of abiotic resources by promoting long life, reuse, refurbishment, remanufacturing, and recycling of products and materials and achieve sustainable use of biotic resources. Biomass is the main biotic resource and limited in its availability. The bioeconomy as provider has to ensure that biomass is produced sustainably and used in a circular way.

The circular economy also requires substitution of non-renewable natural resources with biomass wherever possible. The bioeconomy is therefore essential for the progress of the circular economy. The other way around, the bioeconomy needs to make use of strategies from the circular economy to ensure its circularity. Monitoring the bioeconomy and circular economy therefore goes hand in hand.

Measuring the circular economy in general is well developed with respect to economic indicators, but in most cases they lack the link with material flows (Cingiz and Wesseler, 2019). As a result, it is difficult to quantify the contribution of the circular economy to changes in greenhouse gas emissions, nutrient flows, and air emissions. A further challenge is to measure the rate of recycling, reusing, remanufacturing, downcycling, cascading use of materials, because these cannot be derived from the national accounting systems. Monitoring of the circular economy so far is done mostly on micro- and meso-level, looking at individual products, substances, or industrial symbiosis (Mayer et al., 2019). On that level, there are difficulties with regard to the measurement of circularity already. For example, Rahla et al. (2019) find inter alia the plethora of definitions, assessing sustainability vs. circularity and unrelated, obsolete, and arbitrary indicators as obstacles for the assessment of circular buildings.

However, an economy-wide monitoring approach is required to capture system-wide effects such as displacement or rebound effects (Geyer et al., 2016). Bioeconomy has an important role to play in ecological loop closing. To achieve this, biomass production and discharge have to maintain the regenerative capacities of ecosystems. To monitor this, the currently available data is not sufficient

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(Mayer et al., 2019). The quality of waste statistics is questionable according to Mayer et al. 2019; it varies among EU MSs in completeness of the waste flows. Furthermore, an official concordance between material flow accounts and waste statistics would be valuable for monitoring.

The first steps for an economy-wide monitoring have been undertaken by several actors (Table 4). Eurostat (2019) provides a monitoring framework on EU level for the circular economy with 15 indicators for the dimensions (i) Production and consumption; (ii) Waste Management; (iii) Secondary raw materials; (iiii) Competitiveness and innovation. The Monitoring and Statistics Directorate (SOeS) (2017) presents seven key indicators to measure and monitor the circularity of the French economy. The PBL Netherlands Environmental Assessment Agency (2018) has proposed a monitoring framework to assess the plans of the Dutch government for a transition to a circular economy. They present a range of indicators, some already measurable some not, to measure the transition process and its effects.

In conclusion, the bioeconomy and circular economy are closely connected, as is their indicators to be monitored. The BioMonitor monitoring framework has to measure the circularity of the bioeconomy and to evaluate if synergies between both concepts are utilised. Furthermore, the progress of the bioeconomy is essential in achieving a transition towards a circular economy in the EU. Table 4 summarizes the indicators of some main Circular Economy monitoring frameworks.

Table 4: Circular Economy monitoring framework and their indicators

Origin	Indicators
SOeS[8]	Domestic Material Consumption per capita
	Resource Productivity
	Ecolabel holders
	Number of industrial and territorial ecology projects
	Car-sharing frequency rates
	Waste quantities
	Household spending on maintenance and repair
	Quantities of waste sent to landfill over time
	Use of secondary raw materials
	Employment in the circular economy
PBL	Resource use, direct ($DMI_{resource}$)
	Resource use, chian ($RMI_{resource}$)
	Resource consumption chain (RMC)
	Land use, direct
	Water extraction, direct
	CO2 emissions, direct
	CO2 consumption footprint

[8] The Monitoring and Statistics Directorate (SOeS): 10 Key Indicators for Monitoring the Circular Economy 2017 Edition

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	Economic growth (CE part)
	Employment (CE part)
	Added value recycling industry
	Self-sufficiency resources
	Dutch economy (GDP)
	Employment in the Netherlands
	Material use, direct (DMI)
	Waste production
	Reduce (R2): material productivity
	Reduce (R2): waste production per kilogram of product produced
	Recycling (R8): cyclical use rate
	Recycling (R8): reuse waste
	Recycling (R8): value-based recycling index
	Renewable energy
Eurostat	EU self-sufficiency for raw materials
	Generation of municipal waste per capita
	Generation of waste excluding major mineral wastes per GDP unit
	Generation of waste excluding major mineral wastes per domestic material consumption
	Recycling rate of municipal waste
	Recycling rate of all waste excluding major mineral waste
	Recycling rate of packaging waste by type of packaging
	Recycling rate of e-waste
	Recycling of biowaste
	Recovery rate of construction and demolition waste
	Contribution of recycled materials to raw materials demand- End-of-life recycling input rates
	Circular material use rate
	Trade in recyclable raw materials
	Private investments, jobs and gross value added related to circular economy sectors
	Patents related to recycling and secondary raw materials

4.2.4 Ecosystem Services

The concept of ecosystem services was popularized by the Millennium Ecosystem Assessment in the early 2000s and defined as "[...] the benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005, p. 3). Four ecosystem services can be distinguished, namely provisioning ecosystems, such as the production of food and water; regulating ecosystems, such as the control of climate and disease; supporting ecosystems, such as nutrient cycles and crop pollination; and cultural ecosystems, such as spiritual and recreational benefits. With a growing world population, the environmental impacts are becoming more apparent, leading to a deterioration of air and water quality, overfishing of oceans, deforestation, etc. It is clear that ecosystem services play a role and compete with other sectors in getting access to sustainable processes and biomass products. The society is aware that ecosystem services are limited as well as threatened by human activities (SAT-BBE, 2015b). Therefore, ecosystem services are an important concept to measure the benefits of

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society from ecosystems (TEEB, 2010). They are also covered by the Commission's definition of the bioeconomy (Section 2.1).

The large-scale monitoring of ecosystem services in a comprehensive and precise manner is a complex and resource-intensive task. Several national ecosystem services assessments, such as the United Kingdom National Ecosystem Assessment, the Spanish NEA, or the New Zealand assessment, were commenced following the Millennium Ecosystem Assessment in 2005. The current information on these national ecosystem services assessment is biased towards supply-related aspects of ecosystem services flows. On the other hand, less information on social behaviour, use, demand and governance is available (Geijzendorffer et al., 2017). The BioMonitor project, with its focus on bio-based production, is not in a position to make a significant contribution to fill this gap. However, the BioMonitor statistics and modelling framework can be used as important part of a systematic monitoring system for ecosystem services. For example, our framework can provide spatially-explicit information on primary biomass production and potentially available quantity of biomass.

We acknowledge the importance of a systematic monitoring of ecosystem services, however it is beyond the scope of this project.

