Monitoring Socio-Economic Aspects of The European Bioeconomy

From Output-Based Quantification to Screening for Policy Coherence

Tévécia B. Ronzon

Propositions

1. The labour productivity of the bioeconomy in the new EU Member States is lower than in the old Member States.
   (this thesis)

2. More biomass use due to the bioeconomy transition contradicts SDG 8 on economic decoupling.
   (this thesis)

3. Developing more opportunities for science and policymakers to interact strengthens evidence-based policy processes.

4. Using Artificial Intelligence in research accelerates the research process.

5. The engagement of all actors of the food supply chain is necessary for the transformation of agricultural production systems.

6. Food consumption needs to change to alleviate Western countries' climate and health footprints.

Propositions belonging to the thesis, entitled

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From Output-Based Quantification to Screening for Policy Coherence

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“La paciencia es la madre de la ciencia”

Acknowledgments

As I conclude my PhD dissertation, I feel that I have achieved a significant milestone in my life, the result of years of perseverance and scientific questioning. My PhD journey started late in my professional career, and I had to balance it with many other professional, family and personal commitments. Staying in the course has been made possible thanks to the support and encouragement of many people, to whom I express my gratitude.

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Glossary of terms

CAP	Common Agriculture Policy
DMC	Domestic Material Consumption
ESA	European System of Accounts
EU	European Union
EUR	Euros
FAO	UN Food and Agriculture Organisation
FILM	Fundamental Industry Level Model
GDP	Gross Domestic Product
IOT	Input-Output Table
JRC	Joint Research Center
OECD	Organisation for Economic Co-operation and Development
NACE	French acronym for Statistical Classification of Economic Activities in the European Community
SAM	Social Accounting Matrix
SNA	System of National Accounts
SUT	Supply-Use Table
TFP	Total Factor Productivity
US	United States of America

Chapter 1. General introduction

1.1 Varying bioeconomy visions

Several visions of the bioeconomy co-exist today in the policy, scientific and stakeholders arenas. They are distinguished based on different perceptions of the nature of the relationship between the economy and biological resources. This plurality of visions has been combined in different ways in the bioeconomy policy initiatives that have emerged and developed over the last ten years. As a result, the task of establishing consensual and harmonised monitoring measures is challenging, whilst concerns have also been raised regarding the coherence of said policy initiatives with sustainability objectives.

The "bio-ecology" vision of the bioeconomy

The very first notion of the bioeconomy - at the time termed "bioeconomics" - dates back to the beginning of the twentieth century and refers to the interplay between the economy and the physical world (Birner 2018; Barañano et al. 2021). It was popularised by Georgescu-Roegen (1970, 1975) who introduced a notion of biological boundaries to the economy, considering that according to the law of Enthropy (applied to economics) the quantity of available energy in a system tends to decrease. That vision is contemporaneously coined the "bio-ecology" vision (Bugge et al. 2016; Dalia D'Amato et al. 2020; Neill et al. 2020; Ramcilovic-Suominen et al. 2022). It has generated much debate about the coherence of current bioeconomy policies and the existence of a safe operating space in which the bioeconomy can develop while preserving ecosystems and the services they provide (Bennich et al. 2017; Priefer et al. 2017; Gawel et al. 2019; Heimann 2019; Liobikiene et al. 2019; Barañano et al. 2021; Bringezu et al. 2021).

The "bio-technology" vision of the bioeconomy

In the 1990s, the term "bioeconomy" emerged as a reference to a "biologisation" of the economy (Birner 2018). Advances in genomics and biotechnologies opened new industrial and commercial avenues and brought the expectation that the outcomes of life sciences will generate growth and even potentially push environmental limits further. This green growth perspective gradually permeated into mainstream policy thinking, taking the form of a concrete strategic plan within the Organisation for Economic Co-operation and Development's (OECD) seminal publication "The Bioeconomy to 2030. Designing a Policy Agenda" in 2009 (OECD 2009). The vision of a bioeconomy centred on the application of biotechnologies to strategic sectors (i.e., primary production, health and industry) has been further coined the "bio-technology" vision (Bugge et al. 2016; Hausknost et al. 2017; Meyer 2017; Priefer et al. 2017; Dalia D'Amato et al. 2020; Ramcilovic-Suominen et al. 2022). It has materialised in bioeconomy strategy of the United States of America (US) among others (The White House 2012) . That vision has been criticised mainly for being over-optimistic regarding the capacity of biotechnologies to meet the ecological, environmental and social challenges ahead (Bennich et al. 2017; Priefer et al. 2017; Gawel et al. 2019).

The "bio-resource" vision of the bioeconomy

Deviating from the OECD or "bio-technology" vision, the bioeconomy narrative has reached Canada and the European Union (EU) under the labels "bio-based economy" and "knowledge-based bioeconomy." The two labels put the focus on the substitution of fossil-based resources with bio-based resources, both for energy and material use. The knowledge-based bioeconomy emphasises the role of high-technology industries in transit towards a bio-based economy (Birner 2018). These narratives adopt a "bio-resource" vision in which biological resources are the building blocks of the substitution pathway (Bugge et al. 2016; Dalia D'Amato et al. 2020; Ramcilovic-Suominen et al. 2022). That vision has raised concerns about the quantity of biomass required in the context of a growing bioeconomy and about the potential impacts of an intensified biomass production and/or importation (Bennich et al. 2017; Priefer et al. 2017; Gawel et al. 2019; Heimann 2019).

From bioeconomy visions to strategies, monitoring and evaluation

Since the 2010's the three bioeconomy visions have been integrated and combined to different degrees within the growing number of bioeconomy policy initiatives adopted over the world. In 2018, 49 countries had a policy strategy related to bioeconomy development (German Bioeconomy Council, 2018), with varying focus depending on each country's strategic objectives. Some of them have also had the chance to revise their bioeconomy strategy and redefine their vision by integrating criticism or new strategic orientations (e.g., EU, Germany, Finland).

Thus, the bioeconomy concept takes varying forms even amongst the different EU Member States and continues to evolve. On the one hand, this poses different scientific questions related to the monitoring of the bioeconomy, whilst on the other hand it complicates the evaluation of the multiple sustainability concerns associated with each vision. How to measure a non-stabilised concept and how to assess its impacts holistically are the key questions of this thesis.

1.2 Problem statement: A sound monitoring and evaluation of the EU bioeconomy hampered by a lack of harmonised measures and (industrial) data

The concomitant development of bioeconomy strategies and the rising questioning of the sustainable character of the bioeconomy urged the development of measurement, monitoring and evaluation methods that could be applied to the bioeconomy and strengthen policy coherence.

Progress towards harmonised bioeconomy monitoring framework but quantification hurdles

In the last decade, several monitoring initiatives have been launched, be it at the national or multi-country level (Bracco et al. 2018; German Bioeconomy Council 2018), and scientific studies have flourished (e.g., Meesters et al. (2013); Kwant et al. (2014); Philippidis et al. (2014b); Ronzon et al. (2018); Egenolf et al. (2019); Heimann (2019)). Proposals have also emerged to link the monitoring of the bioeconomy with the compulsory Sustainable Development Goals (SDG) reporting by individual countries (El-Chichakli et al. 2016; Calicioglu et al. 2021). However, the variations in bioeconomy visions and objectives monitored, indicators and quantitative methods used, make cross-country comparisons difficult (Bracco et al. 2018).

The lack of comprehensive monitoring and analytical framework became a concern for scientists (Wesseler et al. 2017; Lier et al. 2018; Schütte 2018; D'Adamo et al. 2020b) and international organisations such as the UN Food and Agriculture Organisation (FAO) and the EU. Therefore, in 2016 the FAO engaged with representatives of many countries to develop a conceptual bioeconomy monitoring framework (Bracco et al. 2019) and associated implementation guidelines (Bogdanski et al. 2021). In the meanwhile, the action plan of the updated EU bioeconomy strategy tasked the European Commission's Joint Research Centre (JRC) to elaborate 'an EU-wide, internationally coherent monitoring system to track economic, social and environmental progress towards a circular and sustainable bioeconomy,' which has been done following the FAO's framework and guidelines and in collaboration with several Commission Services, EU Member States and stakeholders (Giuntoli et al. 2020; Robert et al. 2020a). These international initiatives are important steps towards a better understanding of bioeconomy dynamics. However, the quantification of many indicators identified for the monitoring framework remains challenging or absent.

Quantification methodologies for socio-economic indicators of the bioeconomy

Different methodologies have been proposed in the literature to inform about the economic dynamics and impacts of the bioeconomy. By filling existing data gaps, they directly serve the monitoring of the bioeconomy and provide data inputs for modelling studies. They are usually classified as "output-based," "input-based," life cycle assessments (LCAs) and modelling methodologies (Piotrowski et al. 2018; National Academies of Sciences 2020).

Output-based methodologies quantify the size of the bioeconomy (most often economic and employment size) by combining information from product- and industry-level statistics. The term “output” mainly refers to using production data from product-level statistics (Porc et al. 2020; Ronzon et al. 2020b).

Input-based methodologies quantify the (economic/employment/greenhouse gases) size of the bioeconomy from the proportion of biomass inputs into total inputs used by a given industry. The main data sources used are input-output tables (IOTs), supply-use tables (SUTs) or companies’ cost structure statistics (Efken et al. 2016; Kuosmanen et al. 2020; Cingiz et al. 2021). I present output- and input-based methodologies more extensively in Chapter 4.

LCA methodologies assess the impact of a given bio-based product all along its production and consumption chain. Different types of LCAs can be distinguished; they allow for the monitoring of a variety of economic, environmental and social indicators (Bracco et al. 2019).

Finally, the main modelling approach used for bioeconomy analysis is economy-wide computable general equilibrium (CGE) models. By modelling the functioning of the whole economic system, CGE models are well-suited to inform about cross-borders and cross-sectors effects of a given bioeconomy transition pathway. Even though CGE models were initially designed for economic analyses, the most recent versions also incorporate environmental and social parameters (Philippidis et al. 2020).

Quantification hurdles remain for the measuring, monitoring and evaluation of the European bioeconomy

At the European level, all the earlier approaches have been used by the JRC and its partners for tracking progress and feeding the European Knowledge Center for the Bioeconomy which hosts a Bioeconomy monitoring system (M'barek et al. 2014; Robert et al. 2020a; European Commission 2023). However, the database of these methodologies is heterogenous across bioeconomy sectors and bio-based products, leading to uneven monitoring and assessments of bioeconomy sectors or sustainability aspects.

The current international and European statistical systems have not yet been adapted to the relatively young bioeconomy policy concept (Wesseler et al. 2017; Ronzon et al. 2018; Kardung et al. 2021a). The traditional activities of the bioeconomy are reasonably well represented in the National Accounts and other industry-level and product-level statistics (i.e., agriculture, forestry, fishing and aquaculture, the manufacture of food, paper and wood), but official statistical systems fail to single out those bio-based activities that have a fossil-based counter-part (e.g., the manufacture of textiles, chemicals, pharmaceuticals, plastics and the production of bioenergies) or whose economic size is too small (e.g., the manufacture of bio-cement).

As a result, the lack of sectoral information seriously hampers the granularity and precision of bioeconomy monitoring. Moreover, traditional bioeconomy sectors tend to be over-represented in economic analyses and modelling compared to hybrid bio-based industries and bioeconomy services. The term 'hybrid' refers here to a mixed production of bio-based and fossil-based outputs by a given sector of activity. Ad hoc studies can be conducted to better inform a given bio-based sector (e.g., Spekreijse et al. 2019), but the results are not always replicable to all EU Member States or easily updatable over time. These drawbacks have motivated the funding of the BioMonitor project by the European Commission as part of the Horizon 2020 European research programme to fill data gaps regarding the bioeconomy industrial sectors in the EU. These knowledge gaps also constitute a central tenet of this thesis (see next section) which has been realised within both research frameworks of the JRC and the BioMonitor project.

1.3 Research objectives and research questions

As introduced in the previous sections, the development of the bioeconomy concept has raised significant policy attention and controversies. Therefore, sound data and analytical tools are crucial to guide policy developments towards efficient and sustainability-oriented measures. The intertwining of the bioeconomy and the broader economy hampers the understanding of the bioeconomy dynamics from official statistics and makes analyses difficult. This diagnostic is particularly acute concerning industry-level data and analyses. As a contribution to tackle that challenge, my thesis seeks to answer the overall research question "How to monitor the transition towards the bioeconomy across economic sectors in the EU and strengthen policy coherence?". To this end, it pursues three main research objectives (ROs).

RO1: Consolidate basic socio-economic indicators of employment, economic growth and labour productivity across all bioeconomy sectors to monitor the bioeconomy in the EU.

RO2: Better characterise the economic motors of the bioeconomy transition and the progresses made in the EU.

RO3: Derive policy recommendations for better policy targeting and coherence.

The thesis is organised following the classical research sequence of analysis (Chapters 2 and 3), methodological discussion (Chapter 4) and policy discussion (Chapter 5) based on four research questions (RQ) listed in Figure 1. The first two research questions relate to the monitoring of the primary and secondary (RQ1) and tertiary (RQ2) bioeconomy sectors and the advancement of EU Member States toward a bioeconomy transition. RQ3 discusses and evaluates the methodological approach that I have taken compared with other methodological options. Finally, RQ4 assesses the degree of policy coherence or incoherence of the EU bioeconomy strategy with the sustainability framework of the SDGs. Table 1 summarises the main insights expected from the research work, respective to the specific research questions investigated and the research objectives of the whole study.

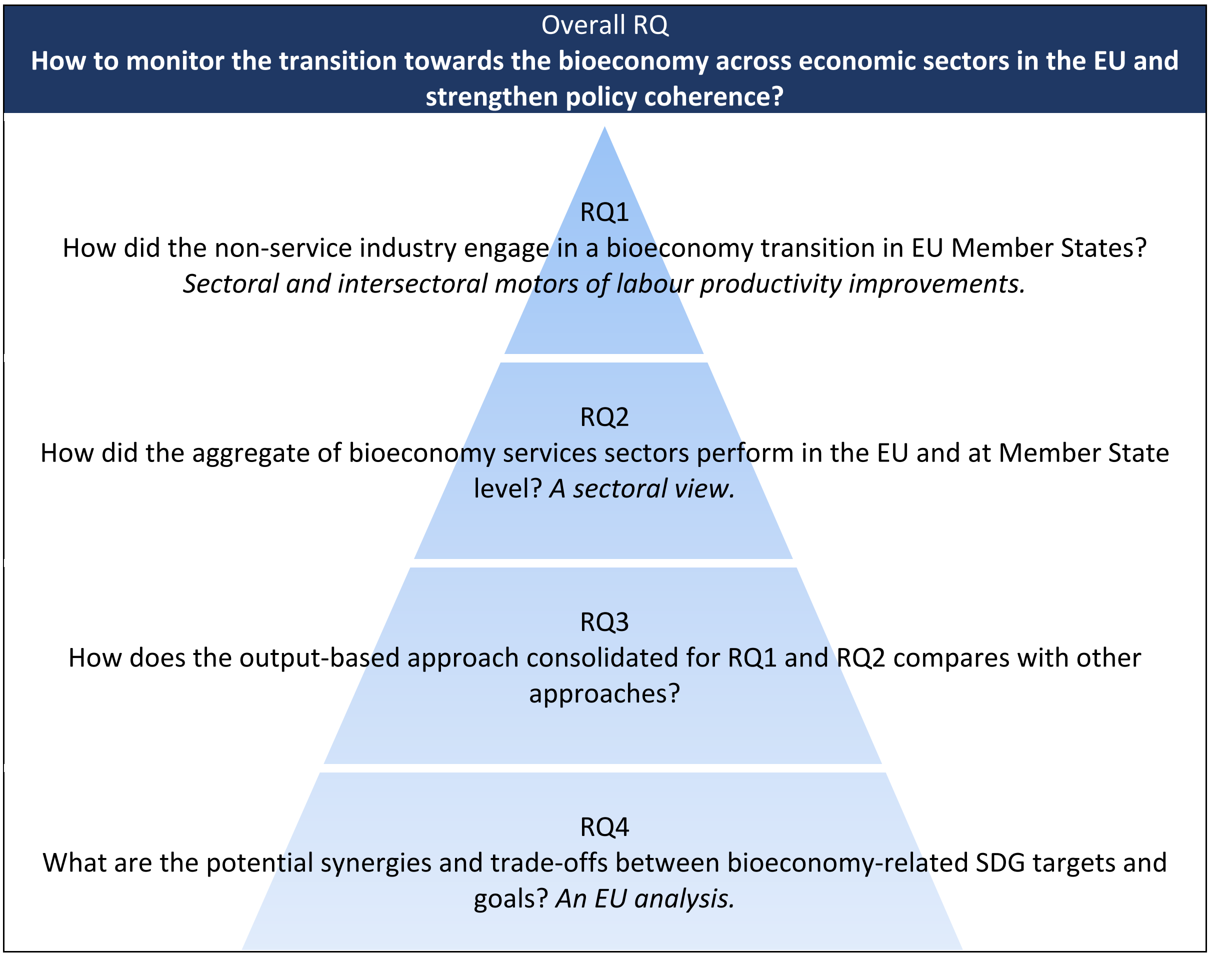

Figure 1. Structure of the PhD research.

Table 1. Expected insights from the investigation of the specific research questions relative to the research objectives of the study

Overall research question: **How to monitor the transition towards the bioeconomy across economic sectors in the EU and strengthen policy coherence?**

Research questions/Research objectives	RO1: **Consolidate basic indicators** of employment, economic growth and labour productivity for the monitoring of the EU bioeconomy.	RO2: **Better characterise** the economic motors of **bioeconomy transition** and the progresses made in the EU.	RO3: Derive **policy recommendations** for a better policy targeting and coherence.
RQ1: How did the **non-service industry** engage in a bioeconomy transition in EU Member States? *Sectoral and intersectoral motors of labour productivity improvements.*	Consolidation of indicators for the non-service bioeconomy at the sectoral and Member State level. Method: output-based approach.	Characterisation of within- and between- sectors effects on labour productivity at the Member State level. Method: Shift-share analysis.	Balancing public and private fundamentals to foster sectoral and structural progress towards the bioeconomy.
RQ2: How did the aggregate of **bioeconomy services** sectors performed in the EU and at Member State level? *A sectoral view.*	Consolidation of indicators for the service bioeconomy at the sectoral and Member State level. Method: output-based approach.	Characterisation of sectoral motors of economic growth and employment within bioeconomy services in the EU and Member States. Method: Descriptive analysis.	Addressing data gaps in industry-level European statistics. Addressing the East-West labour productivity divide in the non-service bioeconomy.
RQ3: How does the output-based approach consolidated for RQ1 and RQ2 **compares with other approaches**?	Clarification on 'value added' data concepts. Method: comparison and discussion of methodologies.	Synthesis of different 'value added' quantifications at the EU level. Method: comparison of methodologies.	Guidance on the mobilisation of scientific data related to the value added of the EU bioeconomy.
RQ4: What are the potential **synergies and trade-offs** between bioeconomy-related SDG targets and goals? *An EU analysis.*	Matching between the EU bioeconomy strategy and SDG indicators. Method: Text interpretation.	Identification of past hotspots of synergies and trade-offs amongst bioeconomy-related SDG targets and goals. Method: Ex-post Spearman correlation analysis.	Strengthening the coherence of EU bioeconomy initiatives and the SDGs regarding the agricultural and industrial models of development, and the decoupling from biomass resources.

RQ1: How did the non-service industry engage in a bioeconomy transition in EU Member States?

Following a sectoral approach, the nova-institute and the JRC have elaborated an output-based methodology and the JRC-Bioeconomics database for monitoring socio-economic indicators of bioeconomy sectors in the EU (Ronzon et al. 2017) from which they posited the existence of an EU transition trajectory characterised by increasing levels of sectoral diversification and labour productivity (Ronzon et al. 2018; Ronzon et al. 2020). Using the same database, D'Adamo et al. (2020a) computed an indicator of socio-economic performance of the bioeconomy and distinguished between three different but overlapping levels of bioeconomy transition. Moreover, EU regional statistical clusters with comparable bioeconomy sector structures have been obtained from social accounting matrices (SAMs) (Philippidis et al. 2014a; Fuentes-Saguar et al. 2017; Philippidis et al. 2018), although no clear conclusions are provided on the stage of the bioeconomy transition.

Considering the state-of-the-art of literature at the time of tackling RQ1, the novelty of the research was (i) to consolidate the JRC-Bioeconomics database to cover the whole non-service bioeconomy, and (ii) to analyse the sectoral and inter-sectoral sources of labour productivity growth in the bioeconomy.

The consolidation of the JRC-Bioeconomics database has been achieved by using new Eurostat data to investigate those sectors that were not covered but whose activity produces bio-based goods or energy (output-based approach). The analysis of the motors of bioeconomy growth builds on "shift-share" analysis that serves the understanding of the transition of a country from a development stage to another in economic transition studies (de Vries et al. 2015; Kuusk et al. 2017; Dobrzanski et al. 2019; Erumban et al. 2019; Moussir et al. 2020) and development economics (McMillan et al. 2017). Applied to the bioeconomy transition, the shift-share analysis measures the gains in labour productivity achieved over a certain period of time in individual bioeconomy sectors thanks to the modernisation of their processes (within-sector effect) and the impact of the reallocation of resources (in this case human resources) from one industry to another (between-sector effect). The between-sector effect can be attributed to the emergence of new bioeconomy sectors, or to the development of existing ones.

The research builds on two main hypotheses:

H1 – Both the modernisation of bio-based industries and the reallocation of employment resources amongst new and old industries characterise a bioeconomy transition.

H2 – Structural changes such as employment reallocation characterise more advanced transitional stages.

RQ2: How did the aggregate of bioeconomy services sectors perform in the EU and at Member State level?

The JRC-Bioeconomics database covers the activities of biomass production, bio-based manufacturing and bioenergy production (i.e., the non-service bioeconomy). This sector coverage was in line with the original EU Bioeconomy Strategy but became too restrictive in the wake of the revised (2018) strategy that included services within the scope of the bioeconomy (European Commission 2018b).

Unfortunately, the revised strategy does not provide a list of such bioeconomy services nor does the literature provide any consensual definition. The novelty of the research was (i) to provide a clear list and classification of bioeconomy services according to an output-based approach and (ii) to elaborate the first consolidated dataset on the value added and employment generated in those service sectors.

Regarding the method, a decision was made to adopt an output-based approach on the basis of the fact that it converges most closely to the European Commission's interpretation of a bioeconomy service activity. To ensure a consistent and comprehensive update of said activities over time and space, the European Commission's official Eurostat data is considered as the main source.

Descriptive analysis and comparisons are then performed to portray the development of EU and Member States bioeconomy services and compare them with the overall economy, the non-bioeconomy and the non-service bioeconomy. The derived indicator of apparent labour productivity, that is the value added generated per worker, is also calculated for the analysis.

The research builds on two main hypotheses (H):

H3 – Bioeconomy services significantly contribute to the overall bioeconomy value added and employment basis.

H4 – Some services dominate the aggregate of bioeconomy services in the EU.

RQ3: How does the output-based approach consolidated in chapters 2 and 3 compare with other approaches?

The analyses provided to answer RQ1 and RQ2 are all based on socio-economic indicators derived from implementing an output-based approach. However, other quantitative approaches have developed in recent years in the literature, leading to different estimations of value added, employment and greenhouse gases generated by the EU bioeconomy. As a consequence, a rigorous assessment of these different methodologies and the results they provide serves as a useful point of departure for cataloguing and assessing currently available approaches to monitoring bioeconomy activities.

If we restrict the discussion to those studies that provide quantitative results for the EU as a whole and present a common indicator for comparison, four quantitative approaches emerge: the "output-based," the "input-based," the "weighted input-output" and the "upstream and downstream" approaches (Kuosmanen et al. 2020; Cingiz et al. 2021b; Ronzon et al. 2022a, 2022b).

The research work conducted to answer RQ3 is very novel in the sense that it sheds light on the meaning of different data concepts that are all labelled the same way by the authors of the above-mentioned studies, that is "the EU28 bioeconomy value added." The discussion does not seek to favour any particular approach, but rather identify their complementarities.

Regarding methods, the discussion is based on the analysis and comparison of the equations employed across methodologies to clarify the definition of each data concept beyond the broad term of "bioeconomy value added." It then compares qualitative results while tracking the sources of quantitative differences across methodologies and pointing at the variety of bioeconomy aspects measured by them.

The research builds on the main hypothesis H5:

H5 – The data concept labelled as "EU bioeconomy value added" in all approaches takes different meanings in each of them.

RQ4: What are the potential synergies and trade-offs between bioeconomy-related SDG targets and goals?

Section 1.1 introduced various types of concerns associated with the different bioeconomy visions which have been emphasised further in the literature (Sodano 2013; Bennich et al. 2017; D. D'Amato et al. 2017; Priefer et al. 2017; Gawel et al. 2019; Heimann 2019). The shortcomings of the original bioeconomy strategy in 2012, were taken into account by the European Commission when devising the updated EU bioeconomy strategy (European Commission 2018b).

At that time, a corpus of literature was pointing at the existence of interlinkages between the internationally agreed SDGs whose identification and understanding would be supportive to more coherent and efficient policy making (Boas et al. 2016; Karnib 2017; Allen et al. 2018; Miola et al. 2019). No quantification of SDG synergies or trade-offs related with the implementation of a bioeconomy strategy was offered although it would bring evidence to the debate on the bioeconomy's sustainability.

The novelty of the research design to tackle RQ4 therefore lies in (i) the first-of-its-kind mapping between the EU Bioeconomy Strategy and the SDG goals and targets and (ii) applying a quantitative

SDG interlinkages assessment method to the bioeconomy topic. Regarding the methodological design, first a semantic match is proposed between the different actions of the EU Bioeconomy strategy's action plan and their corresponding SDGs and targets. Second, the official UN and EUROSTAT SDG indicators databases are screened for data availability at the Member State level and relevancy to the bioeconomy actions assessed. Third, possible trade-offs and synergies are investigated following the methodology elaborated by Pradhan et al. (2017). This methodology consists in running pair-wise Spearman's correlation tests on the selected indicators. It thus considers that the past development of bioeconomy-SDG indicators informs on possible synergies (desired correlation) and trade-offs (undesired correlation) among them and consequently among the actions they assess.

The research builds on two main hypotheses (H):

H6 – The policy measures listed in the action plan of the EU bioeconomy strategies are compatible with the achievement of a broad range of SDGs.

H7 – There are more synergies than trade-offs between bioeconomy-related SDG targets.

1.4 Outline of the thesis

The remainder of the thesis is organised around the four successive research questions (chapters 2 to 5). Chapter 6 concludes with the answers the thesis brings to the specific and overall research questions introduced here, as well as the main contributions of the thesis to the bioeconomy field of research and policy.

Chapter 2. Has the European Union entered a bioeconomy transition? Combining an output-based approach with a shift-share analysis[1]

Abstract

The bioeconomy is a collective of activities charged with the production of biologically renewable resources or 'biomass' (e.g., agriculture, forestry), its diverse application (e.g., food, textiles, construction, chemicals) and subsequent reuse (e.g., compositing, waste management). Since the European Union (EU) launched its bioeconomy strategy in 2012, further bioeconomy policy initiatives have proliferated at regional, national and pan-European levels. Moreover, the EU Green Deal announced in 2019 targets a transition toward a low-carbon sustainable model of growth, food and energy security, biodiversity and natural resource management, where it is envisaged that the bioeconomy will play a key role. Despite a paucity of available data, the surge in policy interest has triggered the need for evidence-based monitoring of bioeconomy sectors and the efficient tailoring of policy support. Thus, on a Member State basis for the period 2008-2017, we (i) adopt an 'output-based' approach to construct a panel data of performance indicators, and (ii) characterise the sources of growth and transitional stage of the bioeconomy. Results reveal that the bioeconomy has maintained its relative importance within the total EU27 economy. At the EU27 level, agriculture and the food industry have played a key role in driving a transition in the primary and industrial bioeconomy sectors due to their significant labour productivity-enhancing impact. Four Northern Member States exhibit a bioeconomy transition by modernising their bioeconomy activities and operating structural changes. Other Northern and Western EU Member States are still in the early stages of a transition, whilst in Eastern and Central Europe, such a transition remains elusive.

Keywords

Bioeconomy, value added, employment, productivity, structural change, transition, Europe

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

2.1 Introduction

The bioeconomy has emerged in the last decade as a new economic paradigm founded on the use and recycling of biological resources in place of fossil resources to help achieve multiple policy objectives relating to employment generation and growth, climate neutrality, food security, energy security, biodiversity and natural resource management (Wesseler et al. 2017). To achieve these goals, governments have implemented bioeconomy strategies or similar policy initiatives targeting the different stages of traditional and emergent bio-based value chains.

For its part, the European Union (EU) launched its first bioeconomy strategy in 2012 to kickstart a transition towards a low-fossil economy while promoting job creation and competitiveness (European Commission 2012). The second EU bioeconomy strategy, released in 2018, strengthens its territorial development and environmental objectives (European Commission 2018b; Kardung et al. 2021a). Moreover, since 2012, the bioeconomy has been placed at the heart of several new EU political initiatives such as the Sustainable Development Goals (2015), the climate ambitions of the Paris Agreement (2015), the European Green Deal (2019) and the Circular Economy Action Plan launched in 2020. As further evidence of the rising strategic importance of the bioeconomy, eleven EU Member States have publicly released dedicated bioeconomy strategies, and in five others they are under development. Macro-regional and micro-regional bioeconomy initiatives have also been launched (Lusser et al. 2018).

As the changing landscape has introduced the virtues of the bioeconomy into the mainstream of political thought, this has also unlocked greater business confidence (Gatto et al. 2021). Research and innovation target the ramping up of new biomass conversion processes, whilst industrial policy measures seek to bring bio-based innovations to market. On the demand side, despite the potential challenges (Sijtsema et al. 2016), consumer awareness campaigns, product labelling (Confente et al. 2020) and green public procurement initiatives (International Advisory Council on Global Bioeconomy 2020) have sought to create high value market outlets for emerging bio-based products.

In tandem with the rise of the bioeconomy on the EU policy agenda, there is an urgent need for a transparent and consistent monitoring framework to assess the development of bioeconomy activities. The ambitions of this study are thus to (i) consolidate basic socio-economic indicators for the monitoring of the job and growth objectives of the EU bioeconomy, and (ii) to tentatively identify the drivers of bioeconomy growth in order to ultimately suggest policy options for realizing the growth potential of EU Member States' bioeconomies. A key challenge facing objective (i) is the lack of official secondary data as bioeconomy activities are often subsumed within broad activity or product classifications.

Different methodologies that seek to disentangle bioeconomy activities from their respective parent industry classifications are discussed in the literature (e.g., M'Barek et al. (2018), Piotrowski et al. (2018) and Cingiz et al. (2021b)). On the one hand, the 'input-based' approach measures the proportion of biomass in the inputs used for producing bio-based products and apply this proportion to value added or job statistics for that sector (Meesters et al. 2013; Efken et al. 2016; Heijman 2016; Iost et al. 2019; Kuosmanen et al. 2020; Robert et al. 2020b). For example, in the input-based approach the food industry is only partially considered bio-based because it uses a mix of bio-based and fossil inputs, whilst under this criterion, even mining activities are 'part' bio-based. In contrast, the 'output-based' approach measures the biomass content of the bio-based products of a given sector (Pellerin et al. 2008; Vandermeulen et al. 2011; Luke 2019; Porc et al. 2020; Ronzon et al. 2020). Thus, under this classification, food industry activities are completely bio-based since their output is fully (edible) biomass, whilst mining activities are not considered bio-based as the core output does not contain biomass.

In seeking to make a judgement on the choice of measurement method, we take a policy perspective. More specifically, biomass producing activities (i.e., agriculture, forestry, fishing and aquaculture), food and beverages and other bio-based sectors (i.e., wood, paper, textile and bioenergy products) are under the remit of the EU bioeconomy strategy. In contrast, mining activities, despite employing biomass inputs, are not. From this perspective, the output-based methodology is entirely consistent with the EU's bioeconomy strategy. Having taken the decision on the methodology of bioeconomy activity measurement, the output-based approach is also applied to quantify so-called 'hybrid' sectors, which mix bio-based and non bio-based activities. As an insightful extension to the input-based approach, in their measurement of the bioeconomy Cingiz et al. (2021b) also account for the influence of non bio-based upstream industries sectors (e.g., financial, insurance, etc.) that provide inputs to bioeconomy sectors. Once again, however, since said upstream industries do not constitute part of the EU bioeconomy strategy, this approach is also discarded in favour of the output-based approach.

As a key novelty of our output-based approach, new data sources and calculation methods are proposed to quantify employment and value added in specific bio-based activities - such as waste management or construction - that were not addressed in previous studies (Porc et al. 2020; Ronzon et al. 2020). The resulting panel dataset comprises of 24 activities from the European System of

Accounts (ESA)[2] and covers the EU27[3] over the period 2008-2017. The ratio of these two concepts is used to calculate labour productivity change for bio-based activities. The combination of value added, employment and productivity forms the basis of a further novel analytical step, namely to isolate sectoral and structural sources of labour productivity growth, which are central for the tailoring of bioeconomy policy measures.

In view of the concept of 'transition', progress is measured through changes in bioeconomy sectors' labour productivity. Furthermore, to understand the structural basis motivating labour productivity in transition, two concepts are explored. On the one hand, we examine the premise that the modernisation and diversification of bio-based value-chains arising from the adoption of new biomass conversion pathways, industrial renewal and growing markets for bio-based goods, should translate into labour productivity growth (i.e., intra-sectoral or 'within-sector' effect). Secondly, the emergence and development of bio-based industries also implies 'structural change' resource reallocations (e.g., in this study represented by employment shifts) 'between-sectors', where such a reallocation generates labour productivity growth if resources are directed toward more productive activities ('productivity-enhancing') or vice-versa ('productivity-reducing').

To measure these concepts, a 'shift-share' analysis decomposes labour productivity into those stemming from 'within-sector' and 'between-sector' effects. The shift-share methodology is commonly used in economic transition studies (de Vries et al. 2015; Kuusk et al. 2017; Dobrzanski et al. 2019; Erumban et al. 2019; Moussir et al. 2020) and in development economics (McMillan et al. 2017). Given its parsimonious data requirements, it is particularly suited to monitor the bioeconomy as a case in point where data scarcity prevents the use of more sophisticated econometric approaches (Havlik 2015).[4]

Section 2.2 describes the methodological approach followed for the generation of panel data on value added, employment and labour productivity in bioeconomy sub-sectors in the EU27 and its Member States over the period 2008-2017. Section 2.3 is structured around three research questions: (i) Has the EU bioeconomy created jobs, economic growth and competitiveness? (section 2.3.1), (ii) What role did modernisation and structural change play in the EU bioeconomy transition? (section 2.3.2), and (iii) What were the sectoral sources of labour productivity gains in the EU bioeconomy (section 2.3.3)? Section 2.4 highlights policy options according to the EU Member States' progress into the

[2] ESA activities are defined by the Statistical Classification of Economic Activities in the European Community (NACE) (Eurostat 2008).
[3] The EU27 follows here the post-Brexit composition of the European Union, that is by excluding the United Kingdom.
[4] To further illustrate, the lack of data on bioeconomy capital resources obstructs the calculation of bioeconomy total factor productivity (Solow 1957).

bioeconomy transition, and acknowledges the interest of complementary indicators for the sustainability assessment of bioeconomy transitions. It also provides some reflections on the choice of methodology. Section 2.5 concludes.

2.2 Methodology and data

2.2.1 Selection of bio-based sectors of activity

Activities are reported according to the NACE classification in European statistics, distinguishing the primary economic sectors of activity by NACE sections A and B, the secondary sectors by sections C to F, and the tertiary sectors by sections G to T. This chapter focuses on the primary and secondary bioeconomy (hitherto referred to as “the non-service bioeconomy”, see glossary in supplementary material SM1). Based on a literature review, the Horizon 2020 European project ‘BioMonitor’ has elaborated a list of NACE divisions that encompass bio-based activities (Kardung et al. 2021a). As a starting point, our study follows the BioMonitor list for those relevant activities in NACE sections A and C to F, although NACE division C19 is excluded and NACE divisions C18 and C32 are included. In the case of NACE C19 for “manufacture of coke and refined petroleum products”, whilst that sector employs bio-based materials, it only produces fossil-based outputs. Taking an output-based approach, it is therefore not considered as part of the bioeconomy in the present chapter. The NACE C18 classification for printing activities and NACE C32 that includes, among others, the manufacture of (wooden) toys and musical instruments, are considered as bio-based activities in the German bioeconomy monitoring system (Iost et al. 2020). Thus, although not included within the list of candidate sectors from the BioMonitor project, these activities were added to our bioeconomy definition.

The final detailed list of bio-based sectors falling under the scope of this study is therefore as follows:

- biomass producing sectors: agriculture (A01), forestry (A02) and fishing and aquaculture (A03),
- the food, beverage and tobacco industries (C10-C12),
- the textile industry (C13-C15),
- the wood products (C16), furniture (C31), paper (C17) and printing (C18) industries,
- the chemical (C20), pharmaceutical (C21) and plastic (C22) industries,
- the manufacture of other non-metallic mineral products (C23) and other manufacturing (C32),
- the water (E36), sewerage (E37) and waste (E38) collection and treatment as well as other waste management services (E39),
- the construction industry (F41-43).

2.2.2 Computation of bio-based output shares for value added and employment

Among the bio-based NACE divisions listed in the previous section, some activities are so broadly defined that they comprise of bio-based and non-bio-based components, which in some cases may even be rival technologies of the same end product. To extract a measure of bio-based activities only from the NACE official statistical divisions, it is necessary to determine the biomass content share $\delta_{n,c,y}$ – the bio-based output share – at the NACE 2-digit level *n* and for each Member State *c* and year *y* (y=2008, …, 2017). The biomass content ranges from 0% (the output of *n* is not bio-based) to 100% (the output of *n* is fully bio-based). When information is missing at the 2-digit NACE sector level *n*, output bio-based shares are determined at the NACE sub-level *m* (NACE 3- or 4-digit code) and then aggregated up to the 2-digit level *n* (see below). Thus, value added (V) and employment (E) bio-based shares are given as:

$$\delta^{V}_{n,c,y} = \frac{\sum_{m}(\delta_{m,c,y} \times V_{m,c,y})}{V_{n,c,y}} \qquad (1)$$

$$\delta^{E}_{n,c,y} = \frac{\sum_{m}(\delta_{m,c,y} \times E_{m,c,y})}{E_{n,c,y}} \qquad (2)$$

Note that when assuming NACE 2-digit bio-based output shares, both employment and value added share values are assumed the same. However, when aggregating up from NACE 3- or 4-digit classifications, because the employment distribution across sector sub-divisions '*m*' differs from the corresponding value added distributions, this leads to different 2-digit '*n*' bio-based output shares for employment and value added:

$$\frac{\sum_{m}(\delta_{m,c,y} \times V_{m,c,y})}{V_{n,c,y}} \neq \frac{\sum_{m}(\delta_{m,c,y} \times E_{m,c,y})}{E_{n,c,y}} \qquad (3)$$

Thus, the 2-digit NACE biobased output share for value added and employment is 100% in the case of biomass producing activities (*n* = NACE divisions A01, A02, A03), the agro-food industry (*n* = C10, C11, C12), water treatment (*n* = E36) and sewerage (*n* = E37)[5] (green rows in Table 2).

[5] The status of water as a bio-based product remains debated. Water is for example considered a biological resource and therefore 100% bio-based in Finnish bioeconomy statistics (Luke, 2020).

Table 2. Data sources for the quantification of sectoral output bio-based shares, value added and number of people employed in the non-service bioeconomy (sector n *or sub-sector* m*, country* c*, year* y*).*

NACE division codes	Range of output bio-based shares $\delta_{n,c,y}$ or $\delta_{m,c,y}$ or literature source (‘n’ denotes 2-digit NACE codes, `m’ denotes 3- or 4-digit NACE codes)	Eurostat codes for data on value added $V_{n,c,y}$ and employment $E_{n,c,y}$
A01-A03	100%	Eurostat nama_10_a64, Eurostat nama_10_a64_e
C10-C12	100%	Eurostat sbs_na_ind_r2
C13-C17	Eurostat Prom DS-066341, Product bio-based shares from nova-Institute*	Eurostat sbs_na_ind_r2
C18	100% C1811, 0-100% C1812-C1814	Eurostat sbs_na_ind_r2
C20-C22	Eurostat Prom DS-066341, Product bio-based shares from nova-Institute*	Eurostat sbs_na_ind_r2
C23	0-100% C2365	Eurostat sbs_na_ind_r2
C31	Eurostat Prom DS-066341, Product bio-based shares from nova-Institute*	Eurostat sbs_na_ind_r2
C32	0-100% C3212 and C3213	Eurostat sbs_na_ind_r2
D35	Eurostat nrg_bal_c (section 2.2.2)	Eurostat sbs_na_ind_r2
E36-E37	100%	Eurostat sbs_na_ind_r2
E38	Eurostat env_wasgen, Eurostat env_wastrt (section 2.2.2)	Eurostat sbs_na_ind_r2
E39	0-100%	Eurostat sbs_na_ind_r2
F41-F43	Eurostat Prom DS-066341, Product bio-based shares from nova*, 0-100% missing Prom codes (section 2.2.2)	Eurostat sbs_na_con_r2

*See Ronzon et al. (2020)

Notes: The NACE groups (3-digit NACE codes) and classes (4-digit NACE codes) that are not reported in the table do not belong to the bioeconomy.
$\delta_{n,c,y}$=100% in green rows, $\delta_{n,c,y}$ is taken from Ronzon et al. (2020) and Porc et al. (2020) in blue rows, 0%<$\delta_{n,c,y}$ <100% in yellow rows (unavailable information). $\delta_{n,c,y}$ is computed as explained in section 2.2.2 in white rows. A glossary of NACE codes is provided in the supplementary material SM1.

