Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe

Maximilian Kardung *, Dušan Drabik

Agricultural Economics and Rural Policy Group, Wageningen University, The Netherlands

ARTICLE INFO

Keywords:
Circular bioeconomy
Markov chains
Transition matrices
European Union

ABSTRACT

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

1. Introduction

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

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

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

* Corresponding author.
E-mail address: maximilian.kardung@wur.nl (M. Kardung).

https://doi.org/10.1016/j.ecolecon.2021.107146
Received 16 September 2020; Received in revised form 13 January 2021; Accepted 1 July 2021
Available online 10 July 2021
0921-8009/© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Many indicators can measure various development characteristics of a trend, such as the transition from a fossil-based economy to a bio-based one. For example, there are 27 indicators to support the Europe 2020 Strategy, 100 EU SDGs indicators, 232 UN SDGs indicators, or 1600 World Bank World Development Indicators. In the same vein, Bracco et al. (2019) reviewed existing monitoring approaches to the bioeconomy and collected 269 distinct indicators from 19 sources that measured a wide range of impact categories, such as food security, biodiversity conservation, and the resilience of biomass producers. Among others, Lier et al. (2018) proposed 161 indicators and the Bio-Monitor project1 84 indicators for a bioeconomy-monitoring framework.

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

Unlike the previous literature, we devise a theoretical framework that accommodates any number of well-defined quantitative indicators and empirically analyze 41 of them. We investigate their distribution to find patterns in the evolution of the circular bioeconomies of ten selected EU MSs. A similar approach to ours has been used in other fields of economics with a single indicator for many regions or sectors. Quah (1993, 1996) was the first in the cross-country growth and income literature to investigate patterns in income distributions using Markov transition matrices. Later, many researchers adopted this approach to analyze trade-specialization patterns by estimating the intra-distribution dynamics of trade-specialization indices over time (e.g., Zaghibini, 2000; Alessandrini et al., 2007; Ferto and Soos, 2008; Chiappini, 2014). Zaghibini (2005) analyzed the probability of new EU MSs moving between different degrees of trade specialization. He examined the intra-distribution dynamics of the Lafay index, considering the difference between the exports and imports of 208 sectors. The variation of the relative ranking of sectors by the Lafay index over time describes these intra-distribution dynamics.

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

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

2. Background

2.1. Circular bioeconomy policy actions

The circular bioeconomy is high on the political agenda, and many policymakers have proposed and already implemented policy actions to support and steer its development. Table 1 presents an overview of policy actions related to the bioeconomy in the EU and the EU-10. Policymakers in the EU have made the bioeconomy a priority to reduce the use of petrochemicals, mitigate and adapt to climate change, reduce dependency on imports of natural resources, and promote rural development (European Commission, 2018). At the EU level, this is reflected in a multitude of EU policy initiatives and research programs, including the EU Bioeconomy Strategy and the European Bio-Based Industries Joint Undertaking (Wesseler and von Braun, 2017). At the MS level, most countries in this study have developed dedicated bioeconomy strategies or other policy initiatives and research programs related to the bioeconomy from 2006 to 2016. The exceptions are Italy and Latvia, who published their bioeconomy strategies only afterwards in 2017, and Slovakia and Poland, who have not yet developed a bioeconomy strategy while it is under development (Joint Research Centre, 2019). However, in Slovakia and Poland, bioeconomy development is recognized in regional and smart specialization strategies (RIS3 SK, 2013; Sosnowski et al., 2014).2

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

2.2. Measuring performance with indicator frameworks

Governments have taken numerous policy actions on the circular bioeconomy that they must monitor, such as the SDGs. Policymakers have used monitoring frameworks with a diverse set of indicators for many policy objectives. The 17 UN SDGs are a widely used framework and include 232 indicators to measure progress towards 169 corresponding targets. However, measuring progress towards the SDGs is complicated by the fact that there are no specific targets for SDG indicators (United Nations, 2017). Nevertheless, three prominent methods to measure SDG performance have been developed: the Bertelsmann

---

1 www.biomoitor.eu

2 We are grateful to an anonymous reviewer for pointing this out.
Table 1 Overview of actions related to the bioeconomy from 2007 to 2017 by countries in this study.

