ASSESSING THE IMPACT OF THE ENERGY TRANSITION, THE INTEGRATION OF DIGITAL TECHNOLOGIES AND THE PROMOTION OF FINANCIAL INCLUSION ON SUSTAINABLE GROWTH DYNAMICS IN THE EUROPEAN UNION

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Abstract

In the context of the European Union's transition towards a sustainable economic model, the circular economy, innovation and resource efficiency play a key role in achieving the goals of climate neutrality and economic competitiveness. This study analyzes the relationship between research and development (R&D) expenditure, renewable energy use, private investment in the circular economy and packaging waste generation in the EU Member States, using a dynamic econometric Arellano-Bond model applied to a panel dataset. The results show that R&D investments are characterized by persistence over time, being positively influenced both by the increasing share of renewable energy in gross final consumption and by the private sector's involvement in financing the circular economy. In contrast, the generation of packaging waste does not show a significant impact on innovation spending, suggesting that waste management is regulated through administrative policies rather than additional research allocations. These findings underline the importance of integrated public policies that support the energy transition and stimulate private sector participation in the development of sustainable solutions. The study also highlights significant disparities between Member States in the level of investment in the circular economy and the uptake of renewable energy, suggesting the need for tailored strategies to bridge the existing gaps.

Keywords: *circular economy, innovation, sustainability, research and development, renewable energy, private investment, European Union*

Clasificare JEL: *Q01, Q4, O3*

1. Introduction and context of the study

In a global context marked by accelerated climate change, depletion of natural resources and the need for a sustainable economic transition, the European Union has adopted several policies and strategies to support the development of an economic model based on circularity, innovation and sustainability. The circular economy, by promoting resource efficiency and waste reduction, is a key pillar in achieving the climate neutrality goals set by the European Green Pact and the Circular Economy Action Plan. These initiatives aim to make Europe a global leader in sustainability by stepping up research and innovation in green technologies, stimulating private investment in the circular economy and integrating renewable energy sources into the European energy system. However, the impact of these factors on research and development (R&D) spending remains insufficiently explored and the interactions between the circular economy, innovation and sustainability require rigorous econometric analysis.

The novelty of this study is to investigate the dynamics of the interdependencies between R&D spending, renewable energy use, private investment in the circular economy and packaging waste generation using a dynamic econometric Arellano-Bond model applied at the level of the European Union Member States. Unlike previous studies that have analyzed these components separately, this research provides an integrated approach that captures the mutually influencing mechanisms between innovation and the circular economy, with direct implications for European public policies.

The main aim of this study is to analyze how the circular economy and the transition towards sustainability influence R&D investments in the European Union. The research objectives include:

(1) Literature review on the dynamics of influences between circular economy, innovation and sustainability in the European Union

(2) Arellano-Bond dynamic econometric applied at the level of EU Member States

(3) Formulation of public policy recommendations.

By integrating these dimensions, the study provides a detailed insight into the factors shaping innovation dynamics in the European Union, contributing to a better understanding of how sustainability policies can be optimized to support the transition towards a competitive and green economy.

2. Literature review

As environmental and economic pressures are driving the need for a reconfiguration of the development model, the European Union is reinforcing its commitment to the transition towards a sustainable economic system. The circular economy, innovation and sustainability are central pillars of contemporary development strategies, embedded in policies to reduce environmental impacts and support economic competitiveness (Rodríguez-Antón et al., 2022). Through initiatives like the European Green Pact (European Commission, 2023a) and the Circular Economy Action Plan (European Commission, 2023b), the EU aims to radically transform production and consumption systems, promoting resource efficiency and waste reduction (Adamowicz, 2022; Agovino et al., 2024).

Within this framework, the literature explores the multiple interactions between the circular economy, innovation and sustainability, emphasizing the importance of an integrated approach to support the adaptation of economic sectors to new environmental imperatives. For example, recent studies demonstrate that technological innovation is a key factor in facilitating the transition towards circular models, offering solutions that optimize material reuse and energy efficiency (Kandpal et al., 2024; Kim et al., 2024). At the same time, public policies play a key role in accelerating the implementation of sustainable practices, and financial and legislative support mechanisms are needed to stimulate investment in this area (Goutte & Sanin, 2024; Mazutis & Sweet, 2022). Thus, a thorough understanding of the dynamics between these three dimensions is essential for the formulation of coherent and effective strategies at European level.

2.1. The circular economy as a driver for sustainability

The circular economy is a model of economic development focused on optimizing the use of resources through reuse, repair, refurbishment and recycling, with the main aim of reducing dependence on primary resources and reducing the amount of waste generated (Kirchherr et al., 2023). This approach proposes a fundamental restructuring of production and consumption processes, promoting a balance between economic growth and environmental protection. In contrast to the linear economic model, based on extracting, using and disposing of resources, the circular economy creates a sustainable system in which materials are kept in use for as long as possible, reducing pressure on ecosystems and minimizing the costs associated with waste disposal.

