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Disparities among EU Countries in the Circular Economy Framework: an Entropy-Based Analysis of Global Sustainability and Resilience

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Abstract. This paper analyzes the circular economy framework within the European Union, focusing on its contribution to global sustainability and resilience during 2023. Using the entropy method, the study examines convergence and divergence among EU member states based on three key indicators: consumption footprint, greenhouse gas emissions, and material import dependency. The results show convergence in terms of consumption footprint, while material import dependency exhibits the greatest divergence. The analysis highlights the uneven implementation of circular economy principles across EU countries, offering insights relevant for future sustainable development policies.

Keywords: *circular economy, sustainability, resilience, European Union, convergence, entropy method*

Introduction

Through the launch of the Roadmap to a Resource Efficient Europe (European Commission, 2011) and the EU Action Plan for the Circular Economy (European Commission, 2015), the European Commission has demonstrated a strong commitment to improving resource efficiency and accelerating the transition from a linear to a circular economic model (Domenech & Bahn-Walkowiak, 2019). These policy initiatives emphasize the need to decouple economic growth from resource use and environmental degradation, thereby promoting a more sustainable and resilient economic system (MacArthur, 2013; Kirchherr et al., 2017).

Against this policy background, this paper examines differences in the implementation of circular economy (CE) principles across EU member states. The main objective is to assess and compare the level of circular economy performance among EU countries using an entropy methodological approach, with the aim of identifying disparities related to global sustainability and resilience.

By applying entropy analysis to selected circular economy indicators for the most recent available year, this study provides an contemporary and comparative assessment of CE performance in Europe. Particular attention is given to key indicators within the global sustainability and resilience pillar, including consumption footprint, greenhouse gas emissions and material import dependency. Unlike earlier studies that primarily rely on static or single country analyses, this research offers a cross-country comparative perspective, contributing new empirical insights into the current state of the circular economy in the EU (Smol et al., 2020).

The structure of this paper is organized into five main sections. The first part, Introduction outlines the research context. The Theoretical Framework presents key concepts related to the circular economy, sustainability, and resilience, with a focus on EU policy development. The Methodology section explains the use of the entropy method and the selection of data for analysis. The Results and Discussion section presents the findings on convergence and divergence among EU member states, followed by an interpretation of their implications for policy and practice. Finally, the Conclusion part summarizes the main findings, research limitations, and suggests directions for future research.

Theoretical background

Transition towards a resource efficient circular economy in Europe

The term "circular economy" (CE), is gaining popularity, particularly in the European Union, and it encourages the prudent and periodic use of resources, which may support sustainable growth. CE is a general term that encompasses many meanings. Some authors such as Webster (2015) said that CE present “a systemic change… with idea is to create a regenerative system where products, components and materials are maintained at their highest value for as long as possible and resources can be productively recovered and reintegrated in the economy or provide nutrients to natural systems”.

Some authors highlight that CE refers to an economic system aimed at minimizing waste and maximizing the use of resources through closed-loop material cycles (Geissdoerfer et al., 2017). Kirchherr et al.., (2017), in their review of over 100 definitions, propose that CE is “an economic system that replaces the ‘end-of-life’ concept with reducing, reusing, recycling, and recovering materials in production, distribution, and consumption processes.” Similarly, the Ellen MacArthur Foundation (2013) defines CE as “a restorative and regenerative system” that aims to maintain the value of products, materials, and resources for as long as possible, emphasizing design, systems thinking, and innovation.

From an industrial ecology view, CE aligns with resource efficiency, eco-design, and industrial symbiosis (Stahel, 2010; McDonough & Braungart, 2002). In policy terms, such as the EU’s Circular Economy Action Plan, it focuses on goals like reducing landfill, boosting recycling, and decoupling growth from resource use (European Commission, 2015). Recent perspectives broaden CE to include social, ecological, and governance dimensions, linking it to sustainability, innovation, and equity (Schröder et al., 2019; Korhonen et al., 2018).

On the basis of a detailed insight into the literature, we can highlight that several schools and opinions of CE existed in the past period. The concept and explanations are presented in Table 1.