| Title | Type | Level | Target policy area | Year |
|-------|------|-------|--------------------|------|
| European Union En route to the European Union | Consultation document | Supranational | Yes | 2007 |
| Innovating for Sustainable Growth: A Bioeconomy for Europe | Policy Strategy | Supranational | No | 2012 |
| Bio-based Industries Consortium | Investment program | Supranational | No | 2012 |
| Germany Erneuerbare Energien Gesetz 2009 | Policy measure | National | Yes | 2009–2011 |
| Erneuerbare Energien Gesetz 2012 | Policy measure | National | Yes | 2012–2016 |
| Nationale Forschungsrstrategie BioÖkonomie 2030 | Research strategy | National | No | 2010–2016 |
| Bioeconomy. Baden-Württemberg Path Towards a Sustainable Future | Policy strategy | Regional | No | 2013 |
| Nationale Politikstrategie Bioökonomie | Policy strategy | National | No | 2014 |
| Finland The Natural Resource Strategy | Policy strategy | National | No | 2009 |
| Distributed Bio-Based Economy – Driving Sustainable Growth | Policy strategy | National | No | 2011 |
| Sustainable Bioeconomy: Potential, Changes and Opportunities for Finland | Policy strategy | National | No | 2011 |
| The Finnish Bioeconomy Strategy - Sustainable growth from bioeconomy | Policy strategy | National | Yes | 2014 |
| The Finnish Bioeconomy Strategy | Policy strategy | National | No | 2014 |
| The Netherlands Groene Groei – Van Biomassa naar Business Framework Memorandum on the Bio-Based Economy | Innovation contract | National | Yes | 2012 |
| Groene Groei: voor een sterke, duurzame economie | Framework paper | National | Yes | 2012 |
| France National Biodiversity Strategy 2011–2020 | Research & innovation | National | Yes | 2011 |
| The new face of Industry in France France Europe 2020 | Research & innovation | National | Yes | 2012 |
| Strategie nationale de transition ecologique vers développement durable A Bioeconomy Strategy for France | Research & innovation | National | No | 2014 |
| Bioeconomy in Italy: A unique opportunity to | Holistic bioeconomy development | National | No | 2017 |

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

Index (BI) by Bertelsmann Stiftung and the Sustainable Development Solutions Network (Lafortune et al., 2018; Sachs et al., 2018), the Organisation for Economic Co-operation and Development’s report linearly interpolates the value of a specific indicator for 2030. For that, the difference between the latest and the first observation is divided by the difference between 2030 and the latest observation and added to the value of the latest observation (Miola and Schilz, 2019). All indicator values are then rescaled between zero and one and aggregated to obtain a performance measure at the goal level. This method is sensitive to outliers in the time-series data because only two observations are included in its calculation. The z-score (standard score) is another method for normalization and is common for composite indices of development, which integrate various social, political, and economic aspects of the development of a country (Booyse, 2002). Its calculation is straightforward and uses the mean and standard deviation of an indicator (see Section 4 for details).

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

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

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

In most cases, we avoided the same indicator being represented multiple times with different dimensions or measurement units in the data. For example, the indicator ‘Employment rates of recent graduates’ from SGD 4 – Quality Education contains disaggregated data for males and females, but we only kept the aggregated total. However, we kept the disaggregated data for indicators that can provide additional insights. For instance, we included the indicators disaggregated by sectors as well as the total for ‘Share of renewable energy in gross final energy consumption by sector’ because they likely move in different directions. Table 2 provides a list of all our indicators and specifies which are aggregated and which are not.

In the next step, we checked the indicators for consistency in their interpretation. For some indicators such as agricultural factor income per annual work unit, a higher value means either the bioeconomy is regressing, has a negative impact on society, or both. To make all indicators consistent, we had to ensure that a higher indicator value indicates a move in the desired direction. Therefore, we assigned a negative sign to the indicators whose desired direction was negative. A similar approach was taken, for example, by the OECD (2019) and Ronzon and Sanjuán (2020). In the case of indicators whose optimal value is zero, we took their absolute value and assigned a negative sign to it. In this way, the positive and negative deviations from the optimum were treated equally. Table 2 shows the desired directions of all the indicators; we adopted the directions of SDG bioeconomy indicators from Eurostat (2019). The circular economy indicators are all designed so that an increase means a move in the desired direction. Having prepared our data, we applied our methodology to the indicator framework, as outlined in the following section.