For NACE divisions C13-C17 (manufacture of textiles, paper and wood products), C20-C22 (manufacture of chemicals, pharmaceuticals and plastics) and C31 (manufacture of furniture), we take the minimum and maximum output bio-based share $\delta_{n,c,y}$ from Ronzon et al. (2020) and Porc et al. (2020) (blue rows in Table 2). These studies define the biomass content of the products (8-digit Prodcom code) produced by the industries C13-C17, C20-C22 and C31. For each product, the multiplication of its production by its biomass content share is an estimate of its bio-based production value (data from Eurostat (2022m)). At the industry level *n*, the sum of the bio-based production values over the total production value of that industry gives the output bio-based share $\delta_{n,c,y}$.

For NACE division D35 (energy production), $\delta_{n,c,y}$ is the proportion of bioenergy in total energy supply expressed in tonnes of oil equivalent as reported in Eurostat (2022g). Bioenergy supply is comprised of solid and liquid biofuels (R52 sub-codes), biogases (R5300), charcoal (R5160) and renewable municipal waste (W6210). In this case, the minimum $\delta_{n,c,y}$ is equal to the maximum $\delta_{n,c,y}$.

For NACE division E38 (waste management), we assume that the biomass content of the wasted product is equivalent to the biomass content of the product itself. For example, the biomass content range of wasted textile is assumed equal to the biomass content range of textile (classification C13 above). Thus, the bio-based output share of the waste management industry (E38) is the sum of the bio-based content of wasted products estimated by type of waste from disaggregated waste statistics on waste generation (Eurostat 2022h) and waste treatment (Eurostat 2022f) (see supplementary material SM2).

For NACE divisions F41-F43 (construction), the biobased output share is the proportion of biomass embedded in constructed buildings and civil engineering. Following the treatment of NACE divisions C13-C17, C20-C22 and C31, the biomass content of construction materials that remain in final constructed buildings and civil engineering[6] (outputs) is defined at the product level. The sectoral output bio-based share for NACE division F41-F43 is the proportion of bio-based materials in total construction materials in value terms. The product list of remaining construction materials is derived from the 500+ Eurostat Prodcom products established by the Centre for Industrial Study et al. (2017) for the European Construction Sector Observatory.[7] Where there is data availability, product biomass content ranges are taken from Ronzon et al. (2020) and Porc et al. (2020), or are otherwise assumed to be 0% bio-based.[8] The value of bio-based materials is measured by their domestic sales as suggested by the European Construction Sector Observatory (Eurostat 2022m).

[6] For example, wooden shuttering for concrete, or equipment for scaffolding are not considered as an output of NACE section F because they do not remain in the final building.
[7] https://ec.europa.eu/growth/sectors/construction/observatory_en
[8] See the list of bio-based and non-bio-based construction material in supplementary material SM3.

Unfortunately, there is a lack of information on the biomass content on the output products of the remaining NACE divisions, namely, printing (C18), manufacturing of other non-metallic mineral products (C23), other manufacturing (C32) and remediation activities (E39) (yellow rows in Table 2). We therefore calculate time series values of value added and employment at the most disaggregated 3- or 4-digit NACE sectoral level '*m*' ($E_{m,c,y}$ and $V_{m,c,y}$) by assuming some sub-activities as fully bio-based (i.e., $\delta_{m,c,y}$ = 100% for the printing of newspapers of C1811), partly bio-based (i.e., 0% <$\delta_{m,c,y}$ <100% for other printing activities and services C1812-C1814, the manufacture of fibre cement C2365, the manufacture of jewellery and imitations C3212-C3213, other waste management services E39) or completely non bio-based (remaining NACE 4-digit C codes). Then, equations (1) and (2) give the sectoral output-based shares for value added and employment.

Assumptions and data sources for the estimation of bio-based output shares are summarised in column 2 of Table 2.

2.2.3 Indicators and data sources

The study computes the ratio of the number of people employed (variable 'E') to value added (variable 'V') to infer a measure of labour productivity (variable 'P') (also called apparent labour productivity in Eurostat datasets). Within-sector labour productivity changes and between-sector changes are part of the shift-share analysis.

The computation of bio-based employment and value added by sector *n*, in country *c* in year *y* ($bbE_{n,c,y}$ and $bbV_{n,c,y}$, respectively) is based on the multiplication of the output bio-based share by sector, Member State and time period by panel data observations of employment and value added (in current prices) retrieved from the Eurostat structural business statistics and from the Eurostat national accounts for the available period 2008-2017 (column 3 of Table 2, Eurostat (2022i, 2022j, 2022k, 2022l)). Thus:

$$\mathrm{bbV_{n,c,y}} = \delta^{\mathrm{V}}_{\mathrm{n,c,y}} \times \mathrm{V_{n,c,y}} \tag{4}$$

and

$$\mathrm{bbE_{n,c,y}} = \delta \mathrm{b}^{\mathrm{E}}_{\mathrm{n,c,y}} \times \mathrm{E_{n,c,y}} \tag{5}$$

It should be reminded that minimum-maximum ranges of output bio-based shares $\delta^{VA}_{n,c,y}$ and $\delta^{E}_{n,c,y}$ were determined in section 2.2.2 to account for uncertainty. This therefore leads to the computation of minimum and maximum bio-based value added and employment.

The term $P_{n,c,y}$ refers to the value added generated per person employed given as:

$$bbP_{n,c,y} = bbV_{n,c,y} / bbE_{n,c,y} \quad (6)$$

Location quotients (variable 'LQ') are also derived from employment data. For the non-service bioeconomy (nsBE), the location quotient calculates the degree of labour concentration of each Member State *c* in those sectors that produce biomass or supply bio-based goods, proxied by each Member State's bioeconomy employment share compared with the corresponding figure for the EU27:

$$LQ_{nsBE,c,y} = \frac{bbE_{nsBE,c,y}/E_{c,y}}{bbE_{nsBE,EU27,y}/E_{EU27,y}} \quad (7)$$

The term $\Delta P_{nsBE,c,y}$ refers to non-service bioeconomy labour productivity changes. Following other studies (de Vries et al. 2015; Kuusk et al. 2017; McMillan et al. 2017; Dobrzanski et al. 2019; Erumban et al. 2019; Moussir et al. 2020), it is decomposed into a 'within-sector' effect (first additive term) and a 'between-sector' effect (second):

$$\Delta P_{nsBE,c,y} = \sum_n ShbbE_{n,c,y0}\, \Delta P_{n,c,y} + \sum_n P_{n,c,y} \Delta ShbbE_{n,c,y} \quad (8)$$

where $ShbbE_{n,c,y}$ denotes the bioeconomy employment share of sector *n* in Member State *c*. Thus, the within-sector effect is the employment share weighted sum of 'within-sector' productivity growth $\Delta P_{n,c,y}$. The between-sector (or structural change) effect is the reallocation of bioeconomy employment between activities *n* in Member State *c* ($\Delta ShbbE_{n,c,y}$) weighted by the corresponding productivity levels, $P_{n,c,y}$.

Note that some authors further split the structural effect into "static" and "dynamic" effects as expressed in the second and third terms of the following equation (de Vries et al. 2015; Havlik 2015; Kuusk et al. 2017):

$$\Delta P_{c,y} = \sum_n ShbbE_{n,c,y0}\, \Delta P_{n,c,y} + \sum_n P_{n,c,y} \Delta ShbbE_{n,c,y} + \sum_n \Delta P_{n,c,y}\, \Delta ShbbE_{n,c,y} \quad (9)$$

The interpretation of the three-component decomposition of labour productivity has been subject to debate.[9] In this paper, we, therefore, analyse the two-component decomposition. It is complemented with an analysis of the individual sector contribution to aggregate productivity gains $ShbbE_{n,c,y0} . \Delta P_{n,c,y}$.

[9] McMillan et al. (2017, page 11) find difficulty interpreting the dynamic term "*when, for example, reductions in the employment share are accompanied by increases in productivity. This is because the term becomes negative, seemingly acting as a drag on productivity, when in fact it could be viewed as a positive development in such sectors as agriculture*".

2.3 Results

2.3.1 Has the EU non-service bioeconomy created jobs, economic growth and competitiveness?

From our results, the value added of the European non-service bioeconomy has grown at a similar pace as the rest of the economy, maintaining a 6% contribution to EU27 value added between 2008 and 2017 (not shown). It has reached between EUR 657 to 706 billion between the 2015-2017 period, half of which coming from agriculture (A01) and the food industry (C10) (three-year average, Figure 2). The EU27 bioeconomy employed between 18.7 and 19.9 million workers in the 2015-2017 period, with more than the two thirds coming from agriculture (A01) and the food industry (C10) (three-year average, Figure 2). However, largely due to the restructuring of the EU27 agriculture sector, between 2008-2010 and 2015-2017, the employment base has reduced by around 2 million workers (of which -1.7 million are agriculture workers). As a result, the European non-service bioeconomy has struggled to maintain its share of total employment over the observed period.

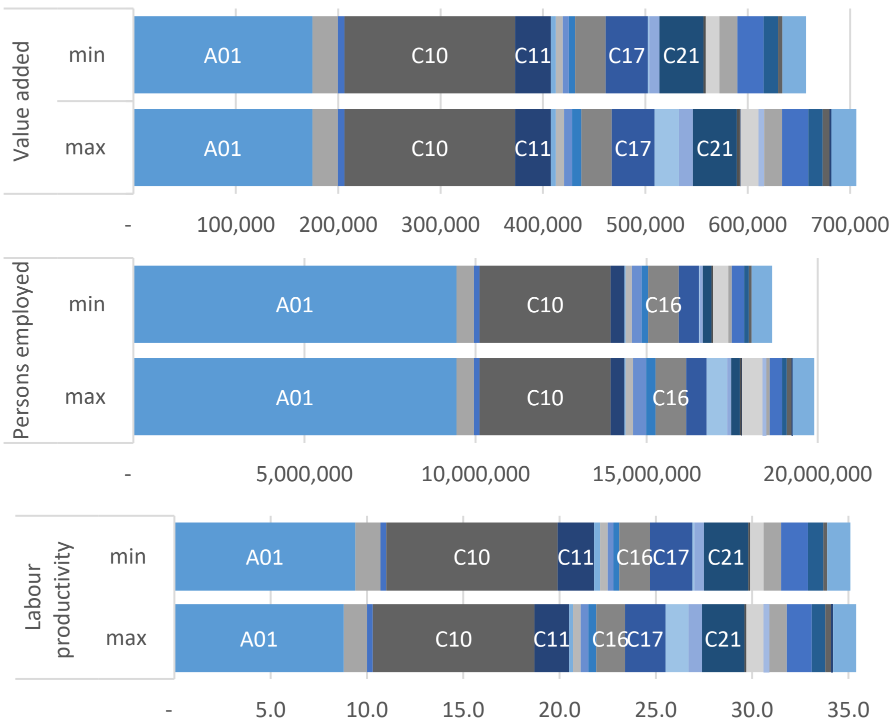

Figure 2. Contribution of NACE activities to the non-service bioeconomy's value added (million EUR, top chart), number of persons employed (middle chart) and labour productivity (thousand EUR per person employed, bottom chart) (EU27, 3-year average for 2015-2017).

Note: min (max) refers to the calculations derived from the minimum (maximum) output bio-based shares (see section 2.2.2).

Our dataset does not allow us to observe the price competitiveness of European bio-based products but it does indicate labour productivity gains of EUR 7,100-8,000 per worker in the non-service bioeconomy between 2008-2010 and 2015-2017 (not shown). In 2015-2017, agriculture and the food industry both contribute approximately 24%-26% to aggregate labour productivity in the non-service bioeconomy and could have played a significant role in this evolution. The manufacture of beverages (C11), paper (C17), wooden furniture (C16), and bio-based pharmaceuticals (C21) each generate labour productivity contributions of 4.5%-6.5% (Figure 2).

It is important to note that labour productivity developments were very uneven across the EU27. Major gains occurred in Denmark, Ireland and Belgium (>EUR 20,000 per person employed between 2008-2010 and 2015-2017), Finland (>EUR 19,000 per person), the Netherlands, Austria, and Sweden (>EUR 10,000 per person), while Greece was the only Member State experiencing a reduction in aggregate labour productivity of its non-service bioeconomy[10] (y-axis of Figure 3).

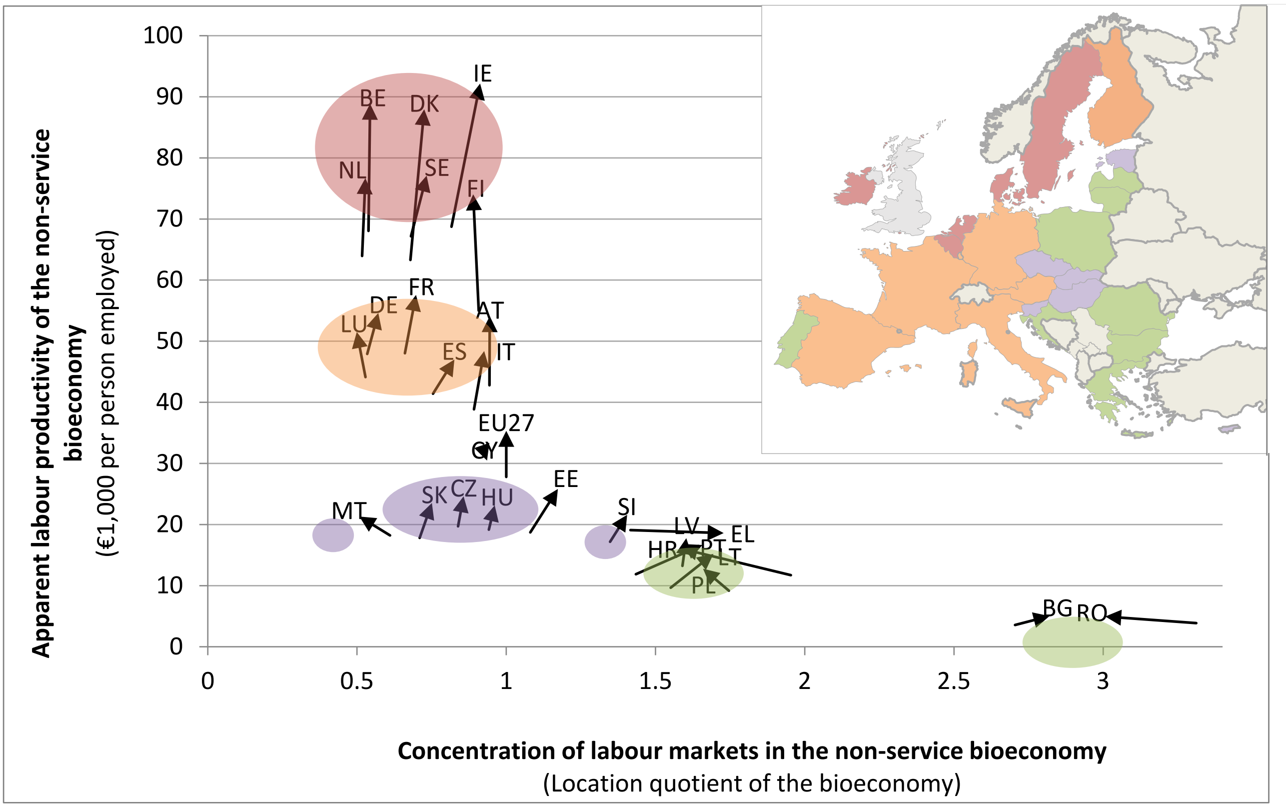

Figure 3. Evolution of the location quotient and apparent labour productivity in the non-service bioeconomy of the 27 EU Member States between 2008–2010 to 2015–2017 (average estimates).

[10] Greece has perhaps been the EU Member State most acutely affected by the 2008-2009 financial crisis. The European Court of Auditors attributed the vulnerability of the Greek economy at that time to "growing macroeconomic imbalances, large stocks of public and external debt, weak external competitiveness, an unsustainable pension system and weak institutions" (European Court of Auditors 2017, page 7). In a report to the European Commission, Rodríguez-Pose et al. (2019) add that population ageing, the rigid labour market and the possible low level of institutional quality are additional causes of poor labour productivity in Greece (2003-2015). They define a low level of institutional quality by a lack of transparency and accountability, corruption, and poor governance performance.

Note: The coloured circle indicates four groups of Member States: (i) Green group: Eastern Member States, Portugal, and Greece characterised by a labour market highly specialised in the non-service bioeconomy ($1.5 \leq LQ_{nsBE,c}$) and a below-average apparent labour productivity of the non-service bioeconomy ($P_{nsBE,c} \leq ½ P_{nsBE,EU}$); (ii) Purple group: Estonia and Central Member States, less specialised in the non-service bioeconomy, but more labour productive ($LQ_{nsBE,c} \leq 1.4$ and $½ P_{nsBE,EU} \leq P_{nsBE,c} \leq P_{nsBE,EU}$); (iii) Orange group: Western Member States with exacerbated characteristics compared to the purple group ($LQ_{nsBE,c} \leq 0.9$ and $P_{nsBE,EU} \leq P_{nsBE,c}$), (iv) Red group: Northern Member States with even higher labour productivity ($LQ_{nsBE,c} \leq 0.9$ and $2.P_{nsBE,EU} \leq P_{nsBE,c}$).

The EU27 Member States are represented by their official country code: Austria (AT), Belgium (BE), Bulgaria (BG), Croatia (HR), Cyprus (CY), Czechia (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (EL), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), Malta (MT), Netherlands (NL), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES) and Sweden (SE).

Although this study extends the sector coverage of Ronzon et al. (2020) to all non-service bioeconomy sectors, we observe the same grouping of countries as that study (Figure 3). A dynamic representation of the scatter plot reveals variations in the level of labour concentration of national economies in the non-service bioeconomy in Eastern Member States and Greece (green group), while it remains almost unchanged in the other EU Member States between 2008-2010 and 2015-2017 (arrows on Figure 3, x-axis variations). At the same time, labour productivity has dramatically increased in the Western and Northern Member States (orange and red groups, y-axis variations).

In sum, the non-service bioeconomy has maintained its position within the total EU27 economy and total labour force over the period 2008-2017 by creating net value added but no net jobs. This entailed growth in labour productivity, especially in Northern and Western EU Member States. Agriculture and the food industry are preponderant in the sectoral structure of the non-service bioeconomy and their intra-dynamics are likely to have influenced the whole aggregate of non-service bioeconomy. The next section will look at the nature of labour productivity developments and verify whether they are related to the grouping of countries observed at Figure 3.

2.3.2 What role did modernisation and structural change play in the EU non-service bioeconomy transition?

Table 3 presents the decomposition of EU non-service bieconomy labour productivity growth into within-sector and between-sector (or employment reallocation) effects following equation (8). Excluding the 2008-2009 crisis period, both within- and between-sector effects were productivity-enhancing (positive sign). The within-sector labour productivity growth largely predominated, varying between 0 and 7 % per annum. In comparison, the reallocation of workers across bioeconomy sectors (between-sector) triggered less than 1.5% growth per annum which indicates that, to a certain extent, bioeconomy workers have moved from low- to high-productivity activities on average. The preponderance of within-sector effects is consistent with observations made on macroeconomies[11] (Fagerberg 2000; Timmer et al. 2000; Peneder 2003; Kuusk et al. 2017).

Table 3. Value added, employment and labour productivity growth, within- and between-effect in the EU27 (average estimate, annual %).

	2008-2009	**2009-2010**	**2010-2011**	**2011-2012**	**2012-2013**	**2013-2014**	**2014-2015**	**2015-2016**	**2016-2017**	**Average**
Value added growth	-5.94	6.53	2.82	-1.14	1.86	1.77	2.08	4.04	5.99	**2.00**
Employment growth	-3.53	-0.92	-1.98	-1.57	-1.85	-0.42	-1.62	-1.20	0.71	**-1.38**
Labour productivity growth	-2.50	7.52	4.90	0.44	3.79	2.20	3.76	5.30	5.25	**3.41**
Within-sector effect	-2.97	7.07	3.99	0.05	2.95	1.81	2.66	3.84	4.38	**2.64**
Between-sector effect	0.48	0.45	0.91	0.39	0.84	0.40	1.10	1.47	0.87	**0.77**

Note: Due to rounding, labour productivity growth does not always appear as the exact sum of within- and between-sector effects.

For the EU27 as a whole, agriculture and the food industry played a significant productivity-enhancing role (Figure 4). On the one hand, employment significantly contracted in agriculture (x-axis), the largest employing sector and also the least labour productive sector of the EU27 non-service bioeconomy (y-axis). On the other hand, the most significant increase in employment share happened in the food industry, also characterized by above-average productivity. The production of bioenergy (D35) and the manufacturing of bio-based pharmaceuticals (C21) appear to be the most labour productive sectors of the non-service bioeconomy but their pull effect on aggregate labour productivity has been less significant due to their relatively small employment base (size of the circles).

[11] With the exception of the shift-share analysis by Dobrzanski et al. (2019) on Central and Eastern European Member States over the period 2004-2018 that shows a dominant role for structural change effects on labour productivity growth.

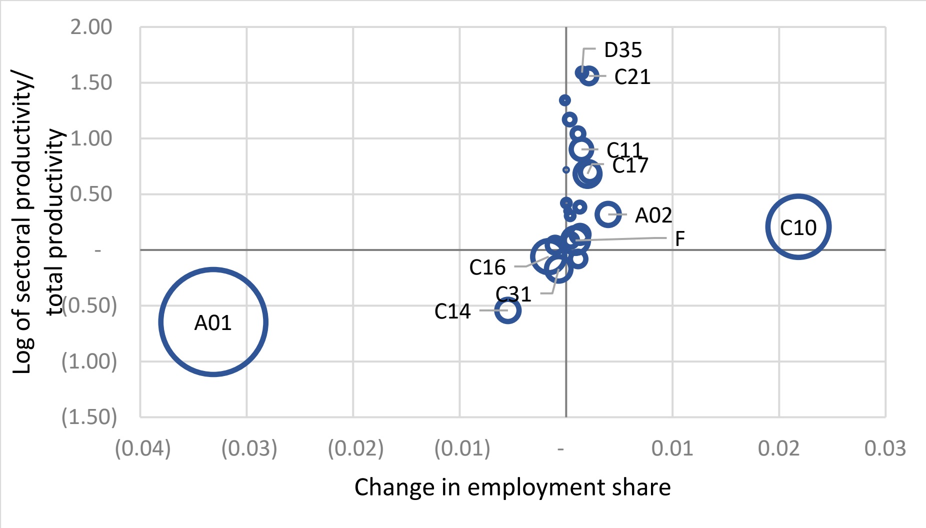

Figure 4. Sectoral productivity and change in employment share in the EU27, 2008–2017 (average estimates, a figure based on McMillan et al. (2011)).

Note: Size of circle represents employment share in 2008-2010. The change in employment share is calculated on the 3-year average 2008-2010 to 2015-2017. The log of the productivity share is calculated at the end of the period (i.e., 2015-2017 average).

A closer look at the Member States' dynamics reveals common traits in the productivity drivers by country group (Figure 5). The Member States of the red group from Figure 3 (in red lettering in Figure 5), experience the highest within-sector productivity gains by some distance (>EUR 1,300 per worker per year). Such gains were accompanied by important productivity-enhancing between-sector effects in the case of four countries out of these six (Belgium, Denmark, Finland and Ireland with annual productivity gains due to employment reallocation higher than EUR 440 per worker). In the Netherlands, employment reallocation hardly affects aggregate labour productivity of the non-service bioeconomy. In Sweden, workers appear to have moved to lower-productivity sectors (between-sector effect of EUR -200 per workers per year).

Those Member States in the orange group from Figure 3 (in orange lettering in Figure 5) occupy an intermediate position. They experienced gains in within-sector labour productivity higher than the EU27 level (>EUR 650 per worker per year, except for Spain) while the positive effect of employment reallocation on aggregate labour productivity was below the EU27 effect (between-sector effect of <EUR 190 per worker per year).

The Member States of the purple and green group experienced low-to-medium within-sector labour productivity gains (ranging from negative productivity changes in Greece to slightly above-EU27 level in Estonia and Slovakia) and negative-to-low between-sector effects (negative in the case of Malta and Slovakia, to almost equal to the EU27 level in the case of Portugal).

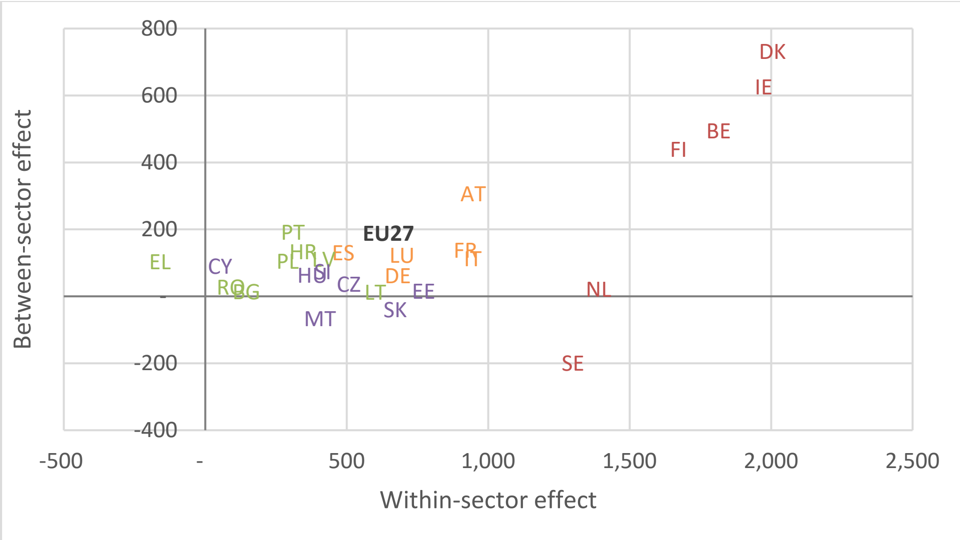

Figure 5. Distribution of the EU Member States according to the within- and between- components of the aggregate labour productivity gains experienced by the non-service bioeconomy between 2008-2010 and 2015-2017 (EUR per person employed and per annum, average estimates).

Belgium, Denmark, Finland and Ireland are interesting country cases of advanced bioeconomy transition from two perspectives: (i) their bioeconomy has performed the highest labour productivity leaps in the EU, and (ii) they operated significant structural changes in their bioeconomy where high labour productive sectors attracted workers from less productive sectors (productivity-enhancing effects). The analysis of their net effects (within + between effects) shows that the manufacture of bio-based pharmaceuticals, of food and agriculture were cornerstones in the bioeconomy transition of Belgium, Denmark and Ireland while forest value chains steered net labour productivity gains in Finland (Figure 6). The attractiveness of workers is noticeable in the manufacture of bio-based pharmaceuticals (the only source of that sector's labour productivity gain in Ireland, and combined with intra-sector gains but dominant in Denmark and Belgium). In Belgium, Denmark and Ireland, labour productivity improvements in agriculture are only the fact of within-sector effects and all combinations of effects happen in the food industry of the three countries. In contrast, forestry has been the strongest driver of improvements in the Finnish bioeconomy's labour productivity – both in terms of within- and between-sectors effects – while intra-sector labour productivity gains steered the productivity in the manufacturing of wood and paper.

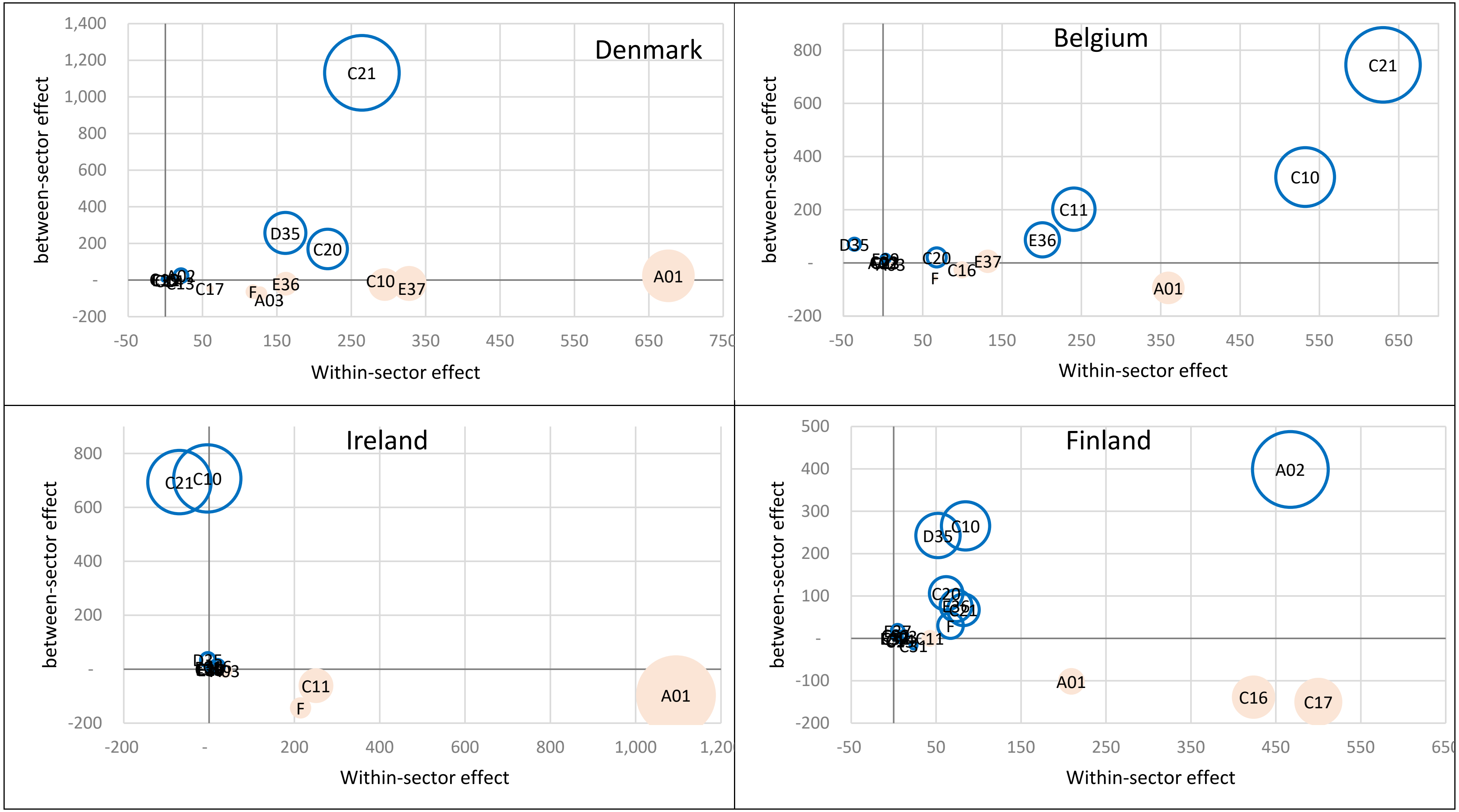

Figure 6. Decomposition into within- and between- components of the annual labour productivity gains experienced by the non-service bioeconomy of Belgium, Denmark, Finland and Ireland between 2008-2010 and 2017-2019 (EUR per person employed and per annum, average estimates).

Note: Size of circle is proportional to the net effect of the within-sectors and between-sectors dynamics. A red fill indicates a negative change in employment share between 2008-2010 and 2017-2019.

2.3.3 How did sectoral labour productivity gains contribute to the EU non-service bioeconomy transition?

For each Member State in Figure 5, the within-sector contribution to variations of the aggregate labour productivity of the non-service bioeconomy is plotted by NACE sector on Figure 7. Not surprisingly, major contributions came from agriculture (A01) and the food industry (C10) which on average triggered aggregate productivity gains of EUR 220 and 130 per worker per annum respectively (crosses on Figure 7). They are followed by the manufacture of paper (C17) and of wood products (C16) (EUR 65 and 50 per worker per annum). Forestry (A02), the manufacture of beverages (C11), bio-based pharmaceuticals (C21), water management (E36) and the construction sector (F) contributed to elevating the aggregate productivity in the order of EUR 30-37 per worker per annum. The remaining non-service bioeconomy sectors showed a lower average contribution.

A number of outliers stress national specificities. Agriculture in Ireland and the Netherlands, the Irish food industry and Finnish paper manufacture were major motors of bioeconomy growth, steering their bioeconomy's aggregate labour productivity by more than EUR 600 per worker per year. The within-sector effects on the food industry in Belgium and the Netherlands and Swedish paper manufacture were also notable (above EUR 400 per worker per year), closely followed by the within-sector effects of agriculture in Denmark, Spain and Slovakia, the manufacture of bio-based pharmaceuticals in Belgium and Denmark as well as the Finnish forestry sector (between EUR 360 and 395 per worker per year).

Outliers also identify cases of within-sector effects that reduce productivity, such as in the case of the Greek food industry (C10), Dutch manufacturing of tobacco (C12) and the Cypriot construction sector (F) that pulled down their respective bioeconomy labour productivity by more than EUR 100 per worker per year. The Swedish and Irish manufacture of bio-based chemicals also caused annual productivity losses in the order of EUR 66 to 77 per worker.

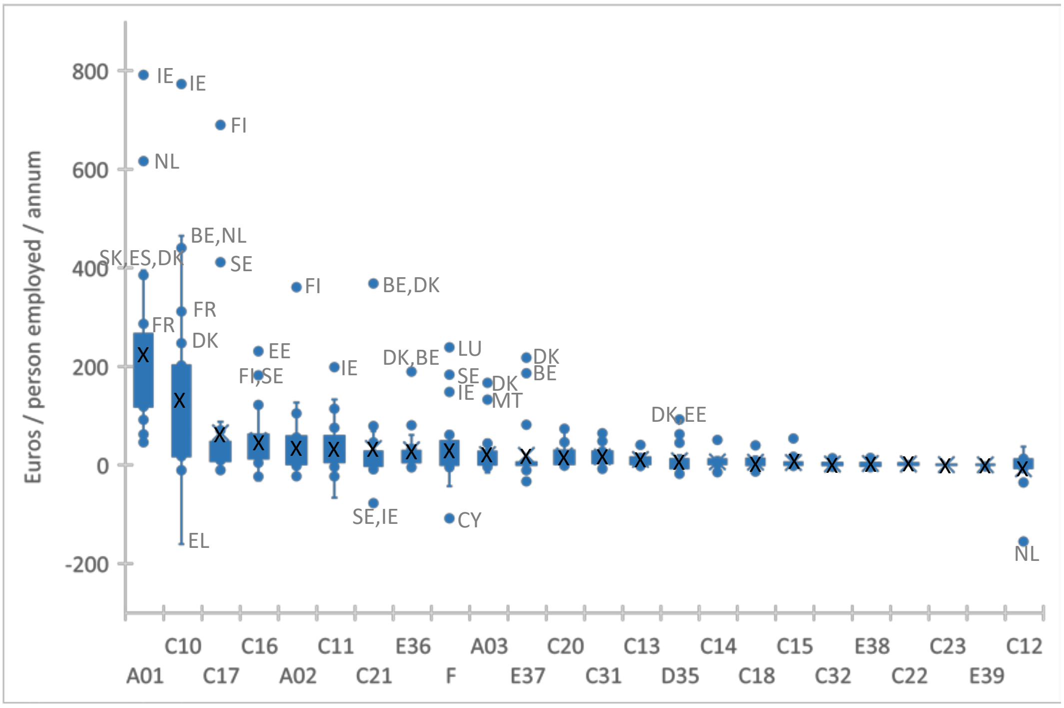

Figure 7. Annual within-sector effect on labour productivity variation ΔPn,c,y between 2008-2010 and 2015-2017 (average estimates, sectors ranked by descending order of the average within-sector effect across the Member States).

Note: For each sector n, *X indicates the mean, the lowest part of the box indicates the 2nd quartile and the upper part the 3rd, the low and high whiskers the 1st and 4th quartiles; outliers are shown with dots and country code.*

2.4 Discussion and caveats

2.4.1 Bioeconomy transition stages in EU Member States

In the field of development economics, McMillan et al. (2017) distinguish sectoral and transversal policies. Sectoral policies aim at moving resources into specific (often “modern”) industries by the means of subsidies, investment incentives or by removing specific obstacles. They usually strengthen the “private fundamentals” (Atolia et al. 2020), that are physical capital, technology, knowledge-skills and the innovation endowment of the targeted industries. Transversal policies aim at developing broad capabilities by investing in “public fundamentals” (Atolia et al. 2020) that are human capital, institutions and infrastructures. While sectoral policies can entail both within-sector and sectoral labour productivity growth, Atolia et al. (2020) observe from developing countries’ growth trajectories that “public fundamentals play a relatively more important role than private fundamentals in the initial jump-starting of structural transformation and economic growth”. Borrowing these concepts from development economics sheds light on different policy needs in EU Member States for realising their bioeconomy growth potential.

First of all, according to our results, the non-service bioeconomy of Belgium, Denmark, Finland and Ireland is among the most labour productive in Europe and has exhibited impressive within-sector and structural labour (or between-sector) productivity gains over the last decade. This suggests that the right conditions (public and private fundamentals) were in place for these countries to transit towards a bioeconomy. Interestingly, all four bioeconomies are governed by either a national or a regional strategy.

Secondly, the non-service bioeconomy of the other Member States of the Northern and Western groups of countries identified (Austria, France, Germany, Italy, Luxembourg, Netherlands, Spain and Sweden) is also highly labour productive but has only shown more moderate aggregate labour productivity gains. With the exception of Austria, the structural labour change effects on aggregate productivity gains have been rather weak (i.e., between-sector effects). All these countries – except Luxembourg - have a bioeconomy strategy in place, that hitherto has not translated into a successful transition. Sectoral measures may well have been successful at modernising their bio-based industries and rising their within-sector labour productivity. Notwithstanding, the soft between-sector effect suggests that the bioeconomy transition is still at its early stage and could be boosted by supports to new bio-based industries and to public fundamentals.

Finally, in the rest of the EU Member States (Bulgaria, Croatia, Cyprus, Czechia, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovenia, Slovakia), the non-service bioeconomy has achieved below-EU27 average labour productivity levels. Within- and between-sector effects are also mostly below-EU27 average. Within these countries only Latvia, Lithuania, and Portugal have a bioeconomy strategy in place while most of the other countries are in the process of designing their own. Our results suggest that both sectoral and transversal measures have to be mobilised in future bioeconomy strategies to engage them in a bioeconomy transition. The sectoral labour productivity differentials with the Northern and Western Member States indeed indicate a large potential for bioeconomy developments, and sector-specific measures could help to bridge these gaps while favouring structural changes at the same time. The identification of productivity enhancing/reducing within-sector effects in section 2.3.3 is important evidence for such a tailoring of future bioeconomy policy instruments.

2.4.2 Economic transition and sustainable bioeconomy transition

While our study touches on the economic (value added indicator) and social (employment indicator) dimensions of the bioeconomy, sustainability is a complex and pluri-dimensional concept. As an example, the internationally agreed framework of the Sustainable Development Goals (SDGs) considers seventeen dimensions, measured with 360+ indicators.[12] However, ecological economists prioritise the ecological dimension pointing out that any human activity is constrained by the biosphere thereby positioning its resilience as a sine quae non condition for sustainable human-driven development (Griggs et al. 2013; Folke et al. 2016). The quantification of planetary boundaries and of a safe operating space for humanity provides a concrete theoretical framework to assess sustainable human development (Rockström et al. 2009; Steffen et al. 2015).

Also looking at the preservation of natural capital, bioeconomy visions are often analysed in the literature according to their position between a weak and a strong sustainability paradigm. The weak sustainability paradigm assumes that the deterioration of natural capital can be offset by technological progress, as opposed to the strong sustainability paradigm that advocates the strict preservation of un-substitutable natural capital and decoupling with economic growth (Neumayer 2003 in Bennich and Belyazid 2017). Bennich et al. (2017), D. D'Amato et al. (2017), Meyer (2017), Bugge et al. (2016) and Ramcilovic-Suominen et al. (2018) observe that the bioeconomy vision defined in the first bioeconomy strategy of the European Union lean toward a weak sustainability paradigm, giving little attention to decoupling bioeconomic growth from the risks of deforestation, loss of biodiversity, land use change and deterioration of water, soil and air. The revision of the EU bioeconomy strategy in 2018 acknowledges such potential risks and makes greater emphasis on the ecological and social base of the bioeconomy with one pillar out of three dedicated to 'understanding the ecological boundaries of the bioeconomy' and a further pillar dedicated to a fair territorial deployment of the bioeconomy in the EU.

In pursuing strong sustainability objectives, Liobikiene et al. (2019) also suggest monitoring the ability of the European bioeconomy in limiting resource 'leakage effects' using the indicators of the land footprint and land biocapacity (i.e., the land footprint of the bioeconomy should not exceed the biocapacity). Quantifying these indicators for the EU Member States, Liobikiene et al. (2020) find that the land biocapacity of the bioeconomy is almost achieved in Estonia and Denmark, and already exceeded in Belgium (purple and red groups of countries). On the other hand, almost 30% of the biocapacity of the land biocapacity of Croatia, Slovenia, Slovakia and Romania remained un-exploited in 2013 (green and purple groups of countries).

Bringezu et al. (2021) extend the measure of the German bioeconomy footprint to agriculture and forestry biomass footprints, agriculture land footprint, climate footprint, water footprint, as well as value added and employment footprint. These recent works will feed the on-going design and

[12] https://unstats.un.org/sdgs/indicators/database/

implementation of a European bioeconomy monitoring system by the European Commission that embraces the multiple dimensions of sustainability (Robert et al. 2020a).