4.3 Products

In the BioMonitor project we follow the EU Statistical classification of products by activity (CPA), which is linked to NACE. In principle, the selection of economic activities according to the NACE classification system already determines the products that are included in the monitoring of the bioeconomy. The official European statistical system is integrated and manufactured products are subordinately linked to economic activities using the NACE code. For example, the inclusion of C10 (Manufacture of food) implies the inclusion of products according to the PRODCOM list such as "Frozen meat, of goats" or "Fats of poultry". PRODCOM uses a product classification system which consists of 8-digit codes that are further breakdowns of the CPA list, in that the first six digits are identical to the CPA codes. Furthermore, there are correspondence tables between PRODCOM codes used for the EU production statistics and the CN (Combined Nomenclature), which is the classification used by the EU for foreign trade custom tariffs and statistics (Eurostat 2008).

For the traditional fully bio-based sectors, the list of products is already sufficiently covered by the selection of NACE sectors. However, with the hybrid sectors this task has to be done on a lower level and for each product following the Classification of Products by Activity (CPA). This is exemplified in work undertaken by the nova-Institute on bio-based shares in the manufacture of chemicals and chemical products (Piotrowski, Carus and Carrez, 2018). For the BioMonitor project, the results of their work can be used and further extended. Furthermore, it is in the scope of the project to promote and support the introduction of new PRODCOM codes for bio-based chemical products. In 2016, three dedicated codes for bio-based products have been introduced to the CN and PRODCOM classification system: bio-based lubricants, succinic acid and 1-4 butanediol Table 5(Table 5). Notwithstanding, there is actually a multitude of chemical products already in CN/PRODCOM which can be identified as being bio-based by their name (e.g. fatty acids, sorbitol, glycerine).

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Table 5 – New codes for bio-based products in the CN/PRODCOM classification system

Product name	CN code	PRODCOM Code
Lubricants having a bio-based carbon content of at least 25 % by mass and which are biodegradable at a level of at least 60 %	34.03.19.20	20.59.41.59
Butane-1,4-diol or tetramethylene glycol (1,4-butanediol) having a bio-based carbon content of 100 % by mass	29.05.39.26	20.14.23.38
Ethane-1,2-dicarboxylic acid or butanedioic acid (succinic acid) having a bio-based carbon content of 100 % by mass	29.17.19.20	20.14.33.82

Source: Eurostat 2017

The list of products from PRODCOM is also an important input to material flow accounts. Statistics Netherlands (CBS) compiled a Material Flow Monitor (MFM) for the Netherlands based on a set of statistics, like PRODCOM, business statistics, economic and environmental accounts. The MFM consists of 2 tables that provide figures on 1) the supply (incl. imports) and 2) the use of products (400) by sectors (130) and final consumption (domestic and export). The tables integrate different type of statistics (among which also statistics on trade, solid waste, extraction and CO2 emissions) and are fully balanced (supply = use). After being extended with more bio-based product and sectors detail this MFM is considered as an interesting tool for monitoring specific sustainability aspects of the bioeconomy. However, availability of data in other countries may be a challenge.

One of the objectives of BioMonitor is to identify and select bio-based products (already on the market or new) that should get an own code in the statistics in order to safeguard its monitoring in the future. This will be part of WP3.

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Value chains

From the *advances in horizontal and vertical integration* (Section 3), it follows that the whole value chain of a sector and product has to be considered to capture sustainability aspects of the bioeconomy. Figure 6 shows the complete value chain of a single bio-based products pillar, Polyhydroxyalkanoates (PHAs). PHAs are biodegradable polymers, which can be used to substitute petrochemical polymers currently used in applications such as coatings and packaging (Christóbal et al., 2016).
To measure the environmental, social and economic impacts of the bioeconomy, all stages have to be taken into account and data from all stages is needed. A first step is the development of input-

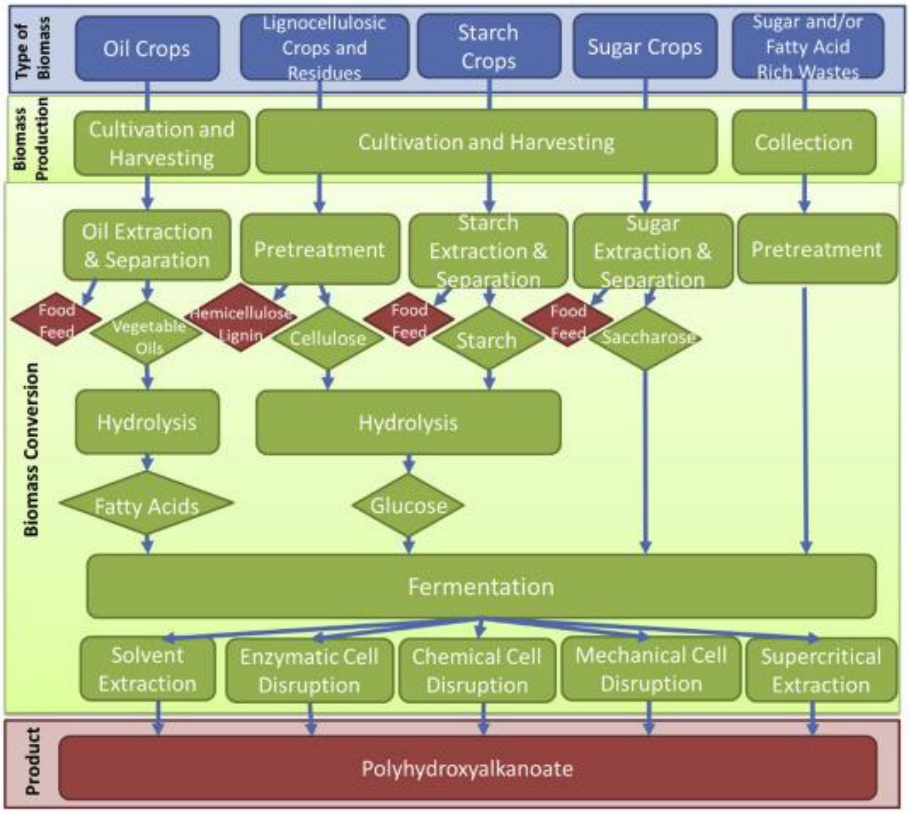

Figure 6: Flowchart of the polyhydroxyalkanoates production process.
Source: Christóbal et al. (2016)

output matrices for the sectors and sub-sectors mentioned above. This allows to identify the shares that different sectors contribute and related interlinkages. This is also relevant to identify the bio-based content of products along the supply chain at the aggregate level as well as the degree of circularity. The European Standardization Institute (CEN) created Technical Committee 411 that develops standards for bio-based products covering horizontal aspects[9].

In principle, value chains are directly linked with monetary supply and use tables, input-output (I-O) statistics. as well as the Material Flow Monitor. Material Flow Accounting and I-O provide

[9] More information is available at: http://www.biobasedeconomy.eu/centc-411-bio-based-products/

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information about changes over time and space, but information on bio-based content is missing so far. Furthermore, as bio-based products and the bioeconomy are integrated in the statistics in the future, they will provide – information about the cascading effects of product usage and their contribution to a circular economy. Information about the use of by-products in combination with the regionality of production will allow identifying the degree of circularity in production.