Table 1. Schools of Thought on the Circular Economy – Explanation, Principles and Focus Areas

Concept	**Explanation of CE**	**Key principles**	**Authors**
Industrial Ecology “cradle to cradle” concept	CE as a system for efficiency and closed loops via technology and innovation	Recycling, resource loops, industrial symbiosis, eco-design	Stahel (2010), McDonough & Braungart (2002)
Ecological Economics	CE as a pathway to reduced material throughput and post-growth economies	Sufficiency, limits to growth, localism, minimal resource extraction	Kallis et al. (2018), Jackson (2016), Raworth (2017)
Social Justice / Just Transition	CE as a vehicle for equity and inclusion, not just material efficiency	Labor rights, community participation, global justice, informal sector	Valenzuela & Böhm (2017), Schröder et al. (2019)
Market-Driven	CE as a business opportunity for innovation, value creation, and growth	Profitability, new markets, servitization, value retention	Lacy & Rutqvist (2015)
Blue Economy	CE as a regenerative system inspired by nature, fostering local solutions and zero waste	Use what you have, zero emissions, cascading use of resources, biodiversity	Pauli (2010)

Source: Author

The EU's shift toward a resource-efficient circular economy is guided by key policy frameworks, including the Europe 2020 Strategy, the Resource Efficient Europe Initiative and Roadmap, and the Circular Economy Action Plan (European Commission, 2010, 2011, 2015). Together, these policies build on traditional environmental pillars like waste management and energy efficiency, integrating circular principles across sectors and governance levels.

Table 2. Circular Economy in the EU – Policy Instruments and Their Main Purposes

Policy Instrument	**Year**	**Main Purpose**
Europe 2020 Strategy	2010	Promote smart, sustainable, and inclusive growth; integrate resource efficiency in EU growth strategy.
Flagship Initiative: Resource Efficient Europe	2011	Decouple economic growth from resource use; encourage sustainable production and consumption.
Circular Economy Action Plan	2015	Support transition to a circular economy; increase recycling rates; reduce landfill; promote eco-design and innovation.

Source: Author, based on European Commission strategies

Another more recent directive is the Proposal for a Regulation establishing a framework for setting ecodesign requirements for sustainable products (European Commission, 2022). It is focused on energy-related products and ecological requirements for products sold in the EU. This directive proposed in 2022 as part of the EU Green Deal and Circular Economy Action Plan, aims to broaden the directive to cover all physical goods, promoting a circular product policy framework.

Measuring the Circular Economy: Insights from Existing Conceptual Frameworks

The CE helps reduce environmental pressures and promote long-term economic and social well-being (Korhonen et al., 2018). Resilience, the ability of systems to absorb shocks and adapt while maintaining key functions (Folke, 2006), has become increasingly important in the EU amid crises like COVID-19 and geopolitical disruptions. As global challenges such as resource scarcity, climate change, and waste grow, interest in circular strategies is rising across micro (products, firms), meso (industrial symbiosis), and macro (cities, regions, nations) levels (Ghisellini et al., 2016).

Despite the growing academic and policy focus on CE, measuring its implementation and outcomes remains a significant challenge. The complexity of CE, which encompasses environmental, economic, and social dimensions, has led to a proliferation of conceptual frameworks and indicator systems aimed at capturing its performance. However, these frameworks vary widely in scope, methodology, and practical applicability, making it difficult to compare results across contexts or to establish a standardized measurement approach (Moraga et al., 2019; Saidani et al., 2019).

Traditional econometric models (for ex. input–output analysis and material flow accounting) offer useful insights but often overlook the dynamic, multidimensional nature of circular economy transitions. To address this, the entropy method has emerged as a robust tool for objectively weighting indicators and analyzing system variability (Siddique et al., 2022). Based on information theory, it quantifies data dispersion, highlighting the most informative variables and reducing subjective bias. This makes it particularly effective for constructing composite indices in CE assessments, as it assigns greater weight to indicators with higher discriminative power (Busu & Busu, 2018). Considering that some authors came to the conclusion that, despite the unified policy vision, substantial disparities persist across EU member states in terms of circular economy performance (Friant et al., 2020), this paper will measure these disparities.

Methodology

The methodology part consists of three main components: study area, The indicators and data sources and The tools and techniques. This approach enables a structured analysis of sustainability performance across the EU.

Selection of study area

This study focuses on the member states of the European Union (EU) for which relevant data on circular economy indicators were available for the year 2023. A total of 27 EU countries are included in the analysis: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, and Sweden. These countries represent a diverse group in terms of economic development, resource dependency, and environmental policies, making them a suitable sample for assessing convergence and divergence in the implementation of circular economy principles within the EU.