Numerous studies (Diaz et al., 2022; Hossain et al., 2024; Khan et al., 2023; Marsh et al., 2022; Sharma et al., 2023) have shown that implementing circular economy strategies can have multiple benefits, not only from an environmental perspective, but also by creating new economic and social opportunities. Reducing dependence on primary resources contributes to the security of critical materials and long-term economic stability, while innovation in recyclable materials and green production processes creates competitive advantages for industries (Nygaard, 2023; Wang et al., 2023). The circular economy also stimulates job creation in emerging sectors such as advanced recycling, sustainable resource management and sustainable product development, thus having a positive impact on the labor market and social cohesion (Coskun et al., 2024; Nademi & Sedaghat Kalmarzi, 2025).

However, the literature points to significant differences between EU Member States in the implementation of circular economy principles. Western European countries such as Germany and the Netherlands are recognized for proactive policies and effective mechanisms to support circular initiatives (Hassel, 2022; Triguero et al., 2022). These economies have adopted advanced legislative measures providing incentives for companies to integrate sustainable solutions into their value chains. In addition, public-private partnerships and significant investments in research and development have led to considerable progress in material use efficiency and industrial waste reduction.

In contrast, Eastern European countries, such as Romania and Bulgaria, face major difficulties in achieving the EU's economic circularity targets (Biekša et al., 2022; Vajda & Drăgan, 2024; Zhu et al., 2023). Challenges identified include poor infrastructure for waste management and recycling, limited access to finance for circular projects and low awareness of the benefits of this business model. In many of these economies, the lack of coherent policies and effective measures to support companies implementing circularity principles contributes to delays in adopting sustainable strategies (Finamore & Oltean-Dumbrava, 2024; Madurai Elavarasan et al., 2022). Moreover, the economic structure of these countries, largely based on traditional resource-intensive sectors, makes the transition to a circular model slower and more difficult.

Thus, these differences between Member States highlight the need for flexible and tailor-made policies adapted to each national context, allowing the implementation of circular economy principles to be accelerated. A uniform approach applied at European level may not be sufficient, and a differentiated strategy is needed that takes into account the economic, social and technological particularities of each country. In the long term, the transition to a circular economy will not only help to protect the environment, but will also stimulate industrial innovation, sustainable economic growth and reduce disparities between European regions.

2.2. Innovation and its role in the circular economy

Recent specialized studies (Di Maria et al., 2022; Ingaldi & Ulewicz, 2024; Sánchez-García et al., 2024) underlines the importance of innovation as a central element in the development of the circular economy, highlighting that technological progress plays a key role in optimizing the use of resources and minimizing the environmental impact of industrial processes. Technological and organizational innovations allow for better integration of circularity principles into existing industries, thus facilitating the development of sustainable products, extending the life cycle of materials and making energy consumption more efficient (Chauhan et al., 2022; Oyejobi et al., 2024; Suchek et al., 2021). Digitization and automation also play an important role in managing resources more efficiently by deploying artificial intelligence systems and blockchain technologies for material traceability and supply chain optimization (Ayub Khan et al., 2023; Vijaykumar et al., 2024).

Other research indicates that innovation in the circular economy is not limited to advanced technologies, but also involves business model transformations (Asgari & Asgari, 2021; Neligan et al., 2023; Peçanha & Ferreira, 2025). New economic models based on services, such as product leasing and the collaborative economy, are helping to reduce over-consumption and promote prolonged use of goods (Tan et al., 2022; White et al., 2025). Moreover, the development of new biodegradable and recyclable materials allows the creation of more sustainable production chains, where resources are used with a high degree of efficiency (Maldonado-Romo et al., 2024; Moshood et al., 2022; Raj et al., 2022). Thus, a systemic approach to innovation, combining technological advances with changes in consumer mindsets and behaviors, is essential for a successful transition to a circular economy.

Another fundamental aspect of innovation in the circular economy is investment in research and development (R&D), which is recognized as a key determinant in accelerating the adoption of circular strategies. According to Eurostat data (Eurostat, 2024c), Countries that allocate substantial funds to R&D, such as Sweden, Belgium and Germany, have demonstrated a significantly higher capacity to implement innovative sustainability solutions, underlining the importance of a favorable framework for funding research in this sector. Public policies also play a key role in stimulating innovation by providing subsidies, tax incentives and support programs for start-ups and companies involved in developing circular solutions (Kasana et al., 2024; Lit et al., 2024; Pardo-del-Val et al., 2024).

The development of collaborative networks between universities, research centers and industry is essential for accelerating innovation and effective implementation of the principles of the circular economy. Partnerships between the private sector and academic institutions allow new technologies to be tested and applied on a large scale, thus reducing the time it takes for sustainable solutions to be adopted by industry (Javaid et al., 2022; Li, 2024; O'Dwyer et al., 2023). In this respect, encouraging technology transfer and interdisciplinary collaboration is becoming a priority for European industrial policy, with the aim of facilitating the integration of circular principles into key economic sectors.

Thus, the literature underlines that technological innovation, organizational change and investment in research and development are fundamental to the success of the circular economy (Sánchez-García et al., 2024; Sehnem et al., 2024; Truant et al., 2024). As the transition towards a sustainable economic model advance, it is essential that public policies support the development and application of innovations, thus ensuring an efficient and sustainable transformation of industrial and business processes.