One of the important challenges for the development of the bioeconomy is the creation of value, which leads to creation of jobs and promotes regional development. This often requires the development of new supply chains and business models. BioMonitor will not develop new supply chains and business models but will monitor those being used. The flagship programmes under the BBI-JU provide a source for different supply chains and business models. This includes the use of labels and certification standards as these provide additional information about supply chains, the growth of the bioeconomy and in particular specific bio-based products such as different kinds of bio-plastics.

4.4 Space

The geographical scope of the bioeconomy is global, but in the BioMonitor project the focus lies on the European Union. The project aims to establish a data and modelling framework for the EU and its Member States (MS). Within the MS level, the collection of data at regional level is also essential as it is where the bioeconomy needs to be investigated and promoted. The deployment of local bioeconomies is one of the action points of the EU Bioeconomy Strategy Update (European Commission, 2018). Therefore, the development of the bioeconomy should be traceable at regional level, which several stakeholders explicitly demanded during a BioMonitor Stakeholder Workshop in October 2018. The stakeholders indicated that data at sub-national (Nomenclature of Territorial Units for Statistics (NUTS) levels 2 or 3) level based on the NUTS 2016 classification by the EU would be very valuable. Subsequently, I-O tables at NUTS2 or NUTS3 level could be used for showing developments.

In addition, international trade in biological resources also matters. The international trade with countries outside the EU will be modelled to a limited extent, similar to existing models such as MAGNET. The international trade within the EU for agriculture, fishery and forestry products and processed products of these primary sectors is well captured by EUROSTAT. In fact, all products (if they are in CPA) are in trade statistics including chemical inputs and outputs. However there not always is a distinction between bio-based or fossil based. It is challenging to introduce this split in the statistics, which requires the development of methods, in order to be able to monitor the progress of the bioeconomy.

4.5 Timeframe

A milestone in the development of the bioeconomy was the Cologne Paper in 2007 that introduced the bioeconomy concept to a wider audience (European Commission, 2007). The Cologne Paper resulted from a high-level workshop with experts from research organizations and companies covering different sectors. It was a deliberate effort to promote the concept in Europe (Birner,

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2018). After the Cologne Paper, the development of the bioeconomy picked up the pace. Considering some time prior to the policy development will allow for identifying potential structural breaks in the time series of indicators and their measures. Hence, the starting point for the time scope of the BioMonitor project is set on the year 2000.

Like each innovation, the take up of the bioeconomy takes time. The development path of a biocluster takes up to 30 years (see Figure 7). There are uncertainties around the driving forces of the bioeconomy (Section 3.1 – 3.4). To understand the influence of uncertainties on the development of the bioeconomy in the future, the BioMonitor project uses a toolkit with models that can deal with scenario analysis. Models capture specific aspects of the bioeconomy market (e.g. focus on forestry, agro-food, bio-based materials, overall economy) and in general can make projections for these markets up to the year 2030 or 2050.

Development stages of innovation process

Most of the new bio-based products are still in their early stages of development. Therefore, policies and strategies with respect to bring these products to the market must follow a mid to long-term innovation process in order to become effective (Negro et al, 2012). Studies on technological change in agriculture consider at least five years before technical or policy changes will be observable in the data and such changes may take even longer in the forestry sector (Alston, 2018).

New businesses follow an innovation process, i.e. from ideas to pilots to business cases to new industries, a financing process, i.e. from public funding to private investments; and a network process, i.e. from early enthusiasts to a strong network of regional actors). The group of actors involved in the innovation process, i.e. entrepreneurs, R&D worker, policymakers, investors and other stakeholders, must have the same ambitions, have to know each other and must be willing collaborate and align their efforts on innovation and business development. This means that solid business innovation ecosystem has to be established in order to foster national and regional development of the bioeconomy; this is often referred to in the literature as the quadruple helix model (Carayannis et al., 2010). Nevertheless, the spontaneous development of the bioeconomy will be important and it is important that enough space is provided that those spontaneous events can happen (Wesseler and von Braun, 2017).

The development of Bioclusters, a geographical concentration of actors in vertical and horizontal relationships in the bioeconomy, passes through three main stages, typically taking 15 years to reach the age of mature production (Figure 7). As it takes considerable time from the launch of a new bio-based value chain/business model until it has achieved a mature stage, 3 stages can be distinguished (BERST, 2015)[10]:

- *Initial stage and take off:* Introducing the bioeconomy in the regional planning agenda and creating the policy, socio-economic and R&D landscape for its establishment and operation.

[10] Inspired by Rostow's stages of growth.

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- *Drive to maturity:* The first competitive bioeconomy products are sold at the market. The cluster grows with the setup of new companies, cluster infrastructure (e.g., incubator, training centre) has been established, and the cluster attracts both private and public funding.
- *Age of mature production:* The cluster produces competitive bioeconomy products at an extensive scale. TRL 8

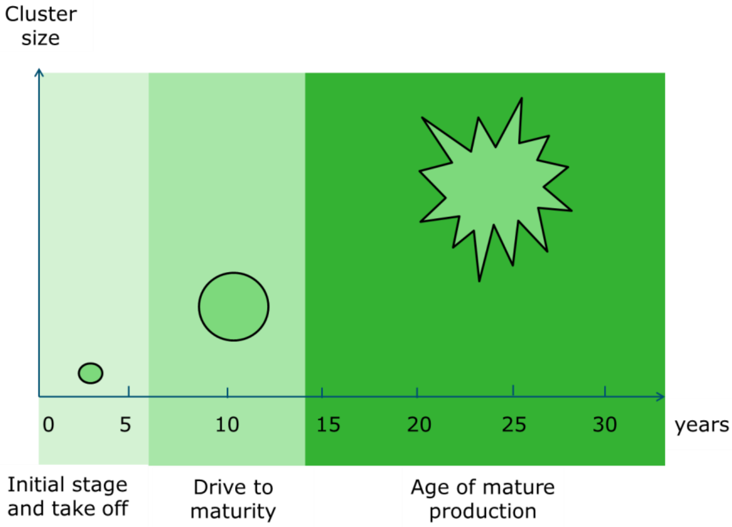

Figure 7: The development path of a biocluster. Source: BERST (2015)

The duration of each of these stages differs from region to region; according to estimates of PwC (2011)[11] the duration of the initial stage and take off is about five years, that of the drive to maturity 5-10 years and that of the age of mature production 10-20 years. Within each stage, they analyze the interaction of the key assets. It is notable that bioclusters studies were considered to be either in the initial stage or in the drive-to-maturity stage. No bioclusters were considered to be fully mature although, in some regions, elements of clusters had reached the mature state of development (e.g. the IAR cluster in France, the Straubing cluster in Germany, BioBased Delta in the Netherlands).

