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ABSTRACT OF PhD DISSERTATION

Circular Economy Development in the European Union

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3.8. Economics, PhD Programme ‘Economics and Management (Industry)’

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The dissertation consists of an introduction, three chapters, a conclusion, scientific contributions, a list of publications, a list of abbreviations and a list of references. The full volume of the dissertation is 155 pages. The list of references comprises of 243 sources: 27 in Bulgarian and 216 in English. The dissertation includes 19 figures and 18 tables. The author has published 4 papers related to the topic of the dissertation, 3 of which are indexed in SCOPUS. Results have been reported at 4 international conferences.

This dissertation was discussed and directed to public defence at the Department Council of the Department of Industrial Economics and Management, Faculty of Economics and Business Administration, Sofia University 'St. Kliment Ohridski', Protocol № 184/17.06.2024.

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General Outline of the Dissertation

Environmental changes and the economic, social and ecological challenges they pose require an urgent energy and resource transformation of the economic system. Thus, the energy transition and the circular economy have emerged as two of the most discussed global topics of the 21st century. A 'circular economy' has practically existed since the dawn of humanity, but the concept known today took shape in the 1960s. The late 1980s marked a turning point in its development with industrial ecology becoming more and more popular and the subsequent rapid spread of various concepts related to politics, management and science.

The transition to a circular economy has diverse impacts on governments, industries, the scientific community, non–governmental organisations and consumers. Therefore, it substantially affects scientific research, technological innovation and the public consciousness by becoming increasingly integrated in various policies, business operations and educational practices. Investigating the challenges and opportunities that may impede or favour the circular transformation can assist different stakeholders in decision making, choosing the means to monitor the transition and creating circular innovations that benefit nature and society. However, the circular economy concept has not yet matured and knowledge fragmentation remains an issue. The lack of a common definition and clear boundaries influences the circular transition monitoring frameworks, while the abundance of relevant indicators further increases the complexity of the task at hand. And yet, everyone involved in the transformation, especially national authorities, needs suitable metrics to assess the circularity of economies and to identify best practices and areas of improvement.

To 'close the loop', the circular economy should create sustainable solutions in three main areas: production and supply, demand and consumption, waste management (Ivanova & Chipeva, 2019). However, circular indicators at the level of design, production, distribution and consumption are either scarce or completely lacking. Meanwhile, the existing metrics have only been accounted for in recent years. Considering data availability, the current dissertation aims to identify and analyse several key material– and energy–related indicators used to track and assess the transition to a circular economy. With their help the author partially addresses all of the abovementioned areas, taking into account the use of secondary materials in production, the consumption of renewable resources and recycling as part of waste management. Given that each indicator has its own peculiarities and specific determinants, the analysed sample sizes are affected by data availability for each independent variable. They also vary in their time periods to ensure a balanced panel and include the maximum number of observations.

The **aim** of this research is to measure the effects of significant macroeconomic and social factors on some of the most commonly used circular economy indicators and to determine their influence on the circular transformation of economic systems in the European Union.

The dissertation's main **thesis** is that a country's economic development, research and development investment and resource productivity significantly impact the transformation of its economic system, therefore facilitating or hindering the transition to a circular economy.

The following **tasks** were performed to achieve the above goal:

1) Critical review of relevant publications in the field of economics and management, ecology and environmental protection, innovations and technologies, public policy and regulation, international relations and development, social sciences, as well as a review of the EU circular economy strategies and legal framework.

   1a) Identification of similarities and differences between the concepts of the circular economy and sustainable development and their interactions.
2) Critical review of the EU monitoring framework on the circular economy, its advantages and disadvantages; a comparative analysis between Bulgaria and the EU regarding the progress on key circular indicators.
3) Identification of the most commonly used material– and energy–related circular indicators as well as identification of potentially significant factors that influence them.

   3a) Collection of macroeconomic quantitative data from regional and global databases; data processing, regression analyses and statistical tests, cluster analysis.
4) Interpretation of the results and formulation of recommendations to improve the EU framework for monitoring the transition and optimise policies promoting the circular transformation of economies.

The **data** required for the analyses originated from Eurostat, the World Bank, the United Nations, the Confederation of European Waste–to–Energy Plants and Climate Watch. Following a thorough literature review and data collection, the rest of the tasks were completed using a wide range of methods, including data visualisation, descriptive statistics, correlation analysis as well as tests for stationarity, cointegration, causality, fixed or random effects, serial correlation and cross–

sectional dependence. To estimate the panel regression models, three methods were used: ordinary least squares, fixed effects and fully modified ordinary least squares.

Results included in the dissertation were reported at four international **conferences**, including: ‘Environmental, Social and Governance Challenges for Recovery and Resilience’, 2021; ‘First Annual International Transform4Europe PhD conference — ‘Societal Transformations and Sustainable Development with Respect to Environment in the Post Covid–19 Digital Era’’, 2021; ‘International Conference Automatics and Informatics (ICAI) 2022’, 2022; and ‘Second BCEA Annual Conference’, 2024.

Summary of the Dissertation

Chapter 1. The Circular Economy Concept

Chapter 1 reviews the development of the circular economy concept over time. Its various theoretical and practical applications in politics, economics and science create a vast body of knowledge. However, it remains fragmented and fails to make the concept more structured, comprehensible and trackable. Based on previous attempts to derive a standardised notion of the circular economy, a new definition was drawn up by the author. The chapter summarises the main principles, strategies and business models of the circular economy system and provides a critical review of the numerous circular indicators and different monitoring frameworks. This section emphasises the contemporary mission of the circular economy: to decouple economic growth from the use of scarce resources through a systemic approach and the involvement of all stakeholders.

1.1. Emergence and Development of the Circular Economy Concept

Crossing the planetary boundaries brings about a pressing need of a sustainable economic and social transformation. The corrected economic system should be modelled after nature itself since people are part of it and the economic product they create should obey natural laws in order to maintain the fragile balance. The notion of a circular economy first appeared in scientific literature in the 1960s in Kenneth Boulding’s essay ‘The Economics of the Coming Spaceship Earth’ (Boulding, 1966). In the paper, rethinking current practices suggested the development of a type of *‘spaceman’* economy with limited raw materials and no possibility to release pollution. Georgescu–

Roegen (1971) also adressed these limitations, integrating the principles of thermodynamics, particularly the concept of entropy, into economic theory. Years later Walter Stahel and Geneviève Ready–Mulvey sketched the idea of a closed–loop economy (Stahel & Reday–Mulvey, 1981). The actual term *'circular economy'* was first used in 1989 by David Pearce and Kerry Turner in 'Economics of Natural Resources and the Environment' where the authors discussed the relationship between the economy and the environment, as well as nature's role in sustaining life on Earth (Pearce & Turner, 1989, p.41).

The concept of closing the loop, which is core to the circular economy, is deeply rooted in **industrial ecology** (Preston, 2012, p. 3; Murray et al., 2017). It emerged in the 1970s contrary to popular belief that industry and nature are two separate entities (Erkman, 1997). In 1998, Frosch and Galloupoulos put a spotlight on industrial ecology, considering it a main prerequisite for the circular economy by means of industrial symbiosis (Frosch & Galloupoulos, 1989). Since 1990 the circular economy has become a major topic of discussion influencing concepts in politics, management and science. Michael Braungart and William McDonough presented the *'cradle to cradle'* business strategy in 2002, aiming to accomplish an infinite cycle of usage where materials and their productivity are constantly maintained and improved, and all transformations are powered by renewable energy (McDonough & Braungart, 2002). The principles upon which the authors built their model later become the key principles of the circular economy.

The contemporary mission of the circular economy is to decouple economic growth from the exploitation of scarce resources. In 2010, the Ellen MacArthur Foundation (EMF, 2023a) was founded and has ever since acted purposefully to accelerate the transition to the new economic system. In 2015, the European Commission announced its intentions to transition to a circular economy (European Commission, 2023). They were upgraded in 2020 under the Circular Economy Action Plan, a basic pillar of the European Green Deal aiming to *'close the loop'*.

The relationship between sustainable development and the circular economy is undeniable, yet not clearly defined (Sauvé et al., 2016; Geissdoerfer et al., 2017). The circular economy is often perceived as a prerequisite for sustainability, a beneficial approach or even a substitute for sustainable development (Geissdoerfer et al., 2017). There are quite a few **similarities**: both concepts stress the importance of engagement, responsibility and cooperation that present and future generations should demonstrate in the face of global environmental challenges; both use a multi and interdisciplinary approach to the integration of non–economic aspects in economic development; both rely on regulations and schemes enhancing innovative business models. There are also some **differences**. Sustainability considerations put people first and conceive economic development as a means to achieve a fulfilling life in harmony with nature. The circular economy, on the other hand, mainly prioritises the technological solutions that allow for traditional economic growth. Another important difference arises with regard to responsibilities. In sustainable development they are shared but not clearly predefined. Meanwhile, the responsibility for the transition to a circular economy falls mainly on the government, regulators and private enterprises. Either way, to ensure the success of both sustainable development and the circular economy, and to avoid shifting the burden from one component to another, the entire economic system should be treated as a single living organism (Velenturf & Purnell, 2021).

Despite the growing interest in the circular economy and the abundance of scientific publications on the subject, many authors fail to provide a complete definition that encompasses all the important aspects of the concept and distinguishes it from other similar notions (Figge et al., 2023). This dissertation reviews the most frequently used definitions of the circular economy (Kirchher et al., 2017; Kirchher et al., 2023; EMF, 2023b) and compiles the following **working definition**:

'The circular economy is a regenerative economic system that replaces the 'end–of–life' concept with long–lasting design, maintenance, repair, reuse, refurbishment, remanufacture and recycling. This system is 'fuelled' by renewable energy and materials, eliminates toxic substances that hinder the reuse of materials, and aims at zero waste though advanced design and innovative business models. The ultimate goal is to enable an efficient flow of materials, energy, labour and information, decoupling economic development from the use of scarce resources, while restoring natural and social capital on the path to economic growth.'

