https://doi.org/10.17221/195/2023-AGRICECON

The European Union's circular bioeconomy: What do the indicators tell us?

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Citation: Kardung M., Drabik D. (2024): The European Union's circular bioeconomy: What do the indicators tell us? Agric. Econ. – Czech, 70: 199–206

Abstract: Prior studies have noted the importance of measurement tools that track the contributions of the circular bioeconomy and other developments towards sustainable development. In this study, we examined the EU-27 as a whole and found that its circular bioeconomy, measured by the 41 indicators we used, generally progressed over the period 2004–2021. Research and development personnel and Persons employed in circular economy sectors were ranked as the most progressing indicators over the studied period, together with Patent applications to the European Patent Office, which supports the idea that the circular bioeconomy uses novel technologies and requires research to develop them.

Keywords: biomass; development; framework; pattern; sustainable

Policymakers in the European Union (EU) seek to transform its fossil-based economy and use natural resources more sustainably. The European Commission (EC) stated that ensuring sustainable land use and conserving natural capital in the bioeconomy can contribute to sustainable development (European Comission 2018). Applying the principle of circularity (i.e. maintaining the value of products, materials and resources and minimising waste generation) in the bioeconomy can increase sustainability (European Comission 2015). Agriculture, which accounts for the largest portion of biomass production for food and non-food use, is an important sector for developing a circular bioeconomy (Avitabile et al. 2023). An increase in biomass demand for various products from processed biomass in the circular bioeconomy is likely to result in an increased demand for land for agriculture and forestry. However, the circular bioeconomy is much larger than this. Bioeconomy-related activities can roughly be classified into the following: *i*) natural resource-based activities that directly exploit a biological resource (e.g. agriculture, fishery and forestry) and provide bio-

Supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 773297 (Monitoring the Bioeconomy – BioMonitor). Dušan Drabik acknowledges the financial support received from the Slovak Research and Development Agency under the contracts APVV-19-0544 and APVV-21-0174: Rural development and agricultural employment: the role of policies, globalisation and climate changes.

https://doi.org/10.17221/195/2023-AGRICECON

mass for further processing; *ii*) conventional manufacturing activities that further process biomass (e.g. the food and wood processing sectors); and *iii*) novel activities that further process biomass or biomass residues (e.g. the bioenergy and bio-based chemical sectors) (Kardung et al. 2021). The diverse nature of the circular bioeconomy makes it challenging for policymakers to keep track of and steer its development.

In terms of a circular bioeconomy policy, the 2012 EU Bioeconomy Strategy represents the first attempt to promote the development of a circular bioeconomy. The 2018 update of the EC's Bioeconomy Strategy affirmed that the circular bioeconomy is high on the political agenda, and it proposed an action plan with 14 concrete measures (European Comission 2018). In 2022, the EC published the EU Bioeconomy Strategy Progress Report, which identified the positive developments and shortcomings of the Bioeconomy Strategy and action plan. The report found that more national and regional bioeconomy strategies have been implemented, focusing on cross-sectoral cooperation and sustainability, especially in Central and Eastern European countries. Private investment, research and innovation in bio-based sectors have increased. However, a gap in the strategy is the alignment of ecological limits, such as land and biomass demand, with economic development (European Comission 2022).

The circular bioeconomy is a broad strategy that is argued to address many different economic, social and environmental challenges simultaneously (Wesseler and von Braun 2017; Zilberman et al. 2018). There are trade-offs with other policies as their linkages increase, making the objectives and elements more complicated. For example, suppose the bioeconomy expansion requires converting natural ecosystems, such as forests and wetlands, into agricultural land. In this case, the objectives of the EU Biodiversity Strategy might not be met. Simultaneous monitoring of indicators that measure the different types of land uses and levels of biodiversity can reveal these trade-offs. As the EU aims to promote a circular bioeconomy and achieve the United Nations (UN) Sustainable Development Goals (SDGs) by establishing a broad policy framework, following this process and its dynamics is important to ensure that resources are used efficiently (Calicioglu and Bogdanski 2021).