2.4.3 Caveats of the study

The principal limitation of the study lies in the determination of output bio-based shares $\delta_{n,c,y}$ for the NACE divisions where there are issues of data scarcity relating to biomass content estimates. As a result, uncertainty was acknowledged with a range of 0% to 100% bio-based output share in the case of "remediation activities and other waste management services" (E39) and for the sub-activities C1811, C1812, C1813, C1814, C2365, C3212 and C3213 (section 2.2.3 and Table 2). This resulted in a particularly wide range of bio-based output share values at the NACE-division level for the printing industry (C18) and remediation activities (E39) (Figure 8). The accumulation of uncertainties at the NACE division and the country level led to an uncertainty interval in the calculation of EU27 non-service-related bioeconomy value added of EUR 49 billion between total lower and upper thresholds of EUR 657 and 706 billion, respectively. Similarly, the bioeconomy employment uncertainty interval is 1.2 million workers, between the total lower and upper thresholds of 18.7 to 19.9 million. Finally, the uncertainty interval for apparent labour productivity is EUR 300 of value added per worker, with an absolute range of between EUR 35,200 to 35,500 per worker.

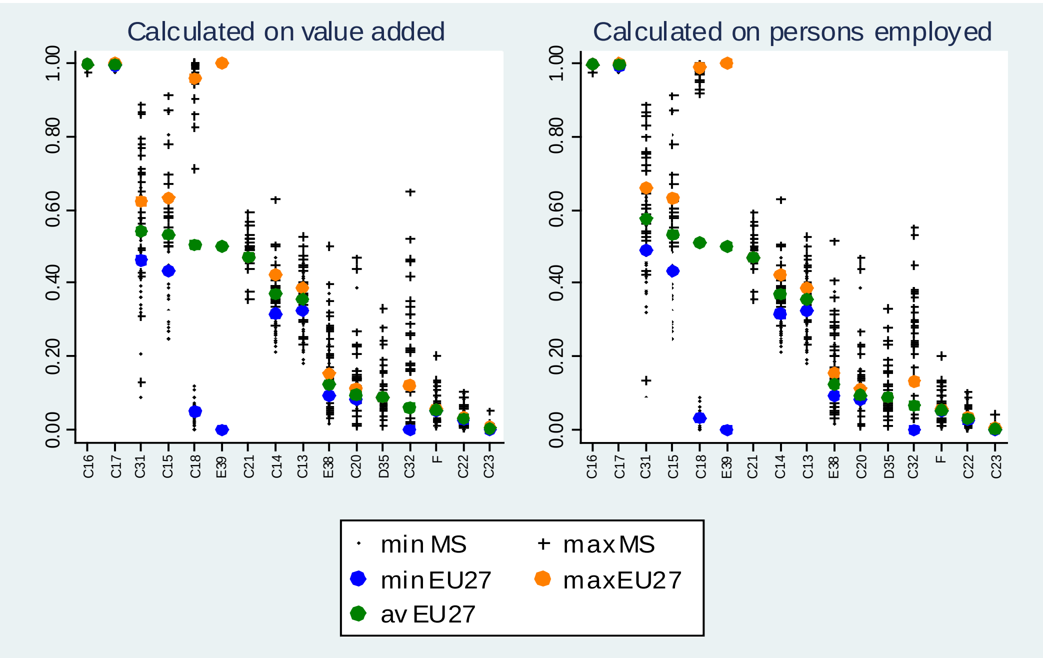

Figure 8. Range of the NACE 2-digit output bio-based shares quantified from value added data (top) and employment data (bottom) for the EU27 (2015-2017), and their distribution across EU Member States.

Note: Large dots represent min, average and max bio-based shares for the EU27. The distribution of the bioeconomy orientation of a given sector within the 27 EU Member States is represented by the `- ' (minimum bio-based share) and `+' (maximum share) points on the figures. For example, while the

EU27 min-max range is relatively narrow for the bio-based chemical sector (C20), the output bio-based share of that sector varies from 0% to nearly 50% in Member States.

The labour productivity developments observed in this study to 2017 could be interpreted as partial short/medium term effects of the EU bioeconomy strategy launched in 2012, however our study does not conclude on causality effects. The time span of the study has been restricted by the availability of bio-based output share estimates for products manufactured by industries C13-C17, C20-C22 and C31. Meanwhile these share estimates have been updated by the nova-institute, thereby offering, in tandem with readily available Eurostat annual observations, an opportunity to extend the time series until 2020.

Another limitation of the analysis of the motors of productivity growth within the non-service bioeconomy sectors relates to data scarcity on the factors of productivity other than employment and value added. A time series of data on investments (capital factors), labour skill types or levels of education (human capital) and technical change would have allowed a more detailed analysis and estimation of total factor productivity (Timmer et al. 2000; McMillan et al. 2017).

2.5 Conclusion

Currently, there is a general paucity of data available from respected secondary data sources for supporting the monitoring and evaluation of the performance of the EU bioeconomy (Robert et al. 2020a). This paper represents an attempt to bridge that gap by employing varied sources, assumptions and data analysis techniques to examine the patterns of productivity growth and transition in the bioeconomy of the EU and its 27 Member States. This research also responds to the need to inform the policy debate on the design and targeting of green growth sustainable investment strategies akin to the EU's 'green list' or Taxonomy under the auspices of the Green Deal (European Union 2020).

We find that the non-service bioeconomy has maintained its position within the total EU27 economy and labour force over the period 2008-2017, by creating net value added but no net jobs. With the exception of Greece that was acutely affected by the 2008-09 crisis, bioeconomy labour productivity growth has ensued in all Member States. Agriculture and the food industry are preponderant in the sectoral structure of the non-service European bioeconomy and have played a significant labour productivity-enhancing role at the EU27 level. On the one hand, employment significantly contracted in agriculture, the largest employer and the least labour productive sector of the EU27 non-service bioeconomy. On the other hand, the most significant increase in employment share happened in the food industry, characterised by above-average productivity.

At the national level, Belgium, Denmark, Finland and Ireland exhibit a bioeconomy transition by modernising their bioeconomy activities and mobilising structural changes. Their bioeconomy transition has been driven by the manufacturing of bio-based pharmaceuticals and the agro-food sector in Belgium, Denmark and Ireland, and by forestry and forest-based activities in Finland. Other Northern and Western EU Member States are still in the early stages of a transition. The modernisation of certain bio-based industries has brought consequent labour productivity gains, although signs of employment reallocation toward emerging bio-based industries remain weak. Finally, a large potential for sectoral labour productivity improvements is identified in Eastern and Central Europe, where the design and implementation of bioeconomy strategies could kickstart a bioeconomy transition.

As the policy focus in Europe (and elsewhere) continues to reconcile market and non-market policy objectives of sustainable growth, the bioeconomy will continue to play a pivotal role. Looking forward, it is perhaps premature to make reasoned judgements on the degree of resilience of the bioeconomy to the current COVID pandemic and the concomitant impact on the stability of the supply chains. Indeed, an interesting hypothesis to test in future research of this type would be the presence of bioeconomy productivity improvements through proposed improvements in research and development and digitalisation driven by the EU's EUR 1.8 trillion recovery plan.

Finally, the economic analysis proposed in this study can only be considered as a very partial contribution to any effort of bioeconomy monitoring or to the assessment of bioeconomy transitions. As the updated bioeconomy strategy of the European Union recalls, the bioeconomy is not sustainable per se, and the jobs and growth objectives of the strategy have to be obtained together with a fair redistribution of the benefits of bioeconomy developments and within the ecological boundaries of our planet. Our study also highlights important data gaps for computing additional socio-economic indicators, which for certain dimensions of bioeconomy development remain challenging (environmental, biophysical, innovation, skills, etc.). The progressive implementation of a Bioeconomy Monitoring System by the European Commission as well as funding attributed to research and innovation in the field of bioeconomy within the Horizon Europe framework programs will support such avenues.

Chapter 3. An output-based measurement of EU Bioeconomy services: Marrying statistics with policy insight[13]

Abstract

In its revised bioeconomy strategy, the European Union (EU) has extended the scope of activities to include services. Employing an output-based approach, this study quantifies the contribution of bioeconomy services to gross domestic product and employment in the EU Member States over 2008-2017. Moreover, it also identifies the main sectoral sources of employment and growth within bioeconomy services. The choice of Eurostat statistics ensures data harmonisation across countries and continuity for future updates, although important data needs are identified to enhance the representation of bioeconomy services within European statistical frameworks. In 2015-2017, economic growth was stronger in bioeconomy services than in the total EU27 economy. Bioeconomy services accounted for between 5.0-8.6% and 10.2-16.9% of EU27 gross domestic product and the EU27 labour force, respectively, whilst three service sectors accounted for more than 60% of bioeconomy services employment and value added. Interestingly, in the decade up to 2017, labour productivity in bioeconomy services improved.

Keywords

Bioeconomy, service, value added, employment, productivity, Europe

[13] This chapter is based on the article:
Ronzon, T., Iost, S., & Philippidis, G. (2022a). An output-based measurement of EU bioeconomy services: Marrying statistics with policy insight. *Structural Change and Economic Dynamics, 60*, 290-301. doi:https://doi.org/10.1016/j.strueco.2021.10.005

3.1 Introduction

The first bioeconomy strategy launched by the European Union in 2012 defined the bioeconomy as "the production of renewable biological resources and the conversion of these resources and waste streams into value added products" (European Commission 2012, p. 3). The strategy supported a higher sourcing of production processes with renewable biological resources and encouraged cascading uses of biomass, bio-based products and bio-based waste streams along pre-existing and novel value chains. In addition, targeted support to research and innovation aimed at bolstering the development of new bio-based products to realise a transition towards a low-carbon economy with the associated benefit of offering new market opportunities to biomass suppliers (i.e., farmers, foresters and fishers). Since 2012, the bioeconomy in Europe has gradually enhanced its credentials as a 'green growth strategy' by broadening its sphere to encompass related services activities and by integrating the notion of environmental preservation. Indeed, this more comprehensive conceptualisation is reflected in the EU's revised definition, where the bioeconomy `*includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (…); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services*'[14] (European Commission 2018b, p. 4).

The bioeconomy - in its revised definition - has become instrumental in recent EU policies, for example, for the realisation of the Circular economy action plan (International Advisory Council on Global Bioeconomy 2020), the blue (bio)economy, the forestry strategy and for the definition of the national strategic plans of the new Common Agricultural Policy (CAP). Moreover, due to its broad sectoral coverage, the bioeconomy is also pivotal for implementing the objectives of the Green Deal. Thus, the emergence and growth of the bioeconomy on the EU policy agenda triggered the need for an appropriate measurement of its size and dynamic as a basis for monitoring and impact assessments (Wesseler et al. 2017).

The international system of national accounts (SNA) and its European equivalent, the 'European System of Accounts' (ESA), are the natural frameworks for economic measurement, monitoring and international comparison. They allow for a harmonised quantification of the emblematic growth indicator of gross domestic product (GDP), of which its statistical components serve as a basis for measuring total factor productivity (TFP). As a cornerstone of macroeconomic analyses, the SNA has adapted as economic knowledge and theory has evolved. In 1957, the Solow model of growth first

[14] Biomedicines and health biotechnology are excluded.

proposed a decomposition of economic growth into the contribution of labour and capital inputs plus a residual described as TFP (Solow 1957). Subsequent growth accounting approaches have sought to reduce this residual in order to better analyse the sources of economic growth and quantify the respective contribution of factor inputs and TFP (Jorgenson 2018; Landefeld 2020). These approaches integrated the KLEMS growth and productivity satellite accounts into the ESA, in which inputs are distinguished between capital (K), labour (L), energy (E), materials (M) and service inputs (S) at the industry-level (Eurostat 2013 p. 502). The KLEMS accounts are closely linked with input-output tables, and with non-SNA complementary data sources (e.g., the Eurostat Labour Force surveys) (Koszerek et al. 2007). In sum, the joint development of economic models and the statistical framework has permitted detailed analysis on the sources of economic growth and the cross-comparison of growth trajectories (e.g. for the EU, Van Ark et al. 2017; Hartwig et al. 2019; Gordon et al. 2020; Inklaar et al. 2020; Jia et al. 2020).

The application of these theoretical growth models to conduct an analysis of the drivers of bioeconomy growth is, unfortunately, severely hampered by data gaps. More specifically, the standard international classifications of economic activities associated to the SNA and ESA frameworks[15] are inadequate for the representation of bioeconomy activities, as many traditional and nascent bio-based industries cannot be singled out from the SNA industry categories. Consequently, the reconstruction of harmonised statistics on bioeconomy activities constitutes the very first and primordial step before any economic analysis. To meet this data need, the Joint Research Center (JRC) of the European Commission has been steadily conducting quantification work on EU bioeconomy developments (M'barek et al. 2014) and most recently launched a bioeconomy monitoring system[16] (Robert et al. 2020a). Methodologies for monitoring the more recent elements of the EU bioeconomy strategy are, however, not yet fully consolidated (i.e., bio-based services, ecosystem services, and the ecological boundaries of the bioeconomy).

From a policy perspective, eleven countries[17] in the world plus the Nordic Council of Ministers and the EU mention the provision of services in their bioeconomy strategic documents (German Bioeconomy Council 2018; International Advisory Council on Global Bioeconomy 2020). However, bioeconomy services remain conspicuously absent from published economic analyses on the bioeconomy. This very same point is made in Capasso et al. (2020, section 4.2) who stress the limitation of neither considering

[15] i.e., the United Nations' International Standard Industrial Classification of all Economic Activities (ISIC) for the SNA, and the statistical classification of economic activities in the European Community (NACE) for the ESA.
[16] https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en
[17] Argentina, Brazil, Canada, Costa Rica, Finland, Germany, Latvia, Norway, Spain, Thailand and the United Kingdom.

services nor public administration in measurements of the European bioeconomy (i.e., Ronzon et al. 2018), thus biasing downward the size of the bioeconomy with respect to the rest of the economy. Therefore, the aim of this paper is to construct reliable harmonised metrics of the bioeconomy services for the Member States of the EU and to provide a preliminary assessment of the performance of said sector. The paper is structured around three research questions: (i) how to define and quantify a bioeconomy service? (sections 3.2 and 3.3), (ii) how does the aggregate of bioeconomy services sectors perform within the economy? (section 3.4.1) and (iii) what are the sectoral sources of employment and wealth creation within bioeconomy services at the EU and Member State levels? (sections 3.4.2 and 3.4.3).

Our analysis is based on the quantification of three key indicators: value added at the economic sector-level (or NACE level[18]), employment in number of persons and labour productivity. The economic growth of bioeconomy services is measured with the growth rate of the aggregated value added for all bioeconomy services sectors; the number of persons employed gives an indication of labour inputs; and the labour productivity is calculated as the ratio of these two concepts. Indeed, in the absence of data on the productivity of capital inputs or on TFP, one cannot apply the aforementioned models of growth, whilst labour productivity remains the only indicator of productivity that one can reconstruct.

To ensure a consistent and replicable application over time and across the 27 EU Member States,[19] this research proposes an SNA-compatible methodology in the sense that it follows the NACE classification (Eurostat 2008) and is principally based on Eurostat statistical data. As a result, the outcomes from this research provide an evidence-based platform for tailoring policy coherent initiatives by Member State.

3.2 Defining the study's quantification approach

In the NACE classification, service sectors are represented by the divisions G to T. This study, therefore, focuses on NACE G to T services that match the European Commission (2018b) definition of activities based on the `*use [of] biological resources and processes to produce (…) services*'[20] or on the services provided by land and marine ecosystems (dark blue frames on Figure 9). The latter includes some

[18] The Statistical Classification of Economic Activities in the European Community (NACE) is the classification in use in the European System of Accounts (ESA) (Eurostat 2008).
[19] The EU27 follows here the post-Brexit composition of the European Union, that is by excluding the United Kingdom.
[20] Biomedicines and health biotechnology are excluded.

marketed ecosystem services (e.g., nature accommodation or "forest-based recreation, sports, and outdoor activities, and educational activities that are not free of charge to the users" (FOREST EUROPE 2020). The valuation of non-marketed or extra-NACE ecosystem services is beyond the scope of this study.

The NACE divisions G to T also embed upstream bioeconomy services supply chains such as research activities or the elaboration and implementation of bioeconomy strategies by public administration (grey frame on Figure 9). In our interpretation, such activities do not directly match the European Commission (2018b) definition of bioeconomy activities which rather targets ecosystem services and biomass using services. They are however, prominent in some EU Member States' bioeconomy scope, which justifies their inclusion within our methodology (sections 3.3.4 and 3.3.5).

Note, that even enterprises producing or processing biomass (NACE A to F represented by the green frames on Figure 9) may produce some services such as forest management, within-firm R&D and many others (see the overlap between the green and light blue frames on Figure 9). These services are beyond the scope of the present study in order to avoid any double counting between the service sectors (NACE G to T) and the non-service sectors (NACE A to F).

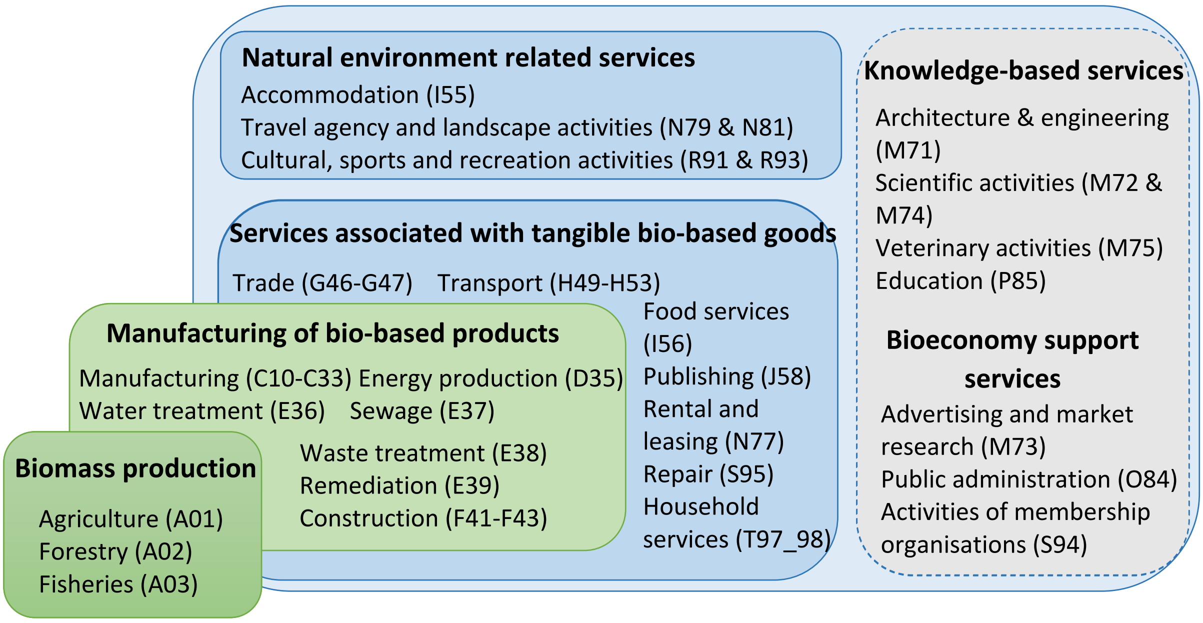

Figure 9. Categorisation of the bioeconomy activities within the NACE classification.

Note: The glossary in the supplementary material SM1 provides full details on the activities represented here by their NACE code.

There are different possible interpretable measurements of a bioeconomy service. The so-called "input-based approach" quantifies a bioeconomy service in proportion to the biomass-based inputs it uses. For example, in Robert et al. (2020b) bioeconomy publishing activities are measured in proportion to the sectors' usage of forestry, wood, paper and paper printing in total input uses from Eurostat Supply and Use tables (SUTs). Efken et al. (2016) quantify biomass input shares from cost structure statistics for services in Germany, except restaurants that are considered fully part of the bioeconomy. Kuosmanen et al. (2020, section 4) propose the use of Input-Output table (IOT) data on agriculture, forestry and fishing inputs to all economic services as a proxy for biomass input cost shares.

Also employing IOT data, Cingiz et al. (2021b) distinguish between a downstream and an upstream component in bioeconomy services. Analogous to the input-based approaches, the downstream component refers to the use of inputs from sectors considered fully belonging to the bioeconomy, namely agriculture, forestry, fishing, the printing industry and the manufacture of food, beverage, tobacco, wood products and paper. The upstream component refers to the provision of inputs to fully bioeconomy activities. In contrast with input-based approaches, the upstream component therefore includes into the bioeconomy size those service activities that use little or no biomass but contribute significantly to the input composition of fully bioeconomy sectors (e.g., banking, financial or technical advisory services). Note that a NACE sector can combine the downstream and upstream components. For example, wholesale and retail trade activities (G45-47) both use inputs from agriculture (agricultural commodities for sale) and source the agricultural sector.

Other approaches restrict the scope of bioeconomy services to the ones that match the EU or national definition of the bioeconomy. These approaches are sometimes called 'output-based' in the sense that the bioeconomy nature of a service is evaluated on the outputs' characteristics instead of on the inputs it uses. For example, Iost et al. (2019) fully include biotechnology research into their bioeconomy scope - no matter the proportion of biomass inputs used by this activity - because of the prominent place of biotechnologies in the German bioeconomy definition (German Bioeconomy Strategy 2013). As another example, the Finnish statistics define bioeconomy services as nature tourism and recreation activities as well as recreational hunting and fishing (Luke 2020). Their quantification is independent of the biomass input used by these activities, but it is derived from data on accommodation and catering in the case of nature tourism and recreation activities, and from the 'non-market output' of hunting, fishing, and aquaculture for recreational hunting and fishing.

Input approaches (or similar) offer a clear and 'systematic' measure of bioeconomy services that is applicable and harmonised across all sectors of the economy when applied to IOTs or SUTs. Rather than this systematic approach to measurement, output approaches tend to respect the specificities of each stakeholder's definition of the bioeconomy in line with adopted policy-priorities. The precision of the output method is very much dependent on data availability and on the level of data disaggregation available to determine the bioeconomy nature of services' outputs.

Following the discussion in the introduction, this study adopts a policy-driven measurement of bioeconomy services, thereby favouring an output-based approach[21] aligned with the EU and Member States' definition of the bioeconomy. For the first time, it permits the application of a comprehensive policy-oriented approach of bioeconomy services across EU Member States.

3.3 Methodology and data

3.3.1 Overall quantification approach

This chapter quantifies value added (variable 'V', expressed in million EUR), employment (variable 'E', expressed in number of people employed) and labour productivity (variable 'P', in thousand EUR per person employed) in the bioeconomy services that are reported under the NACE divisions G to T in Eurostat statistics. Similarly to the quantification performed in Chapter 2 for the non-service bioeconomy, the main challenge lies in the determination of a bio-based output share $\delta_{n,c,y}$ for adjusting official statistics to the measure of bioeconomy services only, where *n* denotes the NACE division level, *c* the country (i.e., the EU27 and the 27 Member States) and *y* the year (y=2008, …, 2017) (see sections 3.3.2 to 3.3.5).

Bio-based output shares $\delta_{n,c,y}$ are retrieved from biomass contents published in the scientific literature or otherwise derived from Eurostat statistics. In the latter option, the precision in the quantification of $\delta_{n,c,y}$ depends on the granularity of statistical data available. Bio-based output shares are preferably determined at the NACE sub-division level data *m* (3- or 4-digit code) and then aggregated to the 2-digit NACE level *n* (equations (1) and (2) in Chapter 2). $\delta_{n,c,y}$ differs when calculated on employment data versus on value added data if the employment distribution across sub-divisions differs from the value added distribution (equation (3) in Chapter 2). The value added, employment and labour productivity of bio-based services is derived according to equations (4), (5) and (6) introduced in Chapter 2 (where the prefix bb of each indicator refers to its 'bio-based' component):

[21] The case of food and beverage services (e.g., restaurant activities) illustrates our choice: an input approach would quantify the value added contribution of this sector to the bioeconomy in proportion of the biomass inputs it uses in total inputs (including, for example, machinery or energy); the consideration of an upstream component like in Cingiz et al. (2021b) would add value added in proportion of the inputs provided by food and beverage services to biomass producing sectors in their total inputs; an output approach would attribute all the value added generated by food and beverage services to the bioeconomy (Iost et al. 2019) because this activity matches the EU policy definition to an activity that `*use biological resources [edible biomass] to produce a service [the serving of food and beverages]'*.

$$bbV_{n,c,y} = \delta^{VA}_{n,c,y} \times V_{n,c,y} \quad (4)$$

$$bbE_{n,c,y} = \delta^{E}_{n,c,y} \times E_{n,c,y} \quad (5)$$

$$bbP_{n,c,y} = bbV_{n,c,y} \ / \ bbE_{n,c,y} \quad (6)$$

Given the availability of NACE disaggregation, panel data for variables V and E are taken from Eurostat structural business statistics (column 3 of Table 4, Eurostat (2022e, 2022d)). Moreover, Eurostat national accounts are employed to complement the NACE divisions not represented in the Eurostat structural business statistics (column 3 of Table 4, Eurostat (2022l, 2022k)). The observation period runs from the most recent NACE classification revision (2008) to the latest available year at the time of publishing this chapter (2017). Note that value added is reported in nominal prices in these data sources.

When bioeconomy services cannot be clearly delimited in available statistics, a low and a high estimation of $\delta_{n,c,y}$ or $\delta_{m,c,y}$ is calculated, referred to as a minimum-maximum range in the text (see summary of assumptions in column 2 of Table 4 and details in sections 3.3.2 to 3.3.6). Variables estimations are made as 3-year averages to reduce year-specific bias (i.e., 2008-2010 and 2015-2017), except for the computation of annual growth rates.

The following sections describe the assumptions underlying the quantification of $\delta_{n,c,y}$ according to the different types of bioeconomy services identified in section 3.2 (see also Figure 9): "services associated with tangible bio-based goods" are addressed in section 3.3.2, "natural environment-related services" in section 3.3.3, “knowledge-based services in the field of the bioeconomy” in section 3.3.4 and “support services for the development of bio-based markets” in section 3.3.5.

Table 4. Data sources for the quantification of sectoral output bio-based shares, value added and number of persons employed in the bioeconomy (sector n, country c, year y).

NACE division - short name	**Range of bio-based output shares $\delta_{n,c,y}$ and/or $\delta_{m,c,y}$ or literature source** ('n' denotes 2-digit NACE codes, `m' denotes 3- or 4-digit NACE codes)	**Eurostat source for value added $V_{n,c,y}$ & employment $E_{n,c,y}$**
G45 – trade/repair vehic.	0%	
G46-H53 - Trade and transport	Product bio-based shares from nova-Institute*, otherwise 0-100%	sbs_na_dt_r2, sbs_na_1a_se_r2
I55 - Accommodation	Eurostat tour_occ_ninatd for I551-I553 (section 3.3.3)	sbs_na_1a_se_r2
I56 - Food services	100%	sbs_na_1a_se_r2
J58 - Publishing	0% J582, 0-100% J5811-J5814 and J5819	sbs_na_1a_se_r2
J59-M70 – ICT, finance…	0%	-
M71 - Architecture and engineering	Same bio-based share as F41-F43 for M711 (section 3.3.4)	sbs_na_1a_se_r2
M72 – Scientific R&D	100% M7211, 0-100% M7219	sbs_na_1a_se_r2
M73 - Market research	0-100% M732	sbs_na_1a_se_r2
M74 - Other scientific	0-100% M741, M749	sbs_na_1a_se_r2
M75 - Veterinary	100%	sbs_na_1a_se_r2
N77 - Rental and leasing	G46-G47 bio-based share for N7729 (section 3.3.2) 0-100% N7739	sbs_na_1a_se_r2
N78 - Employment	0%	-
N79 - Travel agency	0%-(I551-I552) share (section 3.3.3)	sbs_na_1a_se_r2
N80 - Security	0%	-
N81 - Landscape	100% N813	sbs_na_1a_se_r2
N82 - Business support	0%	-
O84 - Public administration	Minimum share=0%, maximum share from gov_10a_exp (section 3.3.5)	nama_10_a64
P85 - Education	Eurostat educ_uoe_fine04, educ_uoe_perp02, educ_uoe_grad02 (section 3.3.4)	nama_10_a64
Q86-Q88 – Health, social	0%	-
R90-R92 - Art, culture	Minimum share=0%, maximum share from cult_emp_n2 (section 3.3.3)	nama_10_a64
R93, S94 - Sport, organis.	0-100%	nama_10_a64
S95 - Repair	Sector bio-based share of the product repaired*, 0-100% S9525 (section 3.3.2)	sbs_na_1a_se_r2
S96 - Personal service	0%	nama_10_a64
T97-T98 – Household services	0-100%	nama_10_a64

*See Ronzon et al. (2023)

Note: The NACE groups (3-digit NACE codes) and classes (4-digit NACE codes) that are not reported on the table do not belong to the bioeconomy (i.e., $\delta_{m,c,y}$=0%). The glossary at supplementary material SM1 provides the full label of the activities represented here by their NACE code.

3.3.2 Bioeconomy services associated with tangible bio-based goods

This category includes trade (G46-G47), transport (H49-H53), rental and leasing (N77) and repairing (S95) of bio-based products, food services (I56), publishing activities (J58) and some household services (T97_98). In the authors' view, these activities match the EU definition of using biological resources for the production of a service. Following an output-based approach, we consider these services part of the bioeconomy to the extent to which the product they are associated with is of biological origin (i.e., bio-based output share $\delta_{n,c,y}$ = biomass content of the associated product). For instance, the $\delta_{m,c,y}$ of wholesaling textile is equal to the biomass content of textile. Concretely:

- For trade, transport, rental and leasing and repairing: minimum and maximum $\delta_{n,c,y}$ of bio-based products are taken from Ronzon et al. (2020) and otherwise assumed unknown ($0\%<\delta_{n,c,y}<100\%$).
- For food services: $\delta_{n=I56,c,y}=100\%$ as the food output is fully (edible) biomass.
- For publishing activities $\delta_{m=J852,c,y}=0\%$ for software publishing since the output is virtual; $0\%<\delta_{m,c,y}<100\%$ for other publishing activities since publishing in print cannot be distinguished from electronic, audio or online publishing in available statistics (see NACE J58 4-digit codes in column 2 of Table 4).
- For household services: $0\%<\delta_{n=T97\_98,c,y}<100\%$ as available statistics do not distinguish between the production of bio-based and other types of products from household activities.

3.3.3 Natural environment-related services of the bioeconomy

This category includes rural accommodation (I55), travel agency activities (N79), landscape service activities (N813) and cultural, (outdoor) sports and recreation activities (R90-R93). More specifically, it refers to the marketed services provided by land and marine ecosystems in the EU bioeconomy definition and those that are not accounted for in section 3.3.2. Landscape service activities (N813) create or maintain ecosystems (e.g., planting, care and maintenance of parks and gardens) while rural accommodation and travel agency activities are classified as beneficiaries of outdoor recreation services (La Notte et al. 2017, p. 70).

Due to the intangible nature of the services of the present category, their bio-based output share cannot refer to their biomass content as for the previous category. They rather correspond to the use of or the valuation of (semi-) natural environments. Concretely:

- For accommodation services: $\delta_{n=I55,c,y}$ is the proportion of nights spent in rural areas (100% natural environment) and towns and suburbs (arbitrarily set as 25-75% natural environments by the authors), using Eurostat (2022c) data at the NACE 3-digit level.[22]

- For travel agencies: $\delta_{n=N79,c,y}$ is the combined bio-based output share of hotels and short-stay accommodations in rural areas (I551-I552) in the absence of ad hoc data.

- For services to building and landscape activities: $\delta_{n=N81,c,y}$ is based on landscape service activities only ($\delta_{m=N813,c,y}$ =100%).

- For sport and recreation: 0%<$\delta_{n=R93,c,y}$<100%, the proportion of outdoor sports activities being unreported.

- For arts, cultural and entertainment activities: within this aggregate only NACE R91 matches a bioeconomy definition (to an unknown proportion) with the sub-activities of libraries (the output "printed books" are essentially bio-based), botanical and zoological gardens and nature reserves activities (natural environment related services). The maximum $\delta_{n=R90\_92,c,y}$ is the proportion of people employed in NACE R91 (Eurostat (2022b) data) on total R90_92 workers (Eurostat (2022k) data). The minimum $\delta_{n=R90\_92,c,y}$=0% in the absence of better data.

3.3.4 Knowledge-based services in the field of the bioeconomy

This category includes architecture and technical consultancy (M71), scientific activities (M72, M74), veterinary activities (M75) and education (P85). In the authors' view, it does not directly link with the EU definition of bioeconomy sectors as it neither refers to an ecosystem service nor to an activity that uses biological resources to produce a service. However, bioeconomy knowledge-based activities (e.g., in life sciences) are integrated into other bioeconomy initiatives. Notably, the bioeconomy concept first reached the EU policy agenda under the name of knowledge bio-based economy (KBBE) and the EU bioeconomy has mainly been supported by research and innovation policies (Birner 2018; Patermann et al. 2018; Kardung et al. 2019). The output of knowledge activities cannot be measured with a biomass content, but rather by determining the proportion of knowledge or knowhow created or disseminated in bioeconomy-related disciplines. Concretely:

- For veterinary activities: $\delta_{n=M75,c,y}$=100% since they deliver knowhow in bioeconomy disciplines (e.g., zoology or husbandry) besides being based on life science knowledge.

[22] Nights spent in cities are not considered bio-based because in this case the accommodation activity is not related with any sort of valorisation of natural environment.

- For architectural activities: $\delta_{n=M711,c,y} = \delta_{n=F,c,y}$, architectural activities are considered bio-based to the same extent construction activities are in Chapter 2 which also follow an output-based approach (Ronzon et al. 2022b).
- For scientific activities: scientific disciplines are classified as 100% bio-based, 0-100% bio-based and 0% bio-based (see NACE M72 and M74 3 and 4-digit codes in column 2 of Table 4).
- For education : the employment $\delta_{n=P85,c,y}$ is the multiplication of the number of teachers and academics teaching at graduating level[23] (Eurostat 2022a) with the proportion of graduates in bioeconomy fields (Eurostat 2022o). The value added $\delta_{n=P85,c,y}$ is the multiplication of the proportion of public expenditure in graduating educational levels with the proportion of graduates in bioeconomy fields (Eurostat 2022o, 2022n). Graduates in bioeconomy fields are reported in Eurostat (2022o), considering that fully bioeconomy disciplines are biological sciences, food processing and agriculture, forestry, fisheries and veterinary. 0-100% bioeconomy-related disciplines are economics, political sciences, environment, earth sciences, statistics, environmental protection technology, electricity and energy, glass, paper, plastic and wood materials, textiles, architecture and building and civil engineering.

3.3.5 Support services for the development of bio-based markets

This category includes advertising and market research (M73), public administration (O84) and activities of membership organisations (S94). Activities in support of bio-based markets are sometimes accounted for as bioeconomy activities, although not explicitly mentioned in the EU bioeconomy strategy.

Available statistics do not indicate the relationship between market research and membership organisation with bio-based products or bioeconomy-related organisations. We therefore consider $0\%<\delta_{n,c,y}<100\%$ for these sectors of activities.

The bio-based output share of public administration corresponds to the proportion of activities realised in bioeconomy domains, such as the administration of programmes in support of the development of the bioeconomy or of bioeconomy sub-sectors (e.g., agricultural policy). Correspondence tables between the NACE classification and the classification of the functions of government (COFOG) (Eurostat 2011) only reveal a list of a few non bio-based 'functions of government',[24] for which government expenditure are reported (see supplementary material SM4).

[23] Upper secondary and tertiary level.
[24] For example, public debt transactions (COFOG GF0107), military defence (GF0201) or social protection (GF1009).

This leads to an over-estimate maximum $\delta_{n,c,y}$ of employment in public administration with the ratio of compensation of employees that do not work in the non bio-based COFOGS over the total (Eurostat (2020a, 2022l) data). A similar approach is undertaken for the calculation of the value added $\delta_{n=O84,c,y}$ (see supplementary material SM5 for more details). Both the employment and value added minimum are set to zero ($\delta_{n=O84,c,y}$=0).

3.3.6 Non bioeconomy services

The NACE divisions of services that do not fall into any of the categories described in sections 3.3.2 to 3.3.5 are excluded from the bioeconomy scope ($\delta_{n,c,y}$=0% on Table 4).

3.4 Results and discussion

3.4.1 Economic and labour productivity growth in European bioeconomy services (2008-2017)

To put our data into context, Figure 10 (a) shows the development of real value added and labour productivity growth for the total EU27 economy. The indicators swings coincide with two crises over the period of observation: the value added growth plunged to a -4.3% rate between 2008 and 2009 as a consequence of the 2008-2009 global financial crisis and again to -0.59% per annum after the 2010-2011 Euro area recession. Economic recovery happens after 2012 and value added stabilises between a 2%-3% annual growth rate at the end of the period (2015-2017). Labour productivity which is a factor of economic growth followed similar developments. Its contribution to value added growth is enhanced after 2012 when employment trends in the total number of persons employed becomes positive (not shown).

If we focus our attention on the categories of bioeconomy services directly linked to the EU (2018) definition, Figure 10 (b) shows that this aggregate of sectors has reacted differently to crises in the EU27. It has been less affected by the 2008-2009 financial crisis than the total EU27 economy aggregate but it has suffered from the general economic downturn. The crisis and its aftermath are characterised by a no-growth period in bioeconomy services (value added and labour productivity growth varying between 0% and -1% per annum). Already vulnerable, bioeconomy services are then hit harder by the 2010-2011 Euro area recession and the indicators of value added and labour productivity growth plunge by -3.1% and -2.7%, respectively, in 2012. Within this aggregate, the services associated to bio-based tangible goods deteriorate most (i.e., trade, transport, rental, repairing of bio-based products, food services, publishing activities and some household services).

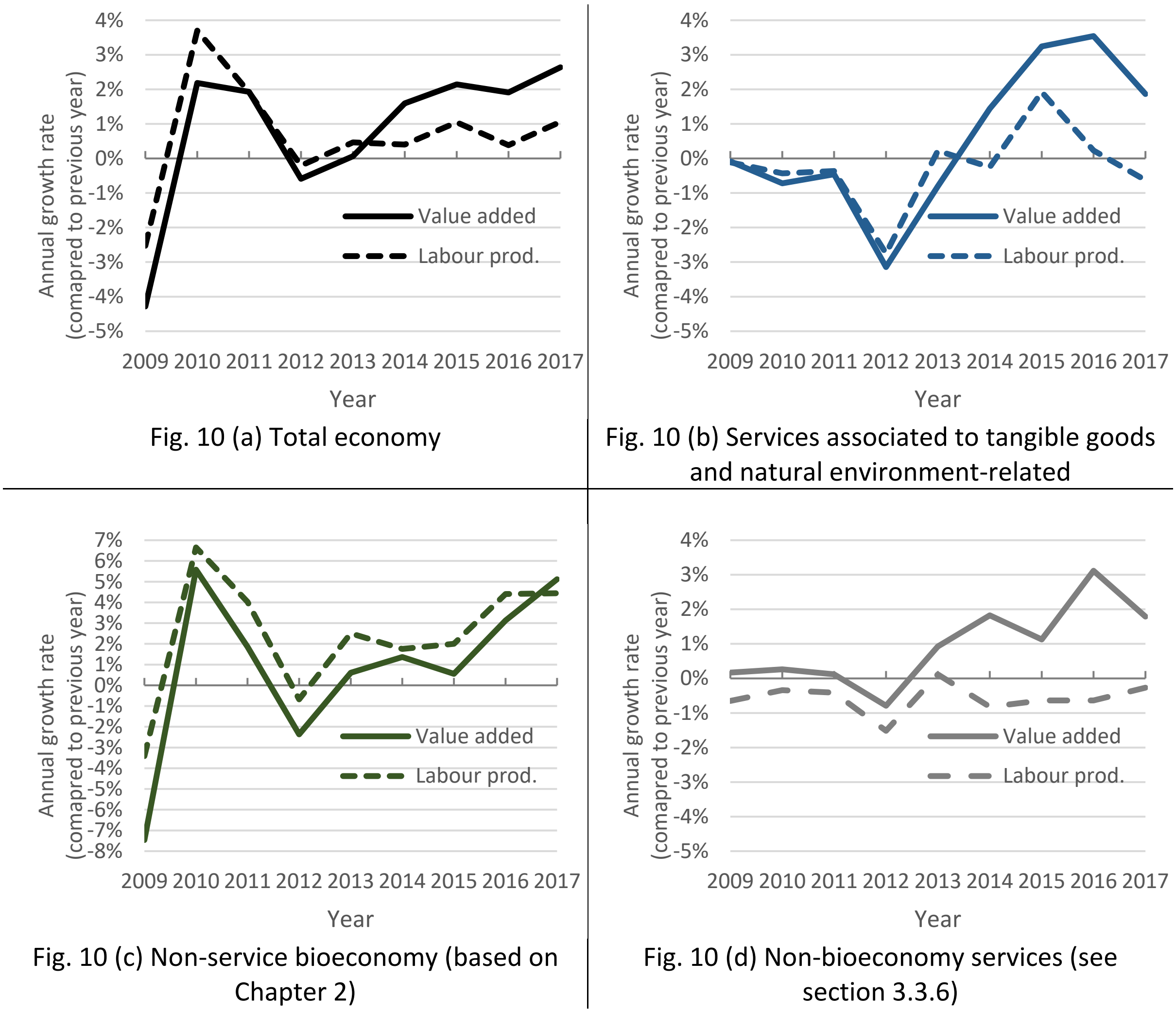

Fig. 10 (a) Total economy

Fig. 10 (b) Services associated to tangible goods and natural environment-related

Fig. 10 (c) Non-service bioeconomy (based on Chapter 2)

Fig. 10 (d) Non-bioeconomy services (see section 3.3.6)

Figure 10. Annual growth rate of real value added and labour productivity for (a) the total economy and selected sub-sets of sectors: (b) the bioeconomy services directly linked to the EU definition, (c) the non-service bioeconomy sectors and (d) the services sectors that are not related with the bioeconomy.