1.2. Principles, Strategies and Business Models of the Circular Economy

In a linear economy, the product life cycle spans from the extraction of raw materials, production of components, assembly and/or packaging, the finished product, distribution, consumption, to the disposal of waste. The circular economy attempts to address the shortcomings of this system by drawing inspiration from ecosystems, where waste is nonexistent and all resources are continuously circulated (Желязкова, 2020). In a circular system, two cycles are distinguished: a **biological cycle** and a **technical cycle**. Biomaterials are safe and fully biodegradable, while technical materials are finite but they can be reused, repaired, remanufactured and recycled, keeping their value over time.

The circular economy is based on **three main principles** (EMF, 2023d):

1) Natural capital regeneration
2) Circulation of products and materials at their highest value
3) Elimination of waste and pollution

The **'ReSOLVE'** framework, developed by Arup and the Ellen MacArthur Foundation translate the three basic principles into six actions: regenerate, share, optimise, loop, virtualise and exchange. Their goal is to create a diversified zero–waste system based on renewable sources, systemic solutions and prices as a feedback mechanism (EMF, 2015). The **circular business strategies**, in turn, help narrow, slow down and ultimately close the resource loop (Bocken et al., 2016).

The implementation of the circular economy principles shapes 5 common **circular business models**: circular supplies, resource recovery, product life extension, sharing platforms, and product as a service (Lacy et al., 2014). They promise economic benefits from reduced energy and resource consumption, as well as social and environmental advantages, such as new jobs, circular use of materials, waste prevention and design of products that are more durable, easier to recycle and environmentally safe (Иванова, 2019). The industry, in fact, emerges as the driving force behind the transition to a circular economy, whether through capital investment, trade, research and development, or, most importantly, the efficient and environmentally responsible use of resources (Иванова, 2018).

1.3. Measuring the Circular Economy

In the transition to a sustainable and circular economy, countries need suitable indicators to track progress. The wide scope and lack of a precise definition of the circular concept make it difficult to assess using a single indicator. Meanwhile, scientific literature is abundant with research on the various circular indicators, their taxonomy and their integration into different monitoring frameworks used by scientists, businesses and national or regional authorities (Ghisellini et al., 2016; Saidani et al, 2019; Parchomenko et al., 2019; De Pascale et al., 2021). Through literature review, two main shortcomings characteristic of the majority of indicator groups were identified:

1) There is a notable imbalance among the three pillars of sustainable development at the micro, meso, and macro levels, with insufficient connectivity between the micro and macro

levels. While macro–level indicators are well–developed, there is a weaker understanding of how to measure and enhance the transition to a circular economy at the micro level (Harris et al., 2021; Hatzfeld et al., 2022; De Oliveira & Oliveira, 2023; Elia et al., 2017).

2) The majority of indicators appear to be associated with preservation of materials. This dimension, however, fails to account for energy, land and water management, environmental impacts, product lifecycle, institutional and social factors (Corona et al., 2019; Llorente–González & Vence, 2019; Moraga et al., 2019; Moraga et al. 2021). Material–related metrics are more easily comprehensible, but they may reduce material consumption at the cost of social, economic and environmental welfare (Corona et al., 2019).

Scientific literature offers a wide variety of circular economy monitoring frameworks as well (Mayer et al., 2018; Parchomenko et al., 2019; Ahmed et al., 2022; Reich et al., 2023; Cagno et al., 2023). Unfortunately, they often lack the ability to assess the circularity of products, processes, organisations, countries or regions all at once (Ahmed et al., 2022; Cagno et al., 2023). Many of them also fail to detect if resources are scarce or of critical importance and cannot account for durability, long–term use, economic and social value, as well as consumer engagement. What is needed is a comprehensive approach (Corona et al., 2019). However, there is not yet a generally accepted monitoring framework to track the progress of each circular goal.

Chapter 2. Institutional Framework of the Transition to a Circular Economy in the EU

Chapter 2 reviews the development of the circular economy in the European Union. It focuses on the Circular Economy Action Plan, its underlying strategies and legal framework. The EU monitoring framework is revised as well, and progress on some key indicators is tracked with the help of a comparative analysis between Bulgaria and the EU. In conclusion, the framework's advantages and disadvantages are critically reviewed, followed by suggestions for its potential improvement with additional energy, environmental, and product–life indicators.

2.1. The Circular Economy and EU Legislation

The European approach to restructuring the economic system is closely associated with Stahel's closed–loop economy and the *'cradle to cradle'* strategy of Braungart and McDonough (Wautelet, 2018). Businesses and organisations, such as the Ellen MacArthur Foundation, significantly contribute to developing and promoting the concept, but legislation stands out as the main pillar of the EU transition to a circular economy. Its foundations were first laid by Germany's Waste Disposal Act of 1976 (Mohajan, 2021), followed by the Closed Substance Cycle and Waste Management Act of 1996 (IISD, 2023). The focus shifted towards a sustainable use of natural resources with the Thematic Strategy on the Sustainable Use of Natural Resources in 2005 (EC, 2005), the Strategy for Smart, Sustainable and Inclusive Growth in 2010 (ЕК, 2010), and the Roadmap to a Resource Efficient Europe in 2011 (ЕК, 2011). The 7th Environment Action Programme, in turn, identified three main areas of interest: protection, conservation and enhancement of the EU's natural capital; a transition to a resource–efficient, green, and competitive low–carbon economy; protection from environment–related pressures and risks to the health and wellbeing of EU citizens (ЕП, 2013).

A series of efforts to create suitable indicators for tracking progress led to the development of the Resource Efficiency Indicators in 2014 (European Parliament, 2015) and the Raw Materials Scoreboard in 2016 (European Commission, 2016). Both set the ground for the first Circular Economy Action Plan adopted in 2015 (ЕК, 2015). It was followed by the introduction of the EU monitoring framework on the circular economy in 2018 (European Commission, 2018b) and the adoption of the new Circular Economy Action Plan in March 2020 (ЕК, 2020). The new 8th Environment Action Programme defined six priority objectives, the circular economy being explicitly mentioned with regard to ensuring a regenerative growth model (ЕП, 2022).

The Circular Economy Action plan supports member states in the transition by establishing an appropriate legal framework and proposing specific measures, financial stimuli and a monitoring framework to track progress. The new plan is aligned with the circular economy principles and sets specific targets to promote sustainable design, prevent waste and pollution, protect consumer rights, raise consumer awareness and increase resource efficiency in priority sectors. Waste legislation plays a pivotal role in the action plan through the implementation of framework directives on product design (ЕП, 2012; ЕП, 2015) and waste management (ЕП, 2008; ЕП, 2018; ЕП, 2019). The legislative framework has gradually expanded over time, adopting additional requirements aimed at waste prevention and moving up the waste hierarchy through eco–design, energy efficiency, restricting hazardous substances, and banning certain products.

2.2. EU Monitoring Framework on the Circular Economy

The European Union Circular Economy Monitoring Framework was introduced in 2018 to track circular progress in line with the Green Deal's main objectives. It is one of the few frameworks, which account for technological progress and materials that are refed into the economy (European Commission, 2018b). The framework is based on the economy–wide material flow accounts, an approach that considers all material inputs and outputs of a national economy (Eurostat, 2018a). Yet, just like many other monitoring frameworks it mainly focuses on material aspects and largely neglects society, the environment and systemic change. It does not include any indication of circular product design, while the preservation of embedded value over time is poorly reflected (ЕСП, 2023). This is a main source of criticism regarding the European evaluation approach.

The first version of the EU framework encompassed 10 indicators divided into 4 categories: production and consumption, waste management, secondary raw materials, competitiveness and innovation (EC, 2018b). Its revised version was adopted in May 2023 to add a new 5th category accounting for global sustainability and resilience (Eurostat, 2023a). The last category includes measures of the consumption footprint, greenhouse gases emissions from production activities, material import dependency and EU self–sufficiency for raw materials. Again, most of them are associated with materials but they now touch upon more social and environmental aspects.

The circular economy facilitates sustainable growth, particularly evident at the EU level through enhanced resource efficiency, reducing dependence on raw materials and minimising waste generation (Ivanova, 2020). The figures that follow show a few comparisons between the EU and Bulgaria with respect to key indicators monitored in the framework. Bulgaria, as one of the most recent EU members, has applied European green policies for a shorter period, which potentially poses challenges to its economic system transformation. Each indicator has its values displayed for 2015/16 (adoption of the first Circular Economy Action Plan), 2018 (adoption of the EU monitoring framework), and the most recent year available. Years vary according to data availability.

Figure 2 reviews the 'Production and Consumption' category. Since the adoption of the EU monitoring framework, there has been a slight increase in the material footprint (2.A) and municipal waste per capita (2.D) in the EU. However, there is an increased resource productivity (2.B) and a slightly decreased total waste generation per capita (2.C).