[11] PriceWaterhouseCoopers (2011), Regional Biotechnology: Establishing a methodology and performance indicators for assessing bioclusters and relevant to the KBBE area; Brussels; via website: http://ec.europa.eu/research/bioeconomyl/pdf/regional-biotech-report.pdf

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5. Monitoring and measuring the bioeconomy

5.1 Stocktaking of monitoring systems

There are efforts of monitoring the EU bioeconomy and single country bioeconomies outside of the BioMonitor project. The European Commission provides their monitoring results for the EU bioeconomy and single MS online at https://datam.jrc.ec.europa.eu. Several countries (Argentina, Australia, Germany, Malaysia, the Netherlands, South Africa, and the United States) are measuring the contribution of bioeconomy to their overall economy or country objectives (FAO, 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 (RVO, 2013). But so far there is, except for the efforts by the EC, no common approach to monitor and measure the bioeconomy across EU states, and therefore it is not possible to compare the results between countries (FAO, 2018).

For the monitoring of physical investments they need to be differentiated by the kind and amount of biomass to be 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 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 kind of investments with patent applications being an important indicator in this respect. The OECD patent data can be used as a source to identify the number of patents filled over time and space in the EU differentiated by the different sectors of the bioeconomy. Again, the sectors identified in section 4.2 provide guidance for the classifying 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 and measuring and benchmarking. This has been followed by a number of previous projects (e.g. European Commission (2018a), Efken et al. (2016)). We improve on previous work by developing a monitoring framework that will be more spatially explicit and with more detail on bio-based production. The EU monitors the developments of the bioeconomy and provides annual reports (European Commission, 2018b). They already provide useful 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. The regional data on bio-based production will be extended by adding the public and private sector investments made, the filing of patents, and the monitoring of policies including those related to certification of products. This has been a need expressed by stakeholders. But this is also important from a conceptual perspective and provides links with other international activities such as at OECD, FAO or the World Economic Forum.

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Monitoring and measuring non-traditional sectors that capture implications on the environment such as changes in greenhouse gas emissions or changes in biodiversity are more difficult to monitor and assess and specific methods will be developed based on approaches used by project partners. One important indicator is the impact of bio-based products on the emission of greenhouse gases.

5.2 Indicators

To monitor and measure the development of the bioeconomy a set of indicators is required. An indicator is a quantitative or qualitative measure, which must be measurable, comparable, replicable, and responsive to fluctuations in the development.

We use two types of indicators, on the one hand those monitoring the evolution (ex-post) of the bioeconomy and on the other hand those evaluating the impact of the bioeconomy on for example targets (often ex-ante and provided as model outcomes). Indicators can help policy-makers to understand and interpret the results of the BioMonitor framework and to formulate clear targets for their policies. They can also reveal trade-offs between different policy measures that have to be taken into account. They should not only be useful for policy-makers, but as well for a diverse range of stakeholders (e.g. decision-makers in industry, researchers or NGOs).

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 a consultation with stakeholders (in October 2018), it was decided to restrict the number of Main Indicators to 25. These are able to provide a condensed view on respectively the transition of the bioeconomy, and on the realised (ex-post) and potential (ex-ante) effects of the EU bioeconomy. The Main Indicators can be disaggregated to Sub-Indicators, which can offer a more detailed view.

The selection of indicators to be used in the BioMonitor project is partly based on consultation with stakeholders, and partly based on a literature review. Firstly, we organized a stakeholder workshop to receive feedback from a wide range of stakeholders on their interest and demand for bioeconomy indicators.[12] The stakeholders provided important input 1) on the type of aspects that should be considered, i.e. socio-economic, environmental, biodiversity, food security; and 2) the geographic and timeframe that should be covered (see chapter 4). Secondly, we relied to a large extent on indicators already identified by Lier et al. (2018). The authors identified the most suitable indicators for assessing and monitoring the progress of a bioeconomy at national level using a survey among ministries and research organizations responsible for national bioeconomy strategies, policies and/or related initiatives. In addition to these consultation, we enriched the potential set of indicators for the BioMonitor project by considering recent literature and other bioeconomy monitoring initiatives (e.g. SAT-BBE, BERST) and indicators that are already being collected (e.g. by EUROSTAT, Forest Europe, European Environment Agency). For example, Eurostat has 100 indicators related to the SDGs and ten indicators under development for the circular bioeconomy and in particular on biomass flows.

[12] For more information on the workshop see Piotrowski et al. (2019).

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When defining a set of indicators, we considered a number of criteria. First, BioMonitor has especially a focus on the bio-based industry. For that reason, the indicator selection was guided by choosing indicators for which a plausible link with bio-based production could be assumed (i.e. there should be a measurable effect). 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, the focus of the BioMonitor project is on the economic dimension of sustainability in particular. 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. MISTICS). Table 6 presents the selected main and sub-indicators in the BioMonitor project.

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Table 6: List of indicators by societal objective for the BioMonitor Project

Main Indicator	Sub Indicator	Possible measuring approach and suggested metric(s)[13]	Sustainability dimension	Aggregation
1. Food and nutrition security				
Availability of food			Society	Economy wide
	Domestic food production	Food Commodities derived from bio-based ingredients (crops, meat, milk products, sih products, wild capture); Share of domestic agriculture production for food production in total available agricultural production (%)		
	Food imports			
	Food quality	Consumption in Kcal per capita per day from novel food products (e.g. veggie burger - impossible food, bug-burgers, clean meat)		
	Development of new food products	New food products registered under novel food in different member state (number)		
Access to food			Society	
	Regional food purchasing power	Regional income per capita in linked with share of bio-based industries divided by Consumer Price Index for food		Regional
	Income per worker in bio-based industries	Real income per worker in bio-based industries divided by Consumer Price Index for food		Sub-sector
Utilization			Society	Sub-sector
	Improved food nutrition by better packaging material	change in shelf life and nutritional values		
	Nutritional value	change in nutritional value by food ingredients derived from bio-based products		
	Meat- or plant-based protein ratio	Land demand for the protein component of the diet or for the whole diet compared to total land available (ratio)		
Stability			Society	Sub-sector
	Import dependency ratio	For novel food and others; Grubel–Lloyd index for food items		
	Value of food imports over total merchandise exports	For novel food and others		
	Price volatility of food	For novel food and others; Derived from CPI basked for food		
2. Sustainable natural resource management				
Sustainability threshold levels for Bioeconomy Technologies		*Maximum Incremental Social Tolerable Irreversible Costs (MISTICs) as a measure for resilience (see appendix 1)* *Reversibel and Irreversible Benefits and Costs*	Environment	Sub-sector
Biodiversity		*Rényi entropy;* *Mean Species Abundance*	Environment	Regional
	Forest biodiversity	*Volume of standing deadwood and of lying deadwood on forest and other wooded land (m3/ha);* *Number of threatened forest species, classified according to IUCN Red List categories in relation to total number of forest species.'*		
	Agrobiodiversity	*Number of livestock breeds;* *Number of crop varieties;* *Registered seeds for crops used for biomass production for industry;* *Number of threatened species in agricultural ecosystems, classified according to IUCN Red List categories in relation to total number of species in agricultural ecosystems* *Mean Species Abundance on agricultural lands*		
	Aquatic biodiversity	*Number of threatened species in water ecosystems, classified according to IUCN Red List categories in relation to total number of species in water ecosystems.*		

[13] The specific approach and metric used to quantify an indicator is subject to change over the course of the BioMonitor project.