Indicators and Data Source

This study relies on three core indicators from the Eurostat Circular Economy Monitoring Framework, specifically under the dimension of Global Sustainability and Resilience. The selected indicators capture different aspects of resource efficiency, environmental pressure, and dependency on external materials. All data were retrieved from the official Eurostat database for the year 2023.

Table 3. List of indicators

	Dimension	Unit of measure	Code	Code in Eurostat
CIRCULAR ECONOMY: Global sustainability and resilience	Consumption footprint	Index, 2010=100	CF	Consumption footprint [cei_gsr010__custom_18183049]
	Greenhouse gases (CO2, N2O in CO2 equivalent, CH4 in CO2 equivalent, HFC in CO2 equivalent, PFC in CO2 equivalent, SF6 in CO2 equivalent, NF3 in CO2 equivalent)	Kilograms per capita	GHG	Greenhouse gases emissions from production activities [cei_gsr011__custom_18183086]
	Material import dependency	Percentage	MID	Material import dependency [cei_gsr030__custom_18183113]

Source: Author

These indicators are particularly relevant for assessing convergence and divergence among EU countries, as they reflect both environmental impacts and structural dependencies within national economies.

Tools and techniques

In this paper, the entropy approach was used to assess differences among EU member states, in accordance with Czyz & Hauke (2015). Entropy-based methods are particularly suitable for comparative regional analysis, as they allow the measurement of how evenly or unevenly a given indicator is distributed across spatial units, such as countries or regions.

The concept of entropy originates from information theory and was formalized by Shannon (1948). In this context, entropy reflects the degree of uncertainty or diversity in a distribution: indicators that are similarly distributed across countries contain less information about differences, while indicators with large cross-country disparities provide more information. This property makes entropy a useful tool for evaluating spatial inequalities and convergence or divergence patterns among regions. In regional and spatial studies, entropy is commonly interpreted as a probabilistic concept describing the outcome of a stochastic process, where higher entropy values correspond to more heterogeneous spatial structures (Nijkamp and Paelinck, 1974; Fedajev et al., 2020). Applied to circular economy indicators, entropy captures how uniformly EU member states perform with respect to a given indicator. Based on Shannon's entropy measure, the Shannon Entropy Index is calculated to quantify inequality among EU countries for each selected indicator. If entropy values are high (close to 1), the indicator values differ substantially across countries, indicating high variability or divergence. Conversely, low entropy values (close to 0) indicate that countries exhibit similar performance levels, suggesting convergence.

This measure of inequality is particularly useful for analyzing spatial disparities among countries or regions and can be expressed by the following equation:

$$I(x) = H(x)_{max} - H(x) = \log_2 n - \sum_{i=1}^{n} p(x_i)\log_2 \frac{1}{p(x_i)}$$

$$= \sum_{i=1}^{n} p(x_i)\log_2[n\, p(x_i)]$$

$$\text{for } 0 \leq I(x) \leq \log_2 n$$

where I(x) = 0 indicates the absence of inequality (or uniform distribution), while I(x) = log2 n indicates the maximum non-uniformity of the selected parameters x.

In our case if entropy is high (close to 1) values vary greatly across countries and it indicates high variability or divergence. If entropy values are low (close to 0) it indicate that values are very similar across countries and explain low variability or convergence between countries.