2.3. Private investment dynamics and their impact on sustainable transition

Besides the intervention of governments and European institutions, the private sector plays a crucial role in financing and implementing circular economy solutions. Private investment can accelerate the uptake of sustainable technologies, improve resource efficiency and reduce environmental impacts. Research shows a positive correlation between the level of private investment in the circular economy and increased resource efficiency, underlining the importance of a favorable economic climate for attracting private capital (Cicchiello et al., 2023; Shobande et al., 2024; Yan & Haroon, 2023).

Some European countries are distinguished by high levels of private investment in the circular economy, benefiting from a favorable legislative framework, advanced infrastructure and easy access to finance (Gura et al., 2023; Ren & Albrecht, 2023; Wasserbaur et al., 2022). These countries have implemented national strategies that stimulate private sector participation in the transition to a circular economy model, providing tax incentives for companies that invest in innovative solutions and creating public-private partnerships to develop infrastructure for recycling and reuse of materials. In these economies, large corporations in sectors such as automotive manufacturing, chemicals and materials technology have integrated circular economy principles into their business strategies, leading to significant progress in resource efficiency.

In contrast, Eastern European countries have difficulties in attracting private capital to finance circular economy projects. Among the challenges identified are limited access to finance, lack of effective support mechanisms for small and medium-sized enterprises and insufficient tax incentives for companies implementing sustainable practices (European Investment Bank, 2024). This underlines the need for public policies to create a more attractive framework for investment and facilitate the active involvement of the private sector in the development of the circular economy.

The literature proposes several measures to stimulate private investment in this area. A first set of measures targets fiscal incentives, such as tax breaks for companies implementing circular solutions and subsidies for the development of recycling and reuse infrastructure. For example, states that offer tax breaks for firms adopting circular business models have shown accelerated growth in private investment in this sector (Chabowski et al., 2023; Chenavaz & Dimitrov, 2024).

Another key strategy is the creation of innovative financing mechanisms such as sustainability impact funds and green bonds. These instruments can facilitate access to capital for startups and companies developing circular economy solutions, thereby supporting innovation and scaling up sustainable projects (Saarinen & Aarikka-Stenroos, 2023). To this end, the European Union has launched several initiatives aimed at mobilizing private investment, including financial support schemes for companies implementing circular business models.

A fundamental aspect of a successful transition to the circular economy is the creation of a favorable ecosystem for private-public collaboration. Strategic partnerships between governments, financial institutions and companies can facilitate the exchange of knowledge and resources, accelerating the implementation of circular solutions. A notable example is the collaboration between major automotive companies and policy makers to create circular supply chains by reusing and recycling vehicle components (Rettenmeier et al., 2024).

The dynamics of private investment in the circular economy vary significantly between EU countries, influenced by the legislative framework, access to finance and the level of awareness of the private sector. A multidimensional approach combining favorable fiscal policies, innovative financing mechanisms and strategic public-private partnerships is needed to stimulate increased investment in this area. In this way, the creation of a stable and predictable economic environment will allow for a faster transition to a circular economic model capable of supporting long-term sustainable development.

The studies reviewed have highlighted the interdependence between the circular economy, innovation and sustainability, demonstrating that an integrated approach is essential to achieve the EU's environmental and economic competitiveness objectives. Although significant progress has been made, discrepancies between Member States and the different pace of implementation of circular policies underline the need for more effective coordination at European level.

In addition, the literature suggests that the success of the transition to a circular economy model depends on a combination of factors, including technological innovation, government support and the involvement of private capital. Future research directions should focus on assessing the impact of national policies on the circular economy, as well as on developing effective mechanisms for integrating innovation into sustainable strategies. Strengthening public-private collaboration, together with stepping up research and development efforts, is therefore fundamental to the success of the circular economy in the European Union.

3. Methodology

In the current context in which the European Union is promoting the transition towards a sustainable economic model, this study aims to analyze the interdependencies between the circular economy, innovation and sustainability, using an advanced econometric framework based on the Arellano-Bond model for dynamic panel data. The main objective is to investigate the impact of packaging waste generation, the share of renewable energy and private investment on R&D expenditure, taking into account the specificities of each EU Member State. The choice of this model is justified by its ability to control for the endogeneity problem and to capture the dynamic adjustment mechanisms of investment in innovation, thus being suitable for the analysis of long-run economic processes. The data used in this study are extracted from the Eurostat database, comprising a set of 270 observations for the EU Member States presented in Table 1.

Table no. 1 Presentation of the analyzed indicators

Symbol	Indicators	U.M	Source
RDGDP	Gross domestic expenditure on R&D	%	Eurostat (Eurostat, 2024b)
GPW	Generation of packaging waste per capita	Kilograms per capita	Eurostat (Eurostat, 2024a)
SRENEW	Share of renewable energy in gross final energy consumption%	%	Eurostat (Eurostat, 2024d)
PRINV	Private investment and gross added value related to circular economy	Million euro	Eurostat (Eurostat, 2022)