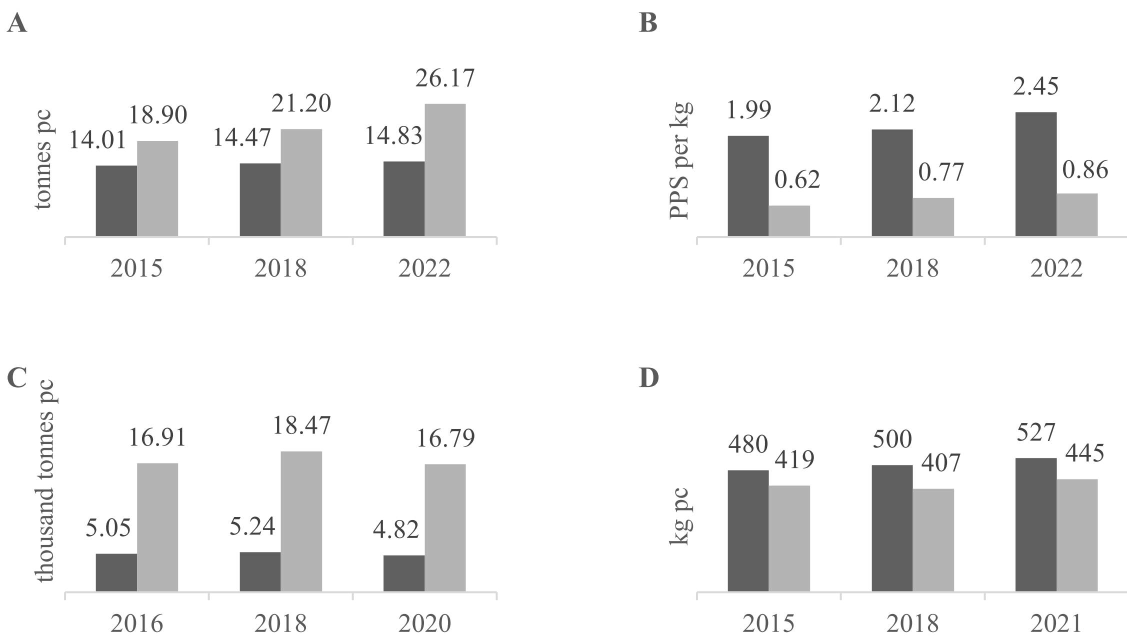

Figure 2. Production and Consumption: A. Material footprint; B. Resource productivity; C. Total waste generation per capita; D. Generation of municipal waste per capita. EU values are in dark grey and Bulgaria's values are in light grey. The charts are created by the author using Eurostat data (Eurostat, 2023b).

Bulgaria demonstrates an increase in all four indicators. The results are not flattering with respect to the material footprint (35% and 76% higher than the EU average in 2015 and 2022, respectively) and total waste per capita (235% and 249% higher than the EU average in 2016 and 2022, respectively). This poor performance may be the result of a combination of factors, including high resource intensity of the industry, an inefficient waste management system or gaps in the regulatory framework affecting waste and resource efficiency.

In 'Waste Management', the recycling rate of all waste (excluding major mineral waste) and the recycling rate of municipal waste slightly increase in the EU over the years. In Bulgaria, the recycling rate of municipal waste has gone up since 2015, reaching 34.6% in 2019, but then it drops to 35.2% in 2020. With more municipal waste per capita in 2021, the recycling rate decreases even further to 28.2%.

While the circular material use rate in the EU remains rather stable (Figure 4.A), the one in Bulgaria has increased in recent years indicating that a larger share of recycled materials is being fed back in the economy. However, given the country's high material footprint and relatively low resource productivity, secondary raw materials obviously do not substitute for primary raw materials. Recyclable material exports (Figure 4.B) have also increased in both the EU and Bulgaria over the years. This trend can hardly be considered flattering since these materials are often shipped to countries with lower regulatory standards or lack of appropriate treatment facilities.

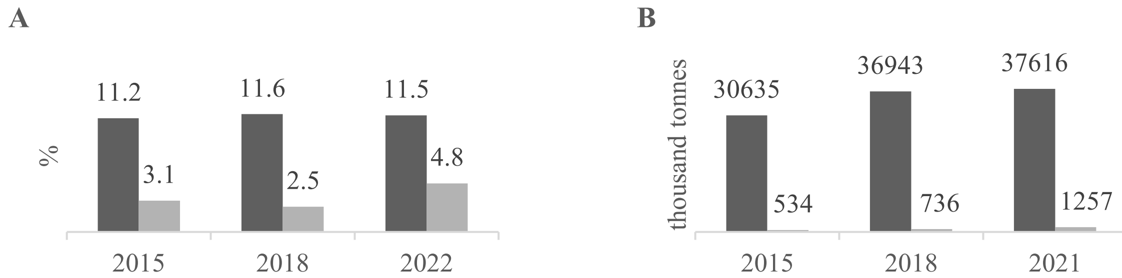

Figure 4. Secondary Raw Materials: A. Circular material use rate; B. Trade in recyclable raw materials (exports outside the EU). EU values are in dark grey and Bulgaria's values are in light grey. The charts are created by the author using Eurostat data (Eurostat, 2023b).

In the 'Competitiveness and Innovation' group the framework considers three indicators. The private investment and gross added value related to circular economy sectors remain constant in the EU, while Bulgaria nearly reaches the average level. A similar situation is observed regarding the share of people employed in these sectors. According to 2020 data, there are still no registered patents related to recycling and secondary raw materials in Bulgaria, while the number of patents in the EU has significantly decreased.

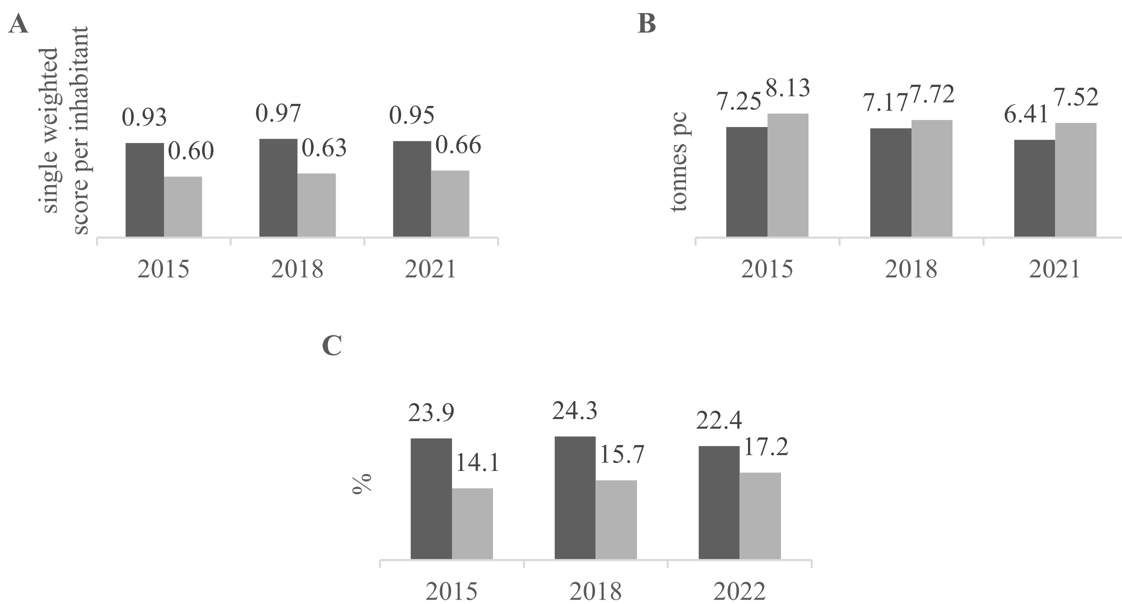

Figure 6. Global Sustainability and Resilience: A. Consumption footprint; B. Greenhouse gases emissions from production activities; C. Material import dependency. EU values are in dark grey and Bulgaria's values are in light grey. The charts are created by the author using Eurostat data (Eurostat, 2023b).

The sustainability indicators shown in Figure 6 do not demonstrate notable changes over time. The consumption footprint (6.A) remains almost constant, with Bulgaria's footprint being smaller mainly due to the country's lower GDP. Greenhouse gases emissions from production activities (6.B) decline a little but remain relatively higher in Bulgaria. This may be a result of higher resource intensity, lower efficiency of the production activities or lack of proper standards and control over production. The material import dependency (6.C) shows a decrease in the EU's last reporting period, however, in Bulgaria, it has increased by 3.1 percentage points since 2015. This further supports the argument that an increased circularity rate only adds up to the growing material consumption. When local sources are scarce raw materials need to be imported from abroad.

In conclusion, among the 14 indicators reviewed at the European level, the following trends are observed: a **worsening** of 4 indicators (material footprint, municipal waste, exports of recyclable materials outside the EU and number of patents related to recycling and secondary raw materials); an **improvement** of 5 indicators (resource productivity, total waste, recycling rate of all waste, recycling rate of municipal waste and material import dependency); and **stagnation** of 5 indicators (circular material use rate, private investment and gross added value, employment in the circular sector, consumption footprint and greenhouse gases emissions from production activities). This confirms the findings of the European Court of Auditors that there has been little progress towards the EU's circular economy transition since the first Circular Economy Action Plan was adopted in 2015 (ЕСП, 2023). Trends in Bulgaria are even more unfavourable. Иванова (2022) reaches a similar conclusion, examining a different set of indicators. The author reports that Bulgaria generally lags behind the EU average not only due to its low resource potential but also due to the slow circular transformation of business models.

Suitable indicators to address the EU circular economy monitoring framework are already available in the Eurostat database. For instance, the framework can be supplemented by energy–related metrics, such as the **share of renewable energy production and consumption**, **energy productivity** and **greenhouse gas intensity of energy consumption**. Additional indicators associated with society and the environment could include **land cover**, **net greenhouse gas emissions per capita** and **CO_2 emissions from passenger cars**. In case indicators are missing, they should be developed. For example, the **share of recycled energy consumption** could be an important energy indicator revealing whether the energy resources in use are aligned with the circular economy principles. **Planned obsolescence**, in turn, can be assessed through a combination of indicators for **energy efficiency**, **average product lifespan**, **recycled content** and a **reparability index**. Reporting this information on products labels and in aggregated macro–level data would create significant benefits, enabling consumers to distinguish between products and choose repairable and durable goods. The improved framework will be more efficient, contributing to the identification of areas for improvement and better target setting.