A rich set of well-defined quantitative indicators is essential to track the development of the circular bioeconomy. An indicator is a quantitative variable that must be measurable, comparable, replicable and responsive to fluctuations in development. Indicators can help policymakers monitor the development of the circular bioeconomy, understand and interpret results, identify trade-offs between policies and formulate more precise objectives for the future.

Several initiatives related to monitoring the circular bioeconomy have proposed sets of indicators, and organisations are already collecting data for these indicators (e.g. Eurostat, Forest Europe and the European Environment Agency). Eurostat follows 100 indicators related to the SDGs and 10 indicators for the circular economy, particularly for biomass flows. The 10 circular economy indicators are part of a circular economy monitoring framework that includes four thematic areas: production and consumption, waste management, secondary raw materials, and competitiveness and innovation.

The SDG indicators are important, as some measure the contributions of the circular bioeconomy to sustainable development, as documented by Ronzon and Sanjuán (2020). For instance, the latter found that the 2018 EU Bioeconomy Strategy Update could contribute to 53 targets in 12 of the 17 SDGs by mapping the Strategy's action plan to the SDGs.

Governments and non-governmental organisations widely use indicator frameworks to track progress towards important societal goals, but these frameworks are complex and fraught with pitfalls (Lyytimäki et al. 2020). A prominent example is the UN SDGs, which include 231 indicators to measure progress towards 169 corresponding targets (United Nations 2022). Researchers have noted the risk of overuse, non-use and misuse of these indicators, which could affect the implementation of the SDGs (Lyytimäki et al. 2020).

Comprehensive, reliable and user-friendly indicators can be used by policymakers to assess the current state and direction of a desired development at the appropriate level of detail and to implement appropriate policies. Society can use the same information to hold policymakers accountable for their actions (Biermann et al. 2022). A comprehensive framework has indicators that not only measure development and economic, environmental and social impacts but also reveal the trade-offs between them (van Leeuwen et al. 2015). Such a framework would therefore benefit from incorporating many well-defined quantitative indicators and finding patterns in their development (Lier et al. 2018).

In this context, the research question we want to address is whether the EU bioeconomy progressed over the studied period of 2004–2021. Our objective is to use a set of indicators from one of the frameworks to investigate whether progress occurred in all the in-

https://doi.org/10.17221/195/2023-AGRICECON

dicators and whether the indicators maintained their relative positions throughout the period studied. This study contributes to the quantitative literature on the assessment of the EU bioeconomy in that it considers a much broader palette of indicators than what has been the norm so far (typically only value added, share of the total employment or the number of new jobs created). We focus on the EU-27 as a whole to provide EU policymakers with results that they could use in future comparisons of the performance of the EU bioeconomy with that of the bioeconomies of other big global players.

MATERIAL AND METHODS

In reviewing studies dealing with the development of the circular bioeconomy, we observed that most of them assessed it by examining only a few indicators, which could bias the results. An EU Horizon 2020-funded project, BioMonitor, devised an empirical framework that can be applied to any number of well-defined quantitative circular bioeconomy indicators (Kardung and Drabik 2021). These indicators are bioeconomy related and include several measures that help identify more than just the contributions of the circular bioeconomy. We used time-series data from Eurostat's indicator set to measure the progress towards the SDGs and monitoring framework on the circular economy. Regarding the geographical coverage, we focus on the EU-27 as a whole and use the available data for the 2004–2021 period (i.e. 18 years).

Our framework normalises indicators with different units and dimensions and explores patterns using Markov transition matrices. It helps understand indicators covering different economic, environmental and social aspects of a circular bioeconomy.

Following Kardung and Drabik (2021), we calculated how many standard deviations an indicator's value is away from the indicator's temporal mean (i.e. z-score). Converting indicators into z-scores conveniently solves the problem of comparing and further working with indicators of different units. A positive z-score indicates a value above the mean, and a negative z-score indicates a value below the mean. To robustly rank the normalised indicators according to their speeds of development, we ran a simple ordinary least squares regression, $z_t = \beta_0 + \beta_1 t + \beta_2 z_{t-1} + \varepsilon_t$, for each indicator (i.e. a total of 41 regressions), where z_t is the value of the z-score of an indicator at time t, β_0 is the intercept, β_1 is the slope of the time trend ($t = \{0, 1, \ldots, 17\}$), β_2 is the coefficient of the lagged z-score, and ε_t is a disturbance term at time t. A significant positive value of β_1 indicates that an indicator progressed over the 18-year period, whereas a negative one means a deterioration in the bioeconomy in the given indicator. Likewise, a positive significant value of β_2 indicates that the sign of the z-score did not tend to change between years, while a negative value of β_2 suggests an alternation of the signs.