Note: Price index deflator based on the 2010 reference year (Eurostat nama_10_gdp). Calculations based on maximum bio-based output shares $\delta_{c,y,n}$ for a major sector coverage.

After 2012, the total number of persons employed in bioeconomy services starts growing again and amplifies the positive effect of improving labour productivity on value added growth. Bioeconomy services flourish relatively to the whole economy: their value added growth is 0.7 percentage points higher than in the total economy (2015-2017). Interestingly, this observation can be generalised to 21 of the 27 EU Member States (not shown). Maximum differences are observed in Portugal and Romania where value added growth is 4.6 and 6.1 percentage points higher in bioeconomy services than in total national economy. At the other extreme, a difference of -8.8 and -3.0 percentage points is observed in Ireland and Estonia.

Similar trends also hold for a broader coverage of bioeconomy services (i.e., by including the bioeconomy knowledge-based services and the services in support to bio-based markets). They are consistent with Van Ark et al. (2017)'s observation that the EU services sector (bioeconomy and non-bioeconomy included) tended to increase its importance in the economy, and to recover slightly better from the crisis.

Compared to the non-bioeconomy services performance in Figure 10 (d), the aggregate of bioeconomy services in Figure 10 (b) reacted more negatively to the Euro area recession (-3.14% vs. -0.79% of value added growth between 2011 and 2012) but they demonstrated capacity for improving labour productivity in the following years. In contrast, in non-bioeconomy services, the negative labour productivity growth since 2013 has acted as a break on their value added growth.

Finally, from a quick comparison with the non-service bioeconomy's dynamic shown in Figure 10 (c), one cannot clearly discern whether bioeconomy services follow or lead the rest of the bioeconomy. They have been more resilient to the 2008-2009 crisis but they underwent a similar negative value added growth rate in 2012. Both aggregates of sectors recover at a similar pace immediately after 2012. However, after 2015 bioeconomy services' growth has been limited by its reduced labour productivity while non-service bioeconomy value added growth is driven by its increasing labour productivity.

3.4.2 Bioeconomy services within the EU economy

The dynamic of bioeconomy services is largely influenced by their relative size within the broader economy and by their economic structure. Our calculations confirm the significant share of bioeconomy services within the EU's economic activity, whilst further suggesting that this influence is growing over time. Indeed, if we restrict the scope of bioeconomy services to the services associated to tangible goods or related to the natural environment (direct match with the EU definition), we find that they contributed between 5.0-8.6% of EU GDP and between 10.2-16.9% of the EU labour force on average between 2015 and 2017 (i.e., EUR 563-967 billion of annual value added and 20-33 million workers, Table 5). Comparing 2017 with 2008 highlights economic growth and employment creation. More specifically, the collective of bioeconomy services created between EUR 68 and 89 billion of additional annual value added, and between 1.37 and 1.38 million additional workers. This has resulted in per worker labour productivity gains of between EUR 1,000 and 2,000. However the aggregate labour productivity of bioeconomy services remains slightly below non-service bioeconomy labour productivity (approximatively EUR 30,000 of value added per worker vs. EUR 35,000 per worker in Chapter 2 (Ronzon et al. 2022b).

Still restricting the scope of bioeconomy services to the services associated to tangible goods or related to the natural environment (direct match with the EU definition), three sectors account for more than 60% of the value added and employment in EU27 bioeconomy services considering both minimum and maximum estimates, namely wholesale and retail trade of bio-based products, and the food and beverage service activities. Food services were a motor of employment growth and the main contributors to value added increases (net employment rise of 900,000 workers and EUR +20 billion of annual value added in the decade up to 2017, Table 5). The evolution of retail trade of bio-based products has been more stable while wholesale activities employed 100,000 persons less at the end of the observed period according to our maximum estimate (vs. +18,000 according to our minimum estimate).

Accounting for less than 7% the value added and employment of services associated to tangible goods or related to the natural environment in 2017, the sport and recreation sector strongly contributed to growth (EUR +€14 billion value added, +211,000 workers in maximum estimates). Accommodation also played a strong employment role, ending with around 90,000-130,000 additional workers at the end of the period.

Note that bioeconomy knowledge-based services and bioeconomy support services would add 0.2-5.7% of GDP and 0.3-5.6% of total employment. The latter are not well represented in our calculations[25] and not explicitly mentioned in the EU bioeconomy strategy.

[25] The minimum quantification of services in support of bio-based markets was set to zero in the absence of more precise information, thereby excluding the market-supporting sectors from the minimum estimation. One can only infer that these services – advertising and market research, public administration and activities of membership organisations in bioeconomy fields – generate less than EUR 531 billion of value added (4.7% of the EU27 GDP) and employ less than 8.7 million workers (4.5% of the EU27 labour force). The (over-estimated) public administration in support of the bioeconomy accounts for 85% of value added and 75% of employment in bio-based market support services.

Table 5. Value added, employment and labour productivity in bioeconomy services in 2008-2010 and 2015-2017 (3-year averages, output approach).

	Value added (billion EUR)				Number of people employed (thousand)				Labour productivity (thousand EUR per person employed)			
	av. 2008-2010		av. 2015-2017		av. 2008-2010		av. 2015-2017		av. 2008-2010		av. 2015-2017	
	min	max	min	max	min	max	min	max	min	max	min	max
Associated with tangible bb goods	**452**	**752**	**511**	**813**	**16,918**	**27,704**	**18,116**	**28,612**	**27**	**27**	**28**	**28**
G46 - Wholesale	138	226	155	244	2,787	4,697	2,826	4,584	50	48	55	53
G47 - Retail trade	113	182	125	198	5,370	8,469	5,452	8,488	21	21	23	23
H49 - Land transport	27	43	30	47	936	1,506	1,010	1,595	28	29	30	30
H50 - Water transport	4	7	4	6	36	60	34	53	114	114	110	113
H51 - Air transport	-	-	-	1	4	6	4	6	58	58	104	105
H52 - Warehousing	39	64	45	71	727	1,173	805	1,272	54	55	56	56
H53 - Postal activities	14	22	14	22	509	821	520	821	27	27	26	26
I56 - Food services	115	115	135	135	6,475	6,475	7,382	7,382	18	18	18	18
J58 - Publishing	-	33	-	29	-	622	-	549	-	53	-	52
N77 - Rental and Leasing	1	15	2	15	26	136	33	168	51	108	50	88
S95 - Repairing	1	1	1	1	50	86	50	85	15	15	15	15
T97_98 - Households services	-	44	-	44	-	3,654	-	3,608	-	12	-	12
Natural environment-related	**42**	**125**	**52**	**154**	**1,407**	**3,489**	**1,593**	**3,946**	**30**	**36**	**32**	**39**
I55 - Accommodation	23	32	28	40	830	1,142	920	1,272	27	28	31	31
N79 - Travel agency	7	10	8	12	182	246	185	253	41	41	46	46
N81 - Landscape activities	12	12	15	15	396	396	488	488	29	29	30	30
R90_92 - Libraries and cultural	-	22	-	24	-	493	-	509	-	44	-	48
R93 – Sport and recreation	-	50	-	63	-	1,212	-	1,423	-	41	-	44
Bioeconomy knowledge-based	**22**	**86**	**26**	**109**	**470**	**1,956**	**549**	**2,205**	**46**	**44**	**48**	**50**
M71 - Architecture	6	7	7	8	123	130	132	139	51	51	56	56
M72 - Scientific R&D	2	18	3	29	44	394	63	454	53	46	52	64
M74 - Other scientific service	-	23	-	30	-	611	-	738	-	38	-	41
M75 - Veterinary	5	5	7	7	155	155	196	196	34	34	34	34
P85 - Education	8	33	9	36	148	666	158	678	53	49	58	53
Bioeconomy support services	**-**	**472**	**-**	**531**	**-**	**8,579**	**-**	**8,668**	**-**	**55**	**-**	**61**
M73 - Market research	-	7	-	6	-	153	-	136	-	43	-	44
O84 - Public administration	-	403	-	448	-	6,476	-	6,463	-	62	-	69
S94 – Membership organisations	-	63	-	77	-	1,950	-	2,068	-	32	-	37
Bioeconomy services	**516**	**1,435**	**589**	**1,607**	**18,795**	**41,728**	**20,258**	**43,429**	**27**	**34**	**29**	**37**

3.4.3 Bioeconomy services in EU Member States' economies

The contribution of services associated to tangible goods or related to the natural environment varies across EU Member States between 3.0% and 14.5% of GDP and between 5.8% and 27.6% of total employment.

From a sectoral perspective, similar to the EU27 picture commented in section 3.4.2, the wholesale and retail trade of bio-based products are strong pillars of the bioeconomy in EU Member States, contributing each to more than 10% of the total bioeconomy service value added and employment in all Member States (supplementary material SM6). Food and beverage service activities also play a strong employment role (15-47% total employment except in Portugal with 10-18%) and provide more than 10% of bioeconomy services' value added in almost all Member States.

Figure 11 maps the amount of value added generated per worker in the four categories of bioeconomy services quantified in this study (maximum estimate, 2015-2017). A gradient of labour productivity is visible from left to right with services associated with bio-based products being the least labour productive and bioeconomy supporting services being the most productive (columns 1 and 4 in Figure 11).

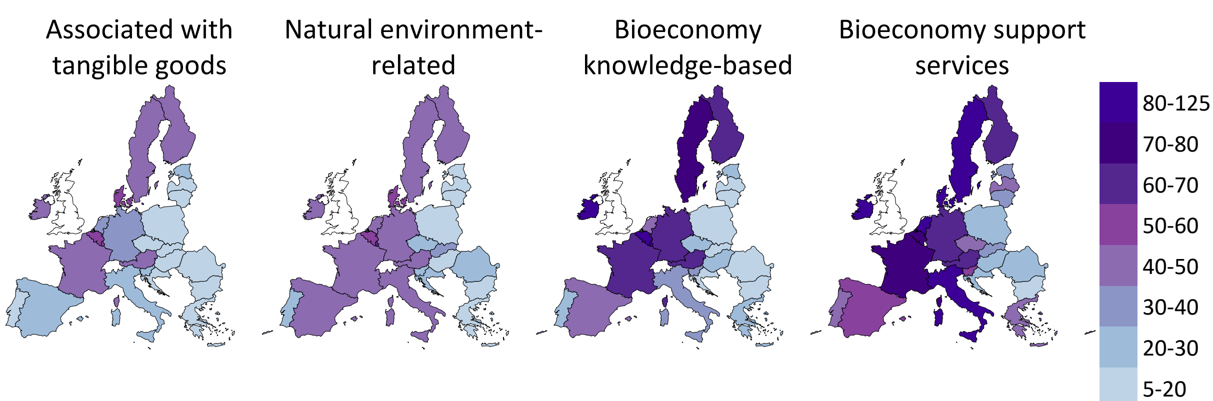

Figure 11. Labour productivity of EU Member States' bioeconomy services in EUR 1,000 per persons employed (maximum estimates, 2015-2017).

Note: Minimum estimates are not shown as they convey messages similar to maximum estimates.

Aside from the heterogeneous outcomes across EU Member States, the map highlights an East-West difference in labour productivity performance. On the one hand, the bioeconomy services of Bulgaria, Croatia, Hungary, Poland and Romania remain below EUR 30,000 per person employed in all four types of services. The same happens in Baltic countries, Czechia, Greece and Portugal if one excludes bioeconomy support services. On the other hand, labour productivity exceeds EUR 40,000 per worker in services related to bio-based products and with the natural environment in Austria, France, Finland and Sweden and exceeds EUR 50,000 per worker in Belgium, Denmark and Luxembourg. In all these Member States plus Germany and Ireland, labour productivity of knowledge and bioeconomy support services is above EUR 60,000 per worker.

3.4.4 Discussion of the results and the methodology

To the best of the authors' knowledge, there is no other published attempt to quantify the size of bioeconomy services in Europe employing an output-based approach. A principle observation is that the estimates presented here – i.e., EUR 589-1,607 million of value added and 19-42 million workers in the broad bioeconomy definition – are far higher than with the input-based approach presented in Kuosmanen et al. (2020, section 4) which estimate approx. EUR 370 billion of value added and 8.5 million workers in the EU28 bioeconomy services sectors of NACE G to T divisions. The difference arises from a low use of bio-based inputs into total inputs by the services industries. Indeed, the bio-based input shares are inferior to 8% in NACE G to T sectors in the above-cited study (EU28, 2015). The only exception is accommodation and food services with a bio-based input share of 35% for the EU28 (2015), which nevertheless remains below the bio-based output share quantified in the present study (i.e., 39-55% for accommodation and 100% for food services in EU27 (2015)). The split between service and non-service bioeconomy sectors following the approach by Cingiz et al. (2021b) was not publicly available at the time of publishing this study. Comparisons are made in Chapter 4, which has been written more recently.

Interestingly, our most conservative quantification (i.e., the minimum range) of bioeconomy services' value added is comparable in size with the value added of the non-service bioeconomy quantified in Chapter 2 (Ronzon et al. 2022b). The employment size of bioeconomy services, measured in number of workers, is even bigger than the one of the non-service bioeconomy. In sum, the integration of bioeconomy services into the updated EU bioeconomy strategy more than doubles the value added and employment size of the bioeconomy compared to the initial strategy definition.

The choice of methodology and associated assumptions does, however, give rise to uncertainty in the estimates. The precision of the estimates is highly dependent on the level of granularity with which bioeconomy fields of activities are represented in official statistics. In the best case, some bioeconomy services or sub-activities can be directly based on Eurostat structural business statistics or national accounts databases and compiled as such in our study ($\delta_{n,c,y}$=100% in Table 4). In the worst case, the broadness of the NACE categories and the scarcity of detailed data from other official statistics permitting their disaggregation at the Member State level, impedes the determination of bio-based output shares ($0<\delta_{n,c,y}<100\%$ or $0<\delta_{m,c,y}<100\%$ in Table 4). Supplementary material SM7 summarises the dispersion of bio-based output shares for the period 2015-2017 (3-year averages) by bioeconomy service sector *n* using the value added (V) or employment (E) data source for calculation. Figure 12 highlights those NACE sectors that show a difference higher than 25 percentage points between the minimum and maximum EU share (coloured dots), both when calculated in value added and in employment terms. These sectors are publishing (J58), scientific activities (M72 and M74), public administration (O84), cultural, (outdoor) sports and recreation activities (R90-R93), membership organisations (S94) and household services (T97_98). In three of these sectors (R93, S94 and T97_98), only the maximum shares ($\delta_{n,c,y}$) could be quantified, whilst the minimum shares were set to zero.

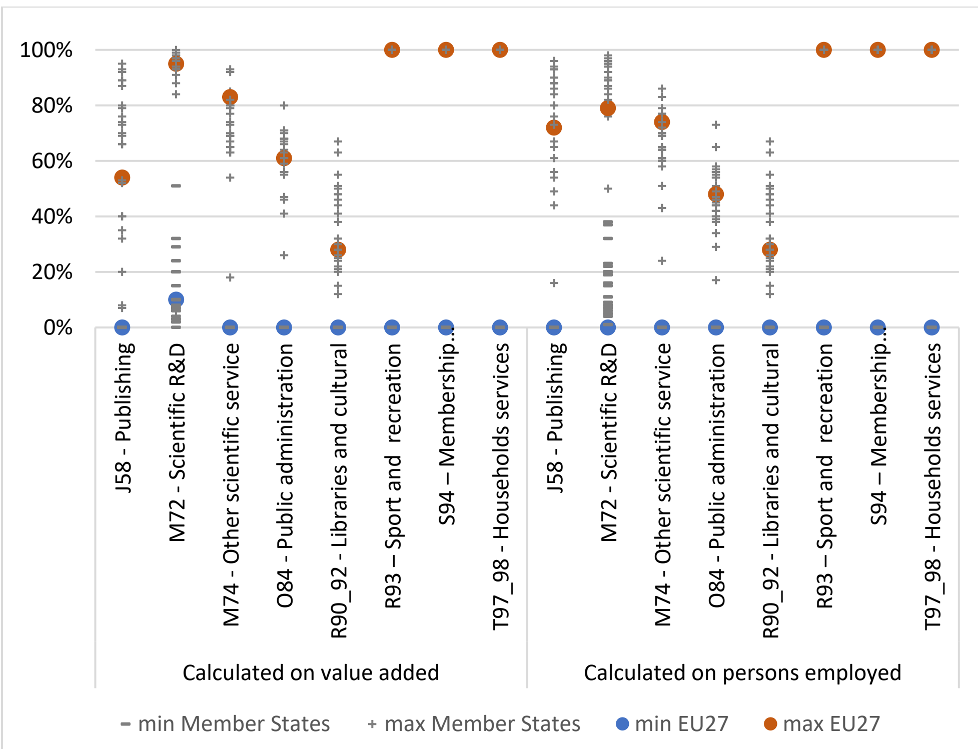

Figure 12. Ranges of employment (E) and value added (V) shares ($\delta_{n,c}$) for the bioeconomy services with a difference higher than 25 percentage points between their minimum and maximum $\delta_{n,c,y}$ in the EU27 (y=average 2015-2017), and EU Member States distribution.

Notes: $\delta_{n,c,y=av.2015\text{-}2017}$ are represented with large blue (for minimum) and orange (for maximum) dots for the EU27, and with `-' (minimum $\delta_{n,c,y=av.2015\text{-}2017}$) and `+' (maximum $\delta_{n,c,y=av.2015\text{-}2017}$) points for the EU Member States. For example, calculated on value added data, $0\%<\delta_{n=J58,y=av.2015\text{-}2017}<54\%$ for the EU27 (large blue and orange squares) and $0\%<\delta_{n=J58,y=av.2015\text{-}2017}<95\%$ in Member States (distribution range of `-' and `+' points).

Figure 13 provides an uncertainty chart that reports the difference between the minimum and maximum value of value added (x-axis) and employment (y-axis) quantified for bioeconomy services. The sectors with the biggest minimum-maximum ranges both for employment and value added are positioned at the top-right corner. Among them, wholesale and retail trade activities (n=G46 and G47) were not identified at Figure 12 among the sectors with a weak representation of their bioeconomy sub-activities in European statistics. Their large economic and employment size implies that slight variations in bio-based shares can result in large variations in their bioeconomy size. Interestingly, three of the five sectors in the top-right corner are "bioeconomy services associated with tangible bio-based goods". Positioned in the bottom left corner, water and air transport (H50, H51), architectural and engineering activities (M71), veterinary activities (M75), travel agencies (N79) and repair of household goods (S95) are quantified with more precision.[26]

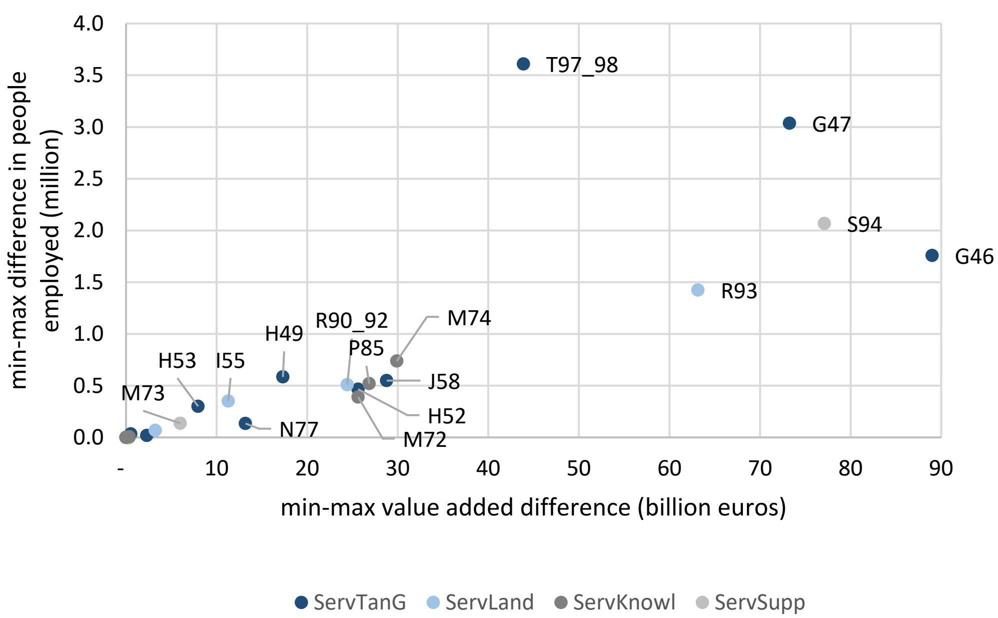

Figure 13. Uncertainty chart associated to the quantification of the value added (x-axis) and employment (y-axis) in bioeconomy services in the EU27 (difference between the minimum and maximum quantification, 3-year averages 2015-2017).

Note: The position (447; 6.5) of O84 is out of scale.

Some methodological assumptions made in this paper are still a matter of debate and could be considered differently in other contexts or by other stakeholders. As introduced in section 3.3.4, veterinary activities

[26] These four sectors of the bottom left corner are not explicitly identified in Figure 13 due to space considerations.

(M75) are given the same treatment as the scientific activities classified under the NACE codes M72 and M74, considering that all three categories deliver knowledge and knowhow in the domain of life science. As a result, the employment and value added generated by veterinary activities is included as part of the bioeconomy's performance. As pointed by an anonymous reviewer, another approach could have been to consider veterinary activities as an input provider to agriculture (A01) to the same extent as any other non-biomass input provider (e.g., machinery). Under that alternative assumption, veterinary activities would not have contributed to the bioeconomy's performance. This particular point of debate demonstrates that the delimitation of the bioeconomy's scope remains under scrutiny.

The distinction between services provided by natural versus biological environments is another point of debate. While Finnish statistics on the bioeconomy include the employment and value added generated by non-bio renewable energies (e.g., from wind or solar resources in Luke (2020)), the present paper takes a stricter interpretation of the bioeconomy where only biological-based services are included.

Finally, there is the issue of regulating the management and protection of natural environments through the correction of market externalities that commonly arise from the use of public goods. For example, private beneficiaries of natural areas such as hotels, campsites (I55) and providers of outdoor sports and recreation activities (R90-R93) may well play an active role in the preservation of the recreational ecosystem services, either directly by participating to local maintenance programs, or indirectly via payment for ecosystem services programs or political engagement. But they also may contribute to the degradation of the natural areas on which their business depends (Capasso 2021, section 3.1). Examining the issue of market regulation, Mauerhofer et al. (2013), posit the use of polluter pays principle and payments for ecosystem services market instruments as complementary measures for internalising the capital costs of such ecosystem services. Moreover, in a bid to increase transparency, further initiatives seek to place monetary value on ecosystem services through the establishment of ecosystem accounts that are compatible with the classical national accounts (e.g., the United Nations' System of Environmental Economic Accounting[27] (SEEA) or the European Integrated system of Natural Capital and ecosystem services Accounting (INCA)). According to the latest edition of the European accounting for ecosystem services, the value of recreational ecosystem services in the EU28[28] is as high as EUR 80.3 billion (Vysna et al. 2021). The integration of the value of ecosystem services to the total value generated by the

[27] https://seea.un.org/
[28] The EU28 corresponds to the composition of the European Union before the withdrawal of the UK on 1 February 2020.

bioeconomy represents an important research avenue and would better reflect the EU definition of the bioeconomy that explicitly includes the services provided by land and marine ecosystems.

3.5 Conclusion

Employing a mix of policy insight and Eurostat statistics, this study tests an output-based methodology for measuring and monitoring the value added and employment size of bioeconomy services. Despite uncertainty issues, our results highlight the growth potential and the considerable size of the bioeconomy services sector. Excluding the crises and post-crisis periods and judging on the most stable part of our period of observation (2015-2017), the aggregate of bioeconomy services exhibited stronger value added and labour productivity growth than the total economy aggregate at the EU level and in a large majority of Member States. The bioeconomy services directly matching the recently extended EU definition account for 5.0-8.6% of the EU27 GDP and 10.2-16.9% of the EU27 labour force. The lower range estimate is comparable in size with the non-service bioeconomy as quantified with a similar methodology in Chapter 2 (Ronzon et al. 2022b). The maximum range is almost double the value added size and more than double the employment size of the non-service bioeconomy. These proportions are likely to grow and labour productivity to improve in the future if past trends continue.

In the context of the Green Deal and the Recovery plan, the study highlights potential for growth and employment creation in specific bioeconomy service sectors. Three sectors play a pivotal role and account for more than 60% of the value added and employment in EU27 bioeconomy services: the wholesale, the retail trade of bio-based products and the food and beverage service activities. Food and beverage services are found to have been the main source of employment and value added creation among the services matching the authors' interpretation of the European Commission definition of bioeconomy services. To a lesser extent, employment creation has also been strong in accommodation and sport and recreation activities. Looking at labour productivity as a source of economic growth, the study finds that the services associated to tangible bio-based goods and the natural environment-related services are the least labour productive bioeconomy services of the four categories identified in this study (the other two being the knowledge-based and market support services). Moreover, cross-country comparisons stress the existence of an East-West difference in labour productivity of bioeconomy services which confirms the usefulness of tailored geographical bioeconomy initiatives in support of levelling-up initiatives, as initiated with the Horizon 2020 CSA-BIOEASTup.

Another outcome of this study is to identify key data knowledge gaps, thereby providing orientation for an improved representation of bioeconomy service activities within national and European statistical frameworks. The knowledge-based services in the field of the bioeconomy and the services in support of the development of bio-based markets suffer from the largest uncertainties in the determination of their bio-based output share (in particular for scientific research, education, public administration and activities of [bioeconomy] membership organisations). The services directly targeted by the EU bioeconomy strategy are reported with more detailed information in European statistics (i.e., the services associated with tangible bio-based products and natural environment-related services) than the other two categories of upstream bioeconomy services. However, in some cases (e.g., rental and leasing, sport and recreation and households service activities), the bioeconomy component remains hidden in European statistics.

Eurostat's business statistics provide (4-digit) disaggregated information on wholesale and retail trade activities but the large economic and employment size of these sectors implies that even slight variations in the quantification of their bio-based output share could result in large variations in the quantification of their bioeconomy size. The ongoing revision of the NACE classification and the foreseen revision of the statistical classification of products by activity (abbreviated CPA) consider stakeholder consultations and therefore constitute opportunities for the inclusion of more bioeconomy-specific codes. In the medium term, this process will help capture a more precise picture of European bioeconomy services and consequently strengthen bioeconomy monitoring frameworks and bioeconomy policy design processes.

Finally, whilst this study sheds light on the economic performance of bioeconomy services, interpreting a growing bioeconomy size as a policy objective per se would not be correct. The socio-economic dimension of bioeconomy services has to be assessed jointly with a comprehensive framework of indicators that reflect stakeholder perceptions of the term "sustainability" (Egenolf et al. 2019; Schweinle et al. 2020). For example, the growth of nature tourism, as any activity related with the natural environment, may lead to degradation of the natural environment and the alteration or destruction of landscapes and biological resources (Capocchi et al. 2019). It seems that such concerns are shared by the European Commission that has devoted the third pillar (out of three) of its bioeconomy action plan to the understanding of the ecological boundaries of the bioeconomy. The European Commission is also building up a comprehensive bioeconomy monitoring system in which socio-economic indicators as the ones quantified in this study will be reported and analysed jointly with physical, ecological, social and innovation indicators.

Chapter 4. Assessing the Bioeconomy's Contribution to Evidence-Based Policy: A Comparative Analysis of Value Added Measurements[29]

Abstract

As the bioeconomy gained importance in European policy agendas, several European research institutes have elaborated ad hoc methodologies to measure the size of the European bioeconomy and aid in the monitoring of its performance. This paper reviews the main approaches found in the literature for such a quantification by comparing the different methodologies and the corresponding quantitative findings. The various estimations published might be confusing at first sight, reporting a value added of the European bioeconomy within the large range of EUR 881 billion to EUR 2.3 trillion. However, the study concludes that each approach is best suited to measuring a different aspect of the bioeconomy. For example, using the different approaches, we estimate that the markets of bio-based products and energy generate EUR 730-790 billion of value added, the use of biomass within the European economy generates EUR 670 billion of value added, the sourcing of core bioeconomy industries with goods and services generates EUR 270 billion of value added. There is no evidence of an increased use of biomass inputs in EU industries in substitution of fossil resources, nor of a decreasing dependence of traditional bioeconomy industries towards fossil resources over the period 2005-2015.

Keywords

Bioeconomy, value added, Europe, input-output tables, bio-based industries, methodologies.

[29] This chapter has been submitted to the journal *Bio-Based Applied Economics*:
Ronzon, T., Gurria, P., Carus, M., Cingiz, K., EL-Meligi, A., Hark, N., Iost, S., M'Barek, R., van Leeuwen, M., Philippidis, G. & Wesseler, J. (under review). Assessing the Bioeconomy's Contribution for Evidence-Based Policy: A Comparative Analysis of Value Added Measurements. *Bio-Based Applied Economics*

4.1 Introduction

The bioeconomy promotes the transition to a sustainable economic model derived from the use of biomass and the application of natural sciences, knowledge, and technologies. Its relevance is well acknowledged by international organisations such as the FAO (FAO 2021; Gomez San Juan et al. 2022) and the OECD (OECD 2018) and, for example in the case of the European Union, represented by a strategy and action plan (European Commission 2012, 2018b). Together with the development of bioeconomy strategies around the world, the need of tools for quantifying the bioeconomy and monitoring its development has become crucial. However, the bioeconomy is a complex concept, encompassing a broad range of economic activities and their associated workers and consumers, while being dependent on the planet's ecological boundaries. Understanding and analysing such a multidisciplinary phenomenon requires implementing several theoretical and conceptual approaches, using a broad range of methodologies.

From global (FAO 2021), macro-regional (European Commission 2022b), to national (Federal Ministry of Food and Agriculture (BMEL) 2014) and regional level (Junta de Andalucía 2018), guidelines and monitoring systems are being developed and implemented. In the case of the EU, the indicators to measure the progress of the European bioeconomy are very broad and numerous (European Commission 2022a). However, a smaller number of headline indicators is used by policymakers and stakeholders to analyse and report on the bioeconomy. Most prominently among those indicators features (gross) value added, which is the focus of the present study.

The European Union's statistical directorate general, EUROSTAT, does not (yet) provide statistics of a specific value added indicator for the bioeconomy and all its sectors spanning a broad range from primary production (e.g., agriculture), via processing (e.g., wooden products) to services (e.g., restaurants). Here, a key scientific challenge relates to the separation of fossil and bio-based production to correctly delimit the bioeconomy (Ronzon et al. 2017). Over the last years different methodologies have been developed to fill this gap. These methodologies, although pursuing a similar overall goal (measuring the economic size of the bioeconomy from the value it creates), can be different, as they may focus on a specific policy or research question and use different data sources.

Indeed, scientists from different European research institutes have elaborated sound methodologies for monitoring the development of the bioeconomy's value added over time and across European countries (for example M'barek et al. (2014); Wesseler et al. (2017); Iost et al. (2019); Iost et al. (2020); Kuosmanen et al. (2020); Cingiz et al. (2021b); Porc et al. (2021); Ronzon et al. (2022a, 2022b)). However, these methodologies have not been consistently used in bioeconomy policy making for two reasons: (i) the calculation methods are difficult to understand by non-specialists, and (ii) the different methodologies yield very different estimates of the European bioeconomy's size, which may appear confusing at first sight.

The aim of this paper is to bring clarity on the estimates of the bioeconomy's value added size across different methodologies already published, in order to optimise their use by policy makers and consequently contribute to more evidence-based bioeconomy policies. To do so, the paper clarifies what are the concepts measured by each methodology (section 4.2) and puts their respective results into perspective (section 4.3). Emphasis is made on pointing to the different aspects of the bioeconomy measured by the different methodologies and on illustrating how each of them can be mobilised to inform on specific policy questions. Finally, conclusions are remarked in section 4.4.

4.2 Presentation of the different methodologies

Different quantitative approaches are proposed in the literature for estimating the value added generated by bioeconomic activities, based on literature analysis and/or statistical databases or on modelling (see an overview in Cingiz et al. (2021b)). Four types of methodologies matching monitoring requirements can be distinguished (i.e., methodologies based on statistical databases that are harmonised across EU Member States and updated over time). In this study, each type of methodology is illustrated by a particular publication that applies to all Member States of the EU (Kuosmanen et al. 2020; Cingiz et al. 2021a; Cingiz et al. 2021b; Ronzon et al. 2022a, 2022b).

All four methodologies are based on industry-level statistics for quantifying the contribution of sector *p* to the bioeconomy in terms of value added (V_p). The bioeconomy being a cross-sectoral concept, the size of its value added is thus the sum of the contribution of all NACE sectors of economic activity represented in the European System of National Accounts (ESA)[30] that are indexed by $p = 1,\dots,n$. They comprise the sectors that fully fall within the scope of the bioeconomy indexed by $q = 1,\dots,l$, the sectors that partly fall

[30] ESA activities are defined by the Statistical Classification of Economic Activities in the European Community (NACE) (Eurostat 2008).

within the scope of the bioeconomy indexed by $r = l+1,\ldots,m$, and the sectors that do not fall at all within the scope of the bioeconomy indexed by $s = m+1,\ldots,n$.[31]

The families of methodologies differ on three main aspects:

(i) The set of sectors q. All methodologies concur in considering the biomass producing sectors fully part of the bioeconomy (i.e., agriculture, forestry and fishing). However, divergences occur on the additional sectors that complete the set q within the full scope of sectors considered (p), see Table 6.

(ii) The level of the contribution of sectors r to the total bioeconomy's value added. Different quantification criteria are considered: the biomass content of products and energy produced or the bioeconomy relevance of the services delivered considering a given policy definition of bioeconomy (see section 4.2.1); the use of biomass; or the provision of inputs to sectors q.

(iii) The (non-)inclusion into the bioeconomy aggregate of the industries providing inputs to sectors q.

The different approaches taken regarding points (ii) and (iii) provide distinct measures of the bioeconomy's value added and inform on a variety of aspects of the bioeconomy. Measurement principles are clarified in sections 4.2.1 to 4.2.4 while measured aspects are presented in section 4.3.

4.2.1 The "output-based" approach

Approach

The "output-based" approach quantifies the value added generated by a sector p in proportion to the biomass content of tangible (i.e., merchandise) outputs or to the bioeconomy relevance of intangible (i.e., services) outputs. The biomass content is calculated in dry matter content (Chapter 2). The 'bioeconomy relevance′ criterion is derived from a policy definition of the bioeconomy. In the context of the EU Bioeconomy Strategy, it covers the services associated to a bio-based product (e.g., transport, trade, repair), the marketed ecosystem services (e.g., nature tourism), the generation of knowledge in bioeconomy fields (e.g., research and development in life sciences) or support to bio-based markets (e.g., market research, public administration) (Chapter 3).

Chapters 2 and 3 quantify the value added V of bioeconomy sectors as:

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[31] We denote here the industries by letters p, q, r and s to differentiate with the original studies that use the same subscripts i, j, k with diverging definitions.

$$\mathrm{bbV}_{\mathrm{n,c,y}} = \delta^{\mathrm{V}}_{\mathrm{n,c,y}} \times \mathrm{V}_{\mathrm{n,c,y}} \qquad (4)$$

The set of sectors *n* in the former chapters is the same as the set *p* in this chapter. Therefore, the value added of the bioeconomy (V_{BE_O}) at a given point in time and space can be written as:

$$V_{BE\_O} = \sum_q \delta_q . V_q + \sum_r \delta_r . V_r + \sum_s \delta_s . V_s \qquad (10a)$$

Considering that δ_q = 100% and that δ_s = 0%, then:

$$V_{BE\_O} = \sum_q V_q + \sum_r \delta_r . V_r \qquad (10b)$$

with δ_r = biomass content share or bioeconomy relevance share of sector *r* (Figure 14). V_q and V_r are the value added of individual sectors *q* and *r*.

As an important note, the quantification of the output bio-based shares of accommodation, scientific research activities, education and public administration have been adjusted compared to what described in Chapter 3 after consulting with the European Commission's service in charge of the European Bioeconomy strategy. These adjustments are described on supplementary material SM8. They have an impact on the bioeconomy value added of the respective economic sectors, reason why the results of this chapter do not exactly align with the results of Chapter 3 (besides that the scope of this chapter is the EU28 in 2015 vs. the EU27 in 2017-2019 in former chapters).

Sectors *q=1,…,l* comprise the biomass producing industries (A01, A02, A03), the manufacturing of food (C10) and beverage (C11), water supply, sewerage and management[32] (E36-E38) for their full biomass content, as well as food and beverage service activities (I56) and veterinary activities (M75) for their bioeconomy relevance.

Sectors *s=m+1,…,n* comprise the mining sectors (B05-B09), the manufacturing of coke and petroleum products (C19), of mineral or metallic products (C23-C25), of electronic or electrical equipment (C26-C27), of machinery and motor vehicles (C28-C30, C33), the wholesale, retail trade and repair of motor vehicles (G45), the industries of information and communication (J59-J63), of financial, insurance and real estate activities (K64-K66, L68) and of management, employment, human health and social work activities (M70, N78, Q86-Q88).

Sectors *r=l+1,…,m* comprise all other NACE sectors.

[32] The dry matter content of water is considered 100% biomass (i.e., organic matter and micro-organisms).

Data sources

The output-based approach builds on a variety of data sources. Industry-level data on value added (V_q and V_r) are retrieved from the Eurostat Structural Business statistics (Eurostat 2022i, 2022d, 2022e) and from Eurostat's National Accounts (Eurostat 2022l) for the sectors not represented in the former databases. Other Eurostat databases are mobilised for the computation of the biomass content share or of the bioeconomy relevance share δ_r (Ronzon et al. 2022a, 2022b). In addition to official data, the output-based approach relies on literature, market reports and expert insights for the estimation of the biomass content of the 875 bio-based products listed in the Eurostat database on the production of manufactured goods (Eurostat 2022m). As δ_r cannot be quantified with precision with available Eurostat data and expert knowledge for all sectors *r*, a minimum and maximum threshold value of δ_r is determined that consequently generates a minimum and a maximum value of bio-based value added V_r.

Time series data of V_r are available from 2008 (the latest revision of the NACE classification), up to the most recent common year of data sources used, typically released with a time lag of two years.

Data interpretation

This approach has been coined "policy-driven" in the sense that the bioeconomy relevance of sectors in set *p* follows the concept of bioeconomy as defined in the EU bioeconomy strategy. By focusing on the bioeconomy nature of sectors' outputs, the output-based approach provides lower and upper thresholds of domestic bio-based markets (min V_{BE_O} - max V_{BE_O}). Over time, market developments in the bioeconomy's valued added, or of an individual bio-based sector's value added, give insight on progress towards policy objectives of bio-based market uptake. Also, the difference between a sector's bio-based output share δ_r attained in one country compared with that of another country, or compared with a 100% δ_r share, gives an indication of the remaining potential for bio-based market development.

4.2.2 The "input-based" approach

Approach

The "input-based" approach quantifies the value added generated by a sector *p* in proportion to its bio-based input cost share. Among the different variants of input-based approaches published in the scientific literature (Meesters et al. 2013; Efken et al. 2016; Heijman 2016; Iost et al. 2019; Iost et al. 2020; Kuosmanen et al. 2020; Robert et al. 2020b), only Kuosmanen et al. (2020) propose quantifications for the EU aggregate. Their methodology, also coined Fundamental Industry Level Model (FILM), is thus proposed here as a benchmark for the families of "input-based" approaches while variations from other input-based approaches are briefly discussed.

The FILM input-based approach relies on the use of monetary flows of input-output tables (IOTs) for quantifying the value added of the bioeconomy (V_{BE_I}) at a given point in time and space, such as:

$$V_{BE\_I} = \sum_q V_q + \sum_r \gamma_r . V_r \quad (11)$$

with q being the biomass producing sectors (agriculture, forestry and fishing) and γ_r being the biomass input cost share of sector r (Figure 14 and equation 12).

$$\gamma_r = \frac{\sum_r I_{qr} + \sum_r \gamma_{r'} I_{r'r} + \gamma_{Mr} M_r}{\sum_r I_{pr} + M_r} \quad (12)$$

Thus, I_{qr} is the cost of inputs from the set of biomass producing sectors q to sector r; $I_{r'r}$ is the cost of inputs from sector r' to sector r with $r' = l+1,\ldots,m$; $\gamma_{r'}$ is the bio-based input cost share of sector r' (equation 13); M_r is the cost of imported inputs to sector r; γ_{Mr} is the bio-based input cost share of imported inputs to sector r; and I_{pr} is the cost of inputs from all sectors to sector r. Note that intra-sector trade is captured when $r' = r$.

$$\gamma_{r'} = \frac{\sum_{r'} I_{qr'} + \gamma_{Mr'} M_{r'}}{\sum_{r'} I_{pr'} + M_{r'}} \quad (13)$$

Data sources

The FILM approach is systematic across all sectors (i.e., does not imply any expert judgement). The data source is the Eurostat IOTs released every five years with some Member States also providing annual estimates (Eurostat 2020b). This data does not offer a complete coverage of all EU Member States but does provide complete data for the EU28 aggregate.

Data interpretation

By focusing on biomass input cost shares, the FILM methodology reports on the value added (V_{BE_I}) generated from the use of biomass across all sectors of an economy. The 5-year time step evolution of V_{BE_I} gives insight on the increasing (decreasing) mobilisation of biomass – measured in value terms - by the economic system considered. The bio-based input cost share γ_r gives an indication of the degree of dependence of sector r towards non-renewable biological resources: the smaller γ_r is, the higher the dependence. The development of γ_r over time indicates progress towards the objective of substituting non-renewable (e.g., fossil) resources with bio-based equivalents. Additionally, the FILM approach allows for the incorporation of other adjustments such as subsidies and taxes as well as the possible contribution of other sectors to primary production. For an example of its application, see Kuosmanen et al. (2020).