Chapter 3. Analysing the Impact of Macroeconomic and Social Factors on the Transition to a Circular Economy in the EU

Chapter 3 explores **three key indicators** that help track and assess the transition to a circular economy in the European Union. The first metric, the **recycling rate of municipal waste**, is well–known to the public and commonly encountered in scientific literature. The second material–related measure is the **circular material use rate**, a metric specifically created by the European Commission to illustrate what proportion of recycled resources are actually refed into economies. The third indicator is of paramount importance for the decarbonisation of economies and the achievement of the European Green Deal objectives. However, it is not yet part of the EU circular economy monitoring framework. In order to link the energy aspect to the other two circular indicators and argue the benefits of its supplementation to the framework, the chapter examines the factors influencing the **renewable energy consumption**. In conclusion, the three indicators and their determinants are consolidated into a common framework. To do this, four **clusters** that characterise certain patterns of transitioning to a circular economy in the EU are outlined. The useful insights into the drivers of the transformation help identify opportunities to bring countries closer to the achievement of carbon neutrality goals.

3.1. Analysing Determinants of the Recycling Rate in the EU

As already mentioned, the wide scope and various interpretations of the circular economy concept involve a large number of stakeholders, which suggests the existence of numerous metrics for assessing circular progress (Corona et al., 2019). While all the aspects of a circular system are equally important, data on the recycling rates are more complete and easily accessible (Espinoza, 2021). Recycling is even often perceived as an equivalent to the circular economy, despite it being just a single strategy (Kirchherr et al., 2017). However, it is important to note that a high recycling rate does not necessarily imply material circularity and countries may still face difficulties in closing the loop (Fellner & Lederer, 2020).

The focus of the study is the **recycling rate of municipal waste** on annual basis, referred to as 'recycling rate' throughout the text. It is an indicator measuring the share of recycled final–consumer waste in the total municipal waste generation. The process involves material recycling, composting and anaerobic digestion. In this context, municipal waste is defined as waste from households and other sources that are similar in nature. Although municipal waste represents only about 10% of the total waste generated in the European Union, its recycling rate acts as an acceptable criterion for the performance of the waste management system, and as an indication of how municipal waste is transformed into a resource to fuel the circular economy (Eurostat, 2022a). This research addresses various social and economic factors that potentially influence the recycling rate. Four **initial hypotheses** were formulated:

H1: GDP per capita as an approximation for economic development has a significant positive impact on the recycling rate.

H2: Research and development expenditure as an approximation for innovation has a significant positive impact on the recycling rate.

H3: Resource productivity has a significant positive impact on the recycling rate.

H4: Landfill bans increase the recycling rate.

The data were sourced from Eurostat (Eurostat, 2023c), the World Bank (World Bank, 2022) and the Confederation of European Waste–to–Energy Plants (CEWEP, 2022). The analysis included 28 EU member states in the period 2013 – 2020. Apart from the recycling rate itself, twelve other variables were considered based on literature review (EEA, 2016; Sidique et al., 2010; Grazhdani, 2016; Park, 2018) and preliminary expectations. Economic and social factors included GDP per capita, research and development expenditure, government effectiveness, digital inclusion and risk of poverty. It should be noted, though, that considering expenditure on environmental protection would have been more appropriate. Due to incomplete data for the specific period, R&D expenditure was used as the closest approximation. To establish the effects of resource efficiency and targeted governmental policies, indicators for resource productivity, energy productivity, greenhouse gas intensity of energy consumption, landfill taxes and landfill bans were taken into account. Finally, the educational aspect was considered through demographic data on the share of early education leavers and the population with secondary or tertiary education.

Landfill bans (of biowaste, hazardous waste or recyclable waste) were of particular interest in this research since they discourage municipalities from waste landfilling and urge them to work out a separate waste collection scheme or consecutive sorting. 16 out of the 28 EU member states had a landfill ban imposed in the studied period (CEWEP, 2022).

Figure 7 reviews EU data on solid municipal waste from recent years. Apparently, the onset of an economic crisis and the coronavirus pandemic that followed had a negative effect on the circular economy. The year 2019 marked a slowdown in economic growth. To avoid a recession many central banks lowered interest rates which stimulated consumer spending. This, in turn, increased waste generation. Then, at the beginning of 2020, the pandemic additionally influenced previous waste generation and recycling patterns. With the sharp increase in medical and household waste, municipalities faced both the extra expenses related to tackling the pandemic and an excessive strain on their waste collection systems.

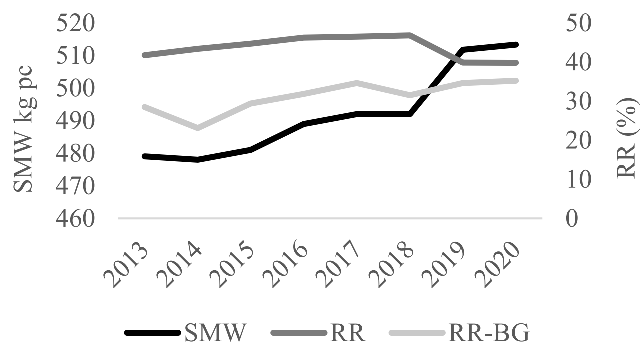

Figure 7. Solid municipal waste generation per capita in EU–28 (SMW, left ordinate) and the recycling rate (right ordinate, RR for the EU and RR–BG for Bulgaria). The chart was created by the author using Eurostat data (Eurostat, 2023c).

Initially, all data were standardised. The correlation analysis indicated that the strongest relationships were observed between the recycling rate and GDP per capita, the frequency of internet use, government effectiveness, landfill bans and research and development expenditure. Strong correlations were also present between some of the independent variables but those were not included in the final regression model. Only GDP per capita and the resource productivity made an exception, however their interaction was tested in the final model and it did not produce a statistically significant coefficient, thus it should not have led to multicollinearity issues.

The unit root tests revealed that the data were integrated of first order and The KAO panel cointegration test (Kao et al., 1999) indicated that the series reached a long–run equilibrium. Then, a Granger causality test was performed. Causality ran from the share of secondary education graduates and the risk of poverty towards the recycling rate. However, it was bidirectional and neither of these independent variables was included in the final model.

To establish the exact effects of the above determinants on the recycling rate, a panel regression analysis was conducted. The *landfill ban* was made a categorical variable. Table 5 shows the final statistically significant model estimated using the ordinary least squares method.

Table 5. OLS estimation of the recycling rate

Variable	Coefficient	t–stat	p–value
GDP per capita	0.145 (0.049)	2.953	0.004
Landfill Ban	0.122 (0.054)	2.268	0.024
R&D Expenditure	0.597 (0.044)	13.547	0.000
Resource Productivity	0.274 (0.047)	5.873	0.000
R^2 = 0.661, **R^2_{adj}** = 0.656, **Number of Observations**: 224			

Standard errors are reported in parentheses.

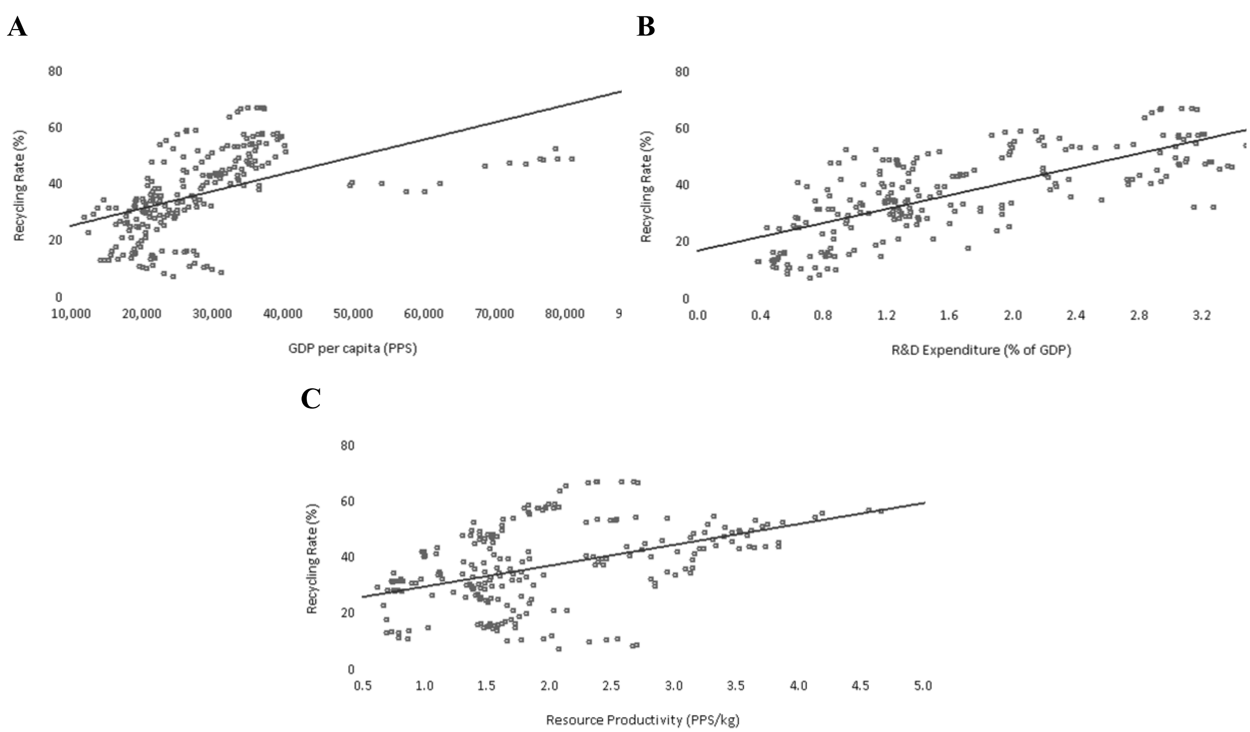

Figure 8. The recycling rate as a function of: A. GDP per capita; B. R&D expenditure; C. Resource productivity. The scatter plots were created by the author using Eurostat data (Eurostat, 2023c).