Our approach of using a large number of quantitative bioeconomy indicators not only created a ranking of the most progressing and most regressing indicators – a piece of information that is useful to policymakers in its own right – but can also be used to examine how the relative performance of individual indicators evolves; that is, we can study the internal dynamics of the performance of the bioeconomy. An appropriate method to do so is to estimate transition probabilities representing the likelihood that the value of an indicator changes a performance category for another one over a selected period. To be more concrete, for every year, we ordered the indicators by their z-scores from the lowest to the highest and created four intervals (quarters, Q). The number of indicators in each interval was equal, save for the last one, as our total number of indicators is 41. We then tracked how many indicators stayed in their initial quarters and how many changed their positions (and where) in the next year. The number of transitions can readily be converted into transition probabilities by dividing the number of indicators in each quarter after the transition by the total number of indicators in the source quarter.

RESULTS AND DISCUSSION

To explore the development of the circular bioeconomy in the EU as a whole, we applied the methodological framework used by Kardung and Drabik (2021), as described above. Table 1 lists all 41 indicators in our analysis and their desired directions. Most indicators are marked with plus signs, meaning that they perform better when their values increase. To compare and interpret the development of all indicators meaningfully, we transformed the indicators marked with minus signs (e.g. ammonia emissions from agriculture) by multiplying their values by –1 so that their development can be interpreted consistently with the indicators with plus signs. Finally, we have two indicators whose desired values are zero (gross nitrogen balance on agricultural land by nutrient and gross phosphorus balance on agricultural land). In this case, we first took the absolute value of the deviation of the indicator's

https://doi.org/10.17221/195/2023-AGRICECON

Table 1. List of indicators used

Description	Desired direction	β_1	β_2
Share of renewable energy in the gross final energy consumption by sector (transport)	+	0.320***	–0.069
Gross added value related to circular economy sectors (million EUR)	+	0.306***	–0.007
Patent applications to the European Patent Office (number)	+	0.302***	0.024
Energy productivity (EUR per kg of oil equivalent)	+	0.270***	0.142
Agricultural factor income per annual work unit	+	0.250***	0.133
Persons employed in circular economy sectors (% of total employment)	+	0.246***	–0.030
Gross added value related to circular economy sectors (% of the GDP)	+	0.235**	0.139
Gross domestic expenditure on R&D by sector – business enterprise sector	+	0.234***	0.176
Area under organic farming – % of utilised agricultural area	+	0.232**	0.252
Persons employed in circular economy sectors (full-time equivalent)	+	0.228**	0.315
Patent applications to the European Patent Office (per million inhabitants)	+	0.202**	0.383
Private investment related to circular economy sectors (million EUR)	+	0.195**	–0.149
Share of renewable energy in the gross final energy consumption by sector (total)	+	0.192**	0.322
Share of renewable energy in the gross final energy consumption by sector (electricity)	+	0.164***	0.436**
Greenhouse gas emissions (metric tonnes *per capita*)	–	0.157***	0.329
Greenhouse gas emissions (base year: 1990)	–	0.154***	0.330
Gross nitrogen balance on agricultural land by nutrient	0	0.138**	0.334
Adult participation in learning by sex (total)	+	0.136**	0.306
Recycling rate of municipal waste (% of total waste generated)	+	0.129**	0.510**
Recycling rate of packaging waste by type of packaging	+	0.129*	0.510**
Ammonia emissions from agriculture (kg/ha)	–	0.093	0.701***
R&D personnel by sector – government sector (% of the active population)	+	0.074	0.675***
Long-term unemployment rate by sex (total)	–	0.073	0.670***
Circular material use rate (% of material input for domestic use)	+	0.067	0.590***
Share of renewable energy in the gross final energy consumption by sector (heating and cooling)	+	0.061	0.730***
Government support to agricultural research and development (million euros)	+	0.059	0.723***
R&D personnel by sector – higher education sector (% of active population)	+	0.056	0.851***
Tertiary educational attainment by sex (total)	+	0.056	0.794***
Material footprint (metric tonnes *per capita*)	–	0.056	0.680***
Resource productivity (EUR per kilogram)	+	0.053	0.710***
Government support to agricultural research and development (EUR per inhabitant)	+	0.051	0.714***
R&D personnel by sector – business enterprise sector (% of the active population)	+	0.047	0.953***
Ammonia emissions from agriculture (metric tonne)	–	0.046	0.782***
Gross domestic expenditure on R&D by sector – government sector	+	0.044	0.431
Patents related to recycling and secondary raw materials (number)	+	0.040	0.631***
Patents related to recycling and secondary raw materials (per million inhabitants)	+	0.038	0.621***
Gross domestic expenditure on R&D by sector – higher education sector	+	0.033	0.746***
Gross phosphorus balance on agricultural land by nutrient	0	0.011	0.749***
Real GDP *per capita* – chain linked volumes (% in previous period, *per capita*)	+	–0.012	–0.278
Private investment related to circular economy sectors (% of the GDP)	–	–0.084	–0.197
Primary energy consumption (million metric tonnes of oil equivalent)	–	–0.214***	0.008