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Main Indicator	Sub Indicator	Possible measuring approach and suggested metric(s)[13]	Sustainability dimension	Aggregation
Land cover		*Share of total area, %*	Environment	Economy wide
	Forest area	*Ha in relation to total ha*		
	Agricultural area	*Ha in relation to total ha*		
	Surface water	*Ha in relation to total ha*		
Primary Biomass production		*kg;* *% for bio-based industry*	Economy	Economy wide
	Forests	*kg;* *% for bio-based industry*		
	Agriculture	*kg;* *% for bio-based industry*		
	Fisheries	*kg;* *% for bio-based industry*		
Sustainable resource use			Environment	Economy wide
	Sustainable forestry	*Ratio of annual increment and fellings in forests (%); Ratio of fellings and estimated maximum sustainable level of cuttings in forests (%)*		
	Sustainable agriculture	*Nitrogen use for agricultural production (kg/ha); Phosphorus use for agricultural production (kg/ha); Soil erosion (tonnes/ha); Ammonia, NOx and SOx emissions (ktonnes); Environmental impact quotient*		
3. Dependence on non-renewable resources				
Bio-energy replacing non-renewable energy		*MJ;* *Share of bioenergy in total energy use (%)*	Environment	Economy wide
	Biofuels	*MJ;* *Share of biofules in total energy fuel use (%)*		
	Biogas	*MJ;* *Share of biogas total gas use (%)*		
Bio-material replacing non-renewable resources			Environment	Sub-sector
	Wood-based constructions	*m3;* *Share in total construction, %*		
	Bio-based textiles	*Tonnes;* *Share in total consumption, %*		
	Bio-based furniture	*Tonnes;* *Share in total consumption, %*		
	Bio-based plastics	*tonnes of oil equivalent;* *Share in total consumption, %*		
Biomass self-sufficiency rate		*potentially available quantity of biomass*	Economy	Economy wide
	Agricultural biomass	*potentially available quantity of biomass (tonnes)*		
	Forestry biomass	*potentially available quantity of biomass (tonnes)*		
	Aquatic biomass	*potentially available quantity of biomass (tonnes)*		
	Biomass from waste	*potentially available quantity of biomass (tonnes)*		
Material use efficiency			Economy	Sub-sector
	Material and waste recycling and recovery rates	*%*		
	Recycling rate of bio-based products	*%*		
	Circularity indicator	*To be developed in Task 3.7*		
Certified bio-based products		*Number;* *Bio-based content, %;* *Consumption*	Environment	Sub-sector
4. Mitigating and adapting to climate change				
Greenhouse gas emissions		*CO2 eq. tonnes*	Environment	Emission-sector

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Main Indicator	Sub Indicator	Possible measuring approach and suggested metric(s)[13]	Sustainability dimension	Aggregation
	Forest carbon emissions and removals	*Gross emissions and removals in CO2 eq. tonnes*		
	Agricultural GHG emissions and removals	*CO2 eq. tonnes per feedstock and land use type*		
	Energy and industrial carbon emissions and removals	*CO2 eq. tonnes*		
Climate footprint		*Using EXIOBASE*	Environment	Sub-sector
Climate change adaptation		*%*	Environment	Economy wide
	Diversity of tree species	*Area of forest and other wooded land, classified by number of tree species occurring*		
	Climate resistant crops in agriculture	*climate resistant crops as percentage of total agricultural*		
5. Employment and economic competitiveness				
Innovation			Economy	Sub-sector
	Innovation hurdle for different industries	*Additional benefits needed in percentage for each euro invested; total amount of fixed (irreversible) investment needed.*	Economy	Sub-sector
	Number of patents submitted and sub-field	*Number and shares per subfield*	Economy	Sub-field
Investments		*EUR per year and sub-sector*		
	Private sector bioeconomy investments: R&D and others	*EUR per year and sub-sector*	Economy	Sub-sector
	Public sector bioeconomy investments/supports/subsidies. R&D and others	*EUR per year and sub-sector*	Economy	Sub-sector
	Establishment and Expansion of biorefineries	*Number; capacity; production; products (including by-products); resources use; people employed*	Economy	Sub-sector
	Internet of Things in bioeconomy	*Mobile Coverage (2G, 2.5G, 3G, 4G, 5G);* *Internet connection speed*	Economy	Economy
Value Added of the bioeconomy sectors		*EUR per year and sub-sector, Share of total economy*	Economy	Sub-sector
	Turnover of bioeconomy sectors	*Turnover in bioeconomy sector as share in total turnover of the sector (bio-based and fossilbased)*		
	Value-added of bioeconomy sectors	*Value added in bioeconomy sector as share in total value added of the sector (bio-based and fossilbased)*		
	Share of SMEs on value added	Numbers, Euros		
	Share of high-tech companies	Numbers, value added		
Comparative advantage			Economy	Sub-sector
	Terms-of-Trade of biomass	*ratio between the index of export prices and the index of import prices per biomass type*		
	Revealed comparative advantage of biomass	Belassa index: (export of biomass in MS(i)/total exports in MS(i))/(export of biomass in EU28 minus NL/total exports in EU28 minus NL)		
Production and consumption of non-food and feed bio-based products		*kind, quantity, turn-over*	Economy	Sub-sector
Import and export of bioeconomy raw materials and products		*EUR per year and sub-sector and country*	Economy	Sub-sector
Employment			Society	Sub-sector
	People employed in the bioeconomy sectors	*FTEs in bioeconomy sector as share in total FTEs of the sector (bio-based and fossilbased)*		
	Quality of employment	*Labour Productivity (FTE/value added) in bioeconomy sector*		
Policies				
	Policy-induced investment hurdles	*Additional reversible benefits needed to compensate for regulations expressed in percentage; fixed regulatory compliance costs.*	Economy	Sub-sector
	Regulatory measures	*GHG emission target;*	Economy	Sub-sector

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Main Indicator	Sub Indicator	Possible measuring approach and suggested metric(s)[13]	Sustainability dimension	Aggregation
		Renewable energy shares target; *Bio-based share target*		
	Training and education policies	*Qualitative*	Economy	Economy wide
	Country level strategies	*Qualitatively*	Economy	Economy wide

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6. Conclusions

The purpose of this deliverable is to develop a conceptual analysis framework for quantifying and analysing the development of the EU bioeconomy. In order to operationalise this framework later in the project, we have determined the general scope and developed a set of indicators.

Our scope uses the European Commission's (2018a) definition as a basis for monitoring and measuring the bioeconomy framework. Therefore, our scope includes a wide range of sectors as part of the bioeconomy, including biomass producing activities, conventional biomass processing activities, and novel biomass processing activities. However, for our improvements of the methodologies for establishing a monitoring and measuring framework we concentrate on bio-based production. In the corresponding sub-sectors of the bioeconomy existing data collecting methodologies and available data sets are lacking the most. Furthermore, we expect at least some of these sectors to undergo a rapid and volatile development. A good monitoring system is therefore essential for public policy-makers to assess and steer these developments and for industrial stakeholders to manage their investment plans.

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 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.