Source: Elaborated by author

The dependent variable is gross domestic expenditure on research and development (GERD) expressed as a percentage of gross domestic product, a key indicator of national innovation intensity. The explanatory variables include the generation of packaging waste per capita (GPW), expressed in kilograms per capita, an indicator reflecting resource efficiency and sustainable waste management. In addition, the share of renewable energy in gross final energy consumption (SRENEW) is used to measure the transition to cleaner energy sources, and private investment and value added in the circular economy (PRINV), expressed in millions of euro, are included to assess the role of private capital in promoting sustainable innovation. To analyze the relationship between these variables, the methodology adopted uses the Generalized Method of Moments (GMM) in a dynamic panel framework, given the autoregressive nature of R&D expenditure. Thus, the model used is expressed by the following econometric equation:

$$RDGDPit = \alpha RDGDPit - 1 + \beta 1GPWit + \beta 2SRENEWit + \beta 3PRINVit + \epsilon it \qquad (1)$$

Where: RDGDPit represents R&D expenditures in country i in year t, RDGDPit-1 is the lag of the dependent variable, GPWit indicates the generation of packaging waste, SRENEWit measures the share of renewable energy, PRINVit reflects private investment in the circular economy, ϵit is the error term.

Based on the literature and study objectives, the research aims to test the following hypotheses:

H1: There is a positive relationship between past R&D spending and the current level of investment in innovation. This hypothesis suggests that R&D investments are characterized by persistence over time, due to long-term commitments by governments to finance innovative activities.

H2: Increasing the share of renewable energy in gross final consumption contributes positively to R&D expenditure. A stronger transition towards renewable energy sources can stimulate the development of innovative technologies and increase research on sustainability.

H3: Private investment in the circular economy has a positive effect on R&D spending. Increased private sector funding can support innovation initiatives, facilitating the development of more sustainable production models.
By applying the described methodology, this study provides an empirical perspective on the interactions between circular economy, sustainability and innovation, contributing to the understanding of how environmental policies and investment strategies can influence the ability of European countries to strengthen their technological edge.

4. Results and discussions

In the context of the European Union's transition towards a sustainable economic model, characterized by the promotion of innovation, resource efficiency and the reduction of environmental impact, the analysis of descriptive statistics of the variables used in this study provides essential insight into the disparities between Member States and the trends that define the dynamics of R&D investment. These statistics provide a general picture of the interactions between the circular economy, sustainability and innovation, facilitating an understanding of how public policies and economic strategies influence the allocation of resources in sectors that are crucial for European competitiveness (Table 2).

Table no. 2 Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
RDGDP	270	1.64	0.884	0.38	3.5
GPW	270	143.812	46.688	46.67	246.14
SRENEW	270	21.94	11.891	3.494	66.287
PRINV	270	3387.83	5900.73	33	34489

Source: Elaborated by the author using the program Stata 18

In multiple regression analysis, the Variance Inflation Factor (VIF) is used to assess the presence of multicollinearity between explanatory variables, a problem that can affect the accuracy of the coefficient estimates in the model. In general, VIF values below 5 do not indicate collinearity, while values above 10 suggest a multicollinearity problem that requires adjustment. The results are presented in Table 3.

Table no. 3 Variance inflation factor

	VIF	1/VIF
GPW	1.422	.703
PRINV	1.414	.707
SRENEW	1.03	.971
Mean VIF	1.289	.

Source: Elaborated by the author using the program Stata 18

The results presented in Table 3 highlight that all variables included in the model have VIF values below 1.5, indicating the absence of significant multicollinearity. The GPW indicator has a VIF of 1.422, PRINV registers a value of 1.414 and SRENEW has the lowest value of 1.03. In addition, the mean VIF factor is 1.289, which confirms that the explanatory variables are independent of each other and there are no collinearity relationships affecting the stability of the estimates.
Table 4 presents the Pearson correlation coefficients between the variables included in the model, providing insight into the linear relationships between them. These values are useful to identify potential collinearity problems and to understand the direction and strength of the relationships between the variables analyzed.

Table no. 4 Pairwise correlations

Variables	RDGDP	GPW	SRENEW	PRINV
RDGDP	1.000			
GPW	0.370***	1.000		
SRENEW	0.391***	-0.159***	1.000	
PRINV	0.433***	0.538***	-0.139**	1.000

**** p<0.01, ** p<0.05, * p<0.1*

Source: Elaborated by the author using the program Stata 18

The correlation results suggest that R&D investment is closely related to circular economy factors such as the use of renewable energy and private sector participation in financing innovation. It is also observed that economies that generate more packaging waste are also those where private investment in sustainable solutions is higher, which may reflect a market response to the need to manage resources more efficiently. The absence of very high correlations between the explanatory variables suggests that the model used is not affected by collinearity problems, which lends robustness to the econometric estimates.

Table 5 presents the results of the Arellano-Bond test for the autocorrelation of first-order differenced errors in the Generalized Method of Moments (GMM) model used to analyze the relationship between the circular economy, sustainability and innovation. This test is essential for model validation, since the Arellano-Bond method assumes the absence of second-order serial autocorrelation (AR(2)) in the differenced errors.