Four variables, *GDP per capita*, *research and development expenditure*, *resource productivity*, and *landfill ban*, turned out to be statistically significant. The absence of the educational variables should not be surprising — they are subsumed in the productivity and GDP–related variables, which serve as overall measures for the degree of societal development. For the same reason, the measure of digital inclusion could not find a place in the final model, although its importance seems obvious.

Figure 8 depicts scatter plots of the recycling rate against each of the statistically significant factors together with a regression line. The *landfill ban* is not shown due to its categorical nature. Remarkably, at least in some years, few of the richest nations recycled below the European average, as Figure 8A indicates. This finding may serve as a hint for more nuanced relationships within the circular economy determinants.

GDP and recycling may not appear directly related at first glance. Economically developed countries, however, undoubtedly allocate a higher budget to research and innovation in the field of recycling and recovery of materials, the development of proper infrastructure and the improvement of waste management systems. A higher living standard also affects consumer behaviour, since people are better educated, more environmentally aware and more inclined to recycle.

R&D as a share of GDP turns out to be the single most influential determinant of waste recycling, and more generally, of the advancement of the circular economy in the EU. Of course, this is valid when efforts are primarily directed towards eco–innovations related to clean, resource–efficient and circular technologies (Ivanova & Chipeva, 2021). Research and development is crucial to both prevention of waste and its subsequent transformation into valuable resources. Innovations in recycling begin with technologies for separate collection and sorting of waste. They help refine the processes in order to restore a larger portion of input materials, obtain a high–quality output, reduce costs and decrease pollution and the required energy. Research also contributes to the development of proper policies to raise awareness and engagement in the transition to a circular economy.

Second comes the **resource productivity**, another indication of economic development. An increased resource productivity is an important step towards waste prevention. Businesses can benefit from prioritising resource productivity and closing the production cycle as this helps them reduce costs. Meanwhile, intentions to close the loop imply that the end product should be designed for reuse and recycling. This facilitates the process and encourages businesses to invest in recycling technologies to recover and refeed their resources.

The link between **landfill bans** and the recycling rate is more obvious and the regression model confirms its positive contribution. Imposing such bans stimulates the development of proper infrastructure and recycling technologies, contributing to a higher share of recycled waste. This directly influences the capacity of landfills and mitigates their negative environmental impacts.

3.2. Analysing Determinants of the Circularity Rate in the EU

Most circular indicators provide insight into the recycling activities in an economy but rarely consider the increased renewable or recycled content in new materials and products (Corona et al., 2019). However, a system which puts quantity over quality causes natural resource depletion, waste and pollution (Bocken & Short, 2021). To enhance the circular transition, recycling and material substitution targets should be combined to ensure the share of renewable or secondary materials in products (Fellner and Lederer, 2020).

In an attempt to create a single macroeconomic circular indicator, Eurostat has developed the **circular material use rate**, known as the circularity rate. It measures the share of domestically recovered materials, which are refed into the economy. The circularity rate is often used as an approximation for the circular economy (Giannakitsidou et al., 2020; Kumar et al., 2021; Neves & Marques, 2022; OECD, 2020). However, this metric is less studied than the recycling rate.

This research conducted an econometric analysis of 27 European countries from 2010 to 2019. Its main purpose was to identify important factors that promote the circularity rate among a set of macro–level indicators related to socio–economic and sustainable development. Five **initial hypotheses** were formulated:

H1: GDP per capita as an approximation for economic development has a significant positive impact on the circularity rate.

H2: Research and development expenditure as an approximation for innovation has a significant positive impact on the circularity rate.

H3: Resource productivity has a significant positive impact on the circularity rate.

H4: The environmental tax revenues influence the circularity rate positively.

H5: Government effectiveness is positively correlated with the circularity rate.

A total of 11 basic independent variables were selected for the analysis. The data were sourced from Eurostat (Eurostat, 2023c) and the World Bank (World Bank, 2022). GDP accounted for economic development, while R&D was used as an approximation of innovation. The energy and resource productivity indicators related to decoupling economic growth from energy consumption and the use of natural resources, respectively.

Member states demonstrated significant differences regarding the circularity rate and the progress was slow (ЕСП, 2023). The average circularity rate increased over the period by approximately 17% starting with 8.44% in 2010 and reaching 9.89% in 2019. As seen from Figure 11, the average circularity rate over the 10–year period was approximately 8.92%. Bulgaria consistently displayed a low circularity rate. The years 2015 and 2016 marked a slight improvement but 2018 set a downward tendency.

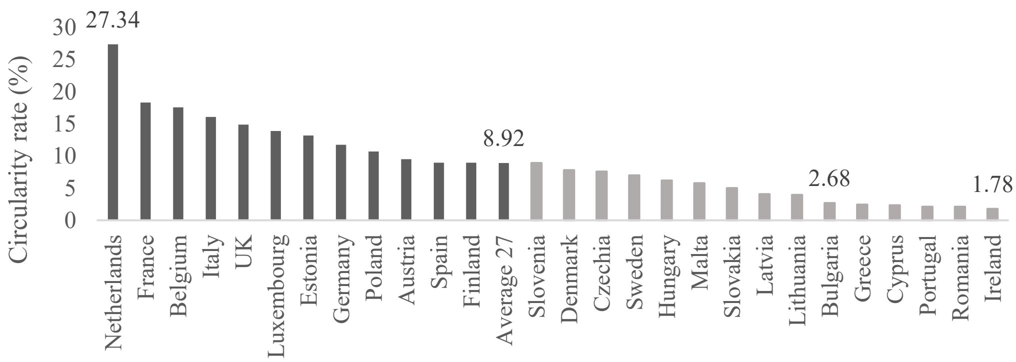

Figure 11. Average circularity rate by country for the 10–year period. The chart was created by the author using Eurostat data (Eurostat, 2023c).

All variables were logarithmically transformed. To gain a general understanding of their relationships, the correlations among the variables were reviewed. The results suggested no potential multicollinearity issues. The strongest positive correlations were found between the circularity rate on the one side and resource productivity and research and development expenditure on the other. Moderate correlations were observed with GDP per capita, government effectiveness, the recycling rate of glass packaging and the trade in recyclable raw materials (imports–intra). The moderate correlation (42%) between the circularity rate and government effectiveness supported H5. However, this variable did not find a place in the final model, neither did the recycling rates of different packaging or trade in recyclable raw materials.

The unit root tests revealed that the data were integrated of first order and The KAO panel cointegration test (Kao et al., 1999) indicated that the series reached a long–run equilibrium which rejected the possibility of spurious relationships. Then, a Granger causality test was performed to find potentially significant factors. The null hypothesis of the test was rejected at 1% – 5% significance level for both research and development expenditure and the resource productivity.

The unidirectional causality suggested that past values of these variables were useful in predicting the dependent variable.

Considering the information so far and following a forward selection procedure, an initial panel regression model was constructed. Table 9 presents the regression output results. Model 1 shows the specifics of a mixed OLS panel regression model. Despite its significant coefficient GDP per capita entered the model with a negative sign, contradicting earlier expectations. The same model was then reevaluated with cross–section fixed effects. To correct for the presence of cross–section dependence, the model was estimated using White cross–section (period cluster) method. The output from the final estimation is presented in Table 9 under Model 2. It corrected the negative sign and confirmed the significance of the other variables. Here, all four factors emerged as equally influential, with a slightly larger positive effect of the environmental tax revenues. Model 2 also introduced a fixed constant term which indicated a country–specific level of the circularity rate, depending on individual characteristics defined outside the model.

Table 9. OLS and FE estimation of the circularity rate

Variable	**(1)**	**(2)**
	Coefficient	
GDP per capita	–0.349*** (0.138)	0.336** (0.146)
R&D Expenditure	0.722*** (0.069)	0.388*** (0.076)
Resource Productivity	0.877*** (0.096)	0.358*** (0.097)
Environmental Tax Revenues	0.177 (0.136)	0.460*** (0.146)
Constant	4.606*** (1.389)	–2.241 (1.521)
R^2	0.522	0.937
R^2_{adj}	0.515	0.929
Number of Observations	270	270
Number of Periods	10	10

*All variables are log–transformed. Standard errors are reported in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.*

Higher **GDP** means better living standards, healthier business climate and new job opportunities. It enhances a more productive use of assets, while higher tax revenues and private investment can be directed to improve the resource productivity, waste prevention, collection, and recycling technologies. A closer look at the relationship between GDP per capita and the circularity rate outlines a certain pattern. Countries with above–average circularity are predominantly Western, Central and Northern European member states. Meanwhile, most countries which have joined the European Union at a later stage demonstrate below–average values. This indicates that countries, especially those with lower GDP that have more recently started implementing green European policies, still struggle to make considerable progress in the circular economy.

Research and development is a source of knowledge for the creation of new products, services and technologies or the improvement of existing ones. R&D is closely linked to innovation and not only provides a competitive edge to businesses but also plays a key role in reducing materials and energy consumption as well as the environmental footprint.

Sustainability requires a permanent reduction of inputs and wastes. Another driver of circularity is the **resource productivity**. An improved resource productivity means that economies become more competitive as they manage resources and pollution efficiently, limiting environmental risks. Producing more with less decouples economic growth from the use of exhaustible resources and reduces raw materials consumption. This is a key prerequisite for promoting the circular economy because a higher circular use of materials does not necessarily indicate sustainability.