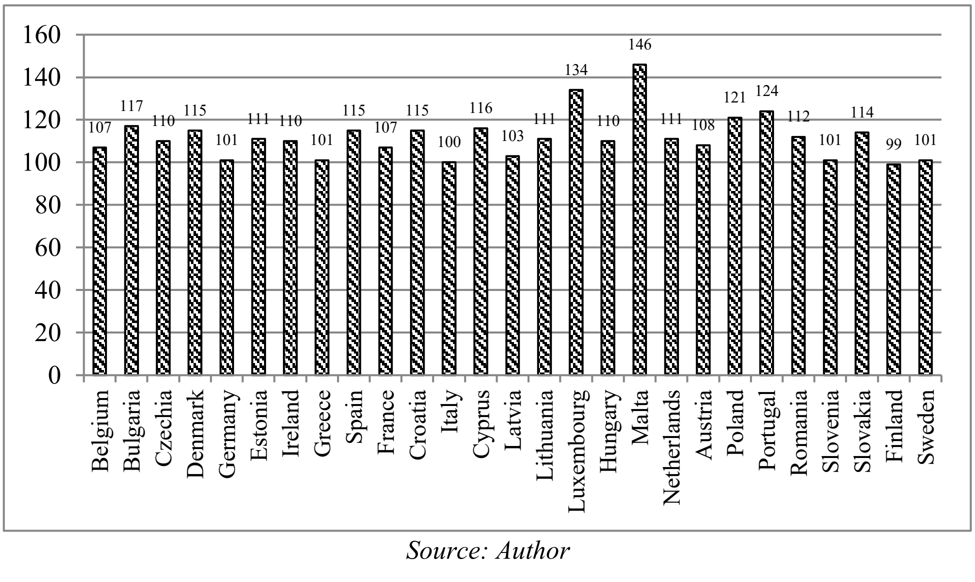
In this context, the entropy approach, or objective weighting, is applied to determine the relative importance of each indicator, by assigning greater weight to criteria that show greater differences between countries, while assigning less weight to those where the situations between countries are more similar.

Results and Discussions

Consumption footprint

The data on consumption footprint reveals notable disparities among EU countries, reflecting differences in resource use intensity and the implementation of circular economy principles.

Figure 1: Index of Consumption footprint in EU, 2023 (Index, 2010=100)



Source: Author

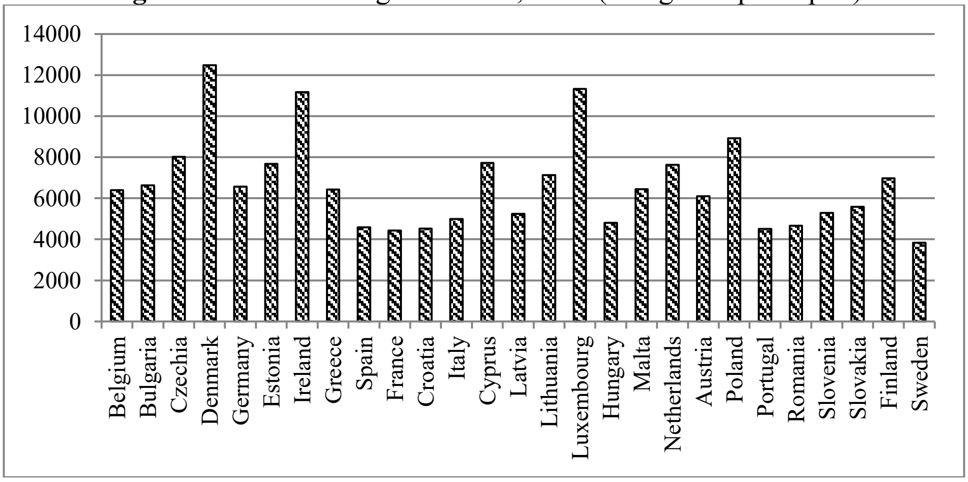
As presented on Figure 1, Malta (146) and Luxembourg (134) stand out with the highest index of consumption footprints, indicating a significant environmental pressure associated with domestic consumption patterns. Such high values may stem from high-income lifestyles, resource-intensive imports, or limited circularity practices (Frendo, 2023). These countries could benefit from stronger policies promoting sustainable consumption and circular production systems.

In contrast, Finland (99) and Italy (100) register the lowest index of footprints, suggesting relatively lower material intensity or higher efficiency in resource use. However, these values could also reflect lower levels of industrial activity or consumption, which must be interpreted carefully in the context of economic structure. The middle-performing group includes countries like France (107), Austria (108), and Belgium (107), which likely have established some circular policies but still exhibit moderate consumption pressures. Interestingly, Baltic countries show variation: Latvia (103) has a low footprint, while the same values are in Estonia and Lithuania (111), suggesting some differences in energy sources, industrial mix, or levels of domestic extraction.

Greenhouse gases

The analysis of greenhouse gas (GHG) emissions across EU member states reveals significant disparities in environmental performance, with implications for circular economy and climate policy alignment. Countries such as Denmark (12481.46461 Kilograms per capita), Luxembourg (11332.23173 Kilograms per capita), and Ireland (11176.06661 Kilograms per capita) exhibit the highest levels of emissions, suggesting greater carbon intensity in their economic activities or slower progress in energy transition. For example Luxembourg's per capita electricity production is nearly half the world average and considerably lower than that of countries like Norway and Sweden (Oberhausen Krippler, 2023). These elevated values may result from reliance on fossil fuels (Hvelplund et al., 2019), energy-intensive industries (Alcantara &Duarte, 2004), or inefficient transport systems (Domagała& Kadłubek, 2022).