Table no. 5 Arellano–Bond test for zero autocorrelation in first-differenced errors

Order	z	Prob> 1
1	-2.2598	0.0238
2	0.16843	0.8662

Source: Elaborated by the author using the program Stata 18

The results of the Arellano-Bond test confirm that the model does not suffer from serial autocorrelation problems that could compromise the validity of the estimates. Although first-order autocorrelation is present, it does not affect the interpretation of the results, and the absence of second-order autocorrelation suggests that the instruments used in the model are appropriate. Therefore, the estimated model is robust and can be used for analyzing the impact of circular economy and sustainability on R&D investment.

The results of the estimation of the dynamic model for panel data, presented in Table 6, provide a clear insight into the relationships between research and development expenditure (RDGDP) and circular economy and sustainability factors. The model employs the Generalized Method of Moments (GMM) method, allowing endogeneity control and capturing the dynamics of innovation investment.

Table no. 6 Arellano–Bond dynamic panel-data estimation

RDGDP	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
L	0.474	0.035	13.43	0	0.405	0.543	***
GPW	0	0	-0.26	0.797	-0.001	0	
SRENEW	0.012	0.002	6.65	0	0.008	0.015	***
PRINV	0	0	3.09	0.002	0	0	***
Constant	0.557	0.048	11.59	0	0.463	0.651	***

Mean dependent var	1.645	SD dependent var	0.882
Number of obs	216	Chi-square	1896.949

**** p<.01, ** p<.05, * p<.1*

Source: Elaborated by the author using the program Stata 18

The results of estimating the Arellano-Bond model for panel data confirm the validity of the hypotheses formulated, demonstrating significant relationships between R&D expenditures and the circular economy and sustainability factors. The hypothesis that R&D investment is characterized by persistence over time is supported by the positive and significant lag coefficient of the dependent variable, indicating that the current level of R&D spending is influenced by past allocations. This result suggests that national innovation strategies are based on a long-term commitment in which countries continue to invest in research even during periods of economic transition, thus confirming hypothesis H1. Regarding the hypothesis that the increase in the share of renewable energy in gross final consumption contributes positively to R&D expenditure, the model results indicate a positive and significant coefficient on this variable, thus validating hypothesis H2. This result suggests that countries that allocate resources to expand the use of renewable energy sources are also those that invest more in innovation activities, probably due to the need to develop efficient and sustainable technologies to support the energy transition. This underlines the importance of sustainability-oriented policies not only in the context of reducing carbon emissions, but also as drivers of technological progress and economic competitiveness. Similarly, hypothesis H3, that private investment in the circular economy has a positive effect on R&D expenditure, is validated by the positive and significant coefficient associated with this variable. This result highlights that an increase in private sector funding for circular economy initiatives is correlated with an increase in R&D activities, suggesting that private investment support is crucial for stimulating sustainability innovation. Thus, countries with more active private sector participation in circular economy projects tend to direct more resources towards research, strengthening the transition towards more resource-efficient economic models.

Thus, the econometric analysis confirms hypotheses H1, H2 and H3, demonstrating that R&D investment is positively influenced both by past R&D spending and by the transition to renewable energy and increased private investment in the circular economy. The results underline the importance of integrated policies that stimulate both the use of renewable energy sources and the involvement of private capital in sustainable initiatives, thus highlighting the central role of innovation in strengthening a competitive and sustainable economic model in the European Union.

Figure 1 shows the level of Gross Domestic Expenditure on Research and Development (GERD) as a percentage of Gross Domestic Product (GDP) in the EU Member States. This distribution highlights significant disparities between the countries analyzed, reflecting differences in policy priorities, research funding capacity and the level of technological development in each Member State.