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 for this is the recycling of bio-based products. Our set of indicators is designed to be able measure the degree of circularity of the bioeconomy as well as its contribution to the Sustainable Development Goals.

However, there are limits to a monitoring framework considering the complexity of the task and the available resources. 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. It is not in the scope of the BioMonitor project to systematically collect data, but to develop methodologies for collecting new and improving existing data.

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In BioMonitor, the monitoring and measuring framework outlined in this deliverable will be implemented. This will enable the quantification of the bioeconomy and its economic, environmental, and social impacts in the EU and its Member States in more detail.

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Appendix 1

Sustainable development and the Bioeconomy

The EU Bioeconomy Strategy Update stresses "[...] the need to achieve sustainability constitutes a strong incentive to modernise our industries and to reinforce Europe's position in a highly competitive global economy, thus **ensuring the prosperity of its citizens**. (European Commission, 2018a, p.4)" Hence, the overall objective is to ensure the "prosperity" of EU citizens. This raises the questions of how to measure "prosperity of its citizens" which is directly linked with sustainable development (EU, 2018; OECD, 2009; von Braun, 2018). Having a good understanding of how to measure sustainable development is important for deriving indicators for measuring the development of the bioeocnomy to ensure that such indicators can be directly linked with sustainable development. Sustainability measurement is a topic both acute and controversial. The literature includes several suggestions for measuring sustainability: examples include the Ecological Footprint (EF) (Wackernagel and Rees, 1996), the UN's Human Development Index (HDI) (Sagar and Najam, 1998), Bhutan's Gross National Happiness Index (Mukherji and Sengupta, 2004). Much discussed are the World Bank's measure of *genuine savings* and Arrow, Dasgupta and Mäler's approach on *inclusive wealth* and *genuine investment*. Both concepts serve as a measure of sustainable economic development over time. To compute the genuine savings rate, resource depletion and environmental degradation are subtracted from traditional net savings, while investment in human capital is added (Hamilton, 2000; Hamilton and Clemens, 1998). The concept of inclusive wealth and genuine investment is 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.). 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) present a theoretical framework for analysing the sustainability of economic development over time, using the concepts of intergenerational well-being $V(t)$ and genuine investment $\Delta V(t) = dV/dt$ – amongst others. The authors define intergenerational well-being 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. then define sustainability as non-declining intergenerational well-being over time $\Delta V(t) \geq 0$ and genuine investment is defined as a measure of changes in well-being $\Delta V(t)$, i.e. 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 well-being $V(t)$ 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 investments' 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 and Fisher, 1974; Dixit and Pindyck, 1994). As an illustration of the first point, sustainability related investment projects mostly aim at long-term goals such as reduction of greenhouse gas emissions, enhanced production and resource use efficiency, preservation of non-renewable capital assets etc., which are inherently uncertain. As an illustration of the second point: the conversion of virgin forests for other uses inevitably entails losses of biological diversity. Also, the expansion into arable land area or coastal areas protecting mangrove forests to provide for a growing population causes irreversible and uncertain change. Finally, 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 change may increase the production efficiency and the markets for bio-based products might improve over time. All three features of investments: uncertainty, irreversibility and flexibility need to be considered for the assessment of genuine investment.

Genuine Investment under Uncertainty, Irreversibility, and Flexibility

Investment might generally be defined as "[…] the act of incurring an immediate cost in the expectation of future rewards." (Dixit and Pindyck, 1994, p. 3) The notion of genuine investment is based on Arrows' et al. contribution on *Sustainability and the measurement of wealth.* For explanatory purposes, the author's formal concepts of both well-being and genuine investment will be briefly illustrated in the following.

Arrow et al. define intergenerational well-being $V(t)$ as the discounted flow of current and future generations' utilities U. Utility is derived through consumption C of the economy's stock of capital assets K, including manufactured goods, services provided by nature, health services, and many more. The term $U(C(s))$ is interpreted as felicity at date s. Accordingly, δ denotes the felicity discount rate. Continuous time is denoted by s and t, $s \geq t$ (underlying assumptions: closed economy, infinite time horizon, constant population, changes in time-varying factors are exogenous). Consequently, intergenerational well-being $V(t)$ is formalized thus (Arrow, p. 322):

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

Arrow et al. (2012) then define sustainability as non-declining intergenerational well-being over time $dV/dt \geq 0$. Genuine investment is determined as a measure of changes in well-being, where well-being is a function of its determinants, namely the economy's stock of capital assets K and time t: $V(t) = V(\underline{K}(t), t)$. $r(t)$ $(= \partial V/\partial t)$ denotes the shadow price of time at t, and $p_i(t)$ $(\equiv \partial V(t)/\partial K_i(t)$, for all i) the shadow price of the i^{th} capital asset at time t. By letting $Q_i(t)$ equal $\Delta K_i(t)/\Delta t$, genuine investment is (Arrow, 2012, p. 325):

$$\Delta V(t) = r(t)\Delta t + \sum p_i(t)Q_i(t)\,\Delta t \quad (2)$$

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Equation (2) shows that the changes in an economy's set of capital assets weighted at shadow prices, including time, equals the change in well-being. Looking at Equation (2) in more detail, it shows that positive genuine investment increases well-being, while negative genuine investment decreases intergenerational well-being. Hence, positive genuine investment facilitates sustainable development.

The costs of irreversible change are implicitly captured in Arrows' genuine investment model by using shadow prices in Equation (2). What Equation (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 well-being over time ($dV/dt \geq 0$) helps to formally solve the described dilemma. Considering that future benefits and costs of genuine investment always will 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.

A stochastic process fulfilling the property of non-negativity through time is the Geometric Brownian Motion (GBM). By letting intergenerational well-being $\hat{V}$ follow a GBM, uncertainty over future intergenerational well-being 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 (2) can be reformulated thus:

$$d\hat{V}(t) = \alpha\big(\hat{V}(t), t\big)dt + \sigma\hat{V}(t)dz \tag{3}$$

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 (3) is continuous in time but not differentiable, we need to make use of Ito's Lemma and obtain as a result (Oksendal, 2018):

$$\hat{V}_t = \hat{V}_0 exp\left(\left(\alpha - \frac{\sigma^2}{2}\right)t + \sigma dz\right) \tag{4}$$

Thus far, it has been explained how uncertainty about the future level of intergenerational well-being $\hat{V}$ is included in our model of genuine investment. In the following, we will analyze how flexibility of investment timing might be taken account of. McDonald and Siegel (1986) develop the basic model of the value of waiting to invest under uncertainty, irreversibility, and flexibility known as real option model. Scatasta et al. (2006) are one amongst many researchers who suggest making use of the real option model, i.e. to compare 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.