### Table 2

| Code       | Description                                                                 | Desired Direction |
|------------|-----------------------------------------------------------------------------|-------------------|
| cei_cie010 | Value added at factor costs (Mio Euro)                                      | +                 |
| cei_cie010 | Value added at factor costs (% of GDP)                                      | +                 |
| cei_cie010 | Gross investment in tangible goods (Mio Euro)                               | +                 |
| cei_cie010 | Gross investment in tangible goods (% of GDP)                               | +                 |
| cei_cie010 | Persons employed (number)                                                   | +                 |
| cei_cie010 | Persons employed (% of total employment)                                    | +                 |
| cei_wm030  | Recycling of biowaste (kg per capita)                                       | +                 |
| sdg_02_20  | Agricultural factor income per annual work unit                             | +                 |
| sdg_02_30  | Government support to agricultural research and development (Mio Euro)      | +                 |
| sdg_02_30  | Government support to agricultural research and development (Euro per inhabitant) | +             |
| sdg_02_40  | Area under organic farming - % of utilised agricultural area (UAA)          | +                 |
| sdg_02_50  | Gross nutrient balance on agricultural land by nutrient (nitrogen)          | 0                 |
| sdg_02_50  | Gross nutrient balance on agricultural land by nutrient (phosphorus)        | 0                 |
| sdg_02_60  | Ammonia emissions from agriculture (tonne)                                  | –                 |
| sdg_02_60  | Ammonia emissions from agriculture (kg/ha)                                  | –                 |
| sdg_02_20  | Tertiary education attainment by sex (total)                                | +                 |
| sdg_02_40  | Employment rates of recent graduates by sex (total)                         | +                 |
| sdg_02_60  | Adult participation in learning by sex (total)                              | +                 |
| sdg_07_10  | Primary energy consumption (Mio tonnes of oil equivalent)                  | –                 |
| sdg_07_30  | Energy productivity (Euro per kg of oil equivalent)                         | +                 |
| sdg_07_40  | Share of renewable energy in gross final energy consumption by sector (total) | +                 |
| sdg_07_40  | Share of renewable energy in gross final energy consumption by sector (transport) | +              |
| sdg_07_40  | Share of renewable energy in gross final energy consumption by sector (electricity) | +            |
| sdg_07_40  | Share of renewable energy in gross final energy consumption by sector (heating and cooling) | +           |
| sdg_08_30  | Real GDP per capita – Chain linked volumes (% on previous period, per capita) | +                 |
| sdg_08_40  | Long-term unemployment rate by sex (total)                                  | –                 |
| sdg_09_10  | Gross domestic expenditure on R&D by sector – Business enterprise sector | +                 |
| sdg_09_10  | Gross domestic expenditure on R&D by sector – Government sector            | +                 |
| sdg_09_10  | Gross domestic expenditure on R&D by sector – Higher education sector      | +                 |
| sdg_09_20  | Employment in knowledge-intensive services                                  | +                 |
| sdg_09_20  | Employment in high- and medium-high technology manufacturing               | +                 |
| sdg_09_30  | R&D personnel by sector - Business enterprise sector (% of active population) | +                 |
| sdg_09_30  | R&D personnel by sector - Government sector (% of active population)       | +                 |
| sdg_09_40  | Patent applications to the European Patent Office (number)                  | +                 |
| sdg_09_40  | Patent applications to the European Patent Office (per million inhabitants) | +                 |
| sdg_11_60  | Recycling rate of municipal waste (% of total waste generated)              | +                 |
| sdg_12_41  | Circular material use rate (% of material input for domestic use)          | +                 |
| sdg_13_10  | Greenhouse gas emissions (base year 1990)                                   | –                 |
| sdg_13_10  | Greenhouse gas emissions (tonnes per capita)                               | –                 |
| sdg_14_10  | Surface of marine sites designated under NATURA 2000 (km²)                  | +                 |

“+” denotes indicators that progress with a higher value; “-“ denotes indicators that regress with a higher value; and “0” denotes indicators whose desired value is zero.

---

3 We downloaded the data from the official website of Eurostat, which is freely available at [https://ec.europa.eu/eurostat/data/bulkdownload](https://ec.europa.eu/eurostat/data/bulkdownload).

4 An alternative to reverting the sign would be taking the reciprocal of the value. This method would, however, not work for the balance indicators whose desired value is zero.
4. Methodology

4.1. Z-scores

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

As all indicators have different units and magnitudes, they need to be normalized for meaningful comparison and aggregation. Although several normalization methods exist, they suffer from deficiencies, as pointed out in Section 2. We calculated the z-score (standard score) for each indicator to put our data onto a standardized scale. The z-score of a given indicator in a given year measures how many standard deviations the indicator value is away from the indicator’s mean. A positive z-score denotes a value above the mean, and a negative z-score corresponds to a value below the mean over the whole period. The z-score of indicator \( i \) in year \( t \) is given by

\[
z_{it} = \frac{x_{it} - \bar{x}_i}{s_i}
\]

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

\[
\hat{\beta}_i = \frac{\text{Cov}(z_{it}, t)}{\text{Var}(t)}
\]

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

4.2. Markov transition matrices

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

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

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

\[
\sum_{j=1}^{m} p_{ij} = 1 \quad \forall i \in S
\]

are satisfied. The transition matrix \( P \) can be defined as follows:

\[
P = \begin{pmatrix}
p_{11} & p_{12} & \cdots & p_{1m} \\
p_{21} & p_{22} & \cdots & p_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
p_{m1} & p_{m2} & \cdots & p_{mm}
\end{pmatrix}
\]

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

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

\[
M_1 = \frac{n - \text{tr}(P)}{n - 1}
\]

and

\[
M_2 = 1 - |\text{det}(P)|,
\]

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

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

5. Results

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

To analyze the movement of all circular bioeconomy indicators, we examined the external shape of the z-score distribution across all countries over time. The graph in Fig. 1 shows that the aggregated distribution comes close to a normal distribution, which results from the calculation of a z-score, and that most indicators have a z-score between −2 and 2. In the graph in Fig. 2, the distribution for each consecutive year shifts to the right and therefore peaks at a higher z-score level. Circular bioeconomy indicators, on average, improve over time for the EU-10 aggregate.

To further describe and analyze the external shape of the distribution of circular bioeconomy indicators, we present brief descriptive statistics for the EU-10 in Table 3. It shows that the EU-10 mean z-score progressed from −0.622 in 2006 to 0.466 in 2016. This progression is nearly continuous over the whole period except for an interruption between 2008 and 2010. The national bioeconomies’ developments confirm this positive trend to varying extents. Germany progressed from a mean of −1.001 in 2006 to 0.769 in 2016; Slovakia increased its mean by 1.504 from 2006 to 2016 and Portugal by 1.186. Finland progressed the least, from a mean of −0.35 in 2006 to only 0.045 in 2016. Latvia, The Netherlands, Poland, Italy, Spain, and France have successively greater progress but still lag behind Germany and Slovakia. The range of z-scores for the EU-10 is generally higher in the first four years of the examined period, then relatively low around 2.5 from 2010 to 2013, before increasing again in 2014 and 2016.