Figure 2: Greenhouse gases in EU, 2023 (Kilograms per capita)



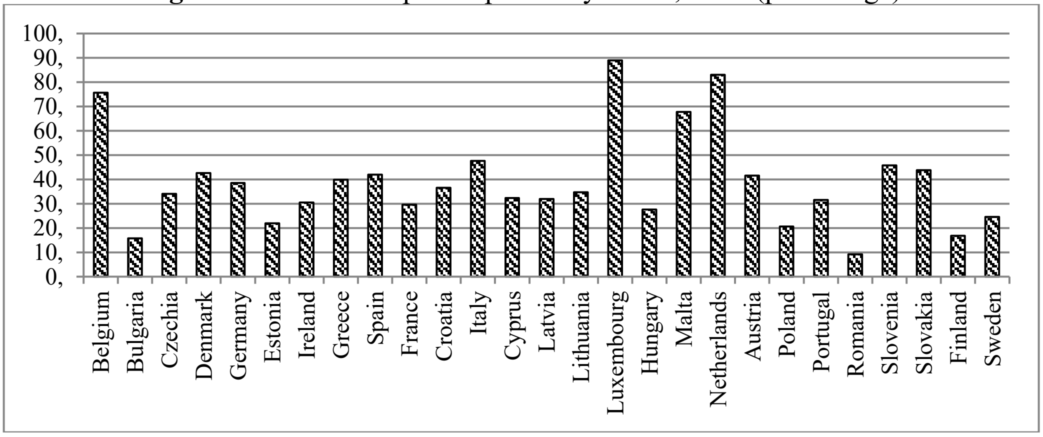
Source: Author

In contrast, Sweden (3,833.55), France (4,424.19) and Spain (4,590.57) demonstrate lower emissions, likely reflecting investments in renewable energy, technological innovation, and stricter environmental regulations. The mid-range group, including countries like Austria and Belgium points to moderate performance that still demands improvement.

Material import dependency

The material import dependency data highlights substantial variation in how EU countries source their raw materials, reflecting differing levels of resource self-sufficiency and exposure to external supply risks. Countries like Luxembourg (89%), Belgium (75.6%), and the Netherlands (83%) exhibit the highest dependency on material imports, indicating a strong reliance on global supply chains (Notteboom, 2009) and limited domestic extraction or recycling capacity (Bandera, 2021) . These high levels underline the urgency of adopting circular practices such as material substitution, reuse, and increased recycling.

Figure 3: Material import dependency in EU, 2023 (percentage)



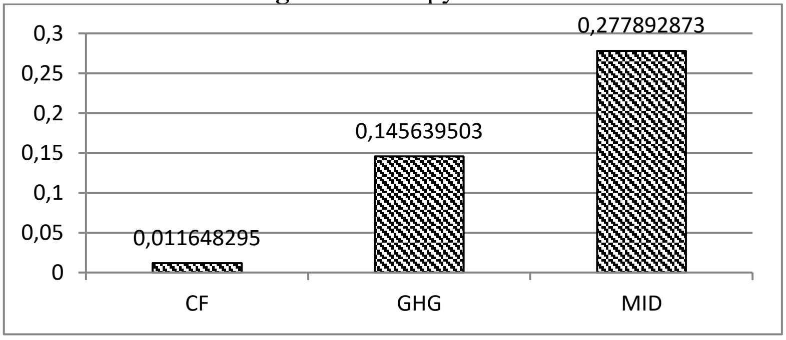
Source: Author

On the other end of the spectrum, Romania (9.2%), Bulgaria (15.8%), and Finland (16.8%) show very low dependency, implying a higher degree of material self-reliance—either due to domestic resource availability or lower industrial import needs. The mid-range countries, including Germany (38.6%), France (29.6%), and Italy (47.6%), balance import reliance with domestic resource management, potentially offering a foundation for building resilient circular systems.