Green policies regarding **environmental taxation** provide incentives to increase efficiency and switch to renewable resources and environmentally friendly technologies by putting a price on the generation of negative externalities. They are intended to tax production and consumption practices that threaten the environmental health. Moreover, revenues from environmental taxes can be used to subsidise the recycling and recovery industry. In fact, while the four factors appear equally influential, the share of environmental tax revenues in GDP stands out as having somewhat higher impact on circularity.

3.3. Analysing Determinants of the Renewable Energy Consumption in the EU

Energy sources drive economic growth but their use is linked to environmental pollution and climate change. That is why the energy aspect, which is of particular interest to the circular economy, should be accounted for in monitoring frameworks. It is important to understand that sustainable energy and the circular economy are complementary. To manage their relationship successfully, stakeholders should target and monitor them alongside, while incorporating circular strategies in the renewable sector.

A single metric cannot fully grasp the concept of energy transition. And yet, the share of **renewable energy** in gross final energy consumption emerges as one of the most commonly used indicators (Vera & Langlois, 2007; Sheinbaum–Pardo et al., 2012; Yu et al., 2020; Niu et al., 2023). However, while it typically serves as a comprehensive measure of the green transition, to ensure a more accurate assessment, it should be analysed along with the energy mix, total energy consumption and potentially negative environmental impacts of the technologies in use (EEA, 2015; Wang et al., 2021).

The links between renewable energy and the environmental quality have been widely discussed but only a few studies in literature focus on the factors that promote or impede renewable energy production and consumption in countries or regions. Exploring these determinants is essential in policy making and business decisions to address challenges and benefit from the opportunities before the energy transition. Recent papers find various factors to be instrumental in the development of the renewable energy sector. These are, for example, institutional factors, such as good control of corruption (Saba & Biyase, 2022; Marra & Colantonio, 2022; Tu et al., 2022), as well as technological innovation and digitalisation (Mishra et al., 2022). Factors, such as economic growth, urbanisation, industrialisation and population growth and density, also have an impact on the share of renewable energy (Malik et al., 2014). Other studies add to these determinants R&D expenditure, foreign direct investment, trade openness and government effectiveness (Kocsis & Kiss, 2015; Akarsu & Korucu–Gümüşoğlu, 2019; Alam et al., 2020; Adedoyin et al., 2020; Islam et al., 2022).

The Covid–19 pandemic and the Russian–Ukrainian conflict have presented both stimuli and challenges for the energy transition. A contraction of economic activity and the ongoing crisis have led to severe social, economic and environmental impacts (Nicola et al., 2020; Baker et al., 2020; Pereira et al., 2022). The pandemic triggered an unprecedented drop in fuel and energy demand, clearing the way for an accelerated transition to more sustainable energy sources (Chiaramonti & Maniatis, 2020; Zhong et al., 2020). Renewable energy generation was indirectly enhanced by the reduced air pollution — greenhouse gas emissions, in particular (Naderipour et al., 2020). Aided by a decline in renewable energy costs, the share of renewable energy (mainly solar and wind) in the energy mix of many countries and regions grew (Zhong et al., 2020; Klemeš et al., 2020; Li et al., 2022). However, the rising uncertainty interfered with investment decisions and the completion of renewable projects (Tsao et al., 2021). Apart from scarce funding, factors, such as supply–chain delays, also hindered their finalisation (IEA, 2020a; 2020b).

This study analysed a panel of 27 EU countries for the period 2008 – 2020. The research aimed to identify important macroeconomic and social factors that promoted or hindered renewable energy consumption. Five **initial hypotheses** were formulated:

H1: GDP per capita as an approximation for economic development has a significant positive impact on renewable energy consumption.

H2: Research and development expenditure as an approximation for innovation has a significant positive impact on renewable energy consumption.

H3: Digitalisation, approximated by the frequency of internet use and electronic interaction with public authorities, has a positive impact on renewable energy consumption.

H4: Education is a significant factor for renewable energy consumption.

H5: High levels of greenhouse gas emissions influence renewable energy consumption negatively.

The data used in the analysis were sourced from Eurostat (Eurostat, 2023c), the World Bank (World Bank, 2023), the United Nations (UN, 2023b) and Climate Watch (2023). The thirteen variables of interest were closely linked to SDGs and the compilation of explanatory variables was made by the author based on extant literature and identification of new potentially influential factors. Macroeconomic variables, such as GDP per capita, research and development expenditure and trade openness had been previously found to influence renewable energy consumption. The role of the government was also considered in this paper via the regulatory quality index because of its potential positive impact (Ibarra–Yunez & Pérez–Henríquez, 2017). Digitalisation as an important driver of the renewable energy sector had been identified in various papers (Xu et al., 2022; Shahbaz et al., 2022; Haldar et al., 2023). This research focused on the potential effects of the frequency of internet use and digital government interactions. The effect of educational attainment on renewable energy consumption was tested in this study via a specific collective variable, EST (secondary, post–secondary and tertiary education).

Indicators, regarding the population, such as population density, population growth rate and urbanisation (Salim & Shafiei, 2014), were considered in view of their links to energy consumption. A number of studies (Pagliaro & Meneguzzo, 2020; Biernat–Jarka et al., 2021; Wang et al., 2022) had examined the alleviation effect of renewable energy on energy poverty. The current study, however, assumed a different approach and tested whether energy poverty itself influenced renewable energy consumption. Since other greenhouse gases, less known than CO_2, also contribute to climate change (Akarsu & Korucu–Gümüşoğlu, 2019; Naderipour et al., 2020), one more variable, greenhouse gas emissions per capita, was added to the list of potential factors.

To the best of the author's knowledge, this paper was the first to examine the specific impact of energy poverty, the frequency of internet use, digital government interactions, education (as approximated by EST) and greenhouse gas emissions per capita on the consumption of renewable energy. The study also contributed to existing literature by analysing a different period and set of countries.

Figure 15 shows the final and the renewable energy consumption of 27 EU member countries between 2008 and 2021. The year 2021 was not included in any further analysis. It was used only in the chart to gain a general insight into the post–Covid energy consumption.

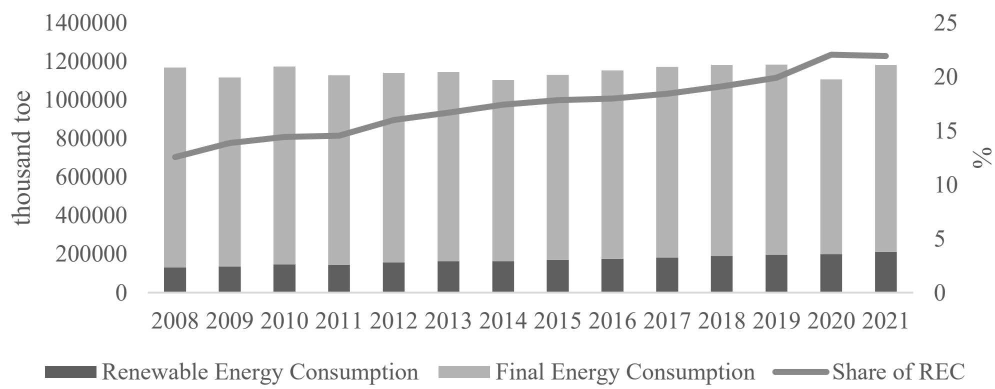

Figure 15. Average EU–27 energy consumption for the period 2008 – 2021. The chart was created by the author using Eurostat data (2023c).

Final energy consumption remained rather stable throughout the years, declining slightly in 2009 due to the Global Financial Crisis and in 2020 at the onset of the pandemic. Meanwhile, the share of renewable energy increased slowly but persistently, starting from 12.55% in 2008 to reach 19.89% in 2019 and jump to 22.04% in 2020. This marked a total increase of 74.70% over the 13–year period. However, 2021 brought a lower renewable energy share of 21.93%.

In the studied period, Sweden demonstrated strong leadership, followed by Finland, Latvia and Austria. Bulgaria kept the EU–average (about 17%), while the Netherlands, Belgium and Malta fell substantially behind their renewable energy targets. Looking at the data, a specific pattern emerged. Global crises reduced the final energy consumption and stimulated the renewable energy sector, but the impact was short–lived and matters quickly went back to pre–crises levels, slowing the growth of the renewable energy share. As much as financial and health crises challenge the world, they also bring it closer to the achievement of climate targets. Governments should take advantage of such events and prolong their effect on energy consumption through sound investment policies and incentives.

All further analysis was performed using logarithmically transformed data. The correlation analysis revealed a moderate correlation between REC and EST, REC and PGR, REC and TO, REC and UP at the 1% significance level (see the List of Abbreviations in the dissertation). Meanwhile, PD demonstrated a strong negative correlation with the dependent variable. There were also strong correlations between FIU and EG, EP and GDPPC, PGR and GDPPC (above 0.7). EG did not make it to the final models. As for the other two strong correlations, GDPPC and PGR were only used as control variables and were not of particular interest in the current study. Strong correlations may usually lead to multicollinearity. However, the choice of determinants was theoretically and/or practically justified and relationships between such explanatory variables are quite natural and expected in general, since economic, social and environmental determinants are interconnected.

The unit root tests revealed that variables were integrated at I(1) and the Kao cointegration test (Kao, 1999) rejected the null hypothesis at the 1% significance level suggesting that the variables demonstrated a stable long–run relationship. The results of the Dumitrescu and Hurlin causality tests (Dumitrescu & Hurlin, 2012) indicated that bidirectional causality ran between: EG and REC; FIU and REC; PD and REC; TO and REC; UP and REC. A unidirectional causal relationship ran from: EP to REC; EST to REC; GDPPC to REC, but it turned out that REC homogeneously caused GHGEPC. No homogeneous causality was revealed between renewable energy consumption and GRQ, PGR and RDE.