Fig. 3 confirms the generally positive trend as the median (the band inside the box) increases over time in the EU-10. The interquartile range (the width of the box) is comparable to the range and shows a similar picture. In the middle of the period (2010–2012), it is generally lower than at the beginning and end. With some small deviations, the same trend can be seen in the development of circular bioeconomy indicators.
in each country (Appendix A).

We ranked all 41 indicators from best to worst according to the
development of their z-scores over time. Table 4 presents the five best
and worst indicators for all countries, which shows how their circular
bioeconomies are progressing or regressing. The rate of progress was
among the highest for the share of renewable energy in gross final en-
ergy consumption in all countries except Italy. The indicators for the
share of renewable energy do not differentiate between the type of
renewable energy and do not allow to assess the progress with respect to
bioenergy only. However, in 2017, the largest part of renewable energy
was still biofuels and renewable waste in all EU-10 countries and

density

z-score

Fig. 1. Indicator distribution over the whole period for all countries (Kernel density estimates).
Note: The graph shows the density estimates for the z-scores aggregated across all indicators and years.

Fig. 2. Indicator distribution by year for all countries (Kernel density estimates).
Note: The graph shows the temporally disaggregated z-scores for all indicators.
therefore, it is likely that bioenergy played a major role in the progress of the share of renewable energy (Borawski et al., 2019).

Also, biowaste recycling, the recycling rate of municipal waste, and the circular material use rate were among the most-improving indicators in seven of the ten countries. By contrast, a negative development took place for ammonia emissions and the nutrient balance on agricultural land in Germany, Latvia, and Slovakia. At least one economic indicator for private investments, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

In contrast, the percentage of total employment for circular economy sectors increased sharply in Spain, Latvia, and Portugal. This development is ambiguous for indicators related to R&D. The indicators for patent applications, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

In contrast, the percentage of total employment for circular economy sectors increased sharply in Spain, Latvia, and Portugal. This development is ambiguous for indicators related to R&D. The indicators for patent applications, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

Therefore, it is likely that bioenergy played a major role in the progress of the share of renewable energy (Borawski et al., 2019). Also, biowaste recycling, the recycling rate of municipal waste, and the circular material use rate were among the most-improving indicators in seven of the ten countries. By contrast, a negative development took place for ammonia emissions and the nutrient balance on agricultural land in Germany, Latvia, and Slovakia. At least one economic indicator for private investments, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

In contrast, the percentage of total employment for circular economy sectors increased sharply in Spain, Latvia, and Portugal. This development is ambiguous for indicators related to R&D. The indicators for patent applications, jobs, and gross value added related to circular economy sectors is regressing in six of the ten countries. Two of these economic indicators are among the worst in Italy, Latvia, Portugal, and Slovakia.

5.2. Intra-distribution dynamics of the circular bioeconomy

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

Now we are in a position to follow each indicator between any two points in time (e.g., t and t + 1 or t + 10) and determine whether the indicator has stayed in the same quarter or has left it for some other quarter. By calculating the proportions of individual moves from a given quarter at time t into any quarter at t + 1, we estimate the transition matrices as presented in Table 5.

The left-hand side of Table 5 presents averages of one-year transition matrices in the period 2006–2016, while the right-hand side presents one transition matrix for each country over the whole period (i.e., ten years).
**Table 4**
The most progressing and the most regressing indicators in the period 2006–2016.

| Country             | Most progressing indicators | Most regressing indicators |
|---------------------|-----------------------------|----------------------------|
| **Germany**         |                             |                            |
| Share of renewable energy in gross final energy consumption – electricity | 0.300 Share applications to the European Patent Office (total number) | –0.291 Share applications to the European Patent Office (number per million inhabitants)  |
| Share of renewable energy in gross final energy consumption – all sectors | 0.299 Share applications to the European Patent Office (number per million inhabitants) | –0.288 |
| Employment rate     | 0.294 Ammonia emissions from agriculture (kg per hectare) | –0.288 |
| Recycling of biowaste | 0.293 Ammonia emissions from agriculture (tonnes) | –0.278 |
| R&D personnel – business enterprise sector | 0.292 Private investments, jobs, and gross value added related to circular economy sectors – value added at factor cost – % of GDP | –0.172 |
| **Finland**         |                             |                            |
| Area under organic farming | 0.298 Employment in knowledge-intensive services | –0.295 |
| Recycling rate of municipal waste | 0.296 Circular material use rate | –0.294 |
| Share of renewable energy in gross final energy consumption – heating and cooling | 0.295 R&D personnel – government sector | –0.277 |
| Share of renewable energy in gross final energy consumption – all sectors | 0.292 R&D personnel – higher education sector | –0.272 |
| Employment in high- and medium-high technology manufacturing | 0.292 Gross domestic expenditure on R&D – higher education sector | –0.234 |
| **The Netherlands** |                             |                            |
| Share of renewable energy in gross final energy consumption – all sectors | 0.296 Government support for agricultural R&D (million euros) | –0.267 |
| Tertiary educational attainment | 0.291 Government support for agricultural R&D (euros per capita) | –0.264 |
| Share of renewable energy in gross final energy consumption – heating and cooling | 0.286 Long-term unemployment rate | –0.246 |
| Recycling rate of municipal waste | 0.284 Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111] | –0.242 |
| Share of renewable energy in gross final energy consumption – transport | 0.282 Employment rate of recent graduates | –0.236 |
| **France**          |                             |                            |
| R&D personnel – higher education sector | 0.302 R&D personnel – government sector | –0.302 |
| R&D personnel – business enterprise sector | 0.302 Employment in high- and medium-high technology manufacturing | –0.290 |
| Recycling rate of municipal waste | 0.301 Long-term unemployment rate | –0.258 |
| Share of renewable energy in gross final energy consumption – heating and cooling | 0.299 Employment rate of recent graduates | –0.253 |
| Employment in knowledge-intensive services | 0.298 Gross domestic expenditure on R&D – government sector | –0.250 |
| **Poland**          |                             |                            |
| Tertiary educational attainment | 0.299 Energy productivity | –0.294 |
|                            | 0.298 | –0.293 |