Findings from earlier studies highlighting the varied adoption of circular economy tactics throughout Europe are consistent with the observed differences in material import dependency among EU member states. Numerous studies have noted that structural flaws in resource management and local material cycles, in addition to economic openness, are reflected in high import dependency (Korhonen et al., 2018; Schröder et al., 2019). Countries such as Luxembourg, Belgium, and the Netherlands, with dependency rates exceeding 75%, are exposed to external shocks and geopolitical risks in global supply chains—an issue increasingly highlighted in the post-COVID and post-Ukraine war contexts (European Commission, 2020). Prior work by Kirchherr et al. (2017) stresses that circular economy efforts must move beyond recycling and waste management toward building systemic resilience, particularly through reduced dependency on virgin and imported materials. Conversely, countries like Romania and Finland demonstrate low import reliance, consistent with findings by the Ellen MacArthur Foundation (2013), which promote local loops and material self-sufficiency as key dimensions of an effective circular economy. This suggests that import dependency is not merely a trade statistic but a strategic indicator of a country's circular readiness, vulnerability, and potential for industrial transformation. Therefore, aligning national circular economy strategies with material security considerations is a necessary step toward achieving the EU's broader Green Deal and climate neutrality targets.

After presenting the data, we calculate the entropy for each of the observed indicators.

Figure 4: Entopy results



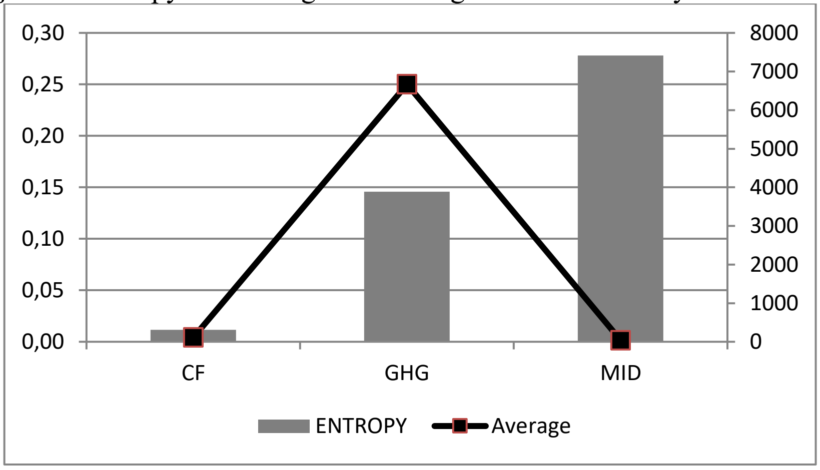
Source: Author

In our study, entropy values close to 1 indicate high variability or divergence among countries, meaning that indicator values differ greatly across EU member states. Conversely, entropy values close to 0 suggest low variability or convergence, where countries show similar performance levels for the given indicator. The entropy values obtained for the three indicators — Consumption Footprint (0.0116), Greenhouse Gases (0.1456), and Material Import Dependency (0.2779) — reflect varying degrees of divergence and convergence among EU countries. Specifically, the very low entropy value for Consumption Footprint indicates a significant convergence in consumption patterns across member states, suggesting that disparities in this area are decreasing. This aligns with the findings of Geissdoerfer et al. (2017), who emphasize that coordinated EU level policies are essential for harmonizing sustainability efforts and reducing differences among countries.

On the contrary, higher entropy values for greenhouse gas emissions and especially for material dependence indicate the existence of a significant divergence. These differences may be the result of different economic structures, industrial policies and access to resources, which is supported by Korhonen et al. (2018) who point out that "divergent development paths and resource bases of countries require tailored policies for an effective transition to a circular economy".

Furthermore, the entropy approach, as reported by Siddique et al. (2022), "enables the objective quantification of differences among variables, thus facilitating the identification of areas in need of further harmonization and focused intervention". This is key to understanding and addressing the problem of divergence that can threaten the EU's common goals for climate neutrality and sustainability (European Commission, 2020). This entropy analysis confirms that there is progress in harmonizing some dimensions of the circular economy (convergence in the consumer footprint), significant differences remain in other areas (emissions and material dependency) that require differentiated but coordinated policies to achieve a sustainable and more resilient European economy (Kirchherr et al., 2017).

Figure 5: Entropy and average values of global sustainability and resilience



Source: Author

Figure 5 shows the results of entropy and average values for the three observed indicators. The dashed line shows the entropy results (primary axis-left side, Clustered Column diagram) which range from 0-1 on the left side of the y-axis. On the secondary axis (values on the y-axis to the right) they show average values. Author include average scores for global sustainability and resilience indicators to provide understanding of both the degree of variability (divergence/convergence) and the central tendency (overall performance) among EU member states.