*,**,*** $P < 0.1$, $P < 0.05$, and $P < 0.01$, respectively; + specifies indicators that progress with higher values; – specifies indicators that regress with higher values; 0 specifies indicators whose desired values are zero

Source: Authors' own elaboration

https://doi.org/10.17221/195/2023-AGRICECON

value from zero, treating both positive and negative deviations equally. As a smaller deviation value is desired, in the next step, we proceeded as with the indicators with minus signs.

The desired direction of the indicators' values in Table 1 considered the indicators in isolation. When we look at the circular bioeconomy as a whole, each (or a subset) of the indicators possibly has a finite optimal value, given the social welfare function and interaction effects with other measures of the bioeconomy. Our present analysis does not consider this eventuality because we do not know these optimal values.

Figure 1 shows a generally positive trend of the EU circular bioeconomy in the period 2004–2021, as the median *z*-score (the band inside the box) increased over time in the EU-27. The interquartile range, represented by the height of the box, was generally smaller in the first half of the period than in the second. In most years, there were outliers beyond the whiskers, indicating that individual indicators deviated from the rest (the outliers tended to be on the positive end in the first half of the analysed period and on the opposite end in the second half).

We ranked all circular bioeconomy indicators from best performing to worst performing based on the estimated slope parameters (β_1), that is, based on how fast they increased (declined) over time. The parameters are presented in the third column of Table 1.

Among the most progressing indicators were the share of renewable energy in the gross final energy consumption in the transportation sector, the gross added value related to circular economy sectors and the patent applications to the European Patent Office. Looking at the list of the indicators with a positive significant time trend coefficient β_1, we could observe a pattern in which energy, human capital and innovation played a key role. We expect this pattern to persist as the Circular Bio-based Europe Joint Undertaking addresses this issue by providing EUR 2 billion in funding from 2021 to 2031 for public-private investments in re-