**Table 4 (continued)**

| Country             | Most progressing indicators | Most regressing indicators |
|---------------------|-----------------------------|----------------------------|
| Italy               |                             |                            |
| Recycling rate of municipal waste | 0.298 Recycling rate of municipal waste | 0.298 |
| Gross domestic expenditure on R&D – business enterprise sector | 0.296 Gross domestic expenditure on R&D – business enterprise sector | 0.296 |
| Recycling of biowaste | 0.296 Circular material use rate | 0.296 |
| Tertiary educational attainment | 0.295 Tertiary educational attainment | 0.295 |
| Spain               |                             |                            |
| Private investments, jobs, and gross value added related to circular economy sectors – % of total employment [V16111] | 0.297 Circular material use rate | –0.293 |
| **Portugal**        |                             |                            |
| Employment in knowledge-intensive services | 0.300 R&D personnel – government sector | –0.283 |
| Tertiary educational attainment | 0.299 Private investments, jobs, and gross value added related to circular economy sectors – gross investment in tangible goods – % of GDP | –0.266 |
|                            | 0.298 | –0.249 |

(continued on next page)
We can illustrate a country that has been less dynamic in the short term by comparing the one-year transition matrices of Portugal and Germany. For Portugal, the diagonal values are relatively high; for example, 65% of the indicators stayed in the best-performing quarter (Q1) from year to year. In contrast, in Germany, the probability for indicators to stay in their initial quarters was generally lower, with 53% (Q1) from year to year. In contrast, in Germany, the probability for indicators to stay in their initial quarters was generally lower, with 53% staying in Q1 in one year and 25% staying in Q2 and Q3 in the next year. The final example shows that 14% (Q1) from year to year improved their performance by moving to Q4 in the next year.

The diagonal values of the transition matrices depict how dynamic a country has been over a given period. Hence, the indicators grow or decline in a homogeneous manner. Consequently, the mobility is higher over ten years than over one year in all countries.

Table 6 also shows mobility indices for one-year and ten-year transition matrices, that is, short-term and long-term dynamics. According to M2, mobility is higher over ten years than over one year in all countries.

| Short-term and long-term mobility |
|----------------------------------|
| Country | One-year | Ten-year | Change in Mobility |
|---------|----------|----------|--------------------|
| Germany | 0.82     | 0.97     | 0.13               |
| Finland | 0.74     | 0.98     | 1.23               |
| France  | 0.75     | 0.98     | 1.23               |
| Poland  | 0.71     | 0.98     | 1.11               |
| Slovakia| 0.79     | 0.99     | 1.24               |
| Italy   | 0.73     | 0.98     | 1.30               |
| Spain   | 0.68     | 0.95     | 1.20               |
| Portugal| 0.65     | 0.95     | 1.17               |
| Latvia  | 0.74     | 0.95     | 1.17               |

Source: Own calculations.

To assess the movement of the whole distribution of z-scores over time, we regressed z-scores on a time variable. The result was a significant slope coefficient for all countries. Fig. 4 depicts the relation between the mobility according to M1, and the z-score slope. We can observe a general pattern of a higher slope with a higher level of mobility. This pattern is unexpected because we previously found an increase in indicators’ z-scores and a decrease in mobility over time.