Under the assumption that $\hat{V}$ 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,

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and β_1 and β_2 are the two roots of the fundamental quadratic: $\beta_1 = \frac{1}{2} - \frac{\delta-\alpha}{\sigma^2} + \sqrt{\left[\frac{\delta-\alpha}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2\delta}{\sigma^2}} > 1$, and $\beta_2 = \frac{1}{2} - \frac{\delta-\alpha}{\sigma^2} - \sqrt{\left[\frac{\delta-\alpha}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2\delta}{\sigma^2}} < 0$ (δ denotes the exogenous discount rate):

$$F(\hat{V}) = A_1\hat{V}^{\beta_1} + A_2\hat{V}^{\beta_2} \tag{5a}$$

Equation (5) is subject to the following boundary conditions, where *I* represents the sunk or irreversible costs of a genuine investment project (Dixit and Pindyck, 1994, p. 141):

$$F(0) = 0 \tag{6}$$
$$F(\hat{V}^*) = \hat{V}^* - I \tag{7}$$
$$F'(\hat{V}^*) = 1 \tag{8}$$

The first condition implies that $A_2 = 0$, so that Equation (5) can be reduced to:

$$F(\hat{V}) = A\hat{V}^{\beta_1} \tag{5b}$$

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 7) is the value-matching condition, and the last condition (Equation 8) is the smooth-pasting condition (Dixit & Pindyck, 1994; Pindyck, 2000; Pindyck, 2002).

We now 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 account of 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 effects of irreversibility. Accordingly, the sustainability criterion shall be non-declining intergenerational well-being under irreversibility as well as uncertainty and flexibility over time $d\hat{Y}/dt \geq 0$, with

$$\hat{Y}(t) = F(\hat{V}_t, I) \tag{9}$$

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 (9) into Equations (7) and (8). Through rearranging we get (McDonald and Siegel, 1986):

$$A = \frac{(\hat{V}^* - I)}{(\hat{V}^*)^{\beta_1}} = \frac{(\beta_1 - 1)^{\beta_1 - 1}}{[(\beta_1)^{\beta_1} I^{\beta_1 - 1}]} \tag{10}$$

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$$\hat{V}^* = \frac{\beta_1}{\beta_1 - 1} I \tag{11}$$

and we have for the value of investment:

$$F(V, I) = \begin{cases} A\hat{V}^{\beta_1} \hat{V} \leq \hat{V}^* \\ \hat{V} - I > \hat{V}^* \end{cases} \tag{12}$$

The result in equation (11) indicates an investment will be sustainable, if the actual value of the project V is larger than $\hat{V}^*$. 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 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 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 12). Not considering these values underestimates the economic value of the bioeconomy. The problem is that estimating these option values will be difficult as they cannot directly be observed, but indicators can be derived. They include the number of patent applications over time and public and private sector investments in the bioeconomy. Third, the size of the threshold value $\hat{V}^*$ is larger than one. A lower threshold level, ceteris paribus, increases incentives for immediate investment while a higher one decreases them. The size of the threshold level not only depends market data such as prices and investment costs but also on policies. Costs for research and development and market approval are an outcome of regulatory policies and many of those can be considered to be a fixed cost and increase I. Policies that reduce these fixed costs can have a positive effect on private sector incentives to in invest and to develop the market for bio-based products. Hence, monitoring the regulatory policy environment becomes even more important.

Equation 11 can be rearranged providing:

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

The last equation 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) call this threshold value the Maximum Incremental Social Tolerable Irreversible Costs ($MISTICs$). It 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 bigger than its irreversible costs so as to be

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considered beneficial (Wesseler et al., 2007). Also, since $\hat{V}_t$ is expected to increase over time, the $MISTICs$ will increase as well.

The MISTIC can be used as an indicator for the resilience of the 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 will be the larger the potential negative environmental impacts can be and the more resilient 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 resilience.

Further, project may not only provide irreversible environmental costs but also irreversible environmental benefits and in the end the net effect will be of relevance. Within the monitoring the bioeconomy the contribution to reduce irreversible environmental damages will be important as well. Also the differentiation between irreversible and reversible benefits and costs will be important.

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Appendix 2

Table A.1: Turnover in the bioeconomy by sectors in EU-28. Source: European Commission (2018)

NACE	Turnover (in million €)								
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Average Annual growth rate**
Agriculture	1039227	972142	1003131	1065059	1107064	1129912	1136953	1153006	1.56%
Food, beverage and tobacco	356958	315142	341027	371804	382517	392255	386091	380164	1.12%
Wood products and furniture	182633	149537	167719	178145	174259	178562	180589	186616	0.72%
Bio-based textiles	175557	149450	159464	166306	161689	159436	166448	177044	0.39%
Paper	155624	144544	156949	162006	156633	159060	166212	173724	1.70%
Forestry	112095	90882	97218	103174	99743	100784	104380	103497	-0.77%
Bio-based chemicals, pharmaceuticals, plastics and rubber (excl. biofuels)	38679	34238	38634	42661	42211	46234	43857	50101	4.19%
Fishing and Aquaculture	13647	11640	13808	17479	14142	13185	14759	12194	-0.11%
Liquid biofuels	9849	10064	10385	10955	10864	10723	11998	11650	2.53%
Bio-based electricity	5026	5401	6447	7386	8504	9391	9164	10831	11.82%

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Table A.2: Employment in the bioeconomy by sectors in EU-28. Source: European Commission (2018)

NACE	People employed (in # of people)								
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**Average Annual growth rate**
Agriculture	10774500	10640700	10521600	10122800	10003600	9673400	9557900	9227200	-2.18%
Food, beverage and tobacco	4733938	4548484	4636186	4599708	4569029	4543345	4533116	4544452	-0.57%
Wood products and furniture	1735270	1552493	1524606	1503916	1445282	1398841	1407395	1407184	-2.89%
Bio-based textiles	1317001	1138003	1079128	1066168	1033515	1012435	1017736	999235	-3.77%
Paper	706814	660407	649146	655459	649128	638945	639088	643104	-1.31%
Forestry	538100	504000	493300	491900	516300	517800	525800	539000	0.08%
Bio-based chemicals, pharmaceuticals, plastics and rubber (excl. biofuels)	445829	417367	417243	426513	419949	421303	424396	444967	0.02%
Fishing and Aquaculture	245359	249179	249533	239702	228864	220035	222867	222392	-1.36%
Liquid biofuels	33458	35313	35112	35296	26699	26968	28995	26271	-2.82%
Bio-based electricity	6275	7695	8971	9113	10324	11751	12029	13844	12.19%

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Table A.3: Inclusion of sectors (economic activities) in countries according to NACE classification. Source: Lier et al. (2018)

NACE	Country	DK	EE	FI	FR	DE	IT	LV	NL	NO	SK	ES	TR	UK	
A01	Crop and animal production, hunting and related service activities	++	++	++	++	++	++	++	++	++	++	++	++	++	Fully bio-based sectors
A01	Hunting	+	++	++	-	+	-	++	-	++	+	-	++	-	
A02	Forestry and logging	++	++	++	++	++	++	++	++	++	++	++	++	++	
A03	Fishing	++	++	++	++	++	++	++	+	++	+	++	++	+	
A03	Aquaculture	++	++	++	++	++	++	++	+	++	+	++	++	++	
C10	Manufacture of food	++	++	++	++	++	++	++	++	++	++	++	++	++	
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	++	++	++	++	++	++	++	+	++	+	++	+	++	
C17	Manufacture of paper and paper products	++	++	++	++	++	++	-	++	++	+	++	++	+	
C20	Manufacture of chemicals and chemical products	+	+	++	+	+	++	+	+	+	+	++	++	++	Hybrid Sectors
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	+	+	++	+	+	++	+	++	+	+	+	++	++	
F41	Construction of buildings	+	-	++	+	+	-	+	-	+	-	+	++	+	
H	Transportation and storage	+	++	++	++	+	-	-	+	+	-	++	-	+	
R	Nature tourism, green care and recreation	+	++	++	+	-	-	+	-	+	-	+	++	-	
D	Renewable Energy	+	++	++	+	+	++	++	++	++	++	++	++	+	
E	Water purification and distribution	+	-	++	+	+	+	++	++	++	+	+	++	+	