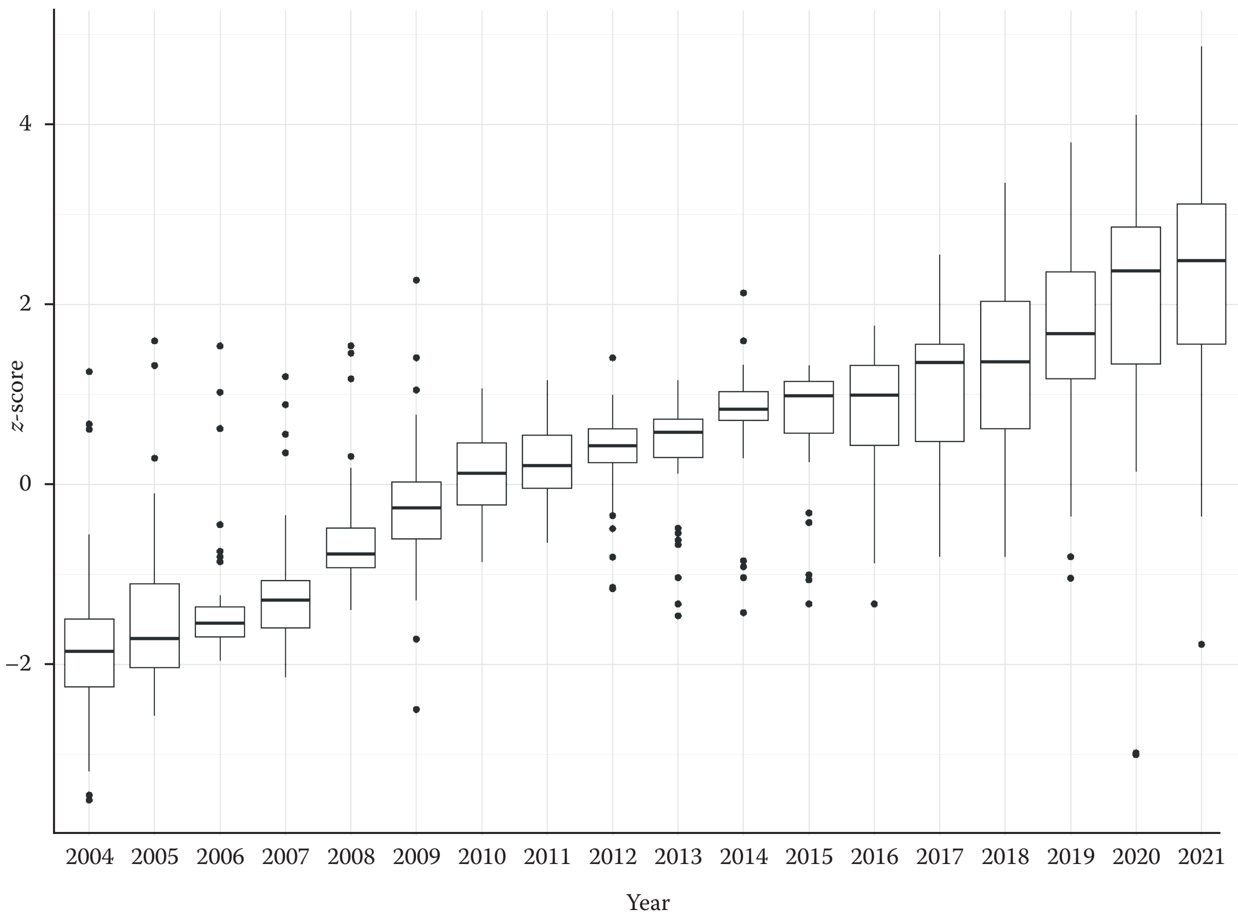

Figure 1. A box plot of circular bioeconomy indicators in the EU-27 from 2004 to 2021

Source: Authors' own elaboration

https://doi.org/10.17221/195/2023-AGRICECON

search and innovation projects (Philippidis et al. 2023). By contrast, primary energy consumption declined the fastest, followed by private investment related to circular economy sectors (although the coefficient on the indicator is insignificant).

Another pattern we can observe in Table 1 is that in the lion's share of cases when the time trend is significant, the lagged value of a *z*-score is not significant and the other way around. This means there are two groups of indicators in our sample: one, in which their development is driven by the time trend and the other, where the sign of the *z*-score in one year determines the sign in the next year (note that all significant values of β_2 are positive, meaning that the signs do not tend to change).

Regarding the future development of the bioeconomy, researchers have highlighted the importance of monitoring the environmental dimension of the bioeconomy (Sinkko et al. 2023). The transition to a bioeconomy, as outlined by the EU, requires the availability of sufficient sustainably produced biomass. Van Leeuwen et al. (2023) predicted that more than 20 000 kilotonnes of agricultural biomass will be available in the EU in 2030 for material and biofuel use. This biomass production puts and will continue to put pressure on the environment. Our analysis showed that environmental indicators, such as nutrient balances and ammonia emissions, did not progress as quickly as the others. Therefore, they need to be kept in check to ensure that the bioeconomy has a net positive impact on the environment.