Variation to the FILM approach

While the FILM approach is homogeneous across all NACE industries and employs data from a single source, Iost et al. (2019); and Iost et al. (2020) adapt the input-based approach to reflect the bioeconomy concept as defined in the previous German Bioeconomy Strategy (BMEL 2014). First, the delineation of the bioeconomy's sectoral scope is restricted to a selection of bio-based sectors that includes only a few bio-based services (i.e., joinery installation and erection of frames and constructional timber works, food and beverage service activities and research and experimental development on biotechnology). Second, several sources of German statistics are employed. The biomass input cost shares of NACE C industries are derived from the Material and Goods received Enquiry (MGrE), for they offer more precise information than IOTs (DESTATIS 2017). The bio-based shares of other NACE industries are derived from additional data sources on energy balance and construction permits (AGEB 2015; DESTATIS 2018). Third, per policy definition, the bio-based share of research activities (M7219) is not determined according to its biomass input cost share but rather from the share of personnel cost incurred in bioeconomy-related research disciplines on total costs (DESTATIS 2016). Data on value added are retrieved from EUROSTAT's structural business statistics.

4.2.3 The "Weighted Input-Output based" approach

The "weighted Input-Output-based" approach provides a middle ground quantification of the bioeconomy's value added, taking into account the parameters δ_p and γ_p quantified by the output-based and the input-based approaches (Figure 14). It quantifies the value added of the bioeconomy (V_{BE_W}) at a given point in time and country as:

$$V_{BE\_W} = \sum_p \theta_p . V_p \qquad (14)$$

where θ_p is the weighted average of the input-based and output-based coefficients. With that purpose, the output bio-based share δ_p is weighed with the ratio of value added on gross output (O), and the input bio-based share γ_p is weighed with the ratio of total cost of inputs on gross output:

$$\theta_p = (\delta_p . V_p + \gamma_p . I_p) / O_p \qquad (15)$$

The data sources used are the same as those employed in the output-based and input-based approaches (see sections 4.2.1 and 4.2.2).

4.2.4 The "Upstream & Downstream" approach

Approach

The "upstream & downstream" approach quantifies two different aspects of the bioeconomy (Figure 14, Cingiz et al. (2021b)):

- $\sum_r D_r$, the "downstream effect" of the bioeconomy which corresponds to the value added size of the sectors *r* that use bio-based inputs in proportion to their respective bio-based input cost share β_r from the set of sectors *q*. The set of sectors *q* represents the biomass producing sectors, the manufacture of food, beverage, tobacco, wood and paper products, and printing.

- $\sum_r U_r$, the "upstream effect" of the bioeconomy which corresponds to the value added size of the sectors *r* that source the set of sectors *q* in proportion to their respective output cost share α_r.

In sum, the "upstream & downstream" approach quantifies the value added of the bioeconomy (V_{BE_UD}) at a given point in time and space as[33]:

$$V_{BE\_UD} = \sum_q V_q + \sum_r (D_r + U_r) \quad (16)$$

Similarly to equation (11), $D_r = \beta_r . V_r$ (17)

$$U_r = \alpha_r (1- \beta_r) V_r \quad (18)$$

where α_r is the output cost share of sector *r* to the set of sectors *q*. α_r is multiplied by $(1- \beta_r)$ to avoid double counting with the downstream effect.

$$\alpha_r = \frac{\sum_q I_{rq}}{\sum_p I_{rp} + F_r + E_r} \quad (19)$$

where F_r denotes the final demand for industry *r* and E_r denotes the exports of industry *r*.

Data sources

Similarly to the FILM approach, the "upstream & downstream" approach is systematic across all sectors and does not imply any expert judgement. The two effects are computed from the OECD's IOTs with annual data series from 2005 to 2015 for the 28 pre-brexit EU Member States (OECD 2021). EU28 data are calculated as an aggregate of the former 28 countries.

[33] Notations have been changed compared to Cingiz et al. (2021b) for the sake of harmonization across the various methodologies presented in the paper.

Data interpretation

Compared to the other three approaches, the "upstream & downstream" method adds information on how much the bioeconomy is integrated with the rest of the economy, in particular to non-bioeconomy sourcing sectors.

The downstream component $\sum_r D_r$ provides similar information as the input-based approach (see section 4.2.2). Additionally, the output cost share α_r used for the quantification of the upstream component U_r illustrates the interconnection between sector *r* and the set of core bioeconomy sectors *q*. The higher α_r is, the larger is the sourcing role of sector *r*. Moreover, the development of the total upstream and downstream effects over time ($\sum_r U_r$ and $\sum_r D_r$) informs whether an increasing (decreasing) value creation from the use of renewable biological resources ($\sum_r D_r$) is concomitant or not with a growth of the economic size of bioeconomy sourcing sectors ($\sum_r U_r$). Finally, the ratio of bioeconomy value added on gross domestic product (GDP) (V_{BE_UD}/GDP) describes how much the bioeconomy is integrated into the whole economy.

As a summary, Figure 14 graphically illustrates the concepts or flows quantified in the four approaches and their related equations and Table 6 compares the main parameters of the four approaches.

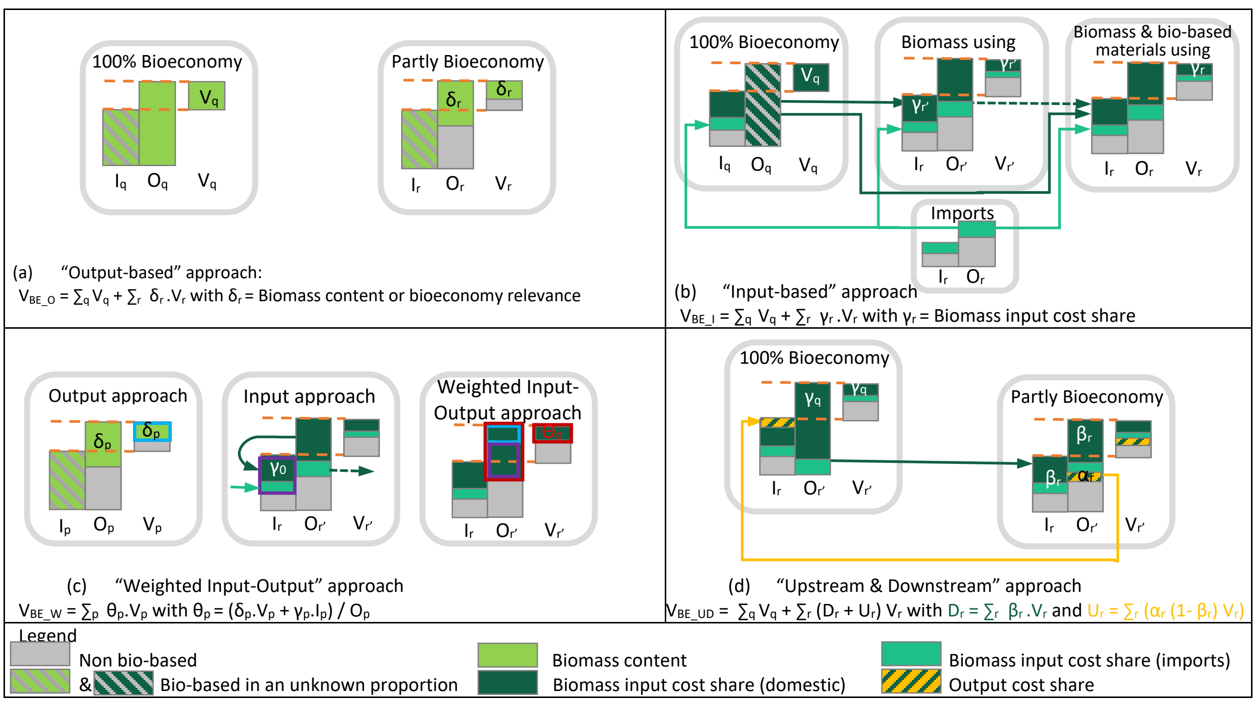

Figure 14. Four methodological approaches for determining the bio-based share of sector p.

Note: I stands for Input, O for Output and V for Value added, all three are measured in monetary terms.

Table 6. Summary comparison of the four approaches introduced in sections 4.2.1 to 4.2.4 .

Approach	"output-based"	"input-based" (FILM)	"weighted Input-Output"	"upstream & downstream"
Quantification criteria	Biomass content of tangible outputs, bioeconomy relevance of intangible outputs	Biomass inputs (biomass input cost share)	See the two previous columns	Biomass inputs (biomass input cost share) and sourcing of industries *q* (output cost share)
Equations	$V_{BE\_O} = \sum_q V_q + \sum_r \delta_r V_r$ *Equation (10b)*	$V_{BE\_I} = \sum_q V_q + \sum_r \gamma_r V_r$ *Equation (11)*	$V_{BE\_W} = \sum_p \theta_p V_p$ with $\theta_p = (\delta_p V_p + \gamma_p I_p) / O_p$ *Equations (14) and (15)*	$V_{BE\_UD} = \sum_q V_q + \sum_r (D_r + U_r)$ *Equation (16)*
Industries *q* (NACE codes)	A01-A03, C10-C12, E36, I56, M75	A01-A03	A01-A03	A01-A03, C10-C12, C16-C18
Industries *s* (NACE codes)	B05-B09, C19, C23-C30, C33, G45, K64-K66, L68, M70, N78, Q86-Q88.	None	None	None
Data sources	Expert knowledge and many Eurostat sources	Eurostat's IOTs	See the two previous columns	OECD's IOTs
Interpretation of the results	Bio-based market size	Use of biomass	Middle ground perspective between the previous two columns	Use of bio-based inputs and integration to the wider economy

4.3 Results and discussion

The four methodologies presented above yield very different estimates of the value added size of the EU bioeconomy in 2015, ranging from EUR 881 billion to EUR 2.3 trillion (Figure 15). Such a large range may be puzzling at first sight or may even confuse policy makers. In fact, differences in numbers reflect the different aspects of the bioeconomy captured by each approach. This section summarises the main results, sheds light on the specific aspects of each methodology and illustrates how the diversity of quantitative evidence produced can be mobilised to answer relevant policy questions.

4.3.1 Aggregated results and complementary information on differences

In order to provide an overview of main results, we focus hereafter on the comparison of the aggregates of primary, secondary and tertiary economic sectors[34] as illustrated by Figure 15. For each of these aggregates, we highlight the reasons leading to differences in value added estimates and give sectoral examples to aid the understanding of the result differences. The weighted input-output approach is not commented though, as it always provides an intermediate quantification between the input-based and the output-based approaches. All quantifications from the "upstream and downstream" approach are taken from the online database published by Cingiz et al. (2021a)[35].

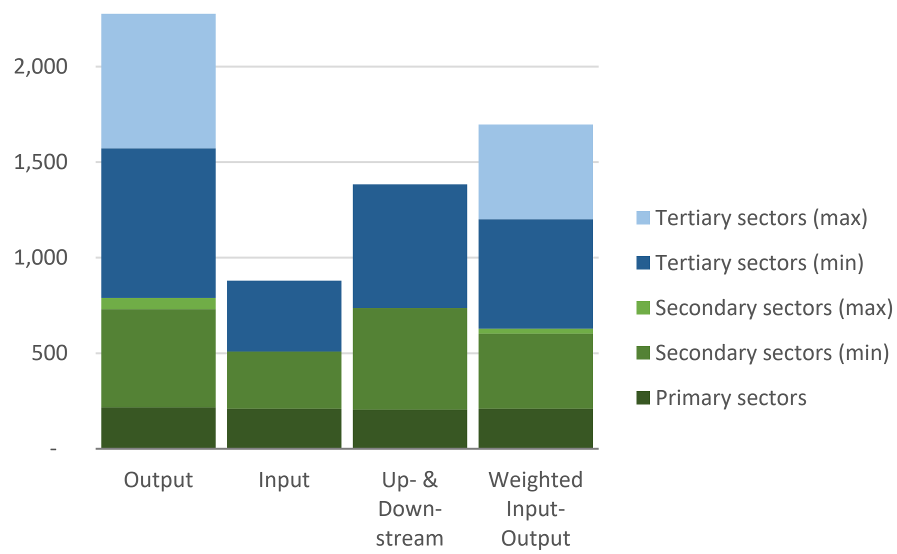

Figure 15. Estimation of the value added size of primary, secondary and tertiary activities of the EU28 bioeconomy according to the four quantitative approaches presented in the study.

Estimations of value added for the bioeconomy industries of the **primary sector** are convergent (EUR 207 to 216 billion) in spite of methodological differences and slight variations from the different data sources employed by each approach. The output-based approach only considers those sectors that produce biomass (EUR 216 billion) while the other three approaches also consider a proportion of the bioeconomy value added coming from the mining sectors. From an input-based perspective, EUR 1 billion of value added is generated from the use of renewable biological material in mining activities such as for bioleaching. Moreover, the upstream effect U_r calculated in the "upstream and downstream" approach

[34] The primary sector refers to NACE sections A and B (biomass production and mining and carrying), the secondary sector to NACE C to F (manufacturing), and the tertiary sector to NACE G to T (services).

[35] Although the methodological comments exposed in section 4.2.4 were derived from Cingiz et al. (2021b).

reveals that EUR 1.2 billion of value added are generated from the sourcing of the set of core bioeconomy sectors *q* by mining industries.

The value added of the bioeconomy industries operating in the **secondary sector** differs more from one approach to the other than in the case of primary sector industries: EUR 299 billion (input-based approach) to EUR 573 billion (output-based approach). The biomass input cost share γ_r (input-based approach) is systematically smaller than the biomass content δ_r of the outputs of the manufacturing sectors (output-based approach), except for those sectors *s* considered non bio-based in the output-based approach (γ_r ranging between 0.6% and 2.5%, Table 7). As a matter of example, only 55% of the inputs of the manufacturing of food, beverage and tobacco are bio-based inputs while that industry generates fully bio-based outputs (i.e., γ_r = 55% and V_r = 152 EUR billion in the input-based approach while δ_r = 100% and V_r = EUR 237 billion in the output-based approach). The manufacturing sectors that rely most on biomass as an input are the manufacturing of food, beverage and tobacco, of wood products, of textile, of paper and the printing sector (γ_r =22-100%). The proportion (α_r (1- β_r)) of outputs that secondary sector's industries sell to bioeconomy sectors *q* ranges from 0.3% to 5.4%.

Table 7. Output bio-based shares (a), biomass input cost shares (b), combined upstream and downstream shares (c) and weighted Input-Output shares (d) at the sectoral level and for the EU28 in 2015.

nace		(a) min – max		(b)	(c)	(d) min– max	
A01_A03	Agriculture, forestry, fishing	100%	100%	100%	100.0%	100%	100%
B05_B09	Mining and quarrying	0.0%	0.0%	1.4%	3.0%	0.6%	0.6%
C10_C12	Food, beverages and tobacco products	100%	100%	54.8%	100.0%	66.4%	66.4%
C13_C15	Textiles, wearing apparel and leather products	35.6%	46.5%	40.9%	6.0%	38.4%	42.8%
C16	Products of wood and cork	99.7%	99.7%	45.7%	100.0%	61.7%	61.7%
C17_C18	Paper products and printing	60.8%	98.9%	30.7%	100.0%	37.3%	53.2%
C19	Coke and refined petroleum products	0.0%	0.0%	0.6%	3.7%	0.5%	0.5%
C20_C21	Chemicals and pharmaceuticals	25.6%	27.1%	4.3%	8.4%	12.1%	12.6%
C22	Rubber and plastics products	3.3%	3.9%	4.6%	9.1%	4.1%	4.4%
C23	Other non-metallic mineral products	0.0%	0.8%	2.5%	5.5%	1.6%	1.9%
C24	Basic metals	0.0%	0.0%	0.9%	1.5%	0.7%	0.7%
C25	Fabricated metal products	0.0%	0.0%	1.5%	4.4%	0.9%	0.9%
C26	Computer, electronic and optical equipment	0.0%	0.0%	1.4%	1.7%	0.9%	0.9%
C27	Electrical equipment	0.0%	0.0%	1.6%	2.1%	1.0%	1.0%

C28	Machinery and equipment, nec	0.0%	0.0%	1.1%	2.7%	0.7%	0.7%
C29	Motor vehicles, trailers and semi-trailers	0.0%	0.0%	1.5%	1.2%	1.1%	1.1%
C30	Other transport equipment	0.0%	0.0%	1.5%	1.4%	1.1%	1.1%
C31_C33	Manufacturing nec; repair and installation of machinery and equipment	8.8%	17.8%	8.3%	9.8%	8.4%	11.3%
D35_E39	Electricity, gas, water supply, sewerage, waste and remediation services	24.0%	25.4%	1.3%	5.6%	10.2%	10.6%
F	Construction	5.3%	5.6%	3.4%	4.4%	3.9%	4.0%
G45_G47	Wholesale and retail trade; repair of motor vehicles	24.8%	39.8%	3.7%	11.0%	15.0%	23.0%
H49_H53	Transportation and storage	20.1%	32.2%	0.9%	3.9%	8.9%	14.0%
I55_I56	Accommodation and food service activities	76.5%	76.5%	34.7%	34.3%	57.7%	56.4%
J58_J60	Publishing, audiovisual and broadcasting activities	0.0%	32.1%	4.6%	12.3%	2.4%	19.1%
J61	Telecommunications	0.0%	0.0%	0.9%	2.1%	0.5%	0.5%
J62_J63	IT and other information services	0.0%	0.0%	0.9%	2.7%	0.5%	0.5%
K64_K66	Financial and insurance activities	0.0%	0.0%	0.6%	3.3%	0.3%	0.3%
L68A	Real estate activities	0.0%	0.0%	0.9%	2.2%	0.2%	0.2%
M69_N82	Professional, scientific and technical activities, administrative and support services	4.0%	11.8%	2.1%	4.9%	2.0%	9.8%
O84	Public administration and defence; compulsory social security	10.5%	15.9%	2.6%	4.7%	0.9%	11.5%
P85	Education	2.2%	4.9%	4.3%	6.7%	0.9%	3.5%
Q86_Q88	Human health and social work activities	0.0%	0.0%	5.4%	5.6%	1.8%	1.8%
R90_S96	Arts, entertainment and recreation and other service activities	0.2%	47.1%	3.8%	6.9%	1.6%	27.1%
T97_T98	Activities of households as employers	0.0%	100.0 %		0.0%	0.0%	0.0%

Sources: Kuosmanen et al. (2020); Cingiz et al. (2021a); Ronzon et al. (2022a, 2022b).

The **tertiary sector** shows a high divergence in terms of value added size estimates from one approach to the other: EUR 370 billion (input-based approach) to EUR 1,488 billion (output-based approach). The four-fold difference is due to relatively small biomass input cost shares (γ_r = 1-5%, except for accommodation and food services where γ_r = 35%) compared with high biomass content or bioeconomy relevance of tertiary outputs (maximum δr = 12-100% in eight out of fourteen tertiary sectors, Table 7). While the approaches based on IOTs (input and “up and downstream” approaches) are systematic and precise, the output-based approach suffers from both a lack of clarity about the definition of a bioeconomy service and a lack of informative data for the quantification of their bioeconomy relevance. In two extreme cases, the bioeconomy relevance of the sector of sport, amusement and recreation activities and the activities of household employers could not be quantified with available data, leading to the very broad assumption of minimum and maximum bioeconomy relevance shares of 0% and 100% (for a discussion of the output-based approach, see Ronzon et al. (2022a)). As regards the upstream effect U_r of tertiary sectors, it ranges from 0% to 7.6% (in the wholesale and retail trade and repair of motor vehicles). Finally, the sectors of telecommunication and information technologies, finance, insurance, real estate, human health[36] and social work are excluded from the sectoral scope of the bioeconomy in the output-based approach (δ_r = 0%). Nevertheless, they use biomass (γ_r ranging between 0.6% and 5.4%) and source core bioeconomy industries *q* with their outputs (α_r (1- β_r) ranging between 0.4% and 2.0%). Consequently, they are worth EUR 75 billion according to the input-based approach and EUR 123 billion in the “upstream & downstream” approach.

4.3.2 Tailoring the right approach to specific policy requirements

Taken separately, the different approaches provide insight on fundamental policy questions:

- (i) What is the size of bio-based markets? What is their potential for development?
- (ii) What is the size of the economic activities that rely on the use of biomass?
- (iii) How does the bioeconomy and the rest of the economy interlink?
- (iv) Is the substitution of non-renewable resources by renewable biological resources happening?

Moreover, sectoral data can also be used to inform on more specific policy questions related with the bioeconomy such as the dependence of the EU economy to fossil resources, the size of the knowledge-based bioeconomy (KBBE) and many others.

Size and development of bio-based markets

The development of bio-based markets is pivotal in the EU bioeconomy strategies, which have been conceived as motors of green growth.

[36] Human health is explicitly excluded from the bioeconomy in the European bioeconomy strategy (European Commission 2018b).

The output-based approach precisely offers the means for monitoring the economic wealth created from the production and selling of bio-based products and bioenergy and from waste treatment (NACE sectors A to F). Taking the year 2015 as a reference for comparison with the other approaches, the value added size of the EU bio-based markets is estimated between EUR 730-790 billion. It has increased by 30-31% in the decade 2009-2019, which has permitted to maintain their contribution to the EU's total value added at approximately 5.5-5.9%. The output-based approach also allows country level and sectoral level analysis. Keeping the EU28 as a geographical scope, bio-based markets are dominated by food and agricultural commodities (respectively EUR 189 billion and EUR 183 billion in value added size 2015, Table 8 (a)). If we follow a stricter definition of "bio-based products" that excludes food and feed products, then the largest markets for bio-based products are the ones of paper products and of bio-based pharmaceuticals, with a value added size of EUR 45 billion each (Table 8 (a)). Interestingly, the four sectors responsible for the biggest biomass-derived markets – agriculture, food, paper and bio-based pharmaceuticals – were also identified as the main motors of productivity growth in the EU over the last decade in Chapter 2, either because these sectors have modernised their production processes (agriculture, the manufacture of paper), or because they have attracted workers from less intensive bio-based industries (manufacture of bio-based pharmaceuticals and food products) or both phenomena. Their market size has grown by 37-43% over the period 2009-2019, except for the food industry (30% growth).

The secondary sector of the EU28 (NACE C to F) is 19-21% bio-based in 2015 ($\delta_{NACE\ C\text{-}F}$). That proportion remains stable over the decade 2009-2019. It is certainly impossible to achieve a fully bio-based secondary sector as some metal, mineral and other non bio-based components of manufactured goods cannot be substituted with biomass. Notwithstanding, a 20% share seems low enough to expect some feasible progress. Output bio-based shares of 35-40% have been achieved by the secondary sectors of Latvia and Lithuania in 2015, thanks to an important manufacture of wood products and food and beverage (both countries), of wooden furniture (Lithuania) and bioenergy industry (Latvia). The Irish case illustrates a bioeconomy less oriented towards wooden biomass, where the manufacture of bio-based chemicals (δ_r=31%) together with a strong food and beverage industry drives a 32-33% bio-based secondary sector.

Table 8. Top 5 markets according to the different criteria discussed in the text (EU28, 2015).

(a) Top 5 markets of bio-based products and energy by value added size*				
	Industry (nace sector)		Value added size (V_p in million euros)	Output bio-based share (δ_p in %)
1	Manuf. of food products	C10	189,000	100%
2	Agriculture	A01	183,441	100%
3	Manuf. of paper and paper products	C17	45,257 - 45,625	99% - 100%
4	Manuf. of bio-based pharmaceuticals	C21	44,827	49%
5	Manuf. of beverages	C11	40,890	100%
(b) Top 5 market industries by value added generated from biomass use				
	Industry (nace sector)		Value added size (V_r in million euros)	Biomass input cost share (γ_r in %)
1	Manuf. of food products, beverage and tobacco products	C10_C12	152,458	55%
2	Accommodation and food service activ.	I55_I56	130,084	35%
3	Human health activities	Q86	29,762	4%
4	Education	P85	29,226	4%
5	Manuf. of textiles, wearing apparel and leather products	C13_C15	28,521	41%
(c) Top 5 industries relying on biomass and bio-based product resources in proportion to their inputs				
	Industry (nace sector)		Value added size (V_r in million euros)	Biomass input cost share (γ_r in %)
1	Manuf. of food products, beverage and tobacco products	C10_C12	152,458	55%
2	Manuf. of products of wood and cork	C16	17,363	46%
3	Manuf. of textiles, wearing apparel and leather products	C13_C15	28,521	41%
4	Manuf. of paper and paper products	C17	17,484	37%
5	Accommodation and food service activ.	I55_I56	130,084	35%
(d) Top 5 sourcing industries to core bioeconomy industries *q*, by value added size				
	Industry (nace sector)		Value added size (V_r in million euros)	Output cost share ($\alpha_r.(1- \beta_r)$ in %)
1	Wholesale and retail trade; repair of motor vehicles	G45_G47	112,945	8%
2	Professional, scientific and technical activities, administrative and support services	M69_N82	34,750	2%
3	Transportation and storage	H49_H53	19,425	3%
4	Electricity, gas, water supply, sewerage, waste and remediation services	D35_E39	15,221	4%
5	Financial and insurance activities	K64_K66	14,152	2%

** sorted on the maximum estimation of value added size.*

Note: the level of disaggregation varies from one methodology to the other (e.g., the aggregate C10-C12 in (b) is broken down into C10, C11 and C12 in (a)).

Use of biomass and value added creation

Side-by-side with market objectives, the two consecutive EU bioeconomy strategies promote the sustainable use of biomass – in particular for industrial purposes – to achieve a bioeconomy transition in Europe. A sustainability assessment is out of the scope of the present study. However, the input-based approach developed by Kuosmanen et al. (2020) and the downstream component quantified by Cingiz et al. (2021a) do provide evidence on the extent to which biomass is used in the different economic sectors of the EU28, and on the ability of each sector to create value added from it.

According to Kuosmanen et al. (2020), the use of biomass and bio-based products generates EUR 670 billion of value added in the EU28 economy, excluding the biomass producing activities[37] (2015 data). In the primary sector, mining and quarrying activities depend on the use of biomass for 1.4% of their input costs, from which they produce EUR 1 billion of value added. The secondary sector is more dependent on biomass inputs than the tertiary sector but less efficient at generating value added from it: with a 9% biomass input cost share, the secondary sector generates EUR 299 billion compared to a 4% share in the tertiary sector, generating EUR 370 billion.

The manufacturing of food, beverage and tobacco and accommodation in rural areas and food services create the largest amounts of value added from biomass usage in the EU28 (EUR 152 and 130 billion each, Table 8 (b). More surprisingly, they are followed by human health activities and education (EUR 29-30 billion each). Human health is excluded from the EU definition of the bioeconomy but it is preponderant in more process-based definitions (e.g., USA, Brazil). Education uses biomass in the form of paper, wooden desks and furniture and in the form of breakfasts served at school in some Member States.

The industries that depend more on biomass usages are traditional industrial activities (again excluding biomass producing activities[37]), see the top four sectors in Table 8 (c). Their sourcing in biomass and bio-based products reaches 37% to 55% of total input costs (γ_r). Tertiary activities come only at the fifth position in the form of accommodation in rural areas and food services (γ_r = 35%).

[37] The industries that produce biomass – i.e., agriculture, forestry and fishing – are fully accounted part of the bioeconomy by Kuosmanen et al. (2020) (industries q). As a result, no biomass cost share γ_r is calculated for those industries and we cannot report here on their use of biomass.

The degree of inclusivity of the bioeconomy within the macroeconomy

The scope of the bioeconomy and its penetration into the rest of the economy is another topic of policy interest. The chronological evolution of bioeconomy-related policy initiatives indeed shows different perceptions of bioeconomy activities. The first policy concept of KBBE put the focus on those scientific and knowledge-productive activities in the domain of life sciences (Patermann et al. 2018). In contrast, the first bioeconomy strategy of the EU turned the spotlight onto primary and secondary bio-based production[38] while the second strategy broadened the scope to all types of activities that use biomass, tertiary activities included[39].

The work from Cingiz et al. (2021a) applies to all three perceptions and quantifies the interlinkages between the bioeconomy and the rest of the economy. At the EU28 level, the production of biomass contributes 1.6% of the total value added in 2015, which rises to 4.6% if we add the other fully bio-based sectors *q* (food, beverage, tobacco, wood products and paper, see Table 6). The trickling down of sectors *q*'s output to partly bio-based manufacturing and service activities permits the generation of an additional 3.9% of the EU28 total value added (EUR 511 billion).

In addition, Cingiz et al. (2021a) claim that the input provision to a variety of sectors is not the only way the bioeconomy penetrates the economy. Bioeconomy sectors also depend on the rest of the economy for input provision. That economic link is quantified in the form of a so-called 'upstream effect' (equation 18) and is worth 2% of the EU28 total value added. The largest upstream effects are observed from tertiary sectors (Table 8 (d)), nearly half of the upstream effect being the fact of trade activities[40] (42%) and transportation and storage (7%). In sum, the authors estimate that fully bio-based industries *q* and the downstream and upstream effect of other industries account for a significant 10.4% of the EU28 value added.

Regarding the size of the KBBE, the results from Cingiz et al. (2021a) are unfortunately not disaggregated enough to inform on the value added generated by the knowledge-productive activities used by the set of sectors *q* (upstream effect of NACE M71-M75 and P85). The estimation could be computed with further research though. Another approximation could be provided from an output-based perspective in the form

[38] `*The bioeconomy includes the sectors of agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries'* (European Commission 2012 footnote 3).

[39] `*[The bioeconomy] includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services'* (European Commission 2018b page 4).

[40] Wholesale, retail trade and repair of motor vehicles (NACE G45, G46, G47).

of the value added created by the production of knowledge in bioeconomy fields from the above quoted NACE activities. Unfortunately, available data sources cannot permit a more precise quantification than EUR 35-121 billion for the EU28 in 2015.

Substitution effect and dependence of the EU bioeconomy to fossil resources

The substitution of non-renewable resources in industrial and energy processes is central in the EU bioeconomy strategy for addressing the two objectives of lowering the EU dependence to non-renewable feedstocks and of contributing to climate change mitigation (European Commission 2012 page 5; 2018b page 9). Such a substitution effect could be observable from the monitoring of sectoral biomass input cost shares (γ_r and β_r) over time in the form of increasing usage of biomass input in proportion to total inputs (in value terms). Time series are only offered for the biomass input cost shares β_r by Cingiz et al. (2021a)[41].

Contrary to the expected upward trend, Cingiz et al. (2021a) indicate a reduction of biomass input cost shares from 2.8% to 2.3% in the secondary sector (excluding the set of sectors *q*) and from 5.2% to 4.4% in the tertiary sector between 2005 and 2015. The authors note, however, that the biomass input cost share of the secondary sector is stabilising since 2010. At the EU28 level, the reduction trend is particularly noticeable in the manufacture of furniture and repair and installation of machinery and equipment (NACE C31-33) and in the sector of publishing, audiovisual and broadcasting (NACE J58-60) but trends differ across countries. A note of caution has to be introduced here on the monitoring of biomass inputs in value terms. Due to differentials in the relative value of biomass compared to other inputs, a decreasing proportion of biomass inputs in value does not always correlate with a decreasing proportion in quantity.

Beyond the capacity of a whole economy to use biologically renewable resources in industrial processes and services, some observers question the capacity of the bioeconomy to source itself with less fossil inputs. In that sense, the upstream component of mining and fossil-based industries provides evidence on the link between the set of sectors *q* and fossil resources. Cingiz et al. (2021a) estimate that 1.1% of the output of the mining and carrying sector and 3.2% of the output of the manufacturing of coke and refined petroleum products source the core bioeconomy sectors *q*. T These proportions have remained fairly steady over the 2008-2015 time period but they vary across EU Member States: from 0.3% to 4.4% in the case of mining and carrying activities and from 0.5% to 8.1% regarding the manufacture of coke and petroleum products in 2015.

[41] At a less disaggregated sectoral breakdown than the one points in time γ_r from Kuosmanen et al. (2020) and with different data source and calculation method. γ_r and β_r are therefore not directly comparable.

The same logic could apply to examine the use of plastics by the set of sectors *q* although the data source used for the quantification of the upstream component does not disentangle fossil-based from bio-based plastic inputs.

4.4 Conclusion

The scientific community has responded well to the challenge of quantifying the economic performance of the EU bioeconomy. As this study demonstrates, a variety of sound methodologies are now implementable to inform on various aspects of value creation in bioeconomy sectors. Nevertheless, the communication of scientific outcomes to policy makers could be improved, avoiding the general term "value added of the bioeconomy" and clarifying instead the source of value added quantified. As a few examples, for the EU in 2015:

- EUR 730-790 billion of value added were created *from the aggregated domestic production of biomass, bio-based products and bioenergy* (output approach), that is 5.5-5.9% of the total EU value added. The agro-food industry is responsible for half of the EU bio-based market, followed by the paper and bio-based pharmaceuticals industries. Services are not yet well captured in the output-based approach.

- EUR 670 billion of value added were created *from the use of biomass in all economic sectors* (input-based approach), that is 5% of the total EU value added. The secondary sector is more dependent on biomass inputs than the tertiary sector but less efficient at generating value added from it (EUR 299 billion vs. EUR 371 billion).

- EUR 270 billion of value added were created *from the use of products and services in the production of biomass and food, wood and paper products* (upstream component of the bioeconomy), that is 2% of the total EU value added.

In addition, contrary to the EU bioeconomy strategy's expectations, our results do not conclude on a clear trend towards an increase of biomass input use in EU industries nor towards a decreasing dependence of traditional bioeconomy industries towards mining, coke and petroleum products over the period 2005-2015.

Pursuing a growing value added from bio-based markets, bio-based feedstock, or bioeconomy inputs should not be the only objective of a functioning bioeconomy. The sustainability of production and consumption within the bioeconomy, the health of natural ecosystems and a fair distribution of bioeconomy’s benefits are also central in the policy narrative. The methodologies presented here have been tested in the literature on other indicators such as the number of persons employed (M'barek et al. 2014; Ronzon et al. 2017; Kuosmanen et al. 2020; Ronzon et al. 2022a) or greenhouse gas emissions (Kuosmanen et al. 2020). However, monitoring sustainability aspects surely requires a much more comprehensive set of indicators and scientific methods.

Finally and beyond the overview given in this paper, the different methodologies could be mobilised for further research on areas closely related to the bioeconomy, such as the size of the knowledge-based bioeconomy, of the circular economy or of paid recreational services. Monitoring the use of biomass and the bio-based substitution of strategic sectors could also provide additional evidence to the debate on the classification of economic activities into green or brown sectors that has become topical in the context of the publication of a Green Taxonomy by the EU (Bohnenberger 2022).

Chapter 5. Friends or foes? A compatibility assessment of bioeconomy Sustainable Development Goals for European policy coherence[42]

Abstract

In October 2018, the European Union (EU) launched an updated bioeconomy strategy with the aim of encouraging the substitution of fossil carbon with biomass feedstock in the industry and in energy production while preserving ecosystem services. The objective of the paper is to analyse the links between the EU bioeconomy strategy and the Sustainable Development Goals (SDGs), and to assess what could be the main points of synergies and tensions between bioeconomy-related SDG targets. By semantically mapping the action plan of the 2018 EU bioeconomy strategy with the SDG targets, the paper finds that the bioeconomy strategy is aligned with 53 targets distributed in 12 of the 17 SDGs. Ex-post correlation analysis on bioeconomy-related SDGs indicators for 28 EU Member States (1990-2018) shows a predominance of synergies over trade-offs. More intense synergetic past developments (positive correlations) are found among clean energies (SDG 7), recycling (SDG 11), ecosystem preservation (SDG 15) and most of all other bioeconomy-related SDGs. Negative correlations are observed between agro-biodiversity (SDG 2), domestic material consumption of biomass (SDG 8 and 12), agriculture and industrial developments (SDG 2 and SDG 9) and a wide array of bioeconomy-related SDG indicators. The hotspots of strong correlations identified might be useful in further enrichment of ex-ante simulation models. From a policy coherence perspective, a wide range of policy instruments are already in place in the EU to foster synergies and may bring co-benefits. Policies oriented at preventing trade-offs are already in place but they have not overcome the antagonisms observed in this study yet. Change in practices, technical and technological innovations and the application of circular and 'cascading principles' are the most common fields of action.

Keywords

Bioeconomy; SDG; Policy coherence; correlation; biomass

[42] This chapter is based on the article:
Ronzon, T., & Sanjuán, A. I. (2020). Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. *Journal of Cleaner Production*, *254*, 119832.

5.1 Introduction

International leaders have committed in 2015 to achieving a set of 17 Sustainable Development Goals (SDGs) by 2030 with the aim of improving the capacity of human beings to live well on a healthy planet. The 17 SDGs, further defined through 169 SDG targets, form a system of interacting components that reflects the highly complex and multi-dimensional nature of sustainable development (United Nations 2015; Pradhan 2019). In the European Union (EU), the bioeconomy concept has been put forward since 2012 as an option matching with the pursuit of many aspects of sustainable development, and therefore with a number of SDG targets as defined later in 2015. Generally speaking, the bioeconomy refers to the substitution of fossil carbon with biomass feedstock in the industry and in energy production while preserving ecosystem services.[43]

The first EU bioeconomy strategy, launched in 2012, has nevertheless been criticised for its unbalanced contribution to sustainable development by those who found the strategy oriented too much towards market (Bugge et al. 2016; Scordato et al. 2017) and technology (De Besi et al. 2015; Hausknost et al. 2017), and neglecting the multi-functionality of biomass production (Brunori 2013; Ramcilovic-Suominen et al. 2018). Questions were also raised regarding the sustainability of biomass production systems and the capacity of the EU to dispose of enough biomass to meet growing uses (Kovacs 2015; Lewandowski 2015; Müller et al. 2015; Giljum et al. 2016; Meyer 2017; Birner 2018; Heimann 2019) as well as the supposed environmental benefits of bio-based products (Bennich et al. 2017; Priefer et al. 2017; OECD 2018; Alpizar et al. 2019).

Thus, in 2018, the revision of the EU bioeconomy strategy put emphasis on balancing the three pillars of sustainable development. This effort is evidenced in the title of the revised strategy itself: “A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment" (European Commission 2018b). The revision also integrated a number of former criticisms by attributing equal importance (i) to the scaling-up of bio-based sectors and (ii) to the understanding of the ecological boundaries of the bioeconomy, as well as (iii) to the development of the bioeconomy at the local level as

[43] This broad definition covers a multitude of variants, two of which are formulated in the two successive EU bioeconomy strategies launched by the EU: (i) the bioeconomy *'encompasses 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 and bioenergy*' (European Commission 2012), and (ii) the bioeconomy *'includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (…); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services'* (European Commission, 2018b).

a way to better distribute the benefits of bioeconomy development. Moreover, ecosystem services were explicitly integrated into the new definition of the bioeconomy.

These adjustments have unquestionably reinforced the coherence between the bioeconomy strategy and the EU engagement towards the SDGs. But the examination of the interlinkages taking place between the multiple objectives of the two initiatives remains a necessary step on the road towards more policy coherence and effectiveness (Lu et al. 2015; Boas et al. 2016; Karnib 2017; Allen et al. 2018). Indeed, identifying and understanding interlinkages would help to leverage positive interactions and foster the necessary transformative changes to avoid that progress towards one SDG target rolls back another one (Pradhan et al. 2017; Buscaglia et al. 2018; Liu et al. 2019).

Accordingly, the objective of this study is to provide a quantitative assessment of synergies and trade-offs as observed among the SDG indicators that relate to the domains of actions of the new EU bioeconomy strategy. With this assessment, the aim of the paper is two-fold: (i) to provide a stepping stone for the incorporation of non-market SDG indicators[44] into simulation modelling frameworks through the interlinkages observed with market-based SDG indicators; and (ii) to provide data-based evidence in support for policy coherence into future EU policy designs. The paper consecutively investigates two research questions: (1) What SDGs and SDG targets does the EU bioeconomy strategy contribute to? and (2) What are the points of synergies and tensions between bioeconomy-related SDG targets?

As described in section 5.2, to answer the first research question, the actions foreseen in the action plan of the current EU bioeconomy strategy are mapped against the SDG targets that share the same objective (semantic mapping). Regarding the second research question, a statistical ex-post analysis of the interactions between bioeconomy-related SDG indicators (i.e., the indicators corresponding to the SDG targets mapped in the first research question) is performed, following closely Pradhan et al. (2017)'s approach that relies on bivariate correlations. The analysis is based on official UN and Eurostat data on SDG indicators, corresponding to 28 EU Member States over the period 1990-2018 (upon data availability for each SDG indicator). Section 5.3 presents the results on the mapping of the action plan and SDG targets as well as on the resulting synergies and trade-offs found. Section 5.4 discusses the quantitative results in the context of the literature and previous knowledge as well as of current and past EU policy actions. The discussion is driven by the two following questions: (1) are the correlations found in this study supported

[44] Market-based indicators are those metrics that can be provided by market-driven price-based simulation modelling frameworks (e.g., manufacturing value added as a proportion of gross domestic product (GDP) in SDG 9), as opposed to non-market indicators (e.g., R&D personnel for SDG 9).

by empirical observations or studies? And (2) if yes, has this knowledge played a role in policy making? Section 5.5 concludes on the two research questions investigated.

5.2 Data and Methods

5.2.1 Data

This study builds on a dataset of bioeconomy-related indicators compiled from the official UN and Eurostat SDG databases (Eurostat 2019; United Nations Statistics Division 2019). The “bioeconomy-related” nature of the selected indicators is established after a semantic mapping of the EU bioeconomy action plan with the SDG targets it contributes to. In other words, a SDG target is considered "bioeconomy-related" when a meaning-based equivalence or similarity could be identified between this target and one or several actions of the EU bioeconomy action plan.