"-" = not included; "+" = partly included; "++" = included

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Appendix 3

Bioeconomy definitions

2018 Updated EU Bioeconomy Strategy

"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. To be successful, the European bioeconomy needs to have sustainability and circularity at its heart. This will drive the renewal of our industries, the modernisation of our primary production systems, the protection of the environment and will enhance biodiversity."

2012 EU Bioeconomy Strategy

"The bioeconomy encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries. Its sectors have a strong innovation potential due to their use of a wide range of sciences (life sciences, agronomy, ecology, food science and social sciences), enabling and industrial technologies (biotechnology, nanotechnology, information and communication technologies (ICT), and engineering), and local and tacit knowledge."

Food and Agriculture Organization of the United Nations

"Bioeconomy can be defined as the knowledge-based production and utilization of biological resources, biological processes and principles to sustainably provide goods and services across all economic sectors. It involves three elements:

1. The use of renewable biomass and efficient bioprocesses to achieve a sustainable production; The use of enabling and converging technologies, including biotechnology;
2. Integration across applications such as agriculture, health and industry."

OECD

"The OECD Project supposes the bioeconomy to be the aggregate set of economic operations in a society that use the latent value incumbent in biological products and processes to capture new growth and welfare benefits for citizens and nations. These benefits are manifest in product markets through productivity gains (agriculture, health), enhancement effects (health, nutrition) and substitution effects (environmental and industrial uses as well as energy); additional benefits derive from more eco-efficient and sustainable use of natural resources to provide goods and services to an ever growing global population."

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“Bioeconomy… • … refers to the set of economic activities relating to the invention, development, production and use of biological products and processes. [It] is a world where biotechnology contributes to a significant share of economic output (OECD, 2009).”

European Commission (others)

“The strategy defined the bioeconomy as "the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products as well as bio-energy".
This includes agriculture, forestry, fisheries, food, pulp and paper production, as well as parts of chemical, biotechnological and energy industries”

“Bioeconomy… • … encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries (EC, 2012)“

Global Bioeconomy Summit

“Bioeconomy is defined in different ways around the world. We have not aimed for a unified definition but note that an understanding of ‘bioeconomy as the knowledge-based production and utilization of biological resources, innovative biological processes and principles to sustainably provide goods and services across all economic sectors’ is shared by many.”

“bioeconomy is 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”

The White House

“Bioeconomy… • … is based on the use of research and innovation in the biological sciences to create economic activity and public benefit (US National Bio-economy Blueprint, The White House Administration 2012)”

Bioökonomierat

“Bioeconomy is defined as the production and utilization of biological resources (including knowledge) to provide products, processes and services in all sectors of trade and industry within the framework of a sustainable economy.”

European Bioeconomy Alliance

“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

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on optimal use of resources and the production of primary raw materials from renewably sourced feedstock”

The Biomass Research and Development Board

“The bioeconomy is defined as the global industrial transition of sustainably utilizing renewable aquatic and terrestrial biomass resources in energy, intermediate and final products for economic, environmental, social, and national security benefits”

Swedish Research Council for Environment, Agricultural Science and Spatial Planning

“We have defined a bio-based economy (bioeconomy) as an economy based on: • Sustainable production of biomass to enable a growth in use within a number of different social sectors. The objective is to reduce climate effects and the use of fossil-based raw materials. • Increased added value for biomass materials, together with a reduction in energy consumption, and recovery of nutrients and energy from the end products. The objective is to optimize the value and contribution of ecosystem services to the economy.”

Bioeconomy Strategic Working Group

“The Bioeconomy encompasses the sustainable production of renewable resources from land and water and their subsequent conversion into food, feed, fiber, bio-based products and bio-energy as well as the related public goods.”

Royal Society of Biology

“The bioeconomy is the economic opportunity of using biology to help solve challenges we face in agriculture, energy, health and more, which has the potential to deliver economic, environmental and social benefits to the UK. The bioeconomy includes all economic activity derived from bio-based products and processes. These have the potential to contribute to sustainable and resource-efficient solutions to the challenges we face in food, chemicals, materials, energy production, health and environmental protection.”

The Chairs of the UK’s three bioscience leadership councils, comprising the Industrial biotechnology leadership forum (IBLF), the Agri-technology leadership council (ATLC) and the Synthetic biology leadership council (SBLC)

“All economic activity derived from bio-based products and processes which contributes to sustainable and resource-efficient solutions to the challenges we face in food, chemicals, materials, energy production, health and environmental protection.”

Bioeconomy in Italy

“The Italian Bioeconomy means integrating the sustain- able production of renewable biological resources and converting these resources and waste streams into value added products such as food, feed, bio-based products and bio-energy.”

Government of Ireland

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"The bioeconomy emphasises the importance of using an increasing list of renewable biological resources and in some cases what would have hitherto been discarded as residues or waste and putting them to more productive uses. It extends across sectors - from farming and the agri-food businesses, marine and maritime industries, forestry, novel protein production, water and waste management, energy suppliers, and biopharmaceutical products. Ireland has many promising pioneers in all of these sectors."

France Bioeconomy Strategy

"It is the photosynthesis economy, and more generally the living world economy. It encompasses all biomass production and processing activities, whether in forestry, farming or aquaculture, directed at the production of food, feed, biobased products and renewable energy."

Government of Spain

"The bioeconomy is, in the framework of this strategy, the set of economic activities that obtain products and services, generating economic value, making efficient and sustainable use of resources of biological origin as fundamental elements"

South Africa Bioeconomy Strategy

"The term "Bio-economy" encompasses biotechnological activities and processes that translate into economic outputs, particularly those with industrial application. Within the South African context these may include, but are not limited to, technological and non-technological exploitation of natural resources such as animals, plant biodiversity, micro-organisms and minerals to improve human health, address food security and subsequently contribute to economic growth and improved quality of life."

Ministry of Agroindustry, Argentina

"sustainable production of goods and services through the use or transformation of biological resources"

Australian government

"the sustainable production and conversion of biomass for a range of food, health, fibre and other industrial products as well as energy"

German National bioeconomy strategy

"the knowledge-based production and utilization of renewable resources in order to provide products, processes and services in all economic sectors, within the context of a future-capable economic system"

Malaysia

"the sustainable production of renewable biological resources and their conversion into food, feed, chemicals, energy, and healthcare and wellness products via innovative and efficient technologies"

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