The Consumption Footprint indicator displays the lowest entropy value (0.0116) and an average of 111.85, suggesting a high degree of convergence among EU countries. This implies relatively uniform performance and possibly a shared baseline in consumer behaviour or environmental impact per capita. However, the low entropy also means this indicator contributes less to distinguishing between countries in composite assessments, despite reflecting a moderate overall footprint.

In contrast, GHG emissions have higher entropy (0.1456) and an average value of 6,668.24, indicating moderate convergence and pointing to a small difference in countries' contributions to climate change. The relatively high average underscores the need for more ambitious decarbonisation policies across the region, particularly in high-emitting member states.

Table 4. Summary table

	Entropy	Average	Interpretation
CF	0.0116483	111.8519	High convergence
GHG	0.1456395	6668.241	Moderate convergence
MID	0.2778929	39.06296	The relatively high Divergence

Source: Author

Among the observed indicators, material import dependency (MID) exhibits the highest entropy value, indicating that this indicator shows the greatest variability across EU member states. In other words, differences between countries are more pronounced for material import dependency than for the other indicators considered. Although the average MID value at the EU level remains relatively moderate (39.06%), given that the index ranges up to 100%, the elevated entropy value suggests a lack of convergence among countries rather than a uniformly high level of dependency. This implies that while some EU member states have reduced their reliance on imported materials, others remain highly dependent, resulting in a divergent pattern.

Such variability reflects differing levels of strategic autonomy and resource self-sufficiency across EU countries, which is consistent with previous studies emphasizing the role of domestic material loops in strengthening circular economy resilience (Korhonen et al., 2018; Schröder et al., 2019). At the same time, the moderate average level of MID indicates that a substantial share of EU countries still relies heavily on imported materials, potentially increasing their exposure to external supply disruptions and geopolitical shocks.

Conclusion

This study applied the entropy method to assess disparities among EU member states in the implementation of circular economy principles, with a specific focus on the global sustainability and resilience dimension through three key indicators: consumption footprint, greenhouse gas emissions, and material import dependency. The results reveal a nuanced landscape. Consumption footprint shows a high level of convergence (low entropy), suggesting relatively similar consumption related environmental pressures across EU countries. In contrast, greenhouse gas emissions and material import dependency display lower levels of convergence, with material import dependency exhibiting the highest entropy value. This indicates persistent structural differences among member states in terms of decarbonisation pathways and resource self-sufficiency, both of which are critical for strengthening a resilient and circular European economy.

Overall, the findings suggest that while EU countries are progressing toward harmonisation in certain circular economy dimensions, particularly consumption-related impacts, other areas require stronger and more differentiated policy efforts to foster convergence. In particular, emissions reduction and material dependency remain key challenges that may widen disparities if not addressed through coordinated EU-level and national strategies. A longer-term observation of these indicators is necessary to determine whether the observed patterns represent temporary fluctuations or persistent trends of convergence or divergence.

The results of this study are particularly relevant for EU policymakers, national governments, and regional planners, as they provide a comparative and data driven basis for identifying priority areas where policy intervention is most needed. By highlighting which dimensions of the circular economy are converging and which are diverging, the findings can support more targeted resource allocation, the design of differentiated policy instruments, and the monitoring of progress toward EU sustainability objectives. In addition, sustainability analysts and researchers may use the entropy framework as a diagnostic tool for cross country benchmarking of circular economy performance.

Despite its contributions, this study has several limitations. First, the analysis is constrained by the selection and availability of indicators, which represent only a subset of the circular economy framework and do not fully capture other important dimensions such as waste management, secondary raw materials, competitiveness, innovation and production side dynamics. Also, the focus on a single year (2023) limits the ability to assess dynamic changes or long-term convergence trends.

Future research should therefore expand the indicator set to include both quantitative and qualitative measures, apply longitudinal analyses to capture temporal dynamics, and combine entropy analysis with complementary approaches such as multi-criteria decision-making (MCDM) or econometric methods. Extending comparative analyses beyond the EU and examining the determinants of divergence would further enhance the understanding of circular economy transitions and support the development of more inclusive and effective policy frameworks.

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