The 2018 EU bioeconomy strategy is composed of 23 sub-actions while the 17 SDGs are defined through 169 targets which are in turn measured through multiple indicators. As a sub-action can match more than one SDG target, the complexity of the mapping exercise was reduced by grouping all measures and objectives announced in the action plan into 13 “matching fields” (see supplementary materials SM9) that are subsequently mapped to the SDG targets.[45] The direct correspondence between sub-actions and SDG targets is then cross-checked and presented on SM10. The matching exercise does not consider the indirect consequences of a given action. For example, action 2.2 on "pilot actions for a local bioeconomy development" is related to the matching field "Local development" and subsequently to targets belonging to SDGs 2, 8, 9 and 14. One might argue that by contributing to local development, action 2.2 will also have an impact on local levels of poverty (SDG 1) and inequality (SDG 10). As the action does not mention these specific aims, it has not been mapped to SDG 1 and SDG 10.

Identified "bioeconomy-related" SDG targets are measured with 268 UN and Eurostat indicators (i.e., variables) to which a series of filters is applied in order to: (i) keep only indicators with at least three observations per EU Member State between 1990 and 2018,[46] (ii) remove non-relevant indicators from

[45] For instance, the sub-action 1.1 "Mobilise public and private stakeholders, in research, demonstration and deployment of sustainable, inclusive and circular bio-based solutions" relates to the matching field "Investment, funding and Public-Private Partnerships (PPPs)" and with the UN SDG target 17.17 that "encourages and promote effective public, public-private and civil society partnerships (…)".

[46] This is an arbitrary selection (as in Pradhan et al. 2017) that aims at minimizing the loss of indicators due to incompleteness of time series.

the bioeconomy action plan perspective,[47] and (iii) avoid the multiple representation of the same indicator expressed in different dimensions or measurement units.[48] As a result, the final dataset comprises 54 bioeconomy-related SDG indicators, 26 of which come from the UN and the rest from Eurostat.

5.2.2 Statistical tests

Diverse quantitative and qualitative methodologies for the analysis of SDG interlinkages are described in the scientific literature. They highlight the context specificity of interlinkages as different directions and strengths are found for the same interaction over time and countries (Nilsson et al. 2016; Pradhan et al. 2017; van Leeuwen 2017; Zhou et al. 2017; Weitz et al. 2018).

This study presents a data-driven approach consisting of bivariate correlations between unique pairs of SDG indicator time series for each EU Member State. Such approach allows the capture of country specificities and the coefficient of correlation informs on the strength of the interaction. In particular, the Spearman rank correlation (ρ) is used as recommended by previous studies on SDGs interactions, such as Pradhan et al. (2017) at the global level; Zhou et al. (2017) on nine selected Asian countries; and Buscaglia et al. (2018) on the EU. In comparison to other correlation statistics (i.e., Pearson), the Spearman correlation does not impose the normality assumption, is suitable for non-linear relations and is little sensitive to outliers.

The analysis is carried out sequentially. First, following closely the methodological approach of Pradhan et al. (2017), indicators are checked for consistency in their interpretation previous to correlation analysis. That is, a positive sign is assigned to those indicators whose increase contributes to narrowing the distance to the official SDG target, and a negative sign is assigned to the ones whose increase widens the distance to the target (SM11). As a result, positive (and statistically significant) correlations show a synergetic effect for the achievement of SDG targets and negative correlations highlight trade-offs.

[47] For example, related to the SDG target 15.a on financial resources to conserve and sustainably use biodiversity and ecosystems, the indicator 15.a.1 only measures "official development assistance" to developing countries. This indicator does not reflect any field of action of the EU Bioeconomy strategy and has been discarded.

[48] An example is the Eurostat indicator sdg_06_60 that measures the degree of water exploitation. Fresh ground water and fresh surface water data are excluded and only the data related with the exploitation of fresh water as a total of the former two are kept.

Second, pairwise correlation tests are carried out between all bioeconomy-related SDG indicators time series identified in section 5.2.1 (54), for each of the 28 EU Member States. As a result, 28 symmetric matrices of size 54 x 54 are obtained.

Third, only statistically significant correlations at the 5-percent significance level (p-value < 0.05) calculated on more than three years were considered for further analysis. Likewise, using 0.6 as a cutting point (as in Pradhan et al., 2017), pairwise correlations were classified as indicating either synergies ($\rho>0.6$), trade-offs ($\rho<-0.6$) or non-classified ($-0.6<\rho<0.6$) relations.

Fourth, the correlation results are aggregated at the EU level by calculating the percentage of synergies, trade-offs and non-classified relations found over the 28 Member States for each pair of indicators and for each SDG pair (intra-SDG and inter-SDG):

(i) SDG results summarise bioeconomy-related SDG intra- and inter-linkages. Among indicators of the same SDG pair (*s,t*), more weight is given to those pairs of indicators (*i,j*) with more significant correlations across the 28 Member States. Weights ($w_{i,j}$) are calculated as $w_{i,j} = \frac{N_{i,j}}{\sum_i \sum_j N_{i,j}}$, where $N_{i,j}$ is the count of significant pairwise correlations between bioeconomic indicators *i* and *j* ($i \neq j$) across countries. $N_{i,j}$ can range up to 28 (i.e., the number of EU countries).

Therefore, the percentage of synergies SYN_s^t between SDG *s* and SDG *t* ($s = t$ for intra-SDG calculations; $s \neq t$ for inter-SDG calculations) is:

$$SYN_s^t = \frac{\sum_i \sum_j S_{i,j} \times w_{i,j}}{\sum_i \sum_j N_{i,j} \times w_{i,j}}$$

where $S_{i,j}$ is the count of significant synergies between indicators *i* and *j* across countries. Similarly, by replacing $S_{i,j}$ with the count of trade-offs and non-classified cases, the respective percentages are obtained.

(ii) Indicator pair results are used to identify specific hotspots of trade-offs. A hotspot of trade-off refers to a pattern of negative correlations found in a high proportion across the 28 Member States (i.e., more than 50% of pairwise significant correlations) between a given indicator (or two) and a series of other SDG indicators.

This particular analysis on the indicator pair level might prove useful in the identification of pairs of non-market and market indicators with stronger links that can, later on, contribute to the enrichment of ex-ante simulation models with more non-market outcome variables.

Results at both levels of analysis (SDG pair level and indicator pair level) will contribute to the second aim of the chapter which is to provide data-based evidence in support to policy coherence into future EU policy designs.

5.3 Results

This section first presents the result of the semantic mapping between the EU bioeconomy action plan and the SDGs. Then, after the bivariate correlations amongst all identified bioeconomy related indicators are calculated, results are grouped for intra– and inter-SDGs to identify the pattern of synergies and trade-offs. Finally, the main hotspots identified at the indicator level are presented.

5.3.1 Contribution of the EU bioeconomy action plan to the SDGs

The mapping exercise depicts a wide multi-dimensionality in the scope of action of the EU bioeconomy strategy. 53 SDG targets, distributed across 12 SDGs, are mapped to one or several EU actions in the domain of the bioeconomy (SM10). Actions are contemplated in domains as varied as the bio-based sectors of activities (SDG 2, 8 and 9), the use and recycling of natural resources (SDG 6, 11 and 12), the biophysical environment (SDG 14 and 15), education (SDG 4), the production of bioenergy (SDG 7), climate action (SDG 13) and partnerships for the implementation of the action plan (SDG 17). Only five of the SDGs are excluded from the mapping either because they have no relation with the EU bioeconomy action plan (SDG 5: Gender equality and SDG 16: Peace, justice and strong institutions) or because their relation is not direct (SDG 1: No poverty, SDG 3: Good health and well-being and SDG 10: Reduce inequalities).

For the understanding of the following results, note that only 29 SDG targets, distributed across 11 SDGs, could be informed with data (SM11), after filtering for the criteria presented in section 5.2.1. The indicator distribution is uneven across SDGs: SDG 17 has no indicator after the filtering and is dropped; SDG 11 is represented by only one indicator (the recycling rate of municipal waste), as are SDG 13 with greenhouse gas (GHG) emissions and SDG 14 with the surface of marine sites designated under Natura 2000. The remaining SDGs are represented with 3 to 9 indicators. Moreover, the SDG framework defines the 'domestic material consumption' (DMC) as an indicator of targets 8.4 and 12.2. This duplication has been respected which statistically strengthens the synergetic relation between SDG 8 and SDG 12 all the more that the DMC is expressed in this study by five indicators for five biomass types: the DMC of wood, crops, crop residues, grazed biomass and fodder, and wild catch harvest.

5.3.2 Synergies and trade-offs between pairs of bioeconomy-related indicators

The intra-SDG analysis applies to only eight SDGs after excluding SDG 11, SDG 13 and SDG 14 that are represented with only one indicator (see grey cells in Figure 16, left panel), and the inter-SDG analysis has been conducted on 55 pairs of SDGs (Figure 16, right panel). Aggregated results for the EU indicate a large predominance of synergies over trade-offs for almost all intra- and inter-SDG pairs. In 59 SDG pairs out of 63, the proportion of synergies is indeed higher than the one of trade-offs (i.e., the 59 cells of Figure 16 where the colour green predominates). This result is consistent with the correlation analysis carried out on all SDGs by Pradhan et al. (2017) at the global level and by Buscaglia et al. (2018) at the EU28 level.

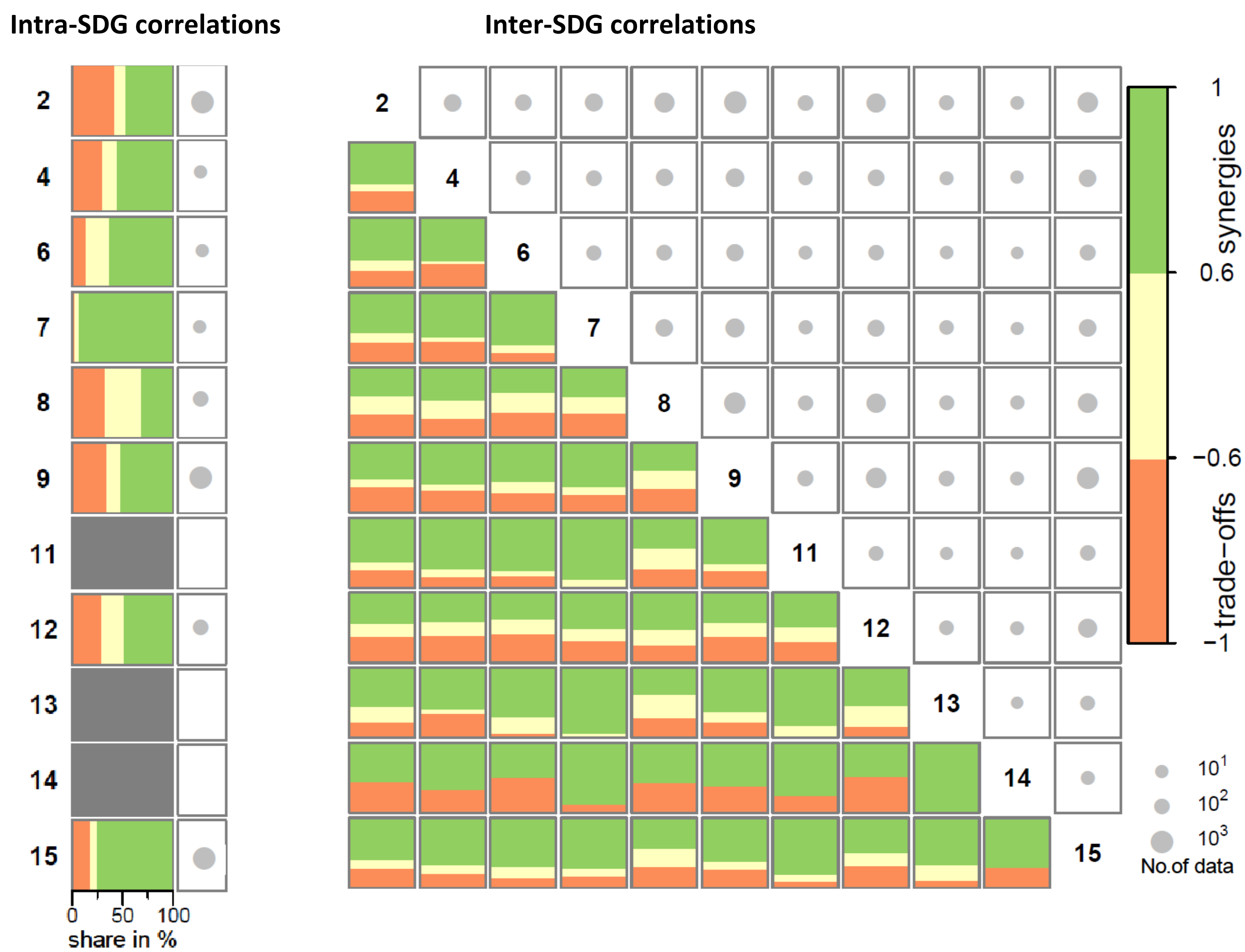

Figure 16. Synergies and trade-offs observed within (on the left) and between (on the right) bioeconomy-related SDGs in the EU.

Note: Numbers in bold identify the SDG; "No. (Number) of data" is the number of data used for the calculation of the proportion of synergies, trade-off and non-classified correlations (i.e., pairs of time series with at least three years and significantly correlated).

The figure reads: across the 28 Member States, 63% of the significant correlations found between SDG 2 and SDG 4 indicators are classified as synergies (green), 28% as trade-offs (orange) and 9% were not classified (yellow). They are calculated on more than 10^2 data pairs (medium dot) (detailed numbers in SM12).[49]

[49] We thank P. Pradhan for providing the R-code used for the graphical depiction of results in this figure.

In order to centre the analysis on the most consensual results across Member States, the SDG pairs have been ranked according to the proportion of synergies and trade-offs found (left and right panels respectively, Table 9). The comparison of the top-10 synergy pair list with the top-10 trade-off pair list shows a clear distinction between SDGs aiming at a lower dependence on fossil energies (SDG 7), recycling (SDG 11) and protection of terrestrial ecosystems (SDG 15) on the one hand, and SDGs dealing with biomass production and consumption on the other hand (SDG 2, 8, 9 and 12). These results are examined in Sections 5.3.3 and 5.3.4 and complemented with indicator level information.

Table 9. The top SDG pairs in terms of synergies (left) and trade-offs (right) of bioeconomy-related indicators in the EU.

Synergies			Rank	Trade-offs		
%	SDG pairs			SDG pairs		%
94%	7 AFFORDABLE AND CLEAN ENERGY	13 CLIMATE ACTION	1	14 LIFE BELOW WATER	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	52%
94%	7 AFFORDABLE AND CLEAN ENERGY	7 AFFORDABLE AND CLEAN ENERGY	2	6 CLEAN WATER AND SANITATION	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	42%
91%	7 AFFORDABLE AND CLEAN ENERGY	11 SUSTAINABLE CITIES AND COMMUNITIES	3	2 ZERO HUNGER	2 ZERO HUNGER	42%
84%	7 AFFORDABLE AND CLEAN ENERGY	14 LIFE BELOW WATER	4	14 LIFE BELOW WATER	2 ZERO HUNGER	41%
82%	11 SUSTAINABLE CITIES AND COMMUNITIES	13 CLIMATE ACTION	5	14 LIFE BELOW WATER	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	41%
79%	11 SUSTAINABLE CITIES AND COMMUNITIES	4 QUALITY EDUCATION	6	14 LIFE BELOW WATER	8 DECENT WORK AND ECONOMIC GROWTH	40%
79%	11 SUSTAINABLE CITIES AND COMMUNITIES	15 LIFE ON LAND	7	6 CLEAN WATER AND SANITATION	8 DECENT WORK AND ECONOMIC GROWTH	39%
79%	11 SUSTAINABLE CITIES AND COMMUNITIES	6 CLEAN WATER AND SANITATION	8	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	2 ZERO HUNGER	38%
77%	7 AFFORDABLE AND CLEAN ENERGY	6 CLEAN WATER AND SANITATION	9	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	37%
76%	15 LIFE ON LAND	15 LIFE ON LAND	10	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	36%

Note: The pair SDG 13 x SDG 14 is excluded from the top-10 synergy list (despite the 100% observed in Figure 16) and the pair SDG 6 x SDG 14 is excluded from the top-10 trade-off list because of the low number of observations (less than 100 data pairs, informing less than 10 significant correlations across Member States).

5.3.3 Hotspots of synergies

The top-10 synergy pair list is dominated by SDG 7 (Clean energy) and SDG 11 (municipal recycling) with six and five occurrences respectively (Table 9, left). Both of them appear strongly positively correlated with SDG 6 (Clean water) and SDG 13 (GHG emissions), suggesting that any improvement towards one of these four bioeconomy-related SDGs will be correlated with progress towards the other three. SDG 7 indicators also correlate positively between themselves in 94% of the significant correlations found (SDG 7 x SDG 7) and with the 'surface of marine sites designated under Natura 2000' (SDG 14) in 84% of the data pairs (Table 9, left). Figure 17 shows another hotspot of synergies between SDG 7 indicators and those SDG 9 indicators related to innovation and CO_2 emissions (see medium and dark green cells for indicators 17-19 x indicators 31-36 in Figure 17 that indicate 75% to 100% synergies on significant correlations calculated on more than 60 data pairs). Similarly, the strong synergy found between SDG 11 (municipal recycling) and SDG 4 (Education) is largely due to the relation of municipal recycling with tertiary educational attainment for which all the 24 significant correlations found are positive (see dark green cell for indicator 10 x indicator 37 in Figure 17).

SDG 15 (Life on land) ranks three times in the top-10 synergy pair list: at the 5th position in association with SDG 11 (municipal recycling) and at the 10th position with itself (SDG 15 x SDG 15) (Table 9, left). Intra-SDG 15 synergies (76% of the data pairs, Table 9) are largely due to a strong homogeneity of the eight SDG 15 indicators. Apart from forest area and forestry biomass yield indicators, they all measure progress in the protection of biodiversity (i.e., Red List index) or ecosystems (i.e., protected freshwater, terrestrial and mountain Key Biodiversity Areas (KBAs), terrestrial sites under Natura 2000, certified forests).

5.3.4 Hotspots of trade-offs

The top-10 trade-off pair list is shared between SDGs related with agricultural production and agriculture impacts (SDG 2), industrial use of biomass (SDG 9) or with the measure of domestic material consumption (SDG 8 and 12) (three or four occurrences each). Surprisingly, although SDG 14 and SDG 15 share similar aims - the protection of marine and terrestrial ecosystems respectively – SDG 14 ranks four times in the top-10 trade-off pair list (Table 9, right) while SDG 15 is well represented in the top-10 synergy list (Table 9, left).

Moving on to the trade-off list, it is interesting to highlight that only in two of the SDG pairs the proportion of trade-offs actually dominate over synergies. These are: SDG 12 (Biomass consumption and production) x SDG 14 (marine Natura 2000 sites) (52% vs. 48% of significant correlations) and SDG 6 (Clean water) x SDG 8 (Industry, innovation and Infrastructure) (39% vs. 35% of significant correlations) (see Figure 16). In other words, even amongst those pairs of SDGs where trade-offs are encountered more frequently, still synergies predominate over trade-offs (with the two exceptions commented).

Therefore, the trade-off analysis makes more sense at the indicator level as shown in Figure 17. This figure highlights only the indicator pairs for which a proportion of significant synergies or trade-offs higher than 50% has been found over a sample of more than 60 data pairs. While the majority of the indicator pairs are characterised with synergies (green cells), four clear hotspots of trade-offs emerge on the heat map (see colour frames around red cells). They correspond to a limited number of indicators that are negatively correlated with almost the whole range of other bioeconomy-related SDG indicators of this study:

- Trade-offs related to SDG 2 indicators (Figure 17, black frame) on agro-biodiversity (i.e., the number of local breeds classified as known being at risk) and the agriculture orientation index for government expenditures.

- Trade-offs related to two SDG 9 indicators (Figure 17, blue frame) on the weight of manufacturing sectors in terms of value-added and jobs.

- Trade-offs related to the same two SDG 8 and SDG 12 indicators (Figure 17, purple frames) on DMC of wood and crop residues.

The trade-offs arising from the employment rate of recent graduates (SDG 4, Figure 17, grey frame) will not be commented further as SDG 4 does not appear on the top-10 trade-off list (Table 9, right).

Figure 17. Hotspots of synergies and trade-offs by pairs of bioeconomy-related SDG indicators

Note: To synthesise results on a single matrix, synergies between pairs of indicators are represented below the main diagonal and trade-offs above the main diagonal. Only cells where more than 50% of the pairwise correlations classified either as significant synergies (green) or trade-offs (red) and based on at least 60 data pairs are coloured. As a reminder, no causality inference can be made on this matrix, and accordingly, results have to be interpreted for the indicator pair (i and j) irrespective of whether indicator i is positioned in a row or in a column.

Legend: dark green (red) cells indicate indicator pairs with 100% synergies (trade-offs), medium green (red) indicate 75% to 100% synergies (trade-offs), light green (red) cells indicate 50% to 75% synergies (trade-offs). For example, the dark red cell corresponding to indicator 1 in row and indicator 2 in column indicates 100% synergies found between those two indicators. Cells highlighted with coloured frames represent indicators (marked in red) where systematically trade-offs are found (i.e., hotspots) (e.g., in purple, two indicators common to SDG 8 and SDG 12; in black, two indicators related to SDG 2).

5.4 Discussion

Section 5.3 presented the findings of the study in answer to the two research questions. The present section discusses these findings in the context of the literature (sections 5.4.2 to 5.4.7) after recognising the limitations and strengths of the methodological approach (section 5.4.1). Strong emphasis is placed at examining if the correlations underlying the main areas of synergies and trade-offs highlighted in the top-10 synergy and trade-off pair lists (Table 9) are supported by empirical observations and scientific studies (i.e., synergies associated with SDGs 7, 11 and 15 and trade-offs associated with SDGs 2, 9 and 8 and 12). Furthermore, the discussion examines whether those correlations play or have played a role in the design of the EU policy framework.

5.4.1 Strengths and limitations of data and methodology

This study draws on the methodological approach proposed by Pradhan et al. (2017) for the identification of synergies and trade-offs amongst SDGs and applies this approach to the field of EU policy coherence between bioeconomy actions and the SDGs achievements. In comparison with Pradhan et al. (2017), the application field has constrained the statistical analysis to a fewer number of countries (only the EU Member States) and SDGs (only those bioeconomy-related), whilst the elimination of redundant SDG indicators has further reduced the database (see section 5.2.1). Nevertheless, the European scope of the study has also allowed the enrichment of the database with additional Eurostat data on specific bioeconomy-related SDG indicators.

As a note of caution, it is necessary to acknowledge the limitations of the study. One important data limitation lies in that neither the UN nor Eurostat covers all the identified bioeconomy-related SDG targets. Indicator incompleteness in terms of years and Member State representation, together with requirements in data harmonisation, have also exacerbated the over-/under-representation of some SDGs and may have created bias in the identification of the reinforcing or restricting bioeconomy-related forces in play. Moreover, SDG indicators are calculated at the national level but do not capture extra-borders impacts. This is an important weakness of this study since the extra-EU impacts of the European bioeconomy are not negligible (Bringezu et al. 2021).

At the methodological level, the paper opted for a fully quantitative analysis. Compared to other qualitative or semi-quantitative approaches, the procedure can be replicated for other time and geographical samples (e.g., other bioeconomy concepts in use in other countries or regions). The reliance on quantitative output also reduces the subjectivity of the results even though, as mentioned earlier, conclusions are tied to data availability and quality. The magnitude of the correlation coefficients and the proportion of positive or negative correlations inform on the strength of the association, but no indication is given on the direction of causality. Finally, the ex-post analysis captures synergies and trade-offs under past conditions that do not necessarily reflect the structural dynamics of the future socio-economic system.

5.4.2 SDG 7: The biofuel case and the evolution of the EU Renewable Energy Directive

SD7 (Clean energy) predominates the top-10 synergy pair list in association with SDG 6 (Clean water), SDG 7 (intra-SDG correlation), SDG 11 (municipal recycling), SDG 13 (GHG emissions) and SDG 14 (maritime protected areas) (Table 9).

In the bioeconomy context, the high synergetic profile of SDG 7 (Clean energy) has to be examined from the perspective of bioenergies (i.e., 65% of the EU renewable energies in volume (Eurostat 2018c). In fact, almost nothing is found in the scientific literature on their relation with municipal recycling (SDG 11) or maritime protected areas (SDG 14). However, it appears that the specificities of biomass as a feedstock for energy production could, in fact, compromise the correlation between bioenergies and energy productivity/efficiency, between bioenergies and water quality and utilisation, and with GHG emissions.

In their literature review, Ji et al. (2016) enumerate multiple concerns on the impact of all types of biofuels on water quality and water usage during the production and processing stages. However, the magnitude of these effects varies according to the processing technology and to the region (especially when irrigation water is mobilised) (Wu et al. 2009). The positive sign or negative relationship between biofuels and energy productivity and between biofuels and GHG emissions depends on the biofuel generation (crop vs. lingo-cellulosic material vs. algae vs. waste), the production system (e.g., natural conditions, fertilisation, irrigation, technologies…) and the method of calculation, even without accounting for indirect land-use change (iLUC) effects (de Gorter et al. 2013; Hennecke et al. 2013; Lewandowski 2015; Ji et al. 2016; García-Condado et al. 2019). Noteworthy, our correlations are run on indicators measured in EU Member States and do not reflect extra-EU effects (e.g., trade and iLUC effects).

Interestingly, scientific debates on the relation between biofuel consumption, energy efficiency and GHG emissions have been reflected in the legislative process with consecutive amendments to the Renewable Energy Directive (Dir. (EU) 2015/1513 and then in Dir. (EU) 2018/2001) (European Union 2015, 2018a). A biofuel transition towards those biofuels with higher potential of GHG emission saving and lower iLUC effect was indeed encouraged with the introduction of specific targets for "advanced" biofuels and sustainability criteria for biofuel accounting in national targets. Water quality and water utilisation are not part of the sustainability criteria but are included in several voluntary schemes in place in EU Member States.

5.4.3 SDG 11: The co-benefits of recycling targeted by the EU waste framework directive

SD11 (municipal recycling) also predominates the top-10 synergy pair list in association with SDG 4 (Education), SDG 6 (Clean water), SDG 7 (Clean energy), SDG 13 (GHG emissions) and SDG 15 (Life on land) (Table 9).

The synergetic profile of municipal recycling found in the present study is confirmed in the following scientific studies. The labour-intensity of recycling activities and their potential for productivity increase are supposed to offer economic and job opportunities in the waste management sector (SDG 8), while the skill adjustments needed for their upscale is also expected to steer education and vocational training (SDG 4) (Schroeder et al. 2019). The relation between waste recycling and SDG 7 (Clean energy) is materialised by the annual production of 676 PJ of energy from waste in the EU (Saveyn et al. 2016). Waste-to-energy processes permit GHG emission savings (SDG 13) from the avoided methane emissions from landfill, and thanks to lower CO_2 emissions per MWh in waste-to-energy power plants than in fossil fuel power plants (AlQattan et al. 2018). They also allow for fertiliser production from waste's nutrients (EBA 2015). In addition, recycling permits to reduce environmental pollution (SDG 6) from landfilling, to reduce raw material demand and to improve resource efficiency (SDG 8 and SDG 12) (Eurostat 2018a). However, Mayer et al. (2019) stress particular cases in which recycling indirectly required more material or energy than the direct use of primary materials.

At the policy level, the expectation of co-benefits from waste reuse and recycling have motivated the elaboration of the Circular Economy package (European Commission 2015). In particular, this package includes the recent setting of municipal waste recycling targets in the directive (EU) 2018/851 (European Union 2018b) and the revision of the Fertilising Products legislation (European Union 2021). The latter aims at easing and fostering the production of organic fertilisers manufactured from secondary raw materials such as agricultural by-products and recovered bio-waste.

5.4.4 SDG 15: Area protection and biodiversity protection, rationale of the Natura 2000 network

SDG15 ranks third on the top-10 synergy pair list (Table 9). In the present correlation analysis, intra-SDG 15 synergies mainly relate to positive correlations between area protection and biodiversity status. This relationship underlies most policy strategies for biodiversity (see EU Member States commitments for Target 1 of the EU 2020 biodiversity strategy (European Commission 2011a), the UN-SDG target 15 and the Convention on Biological Diversity "Aichi-target" 11 (CBD 2010)). At the legislative level, the Nature directives have motivated the implementation of the Natura 2000 network in the EU that has become the largest coordinated network of protected areas in the world (European Union 1992, 2009). This network is found to be beneficial for the biodiversity of common species and species at risk (Jones-Walters et al. 2016) and to have a stabilising and preventing role from further biodiversity decline (EEA 2015). Though, leveraging the synergy between area protection and biodiversity status might not be sufficient as more than 50% of the species identified at risk show an unfavourable status (EEA 2015). A wider ecological representation and better management effectiveness of protected areas are the main proposals for improvement (Watson et al. 2014; Friedrichs et al. 2018; Lemieux et al. 2019), and particularly when freshwater biodiversity is concerned (Juffe-Bignoli et al. 2016; Carrizo et al. 2017; Bastin et al. 2019). Future climate conditions might also trigger changes in species distribution and imply the revision of the geographical coverage of the Natura 2000 network (Araújo et al. 2011; Watson et al. 2014; Blicharska et al. 2016; Juffe-Bignoli et al. 2016; Carlson et al. 2017; Friedrichs et al. 2018). Moreover, the last biodiversity assessment for Europe concludes that a wider range of policies than area protection measures are needed to address direct and indirect drivers of biodiversity loss, the main ones being land-use change, the impacts of climate change, increasing natural resource extraction, pollution and invasive alien species (IPBES 2018).

5.4.5 SDG 2: the difficult challenge of curbing the Agriculture – Agro-biodiveristy trade-off

On the top-10 trade-off pair list (Table 9), negative correlation with SDG 2 indicators mainly relate to agro-biodiversity and the agriculture orientation of a Member State. In the scientific literature, the erosion of agro-biodiversity is directly attributed to the large adoption of new highly productive but little diversified genetic material (FAO 2010, 2015; Govindaraj et al. 2015; UNEP/UNECE 2016;

Bioversity International 2017), the implementation of monocultures and the use of pesticides. Other indirect factors are mentioned like over-exploitation (e.g., over-grazing) and land cover changes (Govindaraj et al. 2015). Nitrogen and Phosphorus pollution from inefficient management of manure and the use of synthetic fertilisers also affect the capacity of plants and animals to survive (Guthrie et al. 2018; Kanter et al. 2019).

Political concerns for curbing the negative effects of agriculture on agro-biodiversity have been materialised by Member States´ efforts for ex-situ conservation in gene banks (FAO 2010) as well as the introduction of greening measures in the EU Common Agriculture Policy (CAP) in 2010 and 2013, that is, crop diversification, maintenance of permanent grassland and Ecological Focus Areas (EFAs) (Hodge et al. 2015; Tzilivakis et al. 2016). However, as posited by Pe'er et al. (2014), these efforts might not meet the agro-biodiversity challenge. Note that the new CAP had not been launched yet during the period spanned by our correlation analysis.

Nutrient pollution from agricultural origin is addressed by several policy instruments: the EU water framework directive, the Nitrates directive (European Union 1991, 2000) and the Gothenburg protocol on ammonia (NH3) volatilisation and nitrogen oxides (NOx) emissions (UNECE 2012). The volatilisation of nitrogen dioxide (N2O) of agriculture origin is not regulated. However, the eight infringement cases to the Nitrate directive give an indication of the difficulty for the Member States to comply with these directives (European Commission 2018a) and the persistence of trade-offs.

5.4.6 SDG 8 and 12: The challenge of decoupling biomass DMC from bioeconomy activities

The many trade-offs related to SDG 8 and SDG 12 indicators mainly relate to the DMC of wood and crop residues. They should be given special attention since the development of the bioeconomy could further exacerbate the consumption of biomass for the production of bio-based products and because over-consumption of biomass is among the points of concern regarding a growing bioeconomy (see sections 1.1 and 5.1). The coupling of natural resources consumption and environmental degradation has been brought to policy discussions in 1987 in the Brundtland report (WCED, 1987). Since then, miscellaneous scientific studies have confirmed the existence of trade-offs between the occidental consumption level and the status of the living environment. The purpose of the present section is not to enumerate them, but rather to observe whether this knowledge plays or has played a role in the design of EU policies.

The 2011 Roadmap for a resource efficient Europe envisaged measures in the fields of research and innovation (R&I), consumer information on the environmental footprint of marketed products and waste management for better re-use and recycling (European Commission 2011b). Waste and secondary material management proposals have been integrated into the EU Circular Economy package (European Commission 2015) while consumer information (including labels and certifications) and R&I supports are part of the EU bioeconomy action plan (European Commission 2018b). Concerning the use of biomass for energy, woody biomass has to meet sustainability criteria and obligations defined by the EU (European Union 2010, 2015) but no criteria apply so far to crop residues.

The bioeconomy is a relatively new concept and it has not been subject to any integrated impact assessment so far. However, the development of footprint quantifications is likely to better inform on the biomass or the GHG footprint of bioeconomy activities in the near future (see for example Bringezu et al. (2021)).

5.4.7 SDG 9: The challenge of ensuring sustainable bio-based manufacturing sectors

The last preponderant SDG on the top-10 trade-off pair list is SDG 9 (Industry, innovation). Trade-offs related to SDG 9 indicators mainly relate to industrial development (measured in terms of proportion of value-added and jobs in the manufacturing sectors). These points of conflict cannot be directly transposed to the development of bio-based industries since they represent a small subset of the industrial sector, that is 27% of jobs and 22% of value-added of total EU28 industry in 2015 (Eurostat 2018b; Ronzon et al. 2023). Bioeconomy promotors claim instead that the development of the bioeconomy will create new markets for agricultural commodities and diversify rural economies. Mengal et al. (2018) expect bio-based industries to boost employment, 80% of which taking place in rural and underdeveloped areas. On the environmental side, new bio-based products would have the potential to save GHG emissions compared to their fossil counterpart (Carus 2017; Mengal et al. 2018). The mobilisation of waste and the cascading and circular uses of biomass in bio-based value-chains would boost biomass productivity compared to the past, thereby lessening the tension between industrial activity and biomass DMC (Bell et al. 2018; Mengal et al. 2018).

Although new bio-based products have recently emerged and advanced technologies are being tested in pilot plants, the scaling up of bio-based industries has not materialised yet and it is difficult to assess the relation between bio-based industry development and the SDGs. Coherently with agricultural, industrial and environmental EU policies, the challenge of the new EU bioeconomy action plan is exactly to address past trade-offs between industry and agriculture and natural resources and ecosystems.

5.5 Conclusions

Relying on a quantitative analysis of pair-wise correlations between bioeconomy-related SDG indicators, the paper aims at (i) identifying relevant interlinkages that later on could inform ex-ante simulation models in terms of SDGs characterisation and impacts and (ii) at providing data-based evidence in support of future EU policy coherence.

Regarding the first aim, this study stresses the strong interlinkages of some common modelling indicators with a wider range of other SDG indicators. The hotspot of trade-offs related to SDG 9 indicators is a good illustration. Examining correlations observed between the indicators 'proportion of manufacturing value added in total gross domestic product (GDP)' and the 'proportion of manufacturing jobs in total jobs', with other non-market SDG indicators, reveals a series of trade-offs. A more advanced econometric analysis could help parametrise such market-nonmarket relationships. Their integration within a price-driven simulation modelling framework, in a second step, would then permit ex-ante assessments of the performance of the selected non-market indicators according to the development of the two SDG 9 indicators above-mentioned under different scenario designs.

Regarding the second aim, the methodology tested in this study can be seen as a screening method to identify important points of synergy and conflict associated with a given policy action plan. Provided data is available, the methodology can be replicated at other national or regional levels to account for different socio-economic and environmental contexts. Future updates are also possible to assess progress at strengthening synergies and addressing trade-offs. The ex-post analysis conducted in this paper shows a high representation of environment-related SDGs in the top 10 synergies pair list: SDG 6 (water), SDG 7 (biofuels), SDG 11 (recycling), SDG 13 (climate action) and SDGs 14 and 15 (aquatic and terrestrial ecosystems). Actions strengthening environmental sustainability thus appear as key enabling forces for the achievement of multiple SDGs related to all three sustainability dimensions. On the other hand, mixed results are found regarding the social and economic pillars of sustainable development. To mention a few examples, indicators of value-added (economic dimension) and employment (social dimension) in the manufacturing sector constitute a hotspot of trade-offs while a synergetic profile is observed from the indicators of the gross domestic expenditure on research and development (economic dimension) or the tertiary educational attainment (social dimension).

Overall, we find that synergetic developments by far dominate over trade-offs among and within bioeconomy-related SDGs. Across the 28 EU Member States, improvements towards energy efficiency and the development of renewable energies (SDG 7), efforts in municipal recycling (SDG 11) and preservation of ecosystems and their biodiversity (SDG 15) have been concomitant to progress towards many other bioeconomy-related targets. The maintenance and improvement of the wide range of EU policy instruments in place in these domains is critical since they can bring many co-benefits. On the other hand, the withdrawal of policy instruments might stop progress or even entail the degradation not only of the targeted indicator but also of other correlated ones. This network of correlations might then accentuate the cost of political inaction.

The discussion highlights that the main domains of trade-offs have most of the time already been identified, triggering the implementation of EU policy instruments. These findings call for more efficient and coherent policy actions. But given the difficulty to overcome trade-offs over the period observed (1990-2018), a broader array of actions might be needed than the only policy ones (e.g., corporate responsibility, consumer awareness, organisational and cultural changes). The trade-offs identified in relation with SDG 2 and SDG 9 call for a change in agricultural and industrial production processes in such a way that they place less pressure on the environment (e.g., water, biodiversity and ecosystems represented in SDG 2, SDG 6, SDG 14 and SDG 15). Change in practices, technical and technological innovations (Wesseler et al. 2017) and the application of circular and 'cascading principles' are the most common suggestions on the table (European Commission 2015). But trade-offs associated with Europeans' consumption of biomass materials (SDG 8 and SDG 12) call for much more than technical solutions.

Chapter 6. Conclusions

6.1 Synthetic answers to specific research questions

RQ1: How did the non-service industry engage in a bioeconomy transition in EU Member States?

Taking an output-based approach Chapter 2 has consolidated a comprehensive dataset with harmonised measures of employment and value added across primary and secondary bio-based NACE sectors and Member States, over the time period 2008 to 2017 (updated until 2019 by Ronzon et al. (2023)). This dataset provides the basis for comparing national characteristics and socio-economic performances. It has allowed us to analyse further the sources of labour productivity gains by means of a novel method in the field of economic analysis of the bioeconomy: the shift-share method.

A first cross-country comparison yields a similar clustering of EU Member States as the ones published by Ronzon et al. (2020) using a more restricted sector coverage, where EU bioeconomies show increasing labour productivity and sectoral diversity along a transition pathway. Labour productivity gains tend to be increasingly higher over time in Northern and Western Member States than in Eastern and Central Member States, widening the bioeconomy labour productivity gap between the two country groups. The decomposition of labour productivity gains in the primary and secondary bioeconomy sectors confirms H1 that these gains are achieved in two ways: by modernising bio-based industries (within-sector effect) and/or by shifting bioeconomy workers from less productive to more productive (and possibly new) bio-based industries (between-sector effect). The magnitude of the two effects varies across countries but is particularly strong in Belgium, Denmark, Finland and Ireland.

Within-sector gains are systematically higher than between-sector gains at the country level, with only two exceptions: Cyprus and Greece. However, it cannot be determined if the sectoral or inter-sectoral source of productivity improvements is more efficient at steering bioeconomies on the transition pathway, as suggested in H2. Rather, it appears that the type of biomass endowment and historical industrial specialisation of an EU Member State influence transition strategies. Amongst the most advanced EU Member States on the bioeconomy transition, Finland – highly endowed in woody biomass – has developed its forestry industry further (within- and between-effect) and modernised the downstream paper and wood manufacturing industries (within-effect). Belgium, Denmark and Ireland have modernised their agricultural industry (within-effect) while modernising and/or developing their food and bio-based pharmaceutical industries (within- and/or between-effect depending on the country).

RQ2: How did the aggregate of bioeconomy services sectors perform in the EU and at Member State level?

Chapter 3 has focused on bioeconomy services. Taking an output-based approach, it has consolidated a comprehensive dataset with harmonised measures of employment and value added across bioeconomy service NACE sectors, Member States and years from 2008 to 2017. This dataset provides the basis for describing the development of the aggregate of bioeconomy services compared to other aggregates of economic sectors and identifying those bioeconomy services that have played a key role in employment and economic growth.

As a first conclusion, bioeconomy services contribute 5.2-14.2% of the EU27 gross domestic product (GDP) and 10.5-22.5% of the EU27 labour force on average over the 2015-2017 period according to an output-based approach, which validates H3. Moreover, the percentage contributions have been growing over time since 2008-2010. The lower range estimate is comparable in size with the non-service bioeconomy quantified with a similar methodology in Chapter 2. In contrast, the maximum range is slightly more than double the size of the non-service bioeconomy. The bulk of the employment and economic contribution to the total economy is attributable to the services associated with tangible goods and to those related to the natural environment (i.e., a combined 5.0-8.6% of the EU27 GDP and 10.2-16.9% of the EU27 labour force), while the contribution of bioeconomy knowledge-based services and bioeconomy support services is minor in comparison. In more general terms, the economic growth of the aggregate of bioeconomy service sectors tends to be stronger than that of the total economy of the EU27, and similarly in a vast majority of EU Member States.