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

6. Conclusions

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

We found that the evolutions of the EU-10 circular bioeconomies were generally progressive considering all indicators; however, this development was not homogeneous. While most of the EU-10 rapidly progressed in their shares of renewable energy and recycling and circular material use rates, agro-environmental indicators rapidly regressed in Germany, Latvia, and Slovakia. Economic indicators related to circular-economy sectors were among the worst indicators in six countries and among the best in only three countries. The indicators related to R&D generally progressed quickly in the private sector and regressed in the public sector, which suggests that one substituted for the other.
|                  | One-year transition matrix | Ten-year transition matrix |
|------------------|---------------------------|---------------------------|
| **Germany**      |                           |                           |
| Q₁               | 0.50                      | Q₁                        |
| Q₂               | 0.26                      | Q₂                        |
| Q₃               | 0.13                      | Q₃                        |
| Q₄               | 0.11                      | Ergodic                   |
| Ergodic          | 0.245                     | Ergodic                   |
| **Finland**      |                           |                           |
| Q₁               | 0.50                      | Q₁                        |
| Q₂               | 0.32                      | Q₂                        |
| Q₃               | 0.13                      | Q₃                        |
| Q₄               | 0.04                      | Ergodic                   |
| Ergodic          | 0.25                      | Ergodic                   |
| **The Netherlands** |                          |                           |
| Q₁               | 0.50                      | Q₁                        |
| Q₂               | 0.34                      | Q₂                        |
| Q₃               | 0.07                      | Q₃                        |
| Q₄               | 0.09                      | Ergodic                   |
| Ergodic          | 0.250                     | Ergodic                   |
| **France**       |                           |                           |
| Q₁               | 0.46                      | Q₁                        |
| Q₂               | 0.26                      | Q₂                        |
| Q₃               | 0.15                      | Q₃                        |
| Q₄               | 0.12                      | Ergodic                   |
| Ergodic          | 0.243                     | Ergodic                   |
| **Poland**       |                           |                           |
| Q₁               | 0.58                      | Q₁                        |
| Q₂               | 0.23                      | Q₂                        |
| Q₃               | 0.14                      | Q₃                        |
| Q₄               | 0.07                      | Ergodic                   |
| Ergodic          | 0.254                     | Ergodic                   |
| **Slovakia**     |                           |                           |
| Q₁               | 0.47                      | Q₁                        |
| Q₂               | 0.27                      | Q₂                        |
| Q₃               | 0.14                      | Q₃                        |
| Q₄               | 0.11                      | Ergodic                   |
| Ergodic          | 0.245                     | Ergodic                   |
| **Italy**        |                           |                           |
| Q₁               | 0.55                      | Q₁                        |
| Q₂               | 0.26                      | Q₂                        |
| Q₃               | 0.12                      | Q₃                        |
| Q₄               | 0.06                      | Ergodic                   |
| Ergodic          | 0.243                     | Ergodic                   |
| **Spain**        |                           |                           |
| Q₁               | 0.53                      | Q₁                        |
| Q₂               | 0.30                      | Q₂                        |
| Q₃               | 0.13                      | Q₃                        |
| Q₄               | 0.05                      | Ergodic                   |
| Ergodic          | 0.241                     | Ergodic                   |
| **Portugal**     |                           |                           |
| Q₁               | 0.53                      | Q₁                        |
| Q₂               | 0.30                      | Q₂                        |
| Q₃               | 0.09                      | Q₃                        |
| Q₄               | 0.06                      | Ergodic                   |
| Ergodic          | 0.253                     | Ergodic                   |
| **Latvia**       |                           |                           |
| Q₁               | 0.53                      | Q₁                        |
| Q₂               | 0.22                      | Q₂                        |
| Q₃               | 0.16                      | Q₃                        |
| Q₄               | 0.08                      | Ergodic                   |
| Ergodic          | 0.243                     | Ergodic                   |
Our results show that the circular bioeconomy is multi-faceted and that, while it generally progressed during the study period, not all indicators moved in the desired direction. This pattern is exemplified in Germany’s circular-bioeconomy indicators, which progressed the most on average in comparison to the rest of the EU-10. At the same time, intra-distribution dynamics were also high for Germany: indicators sharply differed in their developments, and their relative rankings strongly varied in consecutive years. Indicators, such as patent applications and ammonia emissions from agriculture, even regressed rapidly. We recommend that policymakers consider all indicators and not only a few because a country with highly dynamic indicators seems to progress differently in economic, environmental, and social aspects. Therefore, examining only a few indicators can bias the picture of a country’s circular bioeconomy.

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

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

We faced significant challenges in compiling the data needed for our framework. After we had selected our indicators according to their relevance to the circular bioeconomy and data availability, only 41

| Table 6 |
| --- |
| Mobility metrics. |

| Short-term mobility in two periods |  |  | Change in Mobility |
| Country | One-year 2007–2011 | One-year 2012–2016 | Mobility |
| | M1 | M2 | M1 | M2 | ∆M1 | ∆M2 |
| Germany | 0.83 | 0.96 | 0.81 | 0.98 | -0.02 | 0.02 |
| Finland | 0.83 | 0.98 | 0.65 | 0.97 | -0.18 | 0.00 |
| The Netherlands | 0.80 | 0.95 | 0.63 | 0.97 | -0.18 | 0.02 |
| France | 0.77 | 0.97 | 0.73 | 0.98 | -0.04 | 0.01 |
| Poland | 0.68 | 0.98 | 0.75 | 0.99 | 0.07 | 0.01 |
| Slovakia | 0.78 | 0.98 | 0.81 | 0.99 | 0.03 | 0.01 |
| Italy | 0.73 | 0.98 | 0.73 | 0.98 | 0.00 | -0.01 |
| Spain | 0.69 | 0.94 | 0.67 | 0.96 | -0.02 | 0.02 |
| Portugal | 0.72 | 0.94 | 0.59 | 0.96 | -0.12 | 0.02 |
| Latvia | 0.80 | 0.98 | 0.67 | 0.92 | -0.13 | -0.07 |

Fig. 4. Correlation of average one-year mobilities (M1) and time trend of z-scores between countries. Note: The dotted horizontal and vertical lines depict the averages of the minimum and maximum values.
indicators remained. This number of items is feasible but possibly affects the robustness of the results using Markov transition matrices. As soon as additional indicators become available, this issue could be easily addressed by future studies. Moreover, we analyzed the directions, speeds, and dynamics of circular bioeconomies, but we could not assess their initial states with our framework. In an unlikely but theoretically possible case, a circular bioeconomy could already be at its steady state at the beginning of the study period, so zero progress in its indicators' z-scores would not be problematic. This problem could be solved if quantitative targets for all indicators were determined, which would allow us to assess the distance from realizing those targets.