Two methods were used to estimate the panel data regression models and provide ground for robustness and comparison of the results: fixed effects (FE) and fully modified ordinary least squares (FMOLS). All estimation methods followed a forward selection procedure, beginning with a set of explanatory variables identified in extant literature and then testing the rest of the variables for significance. The coefficients of the variables of interest remained rather stable throughout the estimations. Additionally, the final models were rerun by including interaction terms of GDP and EP, FIU, GHGEPC, PGR, RDE as well as interaction terms of EP and FIU, RDE. All trials produced insignificant coefficients for both the interaction term and the variable of interest. Therefore, no statistically significant interaction between the control variables and those of interest was found and the relatively strong correlations mentioned earlier should not have influenced the estimation output substantially.

Table 14 shows the results of the FE estimations with White cross–section and period–cluster standard errors and covariances. The variables demonstrated consistency with respect to signs, significance and size of the effects. GDPPC, PD, RDE, EST, FIU and EP entered the models with positive signs, while GHGEPC, TO and UP had a negative effect on renewable energy consumption.

Table 14. FE estimations of the share of renewable energy consumption

Variable	**Coefficient**					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Constant	-33.953***	-32.265***	-30.283***	-30.478***	-29.566***	-10.296
	(6.113)	(2.967)	(3.035)	(3.409)	(2.878)	(10.338)
lnGDPPC	0.965***	0.438	0.177	0.377	0.518**	0.724***
	(0.184)	(0.262)	(0.264)	(0.242)	(0.187)	(0.201)
lnPD	5.617***	4.352***	4.555***	4.087***	4.013***	3.662***
	(1.186)	(0.839)	(0.807)	(0.772)	(0.731)	(0.672)
lnPGR	0.472	0.487	0.695	0.649	0.567	0.322
	(0.703)	(0.547)	(0.599)	(0.591)	(0.525)	(0.436)
lnRDE	0.745**	0.603**	0.520**	0.534**	0.580**	0.523**
	(0.307)	(0.212)	(0.189)	(0.191)	(0.201)	(0.190)
lnEST		2.240**	1.690	1.796*	1.803*	2.507***
		(0.972)	(0.965)	(1.000)	(0.935)	(0.827)
lnFIU			0.448**	0.399*	0.524***	0.513**
			(0.191)	(0.190)	(0.171)	(0.197)
lnEP				0.155***	0.200***	0.238***
				(0.051)	(0.062)	(0.074)
lnGHGEPC				-0.052	-0.071**	-0.103***
				(0.029)	(0.027)	(0.029)
lnTO					-0.532**	-0.56***
					(0.206)	(0.166)
lnUP						-5.221*
						(2.434)
R^2	0.922	0.946	0.948	0.951	0.953	0.957
R^2_{adj}	0.914	0.940	0.943	0.946	0.948	0.952
Observations	351	351	351	351	351	351
Periods	13	13	13	13	13	13

*Note: All variables are log–transformed. Standard errors are reported in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.*

The FE and FMOLS yielded similar results regarding the statistical significance of the variables. Table 15 presents the long–term coefficients from the FMOLS models. This time even PGR entered most models with a significant coefficient and a positive sign. Results from the econometric analysis supported all five initial hypotheses. Additional factors turned out to be significant drivers of the renewable energy consumption as well. Both FE and FMOLS showed that urbanisation, the population density, education and economic development have the largest impact on renewable energy consumption in terms of magnitude.

Table 15. FMOLS estimations of the share of renewable energy consumption

Variable	**Coefficient**					
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
lnGDPPC	0.853***	0.457***	0.279*	0.516***	0.591***	0.841***
	(0.129)	(0.127)	(0.168)	(0.168)	(0.167)	(0.166)
lnPD	5.697***	4.578***	4.660***	4.081***	4.132***	3.726***
	(0.500)	(0.454)	(0.457)	(0.455)	(0.445)	(0.428)
lnPGR	0.490**	0.453***	0.602***	0.537***	0.476***	0.190
	(0.191)	(0.166)	(0.181)	(0.171)	(0.169)	(0.168)
lnRDE	0.745***	0.581***	0.525***	0.538***	0.603***	0.535***
	(0.113)	(0.099)	(0.102)	(0.096)	(0.096)	(0.091)
lnEST		1.893***	1.604***	1.689***	1.665***	2.453***
		(0.265)	(0.328)	(0.312)	(0.304)	(0.340)
lnFIU			0.284	0.256	0.437**	0.422**
			(0.188)	(0.178)	(0.190)	(0.178)
lnEP				0.186***	0.228***	0.279***
				(0.042)	(0.045)	(0.043)
lnGHGEPC				-0.069	-0.093**	-0.135***
				(0.046)	(0.046)	(0.044)
lnTO					-0.543***	-0.570***
					(0.191)	(0.179)
lnUP						-5.511***
						(1.387)
R^2	0.936	0.952	0.952	0.954	0.956	0.958
R^2_{adj}	0.930	0.947	0.947	0.949	0.950	0.953
Observations	324	324	324	324	324	324
Periods	12	12	12	12	12	12

*Note: All variables are log–transformed. Standard errors are reported in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% level, respectively.*

Gross domestic product per capita (GDPPC) entered most models with a positive sign and high statistical significance. These findings and the established unidirectional supported the hypothesis that economic development exerts a positive influence on renewable energy consumption. While developed countries still heavily rely on non–renewable sources to meet their energy needs, they also allow for larger R&D spending to enhance innovation in the renewable energy sector, more environmentally friendly consumer decisions and better funding opportunities for green investment.

Research and development expenditure (RDE) had a significant positive influence on renewable energy consumption in all models. These results also confirmed previous findings. R&D is a source of innovation and further improvement of the existing green technologies. It helps reduce the input of energy and materials and the associated environmental impact of energy production. Moreover, R&D makes renewable technologies more cost–effective, productive and reliable, raising their competitiveness.

The frequency of internet use (FIU) was used to approximate for digitalisation in the current analysis. The internet provides access to a vast amount of information and educational resources and facilitates knowledge dissemination through various channels. Therefore, it raises awareness among businesses and the public regarding environmental challenges and ways to address them. Additionally, the internet promotes existing initiatives and financial incentives related to renewable energy projects. It also helps citizens participate more actively in public discussions and decision–making processes related to energy policies.

Education (EST) was another variable that entered the models with a positive sign and unidirectionally caused renewable energy consumption. Education enhances human capital through learning and implementation of the accumulated knowledge (Pfeiffer & Mulder, 2013). This can result in technological innovations, higher environmental awareness and change of energy consumption patterns (Ackah & Kizys, 2015).

Greenhouse gas emissions per capita (GHGEPC), as expected, influenced renewable energy consumption negatively. On the one hand, higher concentrations of greenhouse gases worsen the air quality and reduce the productivity of photovoltaic systems. On the other hand, countries with high emissions are usually more dependent on fossil fuels in general whether they exploit them locally or import them under favourable conditions.

Energy poverty (EP), surprisingly, turned out to have a small but positive statistically significant impact. There also existed a unidirectional causal relationship running from energy poverty to renewable energy consumption. A few possible explanations of this phenomenon can be provided. First, countries with higher levels of energy poverty consume less energy in total. This may lead to a relatively larger renewable share. Second, energy poverty usually stems from lack of affordable and easily accessible conventional energy sources, lack of relevant infrastructure, etc. Renewable energy ensures a cheaper and more sustainable alternative, as well as decentralised solutions that can meet the needs of isolated and energy–poor areas or communities.

Trade openness (TO) demonstrated a moderate negative correlation with the dependent variable and Models 5 and 6 further supported that finding. Pfeiffer and Mulder (2013) had discovered such an effect as well. In general, trade drives international competition and helps disseminate knowledge and new technologies. In the case of conventional energy exports, however, some countries may loosen regulations or lower their conventional energy prices to make the most of comparative advantages. Trade openness may also make energy–dependent countries import more foreign fossil fuels instead of developing their own renewable energy sources.

The **population density** (PD) was found to influence renewable energy consumption positively. However, in the correlation analysis it displayed a strong negative correlation with the dependent variable. The bidirectional causality running between the two variables is a potential source of bias in observational findings. Salim et al. (2014), for example, had shown that population density had a negative impact on non–renewable energy consumption but they had failed to detect any causality or a significant effect of the variable on renewable energy consumption. Morikawa (2012) had revealed that higher population density affected energy efficiency positively. Therefore, the improved energy efficiency may reduce overall energy consumption, while the higher population density may decrease non–renewable energy consumption. This, in turn, may increase the relative share of renewable energy.

The **population growth rate** (PGR) did not significantly impact renewable energy consumption at least in the short term. Malik et al. (2014), for example, had discovered a short–run negative influence of higher population growth rate on the consumption of renewable energy. This negative impact disappeared in the long term. The current study revealed that the population growth rate received positive long–run coefficients. An increasing population is a prerequisite for rising energy demand. It is important, however, how this demand is satisfied. It is of key importance whether it raises the dependence on fossil fuels or countries turn it into an opportunity to expand their renewable capacity in the future.

Urbanisation (UP) and its effects on renewable and non–renewable energy consumption are widely discussed and studies point to controversial impacts on the renewable energy consumption. The current research revealed a statistically significant and large in magnitude negative impact. Faster urbanisation means more energy demand and heavier air pollution resulting from higher energy intensity and more traffic. Another important aspect to consider is that people in large cities usually enjoy uninterrupted power supply and better living conditions compared to the rural population. Hence, they rarely think of the way energy is provided, resulting in lower environmental awareness. Despite the negative impacts of urbanisation, cities offer good opportunities for the sharing economy. Local authorities can support carbon neutrality by transitioning away from conventional energy sources and embracing sustainable alternatives.