As posited in H4, some sectors dominate the aggregate of bioeconomy services in the EU. Indeed, at the EU27 level and Member State level, the sectors of wholesale, retail trade of bio-based products, and of food and beverage service activities are large players. In particular, the latter has grown strongly over the period in both terms of employment and value added. The other main sources of bioeconomy service growth at the EU27 level were sport and recreation activities (in both employment and economic terms) as well as accommodation in employment terms. The contribution of public administration calculated in Chapter 3 (maximum estimate) is also considerable. In the ensuing period, the calculation criteria have been refined after consultation with the European Commission's service in charge of the EU Bioeconomy Strategy. The contribution of public administration was thus reduced to the ratio of total bioeconomy (excl. O84) on GDP or employment. The correction is reflected in the figures provided in Chapter 4.

Finally, a labour productivity divide between Western-Northern and Central-Eastern EU Member States is observed, similar to what was observed in non-service bioeconomy industries in Chapter 2.

RQ3: How does the output-based approach consolidated in chapters 2 and 3 compares with other approaches?

Chapter 4 has compared the approach and findings of Chapters 2 and 3 with alternative methods to quantify the EU28 bioeconomy value added. Harmonising of the equations employed in each approach allows one to compare the different methodological logic employed and to clarify the various data concepts valued under the common term "bioeconomy value added."

The findings of Chapter 4 validate the research hypothesis H5 that the data concept labelled as "EU bioeconomy value added" takes a different meaning in each approach. The term value added employed in the output-based approach is a market value; it measures the value added from sales of bio-based goods and bioeconomy relevant services (no matter the quantity of their biomass inputs). The input-based approach is feedstock oriented in the sense that it measures the value added created from the use of biomass by a given sector, whatever the final output. A third concept, the upstream bioeconomy value added quantifies the value created by upstream industries from sourcing core bioeconomy sectors with any kind of goods or services (no matter if those goods are bio-based or if their producing industry uses biomass as a feedstock).

Consequently, Chapter 4 gives guidance on the value added size of each concept. The markets of bio-based products and energy generate EUR 730-790 billion of value added, the use of biomass within the European economy generates EUR 670 billion of value added, the sourcing of core bioeconomy industries with goods and services generates EUR 270 billion of value added. Those numbers are not cumulative since they are derived from overlapping concepts (e.g., the same industry can use biomass and produce bio-based products).

The EU bioeconomy appears to be deeply integrated into the total economy as almost all NACE sectors create value from upstream or downstream relations with biomass producing sectors. However, time comparisons do not provide any evidence of increased use of biomass inputs in EU industries in substitution of fossil resources, nor a decreasing dependence of traditional bioeconomy industries towards fossil resources over the period 2005-2015. Their achievement would have signalled an advanced bioeconomy transition.

RQ4: What are the potential synergies and trade-offs between bioeconomy-related SDG targets and goals?

Using the SDG framework as a normative framework for sustainability assessment, Chapter 5 has looked at the coherence between the actions planned in the 2018 EU Bioeconomy strategy and SDG targets and goals. It first semantically matched said actions with SDG targets and their indicators before running the statistical Spearman analysis on the correlation between all possible pairs of bioeconomy-related SDG indicators for the EU28. Positive correlations indicate a synergistic development while negative correlations indicate an antagonistic development.

The matching exercise validates H6 by which the EU bioeconomy action plan is coherent with the achievement of a broad range of SDGs. The semantic mapping matches bioeconomy actions with 53 SDG targets, distributed across 12 SDGs out of 17. Those are spread across domains as varied as the bio-based sectors of activities (SDG 2, 8 and 9), the use and recycling of natural resources (SDG 6, 11 and 12), the biophysical environment (SDG 14 and 15), education (SDG 4), the production of bioenergy (SDG 7), climate action (SDG 13) and partnerships for the implementation of the action plan (SDG 17).

The correlation analysis validates H7 that there are more synergies than trade-offs between bioeconomy-related SDG targets and that by extension the EU bioeconomy actions are overall synergistic. Synergies are particularly strong between actions in the domain of clean energy (SDG 7) and recycling (SDG 11) and water quality (SDG 6) and mitigation of GHG emissions (SDG 13).

However, concerns arise from identifying a limited number of indicators that are negatively correlated with almost the whole range of other bioeconomy-related SDG indicators. Those are related to the agricultural orientation of governmental budgets, industrial development and the domestic material consumption of wood and crop residues. Therefore, the challenge of the EU bioeconomy strategy is to avoid the trade-offs observed in past data remaining in the future.

A closer look at the EU policy framework shows that the main synergies and trade-offs arising from bioeconomy actions are usually already integrated in different segments of legislation. However, margins of improvement remain to strengthen further synergies and avoid trade-offs.

6.2 Answer to the overall research question and general discussion

To the overall research question "How to monitor the transition towards the bioeconomy across economic sectors in the EU and strengthen policy coherence?" my thesis makes five novel contributions. First, a consolidated dataset on bioeconomy employment and "value added" measured according to an output-based approach and spanning all bioeconomy sectors and EU Member States (RO1). Second, a positioning of EU Member States on the bioeconomy transition pathway and an analysis of individual sectors´ contribution to that transition (RO2). Third, a framework for screening potential points of tension regarding the sustainability of the EU bioeconomy (RO1). Fourth, the identification of points of coherence and incoherence between EU bioeconomy actions and the overarching SDGs (RO2). Fifth, evidence-based policy recommendations for better targeting and coherent bioeconomy initiatives in the EU (RO3, presented in section 6.3).

A consolidated dataset on bioeconomy employment and "value added" (output-based measure)

The bioeconomy is a still-evolving policy concept. The EU bioeconomy strategy has first targeted the biomass-producing and manufacturing sectors before broadening its scope to bioeconomy services. This thesis expands the JRC-Bioeconomics dataset used by the JRC for socio-economic monitoring of the EU bioeconomy to all non-service sectors (Chapter 2) and service sectors (Chapter 3). To that end, it employs an output-based approach consistently throughout all economic services represented in the National Accounts. The resulting dataset meets the monitoring criteria of being replicable, updatable, and providing harmonised data across economic sectors, countries and years. The data sources are all public and annually updated with the only exception of the output bio-based shares calculated by the nova-institute which will become public soon. To ensure consistency with the European Commission´s concept of the bioeconomy, methodological assumptions have been discussed with the service in charge of the EU Bioeconomy strategy and adjusted accordingly in Chapter 4. On that basis, data retrieval and calculation processes have been automatised by the JRC and linked to draft web dashboards. Therefore, a first contribution of this thesis is to provide the European Commission with the means to test, improve and validate the output-based methodology that I have developed and interpret the resulting data. After consultation with EU Member States´ representatives through the European Bioeconomy Policy Forum, no consensus has been found on a list of bioeconomy services. The sectoral breakdown that I offer allows Member States and stakeholders to use the dataset as a menu from which they can recompose their own bioeconomy aggregates and thereby adjust quantifications to their varying bioeconomy concepts. Limits are discussed further down in the conclusion section.

Positioning of EU Member States on the bioeconomy transition pathway and sectoral contribution

As a second contribution, my thesis analyses the positioning of EU Member States towards a more diversified and labour-productive bioeconomy. The transition graph proposed (Figure 3) is a simple visualisation of country groups on a sort of transition pathway that can be easily replicated in the future to spot the evolution of individual Member States from one bioeconomy pattern to another. Further analysis shows that the bioeconomy labour productivity level reached by Member States results from the sectoral composition of their bioeconomy and individual sectors' performance, but also from the development of (new) highly productive bio-based industries that attract resources from less productive sectors (Chapter 2).

I conclude that "*four Northern Member States exhibit a bioeconomy transition by modernising their bioeconomy activities and operating structural changes. Other Northern and Western EU Member States are still in the early stages of a transition, whilst in Eastern and Central Europe, such a transition remains elusive.*" Forest-based value chains, on the one hand, and the agri-food and bio-based pharmaceutical industries, on the other hand have played a key role in pushing up the bioeconomy labour productivity of the four most advanced Member States (i.e., Belgium, Denmark, Finland and Ireland). Chapter 3 also emphasises the significant contribution of bioeconomy services, in particular the sectors of wholesale, retail trade of bio-based products, and of food and beverage service activities.

Recently, Cingiz et al. (2021b) also compared the bioeconomy's value added performance of the EU Member States based on IOT data but did not reach any conclusion on the progress made towards the bioeconomy transition. Kardung et al. (2021b) elaborated Markov transition matrices that span the different dimensions of the bioeconomy from a set of 41 indicators in ten EU Member States. They concluded that Germany occupied a "front-runner" position in the transition and that Slovakia, Poland and Latvia were progressing quickly. The former is consistent with the findings of Chapter 2, the latter suggests that those three countries could be in transition towards the next transition stage. This could be verified on further update of the transition graph (see Figure 3).

Framework for screening potential points of tension regarding the sustainability of the EU bioeconomy

The different bioeconomy visions presented in the introduction are associated with various points of concern regarding the sustainability of a bioeconomy transition that are not easy to evaluate considering the limited data available on the EU bioeconomy. The third contribution of my thesis is to propose a comprehensive (albeit possibly rough) framework for screening interlinkages between the EU Bioeconomy strategy and the SDGs. First, the match between EU bioeconomy policy actions and SDG targets gives a first picture of the coherence between the two policy initiatives. Second, the correlation analysis clarifies the internal (in)coherence of bioeconomy measures. The analytical framework proposed uses the official UN and Eurostat SDG databases (Eurostat 2019; United Nations Statistics Division 2019), which are subject to annual reporting by Member States. Linking bioeconomy measures to mandatory SDG reporting is a workaround solution to bioeconomy data scarcity (El-Chichakli et al. 2016; Calicioglu et al. 2021) although SDG indicators sometimes measure wider concepts (e.g., renewable energy instead of bioenergy, industrial growth instead of bio-based industrial growth).

Points of coherence and incoherence between EU bioeconomy actions and the overarching SDGs

The SDG screening performed at Chapter 5 concludes that the EU bioeconomy actions are overall coherent with the SDGs and goes further by pointing out the strengths and weaknesses of bioeconomy developments in the EU Member States over the period 1990-2018 in the form of hotspots of synergies and trade-offs. These echo the concerns associated with the different visions of the bioeconomy presented in the introduction and indicate where to strengthen policy coherence.

The main hotspots of synergies are found within the areas of bioenergies (SDG 7), recycling (SDG 11) and the preservation of ecosystems and their biodiversity (SDG 15). The decarbonisation of the economy and the circularity of our production and consumption system are indeed at the heart of the EU Bioeconomy. Maintaining actions in these fields is likely to bring many co-benefits. The last identified hotspot of synergies related to SDG 15 echoes very much the "bio-ecology" vision that places the bioeconomy transition within ecological boundaries for the preservation of ecosystem services. It also reaffirms the relevance of the last reorientation of the EU Bioeconomy strategy towards the third pillar of "Understand[ing] the ecological boundaries of the bioeconomy." In this regard, Liobikiene et al. (2020) observe that some Member States have already exceeded the limits of their own land biocapacity (i.e., Belgium), while others show a relative decoupling of their bioeconomy with land usage (i.e., Italy, Lithuania and Spain).

The hotspots of trade-offs point to the EU´s domestic material consumption (DMC) of biomass, agro-biodiversity and agricultural and industrial development. The first point echoes the concerns raised against a "bio-resource" vision of the bioeconomy: will a growing bioeconomy imply growing consumption of natural resources? Beyond the promotion of circular flows of biomass, it suggests (more efficient) actions to curb Europeans´ consumption. The agro-biodiversity and agricultural point crystallises the controversies between the proponents of the "bio-ecology" and the "bio-technology" visions of the bioeconomy: some ecosystem services, such as the ones delivered by (agro)biodiversity, might not be substitutable with technologies unless a disruption occurs in the future. The third point also questions the capacity of technological progress to mitigate the negative externalities of industrial development by providing green solutions ("bio-technology" vision). That question is, however, more rhetorical since the SDG indicators associated with that hotspot measure the whole industry aggregate and might not adequately capture the interlinkages associated with bio-based industrial development.

6.3 Policy recommendations on bioeconomy monitoring and policy coherence

The research conducted in this thesis leads to recommendations for a better monitoring of EU bioeconomy developments, a better targeting of bioeconomy policy measures and better policy coherence in general.

Improving the data basis for a more granular and precise monitoring

The problem statement of the thesis stressed important data limitations for a sound monitoring and evaluation of the bioeconomy. Chapters 2 and 3 have contributed with new quantifications that do not entirely solve the problem but do provide helpful guidance on where to focus further efforts.

One way to fill product- and industry-level data gaps is to propose new product/industry codes in the classifications used in European statistics.[50] EC services and stakeholders are consulted each time those classifications are revised by Eurostat. The market size of a product/industry is a criterion for the adoption of new codes. Chapters 2 and 3 have provided market size estimates that can guide the proposal of new bio-based codes towards those with the biggest market size and the wider estimation uncertainty (i.e., the wider min-max bio-based output share or min-max value added estimate), for example: remediation activities and other waste management services (NACE E39), repair of household goods (S65), scientific research and development (M72) or printing and reproduction of recorded media (C18). Proposals have been sent to Eurostat for the last revision of the NACE classification by the JRC and the BioMonitor consortium. Some suggestions have been postponed to be tackled at the product level in future Prodcom or CPA revisions.

Complementary to more granular classifications for bio-based industries and products, another suggestion is to run ad hoc survey(s). Here, the focus can be put on high-value goods production (in market value added size) and/or on emergent bio-based industries that have not yet reached the market size to be singled out in Eurostat statistics but that present an important potential for development. Additional aspects than employment and value added could also be surveyed to enable more sophisticated analyses (e.g., TFP analysis). For example, Jander et al. (2020) suggested "conducting an explicit survey regarding the bioeconomy or through adding another item in the European Community Innovation Survey (CIS)."

[50] The (2-digit) NACE classification is used in industry level statistics such as the National Accounts and the Structural Business Statistics. The (6-digit) CPA and (8-digit) Prodcom classifications serve product-level statistics such as the Europroms and Comext trade statistics together with (6-digit) HS and (8-digit) CN classifications.

My research also recommends a strengthening of the links between policy makers and scientists to make wider use of existing data. This has been illustrated in Chapter 4 with guidance for using data on the value added size of the EU bioeconomy.

Finally, with the bioeconomy being a multi-faceted and a not yet stabilised concept, it is advisable to display NACE level data in monitoring dashboards. This enables users to re-construct their own bioeconomy scope, acknowledging and respecting the plurality of strategic orientations in EU national bioeconomies.

Orienting bioeconomy policy measures for Member States convergence and for limiting trade-offs

Chapters 2 and 3 have not only stressed a widening East-West gap in labour productivity levels of the non-service and service bioeconomy, but also the existence of a glass ceiling between the two groups of countries that prevents Member States from catching up. Over the period 2008-2017, no Member State has shifted from the second to the third stage of the bioeconomy transition. The EC has already taken action to reduce that divide. For example, the BIOEASTsUp coordination and support action (CSA) funded by EU research framework programme aims at supporting the elaboration of national bioeconomy strategies in Central and Eastern Member States. Chapter 2 has stressed a series of bio-based industries that have efficiently pushed the bioeconomy transition (i.e., those Member States that have accomplished important within- and between-sector productivity leaps). Analysing further their trajectory, identifying effective measures or practices and understanding the contextual elements that made them efficient would help clarify the enabling conditions for a rapid bioeconomy transition. In particular, the development economics literature emphasises the positive effect of combined structural changes (e.g., between-sector effect) and investment in fundamentals (human capital, institutions) (McMillan et al. 2017).

Chapters 4 and 5 have revealed disappointing results regarding resource consumption and called for renewed policy action to transform European consumption patterns. Chapter 4 suggested that the decoupling of European bioeconomies from fossil resources has not happened yet: traditional bioeconomy industries have not curbed their use of fossil inputs (in monetary terms) and secondary and tertiary bioeconomy sectors have not significantly displaced their input costs towards bio-based feedstock. Therefore, if the substitution of fossil resources by biomass is still to come, that could worsen the trade-offs observed in Chapter 5 between the EU biomass DMC and a wide range of sustainable development targets. The EU bioeconomy strategy counts on increasing material circularity and consumer awareness. However, the magnitude of the necessary change may imply coordinated policy action beyond the solely bioeconomy scope (e.g., with agriculture, industrial and trade policies).

Screening for policy coherence with SDGs

Chapter 5 has illustrated an objective approach to anticipate points of tensions between a given strategy and sustainability objectives. The use of the latest internationally agreed sustainable development framework (i.e., the SDGs) and statistical tests for the identification of trade-offs limits subjectivity while bringing elements of answer to on-going (and sometimes heated) debates on the sustainability of the EU Bioeconomy strategy (see section 6.2). Such an approach offers the possibility to be updated in the future, to be restricted to specific EU sub-regions or Member States or even to be adapted to other policy frameworks. More widespread use of such or equivalent SDG screening methods in ex-ante impact assessment is therefore recommendable for their wide span, objectivity and flexibility to varying contexts (Nilsson et al. 2016).

6.4 Limitations and future lines of the research

Limits of the dataset and suggestions

The use of the consolidated dataset elaborated in Chapters 2 and 3 for monitoring purposes suffers from some limitations.

First, the output-based measure of the employment and value added size of some sectors remains very rough due to the unavailability of required data. Sectoral studies could help to gather the missing information to provide better insight on those sectors of high policy relevance. For example, the bioeconomy relevance of knowledge-based sectors could be better quantified if the proportion of teachers and scientists and their expenses in the bioeconomy fields of education and research were quantified or surveyed. The circularity of the bioeconomy would also be better understood with data on the type of products repaired or rented instead of the current aggregates (Llorente-González et al. 2020).

Second, the disaggregation of the dataset consolidated in this thesis at the regional level (e.g., NUTS2 and NUTS3) would help monitor territorial dynamics and better grasp the factors of successful transitions. The JRC has initiated research work in that direction but acknowledges that further refinement is needed concerning the regionalisation of the value added measure of forestry and fishing activities and the regionalisation of the output bio-based shares of secondary sectors (Lasarte Lopez et al. 2022).

Third, the consolidated dataset is restricted to the economic sectors represented in the National Accounts. If the measure of bioeconomy services faces many data gaps, the measure of non-marketed bioeconomy services is completely absent. The valuation of (non-marketed) ecosystem services would complete the picture. That aspect is not a novel research stream. A valuation handbook is provided by the United Nations (2014) and implemented in various studies, including from the JRC (Vysna et al. 2021). The missing link lies in the harmonisation of such measures with the dataset elaborated in this thesis, for example to avoid double-counting marketed ecosystem services (e.g., entrance fees of natural parks). Moreover, the valuation of ecosystem services is not available yet in the form of Member State-level time series, which is one of the prerequisites for EU monitoring.

Limits of the analysis and suggestions

Only two monitoring indicators are quantified in Chapters 2 and 3 from which a few more are derived such as the labour productivity and location quotients. The analysis of the sources of labour productivity growth conducted in Chapter 2 could have been more sophisticated and illustrative if data on additional factors of productivity had been available at the level of bio-based industries: e.g., data on investments (capital factors), labour skill types or levels of education (human capital) and technical change (see estimations of total factor productivity and associated analyses from Van Ark et al. (2017), Inklaar et al. (2020) and Jia et al. (2020)). That limitation links with the earlier suggestion of specific studies or surveys.

Chapters 2 to 4 described trends and relationships between sectoral dynamics and aggregate productivity, but they do not assess causality. Case studies could contribute to a better understanding of the enabling conditions of a bioeconomy transition: the institutional organisation that has supported a successful transition, the policy measures that have happened to be efficient, etc. The JRC´s Knowledge Centre for the Bioeconomy has already collected information on the configuration of governmental and private actors playing a role in each Member State´s bioeconomy and have compiled information on all national bioeconomy initiatives (Lusser et al. 2018). By focusing on a limited number of countries, this information could be matched with the quantitative results our dataset provides on bioeconomies' socio-economic performance and completed with targeted interviews to bring all pieces of the puzzle together and better understand the mechanisms and drivers of success stories.

Furthermore, Chapter 4 drew conclusions on the substitution effect and dependence on fossil resources based on monetary measures. Those phenomena would be more precisely monitored employing quantity measures (i.e., the quantity of material). A methodology for biomass flow monitoring has been elaborated within the BioMonitor project and tested on a few Member States (Delahaye et al. 2022). It appears that the conditions for its replicability are not met in all Member States, in particular, due to the lack of granularity of national statistics. That limit goes beyond scientific solutions.

Finally, the data problem commented on in the introduction goes beyond the lack and imprecision of sectoral economic data, which was the focus of this thesis. The literature highlights the deficit of social indicators for bioeconomy performance and of analyses of cross-border impacts (Giljum et al. 2016; D. D'Amato et al. 2017; Gawel et al. 2019; Bringezu et al. 2021). Chapter 5 concluded that the strong interlinkages of some common modelling indicators[51] with a wider range of other SDG indicators could be a basis for incorporating new SDG indicators in current modelling frameworks. Parametrising the relationships between the former and the latter by means of more advanced econometric analysis could be a way to integrate new social and environmental indicators into economic modelling analysis and test their development under different scenarios. In particular, their integration into economy-wide modelling frameworks would also help capture cross-border impacts as illustrated by Philippidis et al. (2020) or as initiated within the BioMonitor project with the bottoms-up modelling of specific bio-based industry sectors in the EU, as has been done with the BioMat model (Stürm et al. 2023).

[51] For example, 'proportion of manufacturing value added in total GDP' and 'proportion of manufacturing jobs in total jobs.'

Synthesis

The development of the bioeconomy concept has raised significant policy attention and controversies. Policymakers face the challenge of keeping a growing bioeconomy within our planet's ecological boundaries ("bio-ecology" vision of the bioeconomy), nurturing the capacity of biotechnologies to meet the ecological, environmental and social challenges ahead (concerns about a "bio-technology" vision) and recognising the potential threats and resulting impacts that arise from an intensified reliance on natural resources (concerns about a "bio-resource" vision).

Sound data and analytical tools are, therefore, crucial to guide policy developments towards efficient and sustainability-oriented measures and to bring facts to passionate debates. The intertwining of the bioeconomy and the broader economy hampers the understanding of bioeconomy dynamics from official statistics and makes analyses difficult. This diagnostic is particularly acute when considering industry-level data and analyses. As a contribution to tackle that challenge, my thesis seeks to answer the overall research question "How to monitor the transition towards the bioeconomy across economic sectors in the EU, and strengthen policy coherence?"

This thesis expands the JRC-Bioeconomics dataset used by the European Commission for socio-economic monitoring of the EU bioeconomy to all non-service sectors (Chapter 2) and service sectors (Chapter 3). It employs an output-based approach consistently throughout all economic sectors represented in the National Accounts. The resulting dataset meets the monitoring criteria of being replicable, updatable, and providing harmonised data across economic sectors, countries and years.

A first cross-country comparison confirms literature assumptions where EU bioeconomies show increasing labour productivity and sectoral diversity along a transition pathway. The decomposition of labour productivity gains performed in Chapter 2 concludes that Belgium, Denmark, Finland and Ireland exhibit a bioeconomy transition by modernising their bioeconomy activities and operating structural changes. Other Northern and Western Member States of the European Union are still in the early stages of a transition, whilst in Eastern and Central Europe, such a transition remains elusive.

Forest-based value chains, on the one hand, and the agri-food and bio-based pharmaceutical industries, on the other hand, have played a key role in pushing up bioeconomy labour productivity in the four most advanced EU Member States. Chapter 3 also emphasised the significant contribution of bioeconomy services (5.0-8.6% of the EU27 gross domestic product and 10.2-16.9% of the EU27 labour force), in particular the wholesale, retail trade of bio-based products, and of food and beverage service activities. Case studies could contribute to a better understanding of the enabling conditions of a bioeconomy transition by combining the data produced in this thesis with targeted interviews and with the European Commission’s data on national policy initiatives and institutional and private actors involved in national bioeconomies.

Chapter 4 compared the approach and findings of Chapters 2 and 3 with alternative methods to quantify the EU28 bioeconomy value added. It demonstrates that the data concept labelled as “EU bioeconomy value added” in all approaches takes on different meanings. It, therefore, reformulated the “value added” findings of the different approaches to help policy makers use the diverging numbers published. In 2015 in the EU28, the markets for bio-based products and energy generated EUR 730-790 billion of value added, the use of biomass within the European economy generated EUR 670 billion of value added, whilst the sourcing of core bioeconomy industries with goods and services generated EUR 270 billion of value added. Those numbers are not cumulative since they are derived from overlapping concepts (e.g., the same industry can use biomass and produce bio-based products). Time comparisons do not provide any evidence of increased use of biomass inputs in EU industries in substitution of fossil equivalents nor a decreasing dependence of traditional bioeconomy industries on fossil resources over the period 2005-2015. Their achievement would have signalled an advanced bioeconomy transition.

Chapter 5 looked at the coherence between the actions planned in the 2018 EU Bioeconomy strategy and SDG targets and provided evidence-based insights to the controversies introduced earlier. Positive correlations between bioeconomy-related SDG indicators dominate and suggest that core bioeconomy actions in the domain of decarbonisation of the economy (SDG 7), the circularity of our production and consumption system (SDG 11) and land ecosystems (SDG 15) bring many co-benefits. Hotspots of negative correlations are related to the EU´s domestic consumption of biomass, agro-biodiversity and agricultural and industrial development. The first point echoes the concerns raised within the “bio-resource” vision of the bioeconomy: will a growing bioeconomy imply growing consumption of natural resources? The second point crystallises the controversies between the proponents of the “bio-ecology” and the “bio-technology” visions of the bioeconomy: some ecosystem services such as the ones delivered by (agro-)biodiversity might not be substitutable with technologies unless a disruption occurs in the future. The third point also questions the capacity of technological progress to mitigate the negative externalities of industrial development by providing green solutions (“bio-technology” vision).

Finally, Chapter 6 recommends that policymakers continue to improve the data basis for more granular and precise monitoring by better representing bioeconomy activities and bio-based products in the classifications of economic sectors and products used in European statistics. Targeted policy measures are also suggested to reduce the observed East-West bioeconomy productivity divide, ensure the enabling conditions for a bioeconomy transition and support sectoral motors of growth. Further research streams are introduced, aimed at improving bioeconomy data by means of specific studies, surveys and case studies. Strengthening the representation of bioeconomy indicators in modelling framework would also enable more holistic evaluations of the bioeconomy across the three sustainability dimensions, including its cross-border impacts.

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Supplementary material

SM1 – Glossary of NACE sectors quoted in the thesis

NACE_R2	NACE_R2_LABEL
A01	Agriculture and hunting
A02	Forestry
A03	Fishing
B05_09	Mining and quarrying
C10	Manufacture of food products
C11	Manufacture of beverages
C12	Manufacture of tobacco products
C13	Manufacture of textiles
C14	Manufacture of wearing apparel
C15	Manufacture of leather and related products
C16	Woodworking industry
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C1811	Printing of newspapers
C1812	Other printing
C1813	Pre-press and pre-media services
C1814	Binding and related services
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Pharmaceutical industry
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C2365	Manufacture of fibre cement
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C2573	Manufacture of tools
C26	Electronics industry
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, etc.
C30	Manufacture of other transport equipment
C31	Manufacture of furniture
C32	Other manufacturing
C3212	Manufacture of jewellery and related articles
C3213	Manufacture of imitation jewellery and related articles
C33	Repair and installation of machinery and equipment
D35	Electricity, gas, steam and air conditioning supply
E36	Water collection, treatment and supply
E37	Sewerage
E38	Waste collection, treatment and disposal activities; materials recovery
E39	Remediation activities and other waste management services
F41_43	Construction
G45	Trade and repair of motor vehicles, etc.

NACE_R2	NACE_R2_LABEL
G46	Wholesale trade (excl. motor vehicles, etc.)
G47	Retail trade (excl. motor vehicles, etc.)
H49	Land transport
H50	Water transport
H51	Air transport
H52	Warehousing and support activities for transportation
H53	Postal and courier activities
I55	Accommodation
I551	Hotels and similar accommodation
I552	Holiday and other short-stay accommodation
I553	Camping grounds, recreational vehicle parks and trailer parks
I56	Food and beverage service activities
J58	Publishing activities
J5811	Book publishing
J5812	Publishing of directories and mailing lists
J5813	Publishing of newspapers
J5814	Publishing of journals and periodicals
J5819	Other publishing activities
J59	Motion picture, video and television programme production, sound recording and music publishing activities
J60	Programming and broadcasting activities
J61	Telecommunications
J62	Computer programming, consultancy and related activities
J63	Information service activities
K64	Financial activities
K65	Insurance activities
K66	Activities auxiliary to financial and insurance activities
L68	Real estate activities
M69	Legal and accounting activities
M70	Activities of head offices; management consultancy activities
M71	Architectural and engineering activities, etc.
M711	Architectural and engineering activities and related technical consultancy
M72	Scientific research and development
M7211	Research and experimental development on biotechnology
M7219	Other research and experimental development on natural sciences and engineering
M722	Research and experimental development on social sciences and humanities
M73	Advertising and market research
M732	Market research and public opinion polling
M74	Other professional, scientific and technical activities
M741	Specialised design activities
M749	Other professional, scientific and technical activities n.e.c.
M75	Veterinary activities

NACE_R2	NACE_R2_LABEL
N77	Rental and leasing activities
N7721	Renting and leasing of recreational and sports goods
N7729	Renting and leasing of other personal and household goods
N7739	Renting and leasing of other machinery, equipment and tangible goods n.e.c.
N774	Leasing of intellectual property and similar products, except copyrighted works
N78	Employment activities
N813	Landscape service activities
N79	Travel agencies, etc.
N80	Security and investigation activities
N81	Services to buildings and landscape activities
N82	Office administrative, office support and other business support activities
O84	Public administration and social security
P85	Education
Q86	Human health activities
Q87_88	Social work activities
R90_92	Cultural activities and gambling
R93	Sport, amusement and recreation activities
S94	Activities of membership organisations
S95	Repair of household goods
S9523	Repair of footwear and leather goods
S9524	Repair of furniture and home furnishings
S9525	Repair of watches, clocks and jewellery
S9529	Repair of other personal and household goods
S96	Other personal service activities
T97_98	Household service activities

SM2 – Estimation of the output bio-based of NACE E38, "Waste collection, treatment and disposal activities; materials recovery"

The output bio-based share of NACE E38 is estimated by calculating the proportion of biowaste within the total waste generated (WG) and treated (WT) (Eurostat datasets env_wasgen and env_wastrt, (Eurostat 2022h, 2022f)).

1. Estimation of the biowaste generated (Eurostat env_wasgen)

The env_wasgen breaks down WG by NACE sources *i* and by waste categories *j* (according to the European Waste Classification for statistical purposes).

1.1 Attribution of an output bio-based share by waste category
$b_{n,c,y}$ estimated in section 2.2 for the NACE C and F sectors were matched with their corresponding waste category *j* (see Table 10). Filters applied to env_wasgen: NACE_R2 = TOTAL_HH, UNIT = T, HAZARD = HAZ_NHAZ.

For the waste categories *j* from W01 to W09 and W12_13, and with *i* = total households:

$bbWG_{j,c,y} = b_{j,c,y} \cdot WG_{j,c,y}$

with bbWG is the biowaste generated, b is the output bio-based share, WG is the waste generated in quantity, *c* is the EU Member States or EU-27, and *y* is the year.

Table 10. NACE sectors used for the attribution of output bio-based shares per waste category

Waste category *j*	Label	Corresponding NACE sector *n*
W01-05	Chemical and medical wastes	C20
W061	Metal wastes, ferrous	No match needed: 0% bio-based
W062	Metal wastes, non-ferrous	No match needed: 0% bio-based
W063	Metal wastes, mixed ferrous and non-ferrous	No match needed: 0% bio-based
W071	Glass wastes	No match needed: 0% bio-based
W072	Paper and cardboard wastes	C17
W073	Rubber wastes	C22
W074	Plastic wastes	C22
W075	Wood wastes	No match needed: 100% bio-based
W076	Textile wastes	C13_C15
W077_08	Equipment	No match needed: 0% bio-based
W09	Animal and vegetal wastes	No match needed: 100% bio-based
W10	Mixed ordinary wastes	See next step
W11	Common sludges	See next step
W12-13	Mineral and solidified wastes	No match needed: 0% bio-based

Only two waste categories *j* did not match with the NACE categories C and F: Mixed ordinary wastes (W10) and Common sludges (W11). Their biomass content was estimated at next step.

1.2 Biowaste in W10 and W11: attribution of an output bio-based share by NACE source
For the waste categories W10 and W11, the output bio-based shares of NACE A to G sectors were matched with the sources of waste *i*, reported in env_wasgen by NACE sectors. Note that the output bio-based share of G46 (Wholesale trade) was matched with the source of waste "EP_HH" for

"Households". Filters applied to env_wasgen: UNIT = T, HAZARD = HAZ_NHAZ, WASTE = W10 and W11.

$bbWG_{j=W10, c, y} = \sum b_{i, c, y} . WG_{i, c, y}$

The same holds for *j*=W11

1.3 Total biowaste generated
Total biowaste generated $_{c, y} = \sum bbWG_{j, c, y}$

2. Estimation of the biowaste treated (Eurostat env_wastrt)

The env_wastrt breaks down the waste treated by NACE sources *i* and by waste categories *j* (according to the European Waste Classification for statistical purposes).

Total biowaste treated $_{c, y} = \sum bbWT_{j, c, y} = \sum b_{j, c, y} . WT_{j, c, y}$

with WT = Waste treated in quantity. Note that $b_{j, c, y}$ are the same as above for the calculation of biowaste generated (bWG).

3. Estimation of the proportion of biowaste generated and treated in total waste (i.e., the output bio-based share of E38)

If n=NACE E38, $$b_{n,c,y} = \frac{\text{Total biowaste generated}_{c,y} + \text{Total biowaste treated}_{c,y}}{\text{Total waste generated}_{c,y} + \text{Total waste treated}_{c,y}}$$

$$= \frac{\sum \text{ bbWG j,c,y} + \sum \text{ bbWT j,c,y}}{\sum \text{ WG j,c,y} + \sum \text{ WT j,c,y}}$$

with WG is the total waste generated and WT is the total waste treated.

SM3 – Selection of Prodcom codes for the estimation of the output bio-based of NACE F41-F43, "Construction"

The biomass content of the material remaining in construction building has been derived from the Centre for Industrial Study et al. (2017)'s list of material products. This list of 533 Eurostat prom products has been elaborated for the established for the European Construction Sector Observatoryand has been modified as follows for the purpose of this study:

1- Addition of old and new Eurostat prom products that were in use throughout the 2008-2018 period and related with the initial list of 533 products. 55 Eurostat prom products were added to the list.
2- Exclusion of the Eurostat prom products related to construction materials that do not remain in the constructed output (e.g., machinery). 87 Eurostat prom products were removed.
3- Exclusion of "Z codes" that are used for the match between the Prodcom cand CN classification but introduced double-counting otherwise. 12 Eurostat prom products were removed.

The final list of products used for this study finally comprises 489 Eurostat prom products, 103 of which were found bio-based and 386 of which were found not bio-based (see respective lists of Prodcom codes below).

List of Prodcom codes corresponding to bio-based construction material used in the estimation of the output bio-based share of NACE F (103 Eurostat prom products)
13203130 ; 13931100 ; 13931200 ; 13931300 ; 13931930 ; 13931990 ; 13961100 ; 16101010 ; 16101300 ; 16101077 ; 16101277 ; 16102110 ; 16102150 ; 16102210 ; 16102300 ; 16103116 ; 16103200 ; 16212100 ; 16212200 ; 16221030 ; 16221060 ; 16231110 ; 16231150 ; 16231900 ; 16232000 ; 16292130 ; 16292150 ; 16292380 ; 16292400 ; 17127710 ; 17241100 ; 17241200 ; 20301150 ; 20301170 ; 20301225 ; 20301229 ; 20301230 ; 20301250 ; 20301270 ; 20301290 ; 20302213 ; 20302240 ; 20302253 ; 20302255 ; 20302260 ; 20521060 ; 20521080 ; 20595750 ; 22212153 ; 22212155 ; 22212157 ; 22212170 ; 22212920 ; 22212935 ; 22212937 ; 22212950 ; 22212970 ; 22213010 ; 22213017 ; 22213021 ; 22213023 ; 22213025 ; 22213026 ; 22213029 ; 22213030 ; 22213035 ; 22213036 ; 22213037 ; 22213038 ; 22213053 ; 22213059 ; 22213061 ; 22213063 ; 22213065 ; 22213067 ; 22213069 ; 22213070 ; 22213082 ; 22213086 ; 22213090 ; 22214120 ; 22214130 ; 22214150 ; 22214170 ; 22214180 ; 22214230 ; 22214250 ; 22214275 ; 22214279 ; 22214280 ; 22231155 ; 22231159 ; 22231190 ; 22231250 ; 22231270 ; 22231290 ; 22231300 ; 22231450 ; 22231470 ; 22231500 ; 22231950 ; 22231990 ; 22232000.

List of Prodcom codes corresponding to non bio-based construction material used in the estimation of the output bio-based share of NACE F (386 Eurostat prom products)
08111133 ; 08111136 ; 08111150 ; 08111233 ; 08111236 ; 08111250 ; 08111290 ; 08112030 ; 08112050 ; 08113010 ; 08113030 ; 08114000 ; 08121150 ; 08121190 ; 08121210 ; 08121230 ; 08121250 ; 08121290 ; 08121300 ; 08122140 ; 08122160 ; 08122210 ; 08122230 ; 08122250 ; 08991000 ; 19103000 ; 23111212 ; 23111214 ; 23111217 ; 23111230 ; 23111290 ; 23121230 ; 23121330 ; 23141162 ; 23141167 ; 23141210 ; 23141217 ; 23141230 ; 23141237 ; 23141250 ; 23141293 ; 23141295 ; 23141297 ; 23191200 ; 23192500 ; 23201100 ; 23201210 ; 23201233 ; 23201235 ; 23201237 ; 23201290 ; 23201300 ; 23201410 ; 23201430 ; 23201455 ; 23201459 ; 23201490 ; 23311010 ; 23311020 ; 23311030 ; 23311050 ; 23311053 ; 23311057 ; 23311071 ;

23311073 ; 23311075 ; 23311079 ; 23321110 ; 23321130 ; 23321250 ; 23321270 ; 23321300 ; 23421030 ; 23421050 ; 23431030 ; 23431033 ; 23431035 ; 23431039 ; 23431050 ; 23431053 ; 23431055 ; 23511100 ; 23511210 ; 23511290 ; 23521033 ; 23521035 ; 23521050 ; 23522000 ; 23523030 ; 23523050 ; 23611130 ; 23611150 ; 23611200 ; 23612000 ; 23621050 ; 23621090 ; 23631000 ; 23641000 ; 23651100 ; 23651220 ; 23651240 ; 23651260 ; 23651270 ; 23651280 ; 23691100 ; 23691930 ; 23691980 ; 23701100 ; 23701210 ; 23701230 ; 23701260 ; 23701270 ; 23701280 ; 23991253 ; 23991255 ; 23991259 ; 23991290 ; 23991310 ; 23991320 ; 23991400 ; 23991910 ; 23991920 ; 23991930 ; 23991950 ; 23991970 ; 23991990 ; 24103110 ; 24103130 ; 24103150 ; 24103210 ; 24103230 ; 24103310 ; 24103320 ; 24103330 ; 24103340 ; 24103410 ; 24103420 ; 24103510 ; 24103520 ; 24103530 ; 24103540 ; 24103550 ; 24103600 ; 24104110 ; 24104130 ; 24104150 ; 24104200 ; 24104300 ; 24105110 ; 24105120 ; 24105130 ; 24105140 ; 24105150 ; 24105210 ; 24105230 ; 24105330 ; 24105500 ; 24106110 ; 24106120 ; 24106130 ; 24106140 ; 24106190 ; 24106210 ; 24106230 ; 24106250 ; 24106300 ; 24106410 ; 24106430 ; 24106450 ; 24106470 ; 24106510 ; 24106530 ; 24106550 ; 24106570 ; 24106610 ; 24106620 ; 24106630 ; 24106640 ; 24106650 ; 24106660 ; 24106700 ; 24107110 ; 24107120 ; 24107130 ; 24107140 ; 24107200 ; 24107300 ; 24107410 ; 24107420 ; 24107500 ; 2410T231 ; 2410T241 ; 2410T244 ; 24201110 ; 24201150 ; 24201210 ; 24201250 ; 24201310 ; 24201330 ; 24201350 ; 24201370 ; 24201400 ; 24202110 ; 24202150 ; 24202200 ; 24202300 ; 24202400 ; 24203110 ; 24203150 ; 24203210 ; 24203250 ; 24203310 ; 24203340 ; 24203370 ; 24203410 ; 24203430 ; 24203450 ; 24203470 ; 24203500 ; 24204010 ; 24204030 ; 24204050 ; 24204073 ; 24204075 ; 24321011 ; 24321012 ; 24321014 ; 24321016 ; 24321018 ; 24321022 ; 24321025 ; 24321028 ; 24321030 ; 24321040 ; 24321050 ; 24322010 ; 24322020 ; 24322030 ; 24322040 ; 24322050 ; 24322060 ; 24331110 ; 24331130 ; 24331150 ; 24331200 ; 24332000 ; 24333000 ; 24341130 ; 24341150 ; 24341170 ; 24341200 ; 24341300 ; 24422100 ; 24422230 ; 24422250 ; 24422330 ; 24422350 ; 24422430 ; 24422450 ; 24422500 ; 24422630 ; 24422650 ; 24422670 ; 24432100 ; 24432300 ; 24432400 ; 24441100 ; 24442200 ; 24442330 ; 24442350 ; 24442370 ; 24442400 ; 24442500 ; 24442630 ; 24442650 ; 24452200 ; 24452300 ; 24452400 ; 24512000 ; 24513030 ; 24513050 ; 25111030 ; 25111050 ; 25112100 ; 25112200 ; 25112330 ; 25112350 ; 25112355 ; 25112360 ; 25112370 ; 25121030 ; 25121050 ; 25211100 ; 25211200 ; 25211300 ; 25291110 ; 25291120 ; 25291130 ; 25291150 ; 25291170 ; 25291200 ; 25621001 ; 25721230 ; 25721250 ; 25721270 ; 25721440 ; 25721470 ; 25931130 ; 25931150 ; 25931250 ; 25931270 ; 25931343 ; 25931350 ; 25941115 ; 25991110 ; 25991127 ; 25992130 ; 25992150 ; 25992910 ; 25992941 ; 25992945 ; 25992983 ; 25992985 ; 26305080 ; 27121010 ; 27121020 ; 27121030 ; 27121040 ; 27121041 ; 27122130 ; 27122150 ; 27122170 ; 27122230 ; 27122250 ; 27122330 ; 27122350 ; 27122370 ; 27122433 ; 27122435 ; 27122450 ; 27123130 ; 27123150 ; 27123170 ; 27123203 ; 27123205 ; 27124030 ; 27124090 ; 27311100 ; 27311200 ; 27321100 ; 27321130 ; 27321150 ; 27321200 ; 27321340 ; 27321380 ; 27321400 ; 27331100 ; 27331200 ; 27331310 ; 27331350 ; 27331360 ; 27331370 ; 27331380 ; 27331410 ; 27331430 ; 27402500 ; 27512530 ; 27512550 ; 27512560 ; 27512570 ; 27512630 ; 27512650 ; 27521300 ; 27521400 ; 27901230 ; 27904300 ; 27904400 ; 28131417 ; 28141233 ; 28141235 ; 28141373 ; 28221820 ; 28251220 ; 28251250 ; 28251380 ; 302040700.