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

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

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the BioMonitor project, which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 773297. Dusan Drabik acknowledges the financial support received from the Slovak Research and Development Agency under contract No. APVV-19-0544 and from the Operational program Integrated Infrastructure within the project: Demand-driven research for the sustainable and innovative food, Drive4SIFood 313011V336, co-financed by the European Regional Development Fund. We thank two anonymous reviewers for their helpful suggestions. We also thank Justus Wesseler and David Zilberman for their valuable comments on an earlier version of this article.

Appendix A. Development of circular bioeconomy indicators in ten selected European Union Member States from 2006 to 2016 as box plots

---

6 See, for example, the BioMonitor project, JRC Bioeconomy Monitoring, and the German Systematic Monitoring and Modelling of the Bioeconomy (Symobio) project.
Fig. A.2: Finland.

Fig. A.3: The Netherlands.
Fig. A.4: France.

Fig. A.5: Poland.
Fig. A.6: Slovakia.

Fig. A.7: Italy.
Fig. A.8: Spain.

Fig. A.9: Portugal.
Fig. A.10: Latvia.

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

References

Alessandrini, M., Fattouh, B., Scaramozzino, P., 2007. The changing pattern of foreign trade specialization in Indian manufacturing. Oxf. Rev. Econ. Policy. https://doi.org/10.1093/oxrep/grm3113.

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

Booijen, F., 2002. An overview and evaluation of composite indices of development. Soc. Indic. Res. 59, 115–151. https://doi.org/10.1023/A:1016275505152.

Borawski, P., Belyczyk-Borawska, A., Szymańska, E.J., Jankowski, K.J., Dubis, B., Duma, J.W., 2019. Development of renewable energy sources market and biofuels in the European Union. J. Clean. Prod. 228, 467–484. https://doi.org/10.1016/j.jclepro.2019.04.242.

Braga, S., Tani, A., Calluoglu, O., Gomez San Juan, M., Bogdanski, A., 2019. Indicators to Monitor and Evaluate the Sustainability of Bioeconomy: Overview and a Proposed Way Forward. (No. 77). FAO Environment and Natural Resource Management Working Paper, Rome.

Chiappini, R., 2014. Persistence vs. mobility in industrial and technological specialisations: evidence from 11 euro area countries. J. Evol. Econ. 24, 159–187. https://doi.org/10.1007/s00191-013-0331-7.

D’Adamo, I., Falcone, P.M., Morone, P., 2020. A new socio-economic indicator to measure the performance of bioeconomy sectors in Europe. Ecol. Econ. 176, 106724. https://doi.org/10.1016/j.ecolecon.2020.106724.

Effken, J., Dirkmeyer, W., Kreins, P., Knecht, M., 2016. Measuring the importance of the bioeconomy in Germany: concept and illustration. NJAS - Wageningen J. Life Sci. 77, 9–17. https://doi.org/10.1016/j.njas.2016.03.008.

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

European Commission, 2018. A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. Bioecon. Strategy. https://doi.org/10.2777/478385.

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

European Commission, 2019b. Agri-Environmental Indicator - Intensification - Extensification - Statistics Explained [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Agri-environmental_indicator_-_intensification_-_extensification.

Eurostat, 2019. Sustainable development in the European Union — monitoring report on progress towards the SDGs in an EU context — 2019 edition. Statistical Books. https://doi.org/10.2785/44964.

Ferti, L., Soós, K.A., 2008. Trade specialization in the European Union and in postcommunist European countries. East. Eur. Econ. https://doi.org/10.2753/EEDE012-8775460301.

German Bioeconomy Council, 2018. Bioeconomy Policy (Part II) Synopsis of National Strategies around the World. Berlin.

Iost, S., Labonte, N., Bame, M., Geng, N., Jochem, D., Schweinle, J., 2019. German Bioeconomy: Economic Importance and Concept of Measurement, 68, pp. 275–288. IFENA, 2015. Rfmap 2030 Renewable Energy Prospects for Poland (Abu Dhabi), Italian Presidency of Council of Ministers, 2017. Bioeconomy in Italy - A Unique Opportunity to Reconnect the ECONOMY, Society and the Environment, 64.

Jander, W., Grundmann, P., 2019. Monitoring the transition towards a bioeconomy: a general framework and a specific indicator. J. Clean. Prod. 236, 117564. https://doi.org/10.1016/j.jclepro.2019.07.039.

Joint Research Centre, 2019. Bioeconomy Policy | Knowledge for Policy [WWW Document]. URL https://knowledge4policy.ec.europa.eu/bioeconomy/bioeconomy-policy.en.

Kubiszewski, I., Costanza, R., Franco, C., Lawan, P., Tatother, J., Jackson, T., Aylmer, C., 2013. Beyond GDP: measuring and achieving global genuine progress. Ecol. Econ. 93, 57–68. https://doi.org/10.1016/j.ecolecon.2013.04.019.