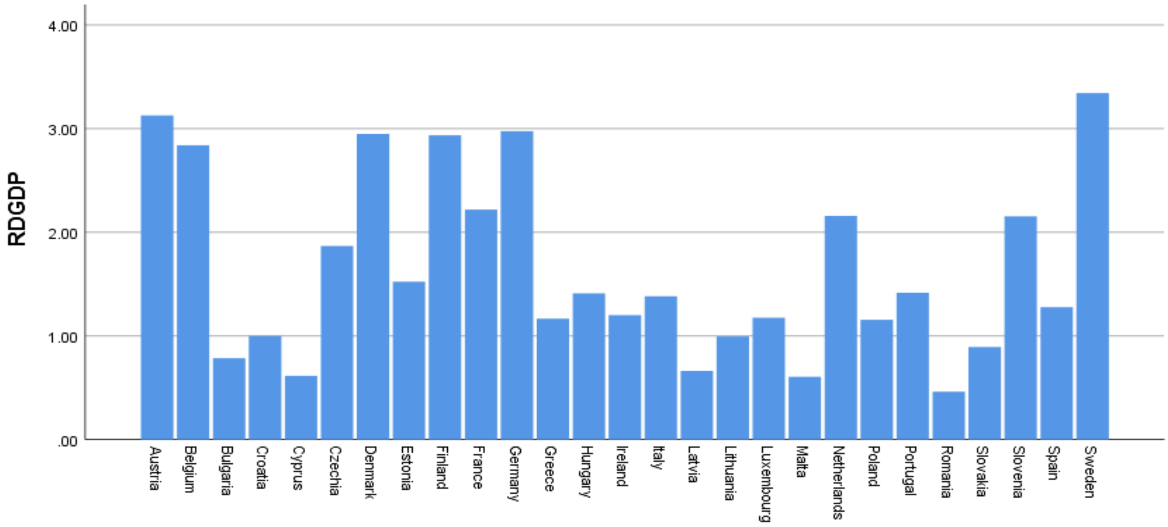

Figure 1. Distribution of R&D expenditure (% of GDP) in the EU Member States

Source: Elaborated by author

Countries such as Sweden, Austria, Denmark, Finland and Germany allocate the highest resources to R&D, with more than 3% of GDP. These economies are characterized by a strong innovation sector, supported by both government investment and a high level of private sector involvement in financing R&D activities. This trend can be explained by the orientation of these countries towards high-tech industries such as IT, biotechnology and high-performance equipment manufacturing. In contrast, countries with the lowest R&D expenditure, such as Romania, Bulgaria, Cyprus, Latvia and Slovakia, are below 1% of GDP, suggesting a limited capacity for innovation and a greater reliance on traditional economic sectors. This can be attributed to a combination of factors, including limited financial resources, underdeveloped research infrastructure and a private sector less oriented towards investment in innovation. There is also an intermediate group of countries, including France, the Netherlands, Belgium and Italy, with R&D expenditure between 1.5% and 2.5% of GDP. These economies benefit from relatively well-developed policies in support of innovation, but the differences with the top countries suggest that there are still challenges in stimulating investment in this sector. This distribution tells us that the European Union does not have a uniform convergence in R&D support, but rather a split between the Nordic and Western countries, which invest heavily in innovation, and those in Central and Eastern Europe, where spending is considerably lower. These differences underline the need for tailor-made European policies that support the efficient allocation of resources to reduce research gaps and strengthen Europe's position as a global leader in innovation and sustainability.

Figure 2 shows the distribution of the amount of packaging waste generated per capita (GPW) in the Member States of the European Union, highlighting the significant differences in resource management and consumption patterns in each economy. These variations reflect economic and demographic factors as well as the impact of national circular economy and sustainability policies.

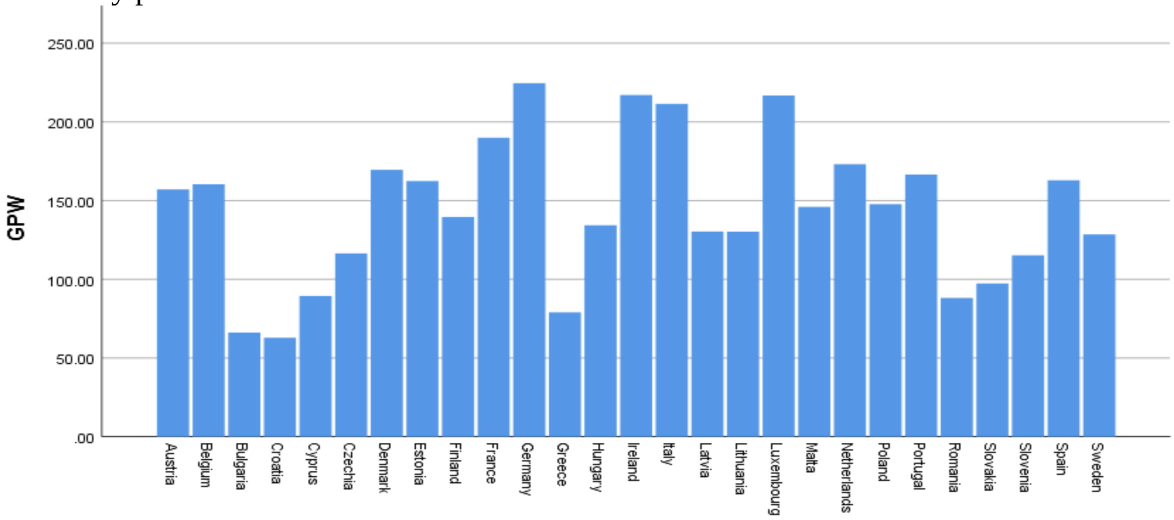

Figure 2. Distribution of packaging waste generation per capita in EU Member States

Source: Elaborated by author

Figure 2 shows that the countries with the highest packaging waste per capita are Ireland, Luxembourg, Germany and Italy, with quantities exceeding 200 kg per capita. These economies are characterized by a high level of consumption, driven by high incomes and advanced economic development, leading to more intensive production and use of packaging. In contrast, countries with the lowest GPW values, including Bulgaria, Croatia, Latvia and Romania, have significantly lower levels, below 100 kg per inhabitant. These values can be explained by a combination of factors, including more moderate consumption, more restrictive policies on the use of packaging and possible under-reporting of waste in some regions. In addition, some of these countries are characterized by a less developed waste collection and recycling infrastructure, which may influence the reporting of packaging generation data. An intermediate category, including countries such as France, the Netherlands, Austria and Spain, show levels of GPW between 150 and 180 kg per inhabitant. These economies maintain a balance between waste generation and prevention and recycling measures implemented at national level, benefiting from more advanced circular economy policies. The distribution of this indicator underlines that the European Union faces major challenges in reducing and managing packaging waste and that strategies tailored to each economy are needed to encourage resource efficiency and a shift towards sustainable production and consumption patterns. Significant differences between countries suggest that while some economies have adopted effective waste prevention and recycling measures, others continue to generate high amounts of packaging, which may have implications for long-term sustainability.