SM4 – List of 0% bio-based COFOGS used for the quantification of bn,c,y for n= O84

COFOG99	COFOG99_LABEL
GF0106	General public services n.e.c.
GF0107	Public debt transactions
GF0108	Transfers of a general character between different levels of government
GF0201	Military defence
GF0202	Civil defence
GF0205	Defence n.e.c.
GF0301	Police services
GF0302	Fire - protection services
GF0303	Law courts
GF0304	Prisons
GF0306	Public order and safety n.e.c.
GF0602	Community development
GF0606	Housing and community amenities n.e.c.
GF0701	Medical products, appliances and equipment
GF0706	Health n.e.c.
GF1009	Social protection n.e.c.

SM5 –Quantification of the maximum bn,c,y for n= O84, calculated on value added data

In the European System of Accounts (ESA), "The output of government (…) is equal to the sum of its costs of production [of which the compensation of employees]" (Eurostat 2013, p. paragraph 20.107). Therefore, the value added of NACE O84 can be reduced by the compensation of employees in the same non bio-based related COFOGS as reported at the supplementary section S4 for an over-estimation of the maximum $b_{n=O84,c,y}$ of public administration's value added.

More concretely, in the ESA:

- **Output** (O)= Compensation of employees (CE) + Intermediate consumption (IC) + Consumption of fixed capital (CFC) + Taxes (T) <u>with T≈0 in governmental sectors</u>

Therefore O ≈ CE + IC + CFC

- **Value Added** (VA) = O – IC

If we substitute O by the former equation: VA ≈ CE + IC + CFC – IC

IC cancels and: VA ≈ CE + CFC

In conclusion, if we deduce the CE from non bio-based related COFOGS (Eurostat (2020a) data) in VA (Eurostat (2022l) data), we have an estimation of the bio-based value added.

SM6 – Sectoral contribution of bioeconomy services to total GDP and national labour force (EU27 and Member States, 2015-2017 3-year average)

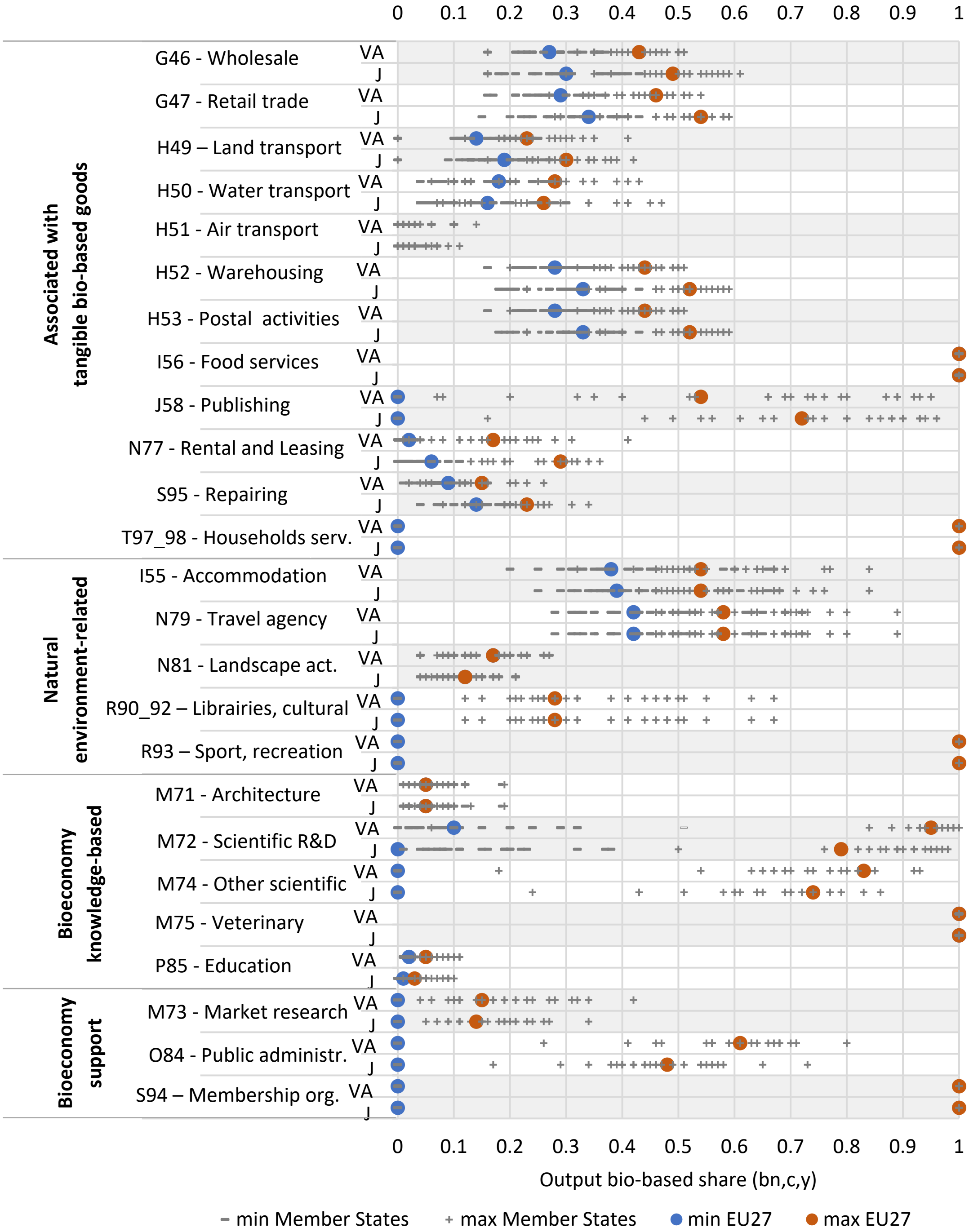
SM6.1. Sectoral contribution of the services that qualify to the EU definition to total GDP (minimum-maximum %, 2015-2017). Cells with a minimum contribution ≥10% are highlighted in light grey, cells with a minimum contribution ≥20% are highlighted in dark grey, cells with a minimum contribution ≥30% are written in red.

geo	G46	G47	H49	H50	H51	H52	H53	I55	I56	J58	N77	N79	N81	R90_92	R93	S95	T97_98
AT	23-24	19-21	5-6	.-.	0-0	6-7	2-2	12-16	15-24	0-2	0-3	1-2	1-1	0-2	0-4	0-0	0-1
BE	31-32	21-22	5-5	1-1	0-0	8-8	3-3	1-2	13-23	0-3	0-2	1-1	2-4	0-3	0-3	0-0	0-1
BG	37-40	18-19	10-10	0-0	0-0	7-8	2-2	6-6	9-14	0-1	0-1	1-1	0-1	0-3	0-3	0-0	.-.
CY	15-17	17-18	1-1	0-0	.-.	12-12	1-1	17-18	20-31	0-1	0-0	2-2	0-0	0-2	0-4	0-0	0-7
CZ	18-26	20-21	7-9	0-0	.-.	4-5	2-2	7-8	17-25	0-4	.-.	3-3	1-2	0-8	0-7	.-.	0-2
DE	25-28	21-22	4-4	1-1	0-0	8-8	3-3	4-4	12-22	0-4	0-2	2-2	3-5	0-1	0-7	0-0	0-3
DK	35-38	11-11	4-5	5-6	0-0	7-7	2-2	2-4	11-22	0-4	0-2	1-2	1-3	0-7	0-5	0-0	0-3
EE	25-27	16-18	8-9	0-0	.-.	14-15	1-1	4-6	10-20	0-3	0-4	1-2	1-1	0-4	0-6	.-.	0-1
EL	27-32	15-18	3-3	2-3	0-0	11-11	2-2	18-23	5-9	0-2	0-0	2-2	0-0	0-4	0-2	0-0	0-5
ES	22-27	19-22	5-6	0-0	0-0	8-10	1-1	5-5	15-25	0-2	0-1	1-1	1-1	0-2	0-9	0-0	0-8
FI	19-22	20-23	7-8	1-1	0-0	5-6	2-3	2-3	15-30	0-7	0-1	1-1	1-1	0-5	0-10	0-0	0-3
FR	22-22	23-25	5-5	0-0	0-0	7-7	3-3	3-4	18-29	0-3	1-2	1-1	2-3	0-2	0-8	0-0	0-2
HR	18-18	20-21	4-5	1-1	.-.	6-6	2-2	18-23	15-23	0-2	0-0	2-3	1-1	0-3	0-6	0-0	0-0
HU	28-32	22-24	9-10	0-0	0-0	11-12	3-3	4-4	8-13	0-3	0-1	1-1	1-1	0-4	0-5	0-0	0-0
IE	30-33	24-24	0-0	0-0	0-0	5-5	3-3	6-6	19-26	.-.	0-2	1-1	1-1	0-2	0-6	0-0	0-0
IT	21-24	20-24	5-5	1-1	0-0	8-9	2-2	5-6	15-26	0-2	0-1	1-1	1-1	0-2	0-5	0-0	0-13
LT	33-35	17-18	19-20	1-1	0-0	9-9	1-1	2-2	7-12	0-1	0-1	1-1	0-1	0-5	0-2	0-0	0-1
LU	37-40	16-17	5-5	.-.	.-.	.-.	.-.	3-4	21-32	0-0	0-3	.-.	2-3	0-2	0-5	0-0	0-5
LV	26-30	19-21	9-10	0-0	0-0	15-17	1-1	2-2	9-16	0-2	0-1	1-1	0-1	0-8	0-4	0-0	0-2
MT	20-25	21-23	2-2	.-.	.-.	.-.	.-.	15-15	17-32	0-1	0-0	3-3	.-.	0-15	0-4	0-0	0-3
NL	36-39	17-18	6-6	1-1	.-.	8-8	2-2	2-2	14-20	.-.	0-0	3-3	2-3	0-2	0-5	.-.	0-1
PL	33-38	26-27	10-11	0-0	0-0	6-7	2-2	2-3	6-10	0-3	0-1	1-1	1-1	0-3	0-4	0-0	0-2
PT	23-26	21-23	5-6	0-0	0-0	8-9	2-2	6-6	17-27	0-1	0-1	1-1	0-1	0-2	0-4	0-0	0-7
RO	35-39	23-25	9-10	0-0	0-0	6-6	2-2	3-3	8-13	0-1	0-1	1-1	1-1	0-7	0-4	0-0	.-.
SE	28-30	20-20	6-6	0-0	0-0	5-5	2-2	3-4	15-27	0-4	0-2	1-1	1-2	0-4	0-8	0-0	0-1
SI	21-22	20-20	10-10	0-0	0-0	9-9	2-2	9-11	14-23	0-3	0-0	2-2	0-1	0-4	0-3	0-0	0-1
SK	23-30	25-29	9-11	0-0	0-0	5-6	2-3	3-4	8-15	0-3	0-2	1-2	1-2	0-13	0-6	0-0	0-1
EU27	25-28	21-22	5-5	1-1	0-0	7-8	2-2	4-5	14-24	0-3	0-2	1-2	2-3	0-3	0-7	0-0	0-5

SM6.2. Sectoral contribution of the services that qualify to the EU definition to total employment (minimum-maximum %, 2015-2017). Cells with a minimum contribution ≥10% are highlighted in light grey, cells with a minimum contribution ≥20% are highlighted in dark grey, cells with a minimum contribution ≥30% are written in red.

geo	G46	G47	H49	H50	H51	H52	H53	I55	I56	J58	N77	N79	N81	R90_92	R93	S95	T97_98
AT	13-14	22-27	4-5	0-0	0-0	2-3	1-2	12-16	27-38	0-1	0-1	1-2	1-2	0-1	0-3	0-0	0-1
BE	15-16	27-27	5-5	0-0	0-0	4-5	3-3	1-2	25-39	0-2	0-1	1-1	3-5	0-2	0-3	0-0	0-6
BG	18-19	33-34	8-8	0-0	0-0	4-4	2-2	5-5	20-28	0-1	0-0	1-1	0-1	0-2	0-3	0-0	.-.
CY	11-14	19-21	1-1	0-0	.-.	6-6	1-1	13-15	23-40	0-1	0-0	1-1	0-1	0-1	0-3	0-0	0-20
CZ	10-14	21-22	7-8	0-0	.-.	2-3	2-2	6-6	31-42	0-2	.-.	2-3	1-1	0-5	0-7	.-.	0-2
DE	11-11	26-26	3-3	0-0	0-0	5-5	4-4	4-5	24-40	0-2	0-1	1-1	3-4	0-1	0-4	0-0	0-12
DK	20-20	16-16	3-3	1-1	0-0	3-3	2-3	3-5	24-45	0-4	0-1	1-2	1-3	0-5	0-8	0-0	0-7
EE	15-16	25-25	9-9	0-0	.-.	6-7	2-2	5-6	19-33	0-3	0-1	1-2	1-2	0-5	0-7	.-.	0-0
EL	11-13	23-25	2-2	0-0	0-0	2-3	1-1	10-11	37-47	0-1	0-0	1-1	0-0	0-1	0-2	0-0	0-5
ES	15-17	23-27	4-5	0-0	0-0	3-4	1-1	3-3	26-40	0-1	0-0	1-1	1-2	0-1	0-5	0-0	0-15
FI	12-12	24-25	7-7	0-0	0-0	4-4	3-3	2-3	22-42	0-5	0-0	1-1	1-2	0-4	0-9	0-0	0-5
FR	14-14	28-29	5-5	0-0	.-.	3-4	4-4	3-3	22-36	0-2	1-1	1-1	2-4	0-2	0-9	0-0	0-5
HR	12-13	24-26	4-5	0-0	0-0	4-4	2-2	10-12	27-39	0-2	0-0	2-2	1-1	0-2	0-4	0-0	0-1
HU	16-17	31-32	8-8	0-0	0-0	6-6	3-3	3-3	19-28	0-2	0-1	1-1	1-2	0-4	0-4	0-1	0-1
IE	13-14	29-30	0-0	0-0	0-0	2-2	2-2	8-8	31-42	.-.	0-1	1-1	1-2	0-1	0-5	0-0	0-2
IT	11-13	21-27	3-4	0-0	0-0	4-5	2-2	3-4	21-41	0-1	0-0	1-1	1-2	0-1	0-3	0-0	0-30
LT	17-18	29-29	16-16	0-0	0-0	5-5	2-2	2-2	15-27	0-2	0-0	1-1	1-1	0-4	0-4	0-0	0-1
LU	15-17	20-22	6-7	.-.	.-.	.-.	.-.	3-5	32-50	0-0	0-0	.-.	2-3	0-1	0-4	0-0	0-11
LV	15-15	30-30	9-9	0-0	0-0	9-9	2-2	2-3	18-30	0-2	0-0	1-1	1-1	0-4	0-5	0-0	0-1
MT	16-16	27-28	2-2	0-0	.-.	6-6	1-1	9-11	26-37	0-1	0-0	2-2	.-.	0-2	0-2	0-0	0-2
NL	16-17	29-31	4-4	1-1	.-.	3-3	2-2	3-3	25-37	0-2	0-1	1-1	2-3	0-2	0-5	0-0	0-2
PL	21-21	36-37	11-11	0-0	0-0	4-4	3-3	2-3	10-18	0-2	0-0	1-1	1-2	0-3	0-4	0-0	0-1
PT	14-15	26-28	4-4	0-0	0-0	2-2	1-1	5-5	27-43	0-1	0-0	1-1	1-1	0-1	0-3	0-0	0-13
RO	22-24	32-33	11-11	0-0	0-0	4-4	3-3	3-3	16-23	0-1	0-0	1-1	1-2	0-1	0-2	0-0	.-.
SE	16-17	23-24	6-6	0-0	0-0	4-4	3-3	4-5	23-41	0-3	0-1	1-1	1-2	0-3	0-9	0-0	0-1
SI	13-15	20-21	8-9	0-0	0-0	3-3	2-2	9-11	25-38	0-2	0-0	2-2	1-1	0-4	0-4	0-0	0-2
SK	16-16	29-30	7-8	0-0	0-0	3-3	2-2	3-4	21-34	0-3	0-1	1-1	2-2	0-3	0-4	0-0	0-2
EU27	**14-14**	**26-28**	**5-5**	**0-0**	**0-0**	**4-4**	**3-3**	**4-5**	23-37	**0-2**	**0-1**	**1-1**	**1-2**	**0-2**	**0-4**	**0-0**	**0-11**

SM7 – Ranges of employment (J) and value added (VA) shares (bn,c) for the bioeconomy services in the EU27 (y=average 2015-2017), and EU Member States distribution



Notes: $b_{n,c,y=av.2015-2017}$ are represented with large blue (for minimum) and orange (for maximum) dots for the EU27, and with `-' (minimum $b_{n,c,y=av.2015-2017}$) and `+' (maximum $b_{n,c,y=av.2015-2017}$) points for the EU Member States. For example, calculated on value added (VA) data, 27%<$b_{n=G46,y=av.2015-2017}$<43% for the EU27 (large blue and orange squares) and 16%<$b_{n=G46,y=av.2015-2017}$<51% in Member States (distribution range of `-' and `+' points).

SM8. Output bio-based shares (revised version)

The output-based shares employed in this study are taken from Ronzon et al. (2022b, 2022a). However, slight adjustments have been applied to the bio-based shares of NACE M72, P85 and O84 after their revision with the service of the European Commission in charge of the European bioeconomy strategy (Directorate General for Research and Innovation). Changes compared to Ronzon et al. (2022a) are highlighted below in green.

NACE sector or aggregate of NACE sectors	Output bio-based share employed
Biomass production and manufacturing (A01+A02+A03)	nova-Institute's shares additional nace (see Ronzon et al. 2022)
Associated with tangible bb goods	
G46 - Wholesale	Product bio-based shares from nova-Institute, otherwise 0–100%
G47 - Retail trade	
H49 - Land transport	
H50 - Water transport	
H51 - Air transport	
H52 - Warehousing	
H53 - Postal activities	
I56 - Food services	100%
J58 - Publishing	0% J582 0–100% J5811-J5814 and J5819
N77 - Rental and Leasing	N7729 proportional to G46-G47 bio-based share. N7739: 0–100%
S95 - Repairing	Sector bio-based share of the product repaired ∗0–100% S9525
T97_98 - Households services	0-100%
Natural environment-related	
I55 - Accommodation	Number of nights spent in rural environment from tour_occ_ninatd
N79 - Travel agency	0%-(I551-I552) share
N81 - Landscape activities	100% N813
R90_92 - Librairies and cultural	Minimum share = 0% Maximum share proportional to cultural employment in R91/R90_92 from cult_emp_n2.
R93 – Sport and recreation	0-100%
Bioeconomy knowledge-based	
M71 - Architecture	Same bio-based share as F41-F43 for M711
M72 - Scientific R&D	Proportional to activity in: - M7211 - Research and experimental development on biotechnology (100%) - M7219- Other research and experimental development on natural sciences and engineering (0–100%).
M74 - Other scientific service	0–100% M741 and M749
M75 - Veterinary	100%

P85 - Education	Proportional to education in: - biological and environmental sciences, environmental protection technology, food processing, agriculture, forestry, fisheries and veterinary (100%). - earth sciences, chemistry and chemical engineering, electricity and energy, materials, textiles, architecture and building engineering (0-100%). Eurostat datasources: educ_uoe_fine04, educ_uoe_perp02, educ_uoe_grad02
Bioeconomy support services	
M73 - Market research	0–100% M732
O84 - Public administration	Value added proportional to total bioeconomy (excl. O84) on GDP Same rule for turnover. Employment proportional to bioeconomy (excl. O84) employment on total.
S94 – Membership organisations	0-100%

SM9 – Match between Action plan, matching fields and the targets of the sustainable development goals (SDGs)

Bioeconomy actions	Matching fields	Associated UN SDG targets
1.1, 1.2, 1.6, 2.1, 2.2	Investment/funding/public-private partnership (PPP) in the bioeconomy	2.3; 2.a; 7.a; 8.3; 9.3; 15.a; 15.b; 17.17
2.1, 2.4	Education-awareness/training/skills in the bioeconomy	4.4; 4.7; 12.8
1.1, 1.3, 1.6, 2.1, 2.2, 3.1, 3.2	Research/Innovation/measurement in the bioeconomy	2.a; 7.a; 8.2; 8.3; 9.5; 9.b; 14.a; 17.19
1.1, 1.2, 1.4, 1.5, 2.1,	Technological upgrade – Demonstration in the bioeconomy	2.a; 7.a; 7.b; 8.2; 9.4; 9.5; 9.b
1.3, 1.4,.2.1, 2.2, 2.3, 3.4	Policy and market incentives, policy planning and awareness	11.a; 11.b; 12.6; 12.7; 15.9; 17.14
1.1, 1.2, 1.4, 1.5, 2.1, 2.2, 3.4	Sustainable production/harvesting of biomass	2.3; 2.4; 14.7; 14.b; 15.1;
1.1, 1.2, 1.4, 1.5, 2.1	Sustainable conversion of biomass/BBI	7.2; 9.2
1.1, 1.2, 1.4, 1.5, 2.1, 2.2	Circular/Resource-efficient production/waste reduction and management/biorefineries	6.4; 6.a; 7.3; 8.4; 9.4; 11.6; 12.3; 12.5
1.4, 1.5,1.6, 2.1, 2.2, 3.1, 3.3	Sustainable management of natural resources and ecosystems	6.3; 6.4; 6.5; 12.2; 14.1; 14.2; 14.7; 15.1; 15.2 15.a; 15.b
3.1, 3.2, 3.3, 3.4	Conservation, biodiversity	2.5; 2.a; 15.1; 15.4; 15.5; 15.a; 15.b
1.6, 2.2, 3.2, 3.3	Restoration, bio-remediation	6.6; 14.2; 14.3; 14.4; 15.1; 15.2; 15.3
1.2, 1.4, 1.5, 3.2	Climate action	13.2; 13.3
1.2, 1.5, 2.1, 2.2	Local development (jobs and growth)	2.3; 2.a; 8.2; 8.3; 8.5; 9.2; 9.3; 14.b

SM10 – Match between actions of the bioeconomy action plan and SDG targets per SDG

Bioeconomy actions	SDG targets
SDG 2 (End hunger)	
action 1.1 - Public-private partnerships action 1.2 - Circular Economy Thematic Investment Platform action 1.4 - Development of environmental labels and standards action 1.5 - Development of integrated biorefineries action 2.1 - National and regional Strategic Deployment Agendas (SDAs) action 2.2 - Pilot actions for a local bioeconomy development actions 3.1 to 3.3 - Data measurement and monitoring action 3.4 - Roadmap to agro-ecology	target 2.3 - "double the agricultural productivity and incomes of small-scale food producers (...), including through access to (…) financial services" target 2.4 - "ensure sustainable food production systems, (…) that help maintain ecosystems" target 2.5 - "maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species" target 2.a - "Increase investment (…) in rural infrastructure, agricultural research and extension services, technology development"
SDG 4 (Quality education)	
action 3.2.4. - Promote education, training and skills across the bioeconomy	target 4.4 - "increase the number of youth and adults who have relevant skills" target 4.7 - "ensure that all learners acquire the knowledge and skills needed to promote sustainable development"
SDG 6 (Clean water)	
action 1.4 - Development of standards and labels action 1.5 - Development of integrated biorefineries action 2.1 - National and regional Strategic Deployment Agendas action 2.2 - Urban Circular Bioeconomy Strategies and "living labs" action 3.2 and action 3.3 - Measurement, monitoring and guidance activities	target 6.3 - "improve water quality by reducing pollution" target 6.4 - "increase water-use efficiency across all sectors" target 6.5 - "implement integrated water resources management" target 6.6 - "protect and restore water-related ecosystems" target 6.a - "including (…) water efficiency, wastewater treatment, recycling and reuse technologies"
SDG 7 (Clean energy)	
action 1.1 - Investment from public-private partnerships action 1.2 - Circular Economy Thematic Investment Platform action 1.4 - Development of labels and standards action 1.5 - Development of integrated biorefineries	target 7.2 - "increase substantially the share of renewable energy in the global energy mix" target 7.3 - "improvement in energy efficiency" target 7.a - "access to clean energy research and technology" and "promote investment in (…) clean energy technology" target 7.b - "upgrade technology for supplying modern and sustainable energy services"

action 2.1 - Research and technological upgrade foreseen in Strategic Deployment Agendas	
SDG 8 (Decent work and economic growth) and SDG 9 (Industry, innovation and infrastructure)	
action 1.1 - Public-private partnerships action 1.2 - Circular Economy Thematic Investment Platform action 1.3 - Guidance to the deployment of bio-based innovations action 1.4 - Development of labels and standards action 1.5 - Development of integrated biorefineries action 1.6 - R&I investments for the development of substitutes to fossil based materials action 2.1 - National and regional Strategic Deployment Agendas action 2.2 - Pilot actions for a local bioeconomy development	target 8.2 - "higher levels of economic productivity through diversification, technological upgrading and innovation (…)" target 8.3 - "support productive activities (…), creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises" target 8.4 - "Improve (…) resource efficiency in consumption and production" target 8.5 - "achieve full and productive employment" target 9.2 - "Promote inclusive and sustainable industrialization (…), significantly raise industry's share of employment and gross domestic product" target 9.3 - "Increase the access of small-scale industrial (…)to financial services (…) and their integration into value chains and markets" target 9.4 - "retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes" target 9.5 - "Enhance scientific research, upgrade the technological capabilities of industrial sectors" target 9.b - "Support domestic technology development, research and innovation (…) for, inter alia, industrial diversification"
SDG 11 (Sustainable cities and communities)	
action 2.1 - National and regional Strategic Deployment Agendas action 2.2 - Sea basin strategies, Urban Circular Bioeconomy Strategies and living labs action 2.3 - European Bioeconomy policy support facility	target 11.6 - " by paying special attention to (…) municipal and other waste management" target 11.a - "by strengthening national and regional development planning" target 11.b - "implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change"
SDG 12 (Responsible consumption and production)	
actions 1.1 and 3.1.2 – Investments action 1.4 - Development of environmental labels and standards action 1.5 - Development of integrated biorefineries action 1.6 - Research and innovation action 2.1 - National and regional Strategic Deployment Agendas action 2.2 - Pilot actions for a local bioeconomy development	target 12.2 - "sustainable management and efficient use of natural resources" target 12.3 - "reduce food losses along production and supply chains" target 12.5 - "reduce waste generation through prevention, reduction, recycling and reuse" target 12.6 - "Encourage companies (…) to adopt sustainable practices" target 12.7 - "Promote public procurement practices that are sustainable" target 12.8 - "ensure that people everywhere have the relevant information and awareness for sustainable development"

action 2.4 - Education action 3.1 - Enhance the knowledge on the bioeconomy (…), and make it accessible actions 1.3, 2.3 and 3.3 - Guidance action 3.4 (iii) - The private sector (…) should be encouraged to use the information (…)	
SDG 13 (Climate action)	
action 1.2 - Circular Economy Thematic Investment Platform action 1.4 - Deployment of standards and labels on the basis of data on climate performance action 1.5 - Development of integrated biorefineries action 3.2 - Bioeconomy monitoring system	target 13.2 - "Integrate climate change measures" target 13.3 - "institutional capacity on climate change mitigation, adaptation, impact reduction"
SDG 14 (Life below water)	
action 1.1 to 3.1.6 - Investments, research and innovation, markets [in particular action 1.6 - free plastic oceans] action 2.1 - national and regional Strategic Deployment Agendas (SDAs) action 2.2 - development of Sea Basin Strategies, pilot actions to the Blue Bioeconomy potential actions 3.2 and 3.3 - observation, measurement and monitoring	target 14.1 - "reduce marine pollution" target 14.2 - "sustainably manage and protect marine and coastal ecosystems" and "take action for their restoration" target 14.3 - "Minimize and address the impacts of ocean acidification" target 14.4 - "science-based management plans, in order to restore fish stocks" target 14.7 - "sustainable management of fisheries, aquaculture' target 14.a - "Increase scientific knowledge, develop research capacity and transfer marine technology" target 14.b - "access for small-scale artisanal fishers to marine resources and markets"
SDG 15 (Life on land)	
action 1.1 - public-private partnerships actions 1.1, 1.2 and 1.6 - investments for land ecosystem management, conservation and restoration/bioremediation action 1.4 - Deployment of standards and labels on the basis of data on environmental and climate performance action 1.5 - development of integrated biorefineries action 2.1 - National and regional Strategic Deployment Agendas (SDAs) action 2.2 - Rehabilitation of urban brownfields, nature-based remediation solutions	target 15.1 - "ensure the (…) sustainable use of terrestrial and inland freshwater ecosystems and their services" target 15.2 - "sustainable management of all types of forests, (…) restore degraded forests and substantially increase afforestation and reforestation" target 15.3 - "restore degraded land and soil" target 15.4 - "conservation of mountain ecosystems, including their biodiversity" target 15.5 - "protect and prevent the extinction of threatened species" target 15.9 - "integrate ecosystem and biodiversity values into national and local planning" target 15.a - "increase financial resources (…) to conserve and sustainably use biodiversity and ecosystems"

action 3.1 - Enhance the knowledge on biodiversity and ecosystems, and make it accessible action 3.2 - Monitoring system to underpin ecosystem conservation and restoration 3.3 - Guidance on integrating ecosystem services into decision making	target 15.b - "finance sustainable forest management (…), including for conservation and reforestation"
SDG 17 (Partnerships for the goals – Policy and institutional coherence)	
actions 1.1, 2.1 and 2.2 - Policy coherence for sustainable development actions 1.3, 2.1, 2.3 and 3.1 - Public-private and society partnerships actions 3.1 and 3.2 - Measurement of progress on sustainable development	target 17.14 - "policy coherence for sustainable development" target 17.17 - "effective public, public-private and civil society partnerships" target 17.19 - "develop measurements of progress on sustainable development", "support statistical capacity-building"

SM11- Characteristics of the bioeconomy related SDG indicators used in the correlation analysis

	SDG	Target	Indicator	Source	Sign	No. MS*	No. of data points	Minimum year	Maximum year
1	2	2.5	Plant breeds for which sufficient genetic resources are stored (number)	UN	1	26	208	1995	2017
2	2	2.5	Local breeds classified as known being at risk (number)	UN	-1	28	786	1990	2018
3	2	2.a	Agriculture orientation index for government expenditures	UN	1	26	372	2001	2016
4	2	2.3	Agricultural factor income per annual work unit (AWU) (source: EC services)	Eurostat	1	28	504	2001	2018
5	2	2.a	Government support to agricultural research and development	Eurostat	1	28	420	2004	2018
6	2	2.4	Area under organic farming	Eurostat	1	28	504	2000	2017
7	2	2.4	N - Gross nutrient balance on agricultural land by nutrient	Eurostat	-1	28	476	2000	2016
8	2	2.4	P - Gross nutrient balance on agricultural land by nutrient	Eurostat	-1	28	476	2000	2016
9	2	2.4	Ammonia emissions from agriculture (source: EEA)	Eurostat	-1	28	756	1990	2016
10	4	4.4	Tertiary educational attainment	Eurostat	1	28	504	2000	2017
11	4	4.7	Employment rates of recent graduates	Eurostat	1	28	336	2006	2017
12	4	4.7	Adult participation in learning	Eurostat	1	28	504	2000	2017
13	6	6.3	Biochemical oxygen demand in rivers (source: EEA)	Eurostat	-1	20	300	2000	2014
14	6	6.3	Nitrate in groundwater (source: EEA)	Eurostat	-1	21	273	2000	2012
15	6	6.3	Phosphate in rivers (source: EEA)	Eurostat	-1	20	300	2000	2014

	SDG	Target	Indicator	Source	Sign	No. MS*	No. of data points	Minimum year	Maximum year
16	6	6.4	Fresh surface and groundwater exploitation index	Eurostat	-1	25	400	2000	2015
17	7	7.a	Primary energy consumption (mtoe)	Eurostat	-1	28	476	2000	2016
18	7	7.b	Energy productivity (EUR/KG oil eq.)	Eurostat	1	28	476	2000	2016
19	7	7.2	Share of renewable energy in gross final energy consumption by sector	Eurostat	1	28	364	2004	2016
20	8	8.2	Annual growth rate of real GDP per employed person (%)	UN	1	28	504	2000	2017
21	8	8.4	Domestic material consumption, Wood (tonnes)	UN	-1	28	491	2000	2017
22	8	8.4	Domestic material consumption, Crop residues (tonnes)	UN	+1	28	504	2000	2017
23	8	8.4	Domestic material consumption, Crops (tonnes)	UN	-1	28	504	2000	2017
24	8	8.4	Domestic material consumption, Grazed biomass and fodder (tonnes)	UN	-1	28	504	2000	2017
25	8	8.4	Domestic material consumption, Wild Catch Harvest (tonnes)	UN	-1	28	503	2000	2017
26	8	8.5	Employment rate	Eurostat	1	27	486	2000	2017
27	8	8.5	Long-term unemployment rate	Eurostat	-1	28	504	2000	2017
28	9	9.2	Manufacturing value added as a proportion of GDP (%)	UN	1	28	504	2000	2017
29	9	9.2	Manufacturing employment as a proportion of total employment (%)	UN	1	28	503	2000	2017

	SDG	Target	Indicator	Source	Sign	No. MS*	No. of data points	Minimum year	Maximum year
30	9	9.3	Proportion of small-scale industries in total industry value added (%)	UN	1	28	405	2000	2015
31	9	9.4	Carbon dioxide emissions per unit of GDP (kilogrammes of CO2 per constant 2010 USD)	UN	-1	28	448	2000	2015
32	9	9.4	Carbon dioxide emissions per unit of manufacturing value added (kilogrammes of CO2 per constant 2010 United States dollars)	UN	-1	28	448	2000	2015
33	9	9.5	Gross domestic expenditure on R&D	Eurostat	1	28	504	2000	2017
34	9	9.b	Employment in high- and medium-high technology manufacturing sectors and knowledge-intensive service sectors	Eurostat	1	28	280	2008	2017
35	9	9.5	R&D personnel by sector	Eurostat	1	28	504	2000	2017
36	9	9.5	Patent applications to the European Patent Office (source: EPO)	Eurostat	1	28	504	2000	2017
37	11	11.6	Recycling rate of municipal waste	Eurostat	1	28	504	2000	2017
38	12	12.2	Domestic material consumption, Wood (tonnes)	UN	-1	28	491	2000	2017
39	12	12.2	Domestic material consumption, Crop residues (tonnes)	UN	-1	28	504	2000	2017
40	12	12.2	Domestic material consumption, Crops (tonnes)	UN	-1	28	504	2000	2017
41	12	12.2	Domestic material consumption, Grazed biomass and fodder (tonnes)	UN	-1	28	504	2000	2017
42	12	12.2	Domestic material consumption, Wild Catch Harvest (tonnes)	UN	-1	28	503	2000	2017

	SDG	Target	Indicator	Source	Sign	No. MS*	No. of data points	Minimum year	Maximum year
43	12	12.5	Circular material use rate	Eurostat	1	28	364	2004	2016
44	12	12.3	Generation of waste excluding major mineral wastes by hazardousness	Eurostat	-1	28	196	2004	2016
45	13	13.2	Greenhouse gas emissions (source: EEA)	Eurostat	-1	28	756	1990	2016
46	14	14.2	Surface of marine sites designated under NATURA 2000 (source: DG ENV, EEA)	Eurostat	1	28	196	2011	2017
47	15	15.1	Forest area (thousands of hectares)	UN	1	28	112	2000	2015
48	15	15.1	Average proportion of Freshwater Key Biodiversity Areas (KBAs) covered by protected areas (%)	UN	1	26	494	2000	2018
49	15	15.1	Average proportion of Terrestrial Key Biodiversity Areas (KBAs) covered by protected areas (%)	UN	1	28	532	2000	2018
50	15	15.2	Above-ground biomass in forest per hectare (tonnes per hectare)	UN	1	26	104	2000	2015
51	15	15.2	Forest area certified under an independently verified certification scheme (thousands of hectares)	UN	1	28	504	2000	2017
52	15	15.4	Average proportion of Mountain Key Biodiversity Areas (KBAs) covered by protected areas (%)	UN	1	21	399	2000	2018
53	15	15.5	Red List Index	UN	-1	28	728	1993	2018
54	15	15.5	Surface of terrestrial sites designated under NATURA 2000 (source: DG ENV, EEA)	Eurostat	1	28	196	2011	2017

*MS stands for EU Member State

SM12- Proportion of synergies, trade-offs and non-classified correlations by SDG pairs

SDG pair					Synergies (green)	Trade-offs (orange)	Non-classified (yellow)		SDG pair					Synergies (green)	Trade-offs (orange)	Non-classified (yellow)
SDG	2	x	SDG	2	47%	42%	10%		SDG	11	x	SDG	12	45%	31%	24%
SDG	2	x	SDG	8	42%	33%	26%		SDG	11	x	SDG	15	79%	9%	12%
SDG	2	x	SDG	9	50%	38%	11%		SDG	12	x	SDG	2	44%	35%	21%
SDG	4	x	SDG	2	63%	28%	10%		SDG	12	x	SDG	4	45%	34%	22%
SDG	4	x	SDG	4	63%	23%	15%		SDG	12	x	SDG	7	50%	32%	17%
SDG	4	x	SDG	9	63%	28%	9%		SDG	12	x	SDG	12	50%	28%	23%
SDG	6	x	SDG	2	59%	24%	17%		SDG	13	x	SDG	2	55%	21%	24%
SDG	6	x	SDG	4	69%	26%	4%		SDG	13	x	SDG	4	60%	35%	5%
SDG	6	x	SDG	6	72%	7%	21%		SDG	13	x	SDG	6	71%	8%	21%
SDG	6	x	SDG	12	38%	42%	21%		SDG	13	x	SDG	7	94%	0%	6%
SDG	7	x	SDG	2	59%	29%	12%		SDG	13	x	SDG	8	38%	33%	30%
SDG	7	x	SDG	4	72%	23%	5%		SDG	13	x	SDG	9	63%	22%	15%
SDG	7	x	SDG	6	77%	12%	10%		SDG	13	x	SDG	11	82%	0%	18%
SDG	7	x	SDG	7	94%	3%	4%		SDG	13	x	SDG	12	57%	16%	28%
SDG	7	x	SDG	8	43%	36%	20%		SDG	13	x	SDG	15	66%	10%	24%
SDG	7	x	SDG	9	66%	25%	9%		SDG	14	x	SDG	2	59%	41%	0%
SDG	7	x	SDG	15	74%	16%	10%		SDG	14	x	SDG	4	67%	33%	0%
SDG	8	x	SDG	4	54%	22%	24%		SDG	14	x	SDG	6	50%	50%	0%
SDG	8	x	SDG	6	35%	39%	26%		SDG	14	x	SDG	7	84%	16%	0%
SDG	8	x	SDG	8	36%	32%	32%		SDG	14	x	SDG	8	60%	40%	0%
SDG	8	x	SDG	12	68%	17%	14%		SDG	14	x	SDG	9	59%	41%	0%
SDG	9	x	SDG	6	55%	28%	17%		SDG	14	x	SDG	11	75%	25%	0%
SDG	9	x	SDG	8	40%	34%	26%		SDG	14	x	SDG	12	48%	52%	0%
SDG	9	x	SDG	9	52%	36%	13%		SDG	14	x	SDG	13	100%	0%	0%
SDG	9	x	SDG	12	42%	37%	21%		SDG	15	x	SDG	2	59%	28%	13%

SDG pair					Synergies (green)	Trade-offs (orange)	Non-classified (yellow)		SDG pair					Synergies (green)	Trade-offs (orange)	Non-classified (yellow)
SDG	9	x	SDG	15	62%	27%	12%		SDG	15	x	SDG	4	72%	15%	13%
SDG	11	x	SDG	2	67%	23%	10%		SDG	15	x	SDG	6	71%	12%	17%
SDG	11	x	SDG	4	79%	9%	12%		SDG	15	x	SDG	8	44%	29%	27%
SDG	11	x	SDG	6	79%	14%	7%		SDG	15	x	SDG	12	48%	31%	21%
SDG	11	x	SDG	7	91%	1%	8%		SDG	15	x	SDG	14	70%	30%	0%
SDG	11	x	SDG	8	44%	29%	28%		SDG	15	x	SDG	15	76%	16%	8%

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