Lafortune, G., Fuller, G., Moreno, J., Schmidt-Trad, G., Kroll, C., 2018. SDG Index and Dashboards - Detailed Methodological Paper. Global Responsibilities. Implementing the Goals.

Latvian Ministry of Agriculture, 2018. Latvian Bioeconomy Strategy 2030.

Lier, M., Aarne, M., Karkkainen, L., Korhonen, K.T., Yi-Viikari, A., Packalen, T., 2018. Synthesis on Bioeconomy Monitoring Systems in the EU Member States-Indicators for Monitoring the Progress of Bioeconomy. Ministriye van, E.Z., 2013. Groene economische groei in Nederland (Green Deal) 1–7. Ministry of Employment and the Economy, 2014. The Finnish Bioeconomy Strategy 31.

The Hague.

Mola, A., Schiltz, F., 2019. Measuring sustainable development goals performance: how to monitor policy action in the 2030 agenda implementation? Ecol. Econ. 164, 106373. https://doi.org/10.1016/j.ecolecon.2019.106373.

O’Brien, M., Wechsler, D., Brinca, S., Schaldach, R., 2017. Toward a systemic monitoring of the European bioeconomy: gaps, needs and the integration of sustainability indicators and targets for global land use. Land Use Policy 66, 162–171. https://doi.org/10.1016/j.jlandusepol.2017.04.047.

OECD, 2016. Measuring Distance to the SDG Targets: An Assessment of where OECD Countries Stand. The Organisation for Economic Co-operation and Development, Paris, France, p. 2018. https://doi.org/10.1787/d20adaa5-en.

OECD, 2019. Measuring distance to the SDG targets 2019, measuring distance to the SDG targets 2019. OECD. https://doi.org/10.1787/888933877546.
Philippidis, G., Bartelings, H., Smeets, E., 2018. Sailing into unchartered waters: plotting a course for EU bio-based sectors. Ecol. Econ. 147, 410–421. https://doi.org/10.1016/j.ecolecon.2018.01.026.

Piotrowski, S., Carus, M., Carrez, D., 2016. European Bioeconomy in Figures 2008–2016. Purkus, A., Hagemann, N., Bedike, N., Gawel, E., 2018. Towards a sustainable innovation system for the German wood-based bioeconomy: implications for policy design. J. Clean. Prod. 172, 3955–3968. https://doi.org/10.1016/j.jclepro.2017.04.146.

Quah, D., 1993. Empirical cross-section dynamics in economic growth. Eur. Econ. Rev. 37, 426–434. https://doi.org/10.1016/0014-2921(93)90031-5.

Quah, D.T., 1996. Empirics for economic growth and convergence. Eur. Econ. Rev. 40, 1353–1375. https://doi.org/10.1016/0014-2921(95)00051-6.

RIS3 SK, 2013. Through Knowledge Towards Prosperity - Research and Innovation Strategy for Smart Specialisation of the Slovak Republic.

Ronzon, T., M’Barek, R., 2018. Socioeconomic indicators to monitor the EU’s bioeconomy in transition. Sustain. 10, 1745. https://doi.org/10.3390/su10061745.

Ronzon, T., Sanjuán, A.L., 2020. Friends or foes? A compatibility assessment of bioeconomy-related sustainable development goals for European policy coherence. J. Clean. Prod. 254, 119832. https://doi.org/10.1016/j.jclepro.2019.119832.

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., Fuller, G., 2018. SDG index and dashboards report 2018: global responsibilities. Glob. Responsib. Implement. Goals 1–476.

Shorrocks, A.F., 1978. The measurement of mobility. Econ. Soc. 46, 1013–1024.

Sosnowski, S., Hetman, K., Grabczuk, K., Cholewa, M., Sobczak, J., Pęcalski, T., Walasek, A., Mocior, E., Habza, A., Janczarek, P., Bartusi, K., Bożek, E., Bryła, K., Bydzra, I., Donica, D., Franaszek, P., Kawalko, B., Nakielska, I., Orzeł, Z., Pieczykołan, A., Rudnicki, W., Sokol, M., Struski, S., Szych, H., Dudziński, R., Pocztowski, B., Rycaj, E., 2014. Regional Innovation Strategy for the Lubelskie Voivodeship 2020: Regional Innovation Strategy for Smart Specialisation (RIS3), United Nations, 2017. Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development. A/RES/71/313 E/CN.3/2018/2. Work Stat. Comm. Pertain. to 2030 Agenda Sustain. Dev. 1–21.

Wesseler, J., von Braun, J., 2017. Measuring the bioeconomy: economics and policies. Ann. Rev. Resour. Econ. 9, 275–298. https://doi.org/10.1146/annurev-resource-100516-053701.

Zaghini, A., 2005. Evolution of trade patterns in the new EU member states. Econ. Transit. 13, 629–658. https://doi.org/10.1111/j.0967-0750.2005.00235.x.

Zhang, Ruonan, Sun, C., Zhu, J., Zhang, Renshe, Li, W., 2020. Increased European heat waves in recent decades in response to shrinking Arctic Sea ice and Eurasian snow cover. Npj Clim. Atmos. Sci. 3, 1–9. https://doi.org/10.1038/s41612-020-0110-8.