To provide an interpretation of the values in the transition matrices, we consider the first line in the one-year transition matrix in Table 2. There was a 58% chance that indicators that started in the first quarter (i.e. indicators with the lowest *z*-scores) remained in that quarter also in the next year; 20% improved their positions by making it to Q2, 11% improved their positions by making it to Q3, and 11% of the least-performing indicators were able to improve their relative positions by switching to the best-performing category Q4. The same transition matrix shows that the changes in the performance of the indicators were not one-way traffic, as only 57% of the best-performing indicators in one year retained their positions, and the rest descended to the third, second and first quarters (19%, 12% and 13%, respectively).

Table 2. Short- and long-term transition matrices for the EU-27

One-year transition matrix					Seventeen-year transition matrix				
–	Q_1	Q_2	Q_3	Q_4	–	Q_1	Q_2	Q_3	Q_4
Q_1	0.58	0.20	0.11	0.11	Q_1	0.00	0.10	0.30	0.60
Q_2	0.19	0.46	0.26	0.10	Q_2	0.10	0.20	0.30	0.40
Q_3	0.09	0.22	0.43	0.26	Q_3	0.30	0.50	0.10	0.10
Q_4	0.13	0.12	0.19	0.57	Q_4	0.55	0.18	0.27	0.00

Q – quartile
Source: Authors' own elaboration

The second matrix in Table 2 sheds light on the dynamics of the development of the EU-27 bioeconomy over a more extended period (17 years). The marked difference from the one-year transition matrix was a significantly lower diagonal probability, which indicates that the indicators were less likely to stay in their initial positions over a longer period. All indicators that started in Q1 moved to Q2, Q3 and Q4 after 17 years, while 40% of those that started in Q2 ended in Q4. Interestingly, none of the best-performing indicators from the beginning of the period examined defended their positions, and 55% fell into the least-performing category.

Our results regarding the best- and least-performing indicators are generally different from the findings of Kardung and Drabik (2021), who performed a similar analysis for 10 selected EU Member States. This is likely due to the granularity of their results, which cannot easily be aggregated to the EU level. Our analysis of the short- and long-term matrices shares similarities with those of Kardung and Drabik (2021) and Gracia de Rentería et al. (2023), who also documented the persistence of the patterns of bioeconomy indicators in the short run but reported much more mobility over a longer period (10 years in their case). The EU Bioeconomy Monitoring System makes more indicators available and fills data gaps, so we expect our framework to become increasingly useful as it benefits from a higher number of indicators (Sanchez-Jerez et al. 2023).

CONCLUSION

Prior studies have noted the importance of measurement tools that track the contributions of the circular bioeconomy and other developments towards sustainable development. The gross domestic product has been the policy- and discourse-dominating economic and general welfare indicator. However, many other indicators describe the status of the bioeconomy and how it evolves over time. In this study, we used a methodological framework that can accommodate a large number of quantitative indicators and distil information from them about the general development of the

https://doi.org/10.17221/195/2023-AGRICECON

bioeconomy, the dimensions in which it progresses or regresses the most and how dynamic the changes in the relative positions of individual indicators are.

We examined the EU-27 as a whole and found that its circular bioeconomy, measured by 41 indicators we used, generally progressed over the period 2004–2021. The list of the indicators with a significant positive time trend included many indicators that could generally be related to energy, human capital and innovation, suggesting that these areas played a key role in the EU circular bioeconomy. On the other hand, primary energy consumption steadily declined, confirming that bioenergy (part of the bioeconomy) replaced traditional forms of energy.

Regarding the limitations of our study, we would like to mention three which could be addressed in the future. First, all indicators had equal weights in our analysis. It would be interesting to compare our results with those considering the weights of indicators perceived by bioeconomy policymakers and stakeholders. Second, the indicators we used were rather heterogeneous. Categorising them into economic, social, and environmental would produce a clearer picture of how the EU performs in these dimensions in order to achieve the SDGs. Third, the study examined only the EU-27. Other important global bioeconomy actors exist, including the USA and Latin America. Unless we have comparable studies for those regions, we cannot say much about the position of the EU vis-à-vis other big bioeconomy players.

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Received: June 9, 2023
Accepted: March 25, 2024
Published online: May 9, 2024