This underlines the need for common policies at European level to reduce disparities and improve resource management in the circular economy.

Figure 3 shows the distribution of the share of renewable energy in gross final energy consumption (SRENEW) in the EU Member States, highlighting significant differences in the degree of transition to sustainable energy sources. These variations reflect national green energy strategies as well as the availability of renewable resources, the level of investments and policies to support sustainability implemented at national level.

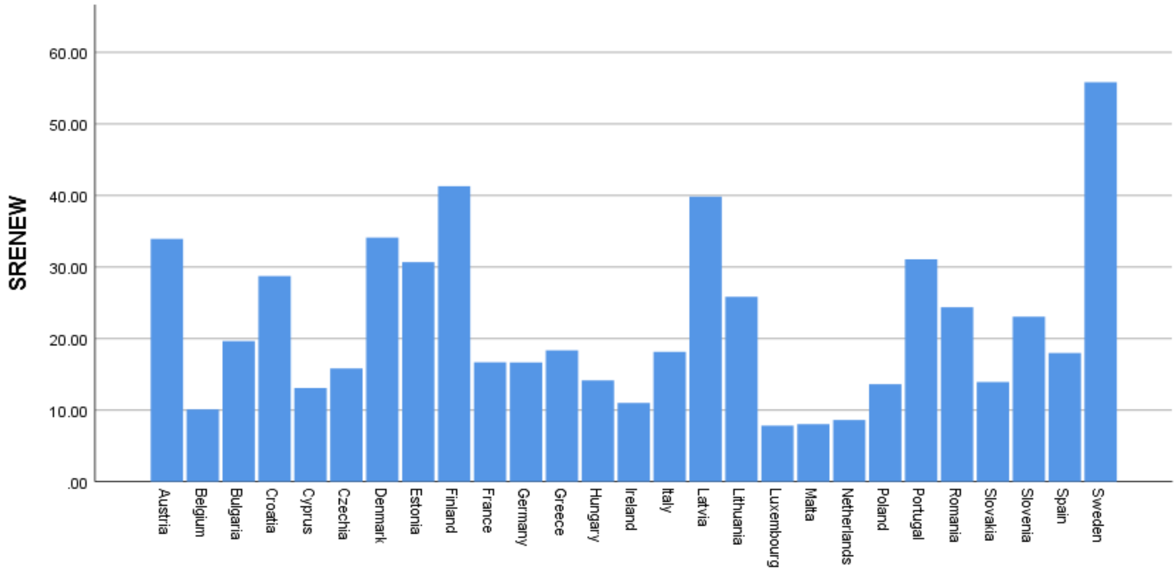

Figure 3. Distribution of the share of renewable energy in gross final consumption in the EU Member States

Source: Elaborated by author

Figure 3 shows that Sweden, Latvia, Finland and Austria are leaders in the use of renewable energy sources, accounting for more than 40% of gross final consumption. These economies benefit from favorable natural conditions, such as abundant hydropower resources in the case of Sweden and Austria, as well as a well-developed energy infrastructure for biomass and wind. These countries have implemented ambitious decarbonization policies and have invested significantly in the development of renewable technologies, allowing them to reduce their dependence on fossil fuels. By contrast, countries with the lowest shares of renewable energy, such as the Netherlands, Belgium, Malta, Luxembourg and Belgium, have shares below 15%, suggesting a high dependence on conventional energy sources. This can be attributed both to geographical constraints, which limit the possibility to produce energy from renewable sources, and to energy policies that are less oriented towards the green transition. For these countries, more effective measures to stimulate the use of renewable energy become essential to achieve the EU's climate neutrality objectives. An intermediate group of countries, including France, Germany, Italy and Romania, have renewable energy shares between 15% and 30%. These countries have active strategies in place to increase renewable energy production capacity, but the pace of the transition varies according to the specific economic and technological context of each country. For example, France and Germany have invested significantly in wind and solar energy, but their historical dependence on other energy sources, such as nuclear in the case of France, influences the dynamics of this process. This distribution highlights the existence of significant disparities between EU countries in the uptake of renewable energy sources, which poses challenges in meeting ambitious greenhouse gas reduction targets. In the longer term, these differences suggest the need for coordinated policies at European level to support countries with lower renewable energy use in accelerating the transition towards a sustainable energy system less dependent on fossil fuels.

Figure 4 shows the distribution of private investment in the circular economy (PRINV) across EU Member States, reflecting the level of private sector involvement in financing sustainability and resource efficiency innovation initiatives. The significant discrepancies observed between the countries analyzed indicate major differences in economic policies, industrial structure and awareness of the circular economy.

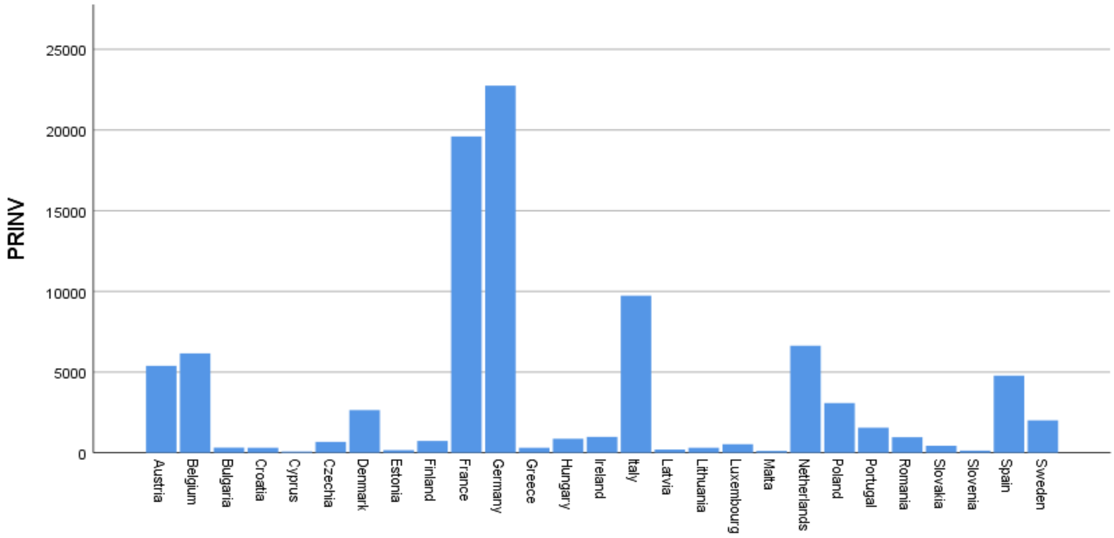

Figure 4. Distribution of private investment in the circular economy in EU Member States

Source: Elaborated by author

Figure 4 shows that Germany and France dominate the ranking, with the highest private investments in the circular economy, with amounts exceeding €20 billion. These advanced economies benefit from a strong industrial sector and well-developed public policies that stimulate business involvement in recycling, waste reduction and resource efficiency initiatives. Moreover, the presence of large sustainability-oriented multinationals is helping to reinforce these investments, having a significant impact on the transition towards a circular economy model. In contrast, most countries in Central and Eastern Europe, including Bulgaria, Croatia, Latvia, Lithuania, Latvia, Lithuania, Slovakia and Romania, show extremely low levels of private investment in the circular economy, below €1,000 million. These figures suggest a limited capacity of the private sector to support the transition towards sustainability, either due to financial constraints or a lack of effective policies to stimulate the circular economy. In these economies, sustainability initiatives are often dependent on public funds and European programs, and the private sector plays a smaller role in financing green innovations. This distribution highlights that there are significant differences in the capacity of countries across the European Union to attract private investment in the circular economy, which may influence the pace of the transition towards more sustainable economic models. While some economies have adopted policies and infrastructures that favour public-private partnerships in sustainability, others face challenges in mobilizing private capital, highlighting the need for further action to reduce these disparities and accelerate the implementation of circular economy principles at European level.

5. Conclusions and Policy Implications

This study investigated the relationships between the circular economy, innovation and sustainability in the European Union using a dynamic econometric model for panel data. The results revealed that R&D investments are characterized by persistence over time, being positively influenced both by the increasing share of renewable energy in gross final consumption and by private investments in the circular economy. At the same time, the analysis has shown that although the generation of packaging waste is a key driver of the circular economy, it does not have a significant direct impact on innovation spending. These findings suggest that an effective strategy to stimulate innovation must include both measures to support renewable energy and mechanisms to encourage private sector involvement in the circular economy. From a public policy perspective, the results of this study underline the need for an integrated approach to strengthen the circular economy in the European Union. First, policies to support the transition to renewable energy need to be linked with strategies to stimulate research and development so that Member States can harness the technological potential to accelerate the decarbonization of the economy. Second, given the positive impact of private investment on innovation, governments should implement fiscal and financial measures to encourage private capital to contribute to the development of sustainable solutions. These measures can include subsidies for circularity startups, tax breaks for companies investing in green technologies and the creation of innovative financing mechanisms such as sustainability impact funds.

While this study provides a detailed insight into the interactions between the circular economy, innovation and sustainability, it has some limitations that need to be taken into account. One of the main limitations is the availability and quality of data, as some EU Member States may differ in the way they collect and report data on circular economy and sustainability. Also, the variables used in the model do not capture all dimensions of the circular economy, such as material use efficiency, recycling of critical resources or the level of education and training in sustainability, which could influence R&D spending.

Given these limitations, future research directions should include additional indicators that better reflect the complexity of the circular economy, such as recycling rates, natural resource use efficiency and the uptake of green technologies by industry. Integrating additional indicators could provide a deeper understanding of the mechanisms through which the circular economy influences innovation and sustainability. Another important aspect worth exploring is the impact of different legislative frameworks and policy initiatives on the circular economy. Comparative analysis of national policies and how they affect R&D investments could provide valuable insights for formulating effective recommendations at European level.

In conclusion, this study underlines the importance of integrated policies that support both renewable energy investments and private sector involvement in the circular economy, thus strengthening the transition towards a sustainable and innovative economic model in the European Union.

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