3.4. Analysing Circular Economy Transition Models in the EU

Analysing the three circular indicators identified a number of factors that influence the transition to a circular economy in the EU. The results revealed that GDP per capita and the share of R&D expenditure are common determinants of all three indicators, while the resource productivity is common to the material indicators, the recycling and circularity rates.

Based on these determinants, certain circular economy transition models were distinguished in the EU. The models were produced through K–means clustering (MacQueen, 1967), a method allowing objects to be grouped according to similar characteristics. Observations of 27 EU member states in the period 2010 – 2021 were included in the analysis. All data were standardised beforehand. Table 16 presents the variables used in the models.

Table 16. Description of the variables

Abbreviation	Full name	Unit	Source
CR	Circularity Rate	%	Eurostat
RR	Recycling Rate	%	Eurostat
RE	Renewable Energy Consumption	%	Eurostat
GDPPC	GDP per capita	PPS pc	Eurostat
RDE	Research and Development Expenditure	%	The World Bank
RP	Resource Productivity	PPS pc	Eurostat

The optimal number of clusters was selected according to the silhouette coefficients that measure similarity. The procedure resulted in four clusters. Both K–means++ (Arthur & Vassilvitskii, 2007) and Random initialisations with a maximum of 300 iterations confirmed that the appropriate number of clusters is four. The distribution of all observations is represented in Figure 18.

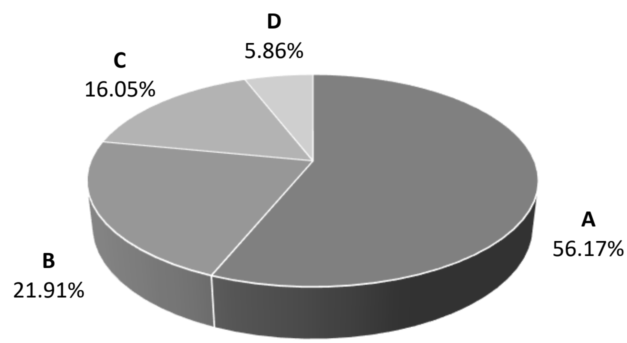

Figure 18. Frequency distribution of the observations

The fourth cluster contained observations from two countries only, yet it made sense to consider them separately from the rest. The silhouette coefficient was higher in this case and the specific countries demonstrated somewhat abnormal values which might have influenced the characteristics of the other clusters if merged. Figure 19 shows radar charts of the circular economy transition models in the EU according to the six main characteristics considered. The positive numbers indicate above–average values, while the negative ones indicate below–average values.

Model 'A' turns out to be the most common but it also lags behind in the circular economy transition. Here, the values of all selected indicators are below the EU average. GDP per capita points to less economically developed countries. The lowest recycling rate among all clusters defines a potential lack of secondary raw materials and leads to the lowest circularity rate. These unflattering characteristics are further solidified through lower–than–usual resource productivity. Surprisingly, although the share of renewable energy in Model 'A' remains below the average, it still ranks second among all clusters. A possible explanation is that the lower income and a likely lack of domestic fossil fuels limit the overall energy consumption and encourage the development of local renewable sources.

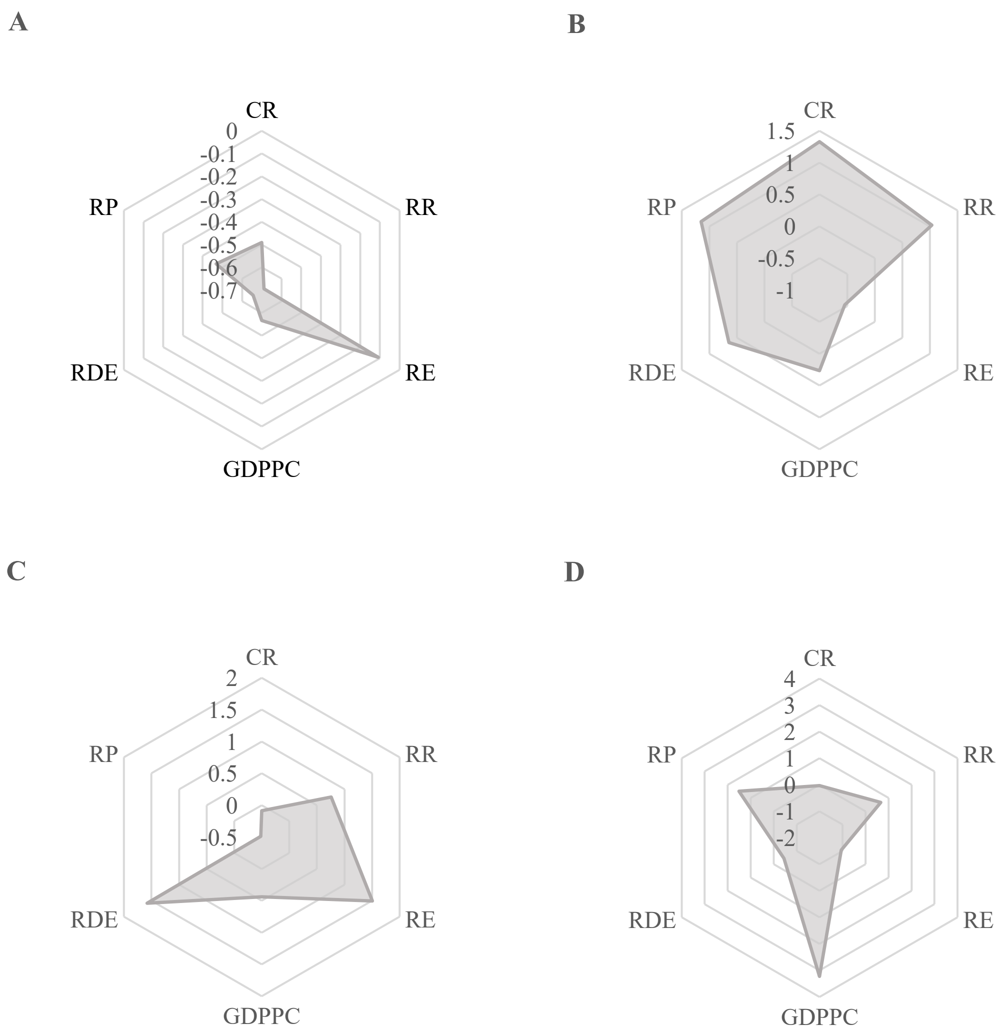

Figure 19. Circular economy transition models in the EU: A. Lagging behind; B. Leading the transition; C. Energy efficient; D. Resource efficient. Note the different scaling of the clusters.

Model 'B' perhaps represents the most successful approach to the circular transition. It is typical of relatively rich countries spending significantly above the average budget on R&D. However, the chart reveals that even strong economies can fall behind in the energy transition. This suggests that they have initiated a successful transformation of their economic systems, focusing on resource productivity and innovation, but they are yet to fully secure the energy pillar, decoupling growth from fossil fuels.

Model 'C' again characterises some of the wealthiest economies. However, their high living standard leads to a high resource intensity to meet the growing demand for goods and services. Although these countries have the highest share of R&D expenditure and prioritise sustainability and innovation, they appear to be more focused on the energy transition rather than material recirculation. This is evident from the lowest resource productivity among all groups and an insufficient reintroduction of secondary raw materials into the economy. On the other hand, the model indicates an effective and consistent waste management policy, achieving recycling rates well above the EU average.

Model 'D' is an intriguing case. It is the smallest group but it is quite different from the rest. This model has the highest GDP per capita. Despite having R&D expenditure and renewable energy share below the EU average, as well as a borderline circularity rate, it demonstrates an outstanding resource productivity. These countries seem to function in a *'more–with–less'* mode. It can prove quite beneficial in the long term since it is well known that that better resource utilisation goes hand in hand with waste prevention, which is always preferred to the treatment of already generated waste. Economies identifying with Model 'D' can further benefit from an increased R&D investment to enhance their renewable energy sector and improve their ability to refeed recycled materials into their economies.

An earlier study based on the system of indicators in the European monitoring framework had derived three transformation models, differentiating specific patterns: a leader, a laggard, and a cluster with mixed characteristics, similar to the successful model (Иванова, 2022).

The three circular indicators, along with their determinants, are of crucial importance for the current state and future development of the circular economy in the EU. The cluster analysis helped identify intriguing nuances in the performance of different groups. It turns out that the wealthiest countries are not always the most circular. Despite their differences, however, the four economic models share the common goal of achieving material and energy sustainability in the long term. Each economy needs to find the right balance to capitalise on its strengths and mitigate its weaknesses. Understanding the characteristics of a particular economic system and the factors influencing its performance aids in making informed policy decisions to achieve sustainable development and overcome economic and environmental challenges.

Conclusion and Contributions

This research reveals the influence of various macro–level determinants on three key circular economy indicators: the recycling rate, the circularity rate and the share of energy consumption from renewable sources.

The recycling rate of municipal waste depends on the level of economic development, research and development and resource productivity of countries. Landfill bans on various types of waste are no less important as they also contribute to an increasing recycling rate. The circular material use rate is influenced by the same three factors. However, instead of landfill bans, environmental taxes play an additional role here. Furthermore, a unidirectional Granger causality is found in the case of R&D expenditure and resource productivity.

The third indicator, namely the share of renewable energy consumption, is still not included in the EU monitoring framework but needs to be tracked in favour of both the energy transition and the development of circular systems. A unidirectional Granger causality runs from economic development, education and energy poverty to the renewable energy consumption. In addition to economic development and R&D, education, digitalisation, energy poverty and the population growth rate have a positive impact as well. Meanwhile, the indicator is negatively influenced by the openness of the economy, urbanisation and per capita greenhouse gas emissions.

Three factors serve as the intersection among the different indicators. GDP per capita is identified as the most influential determinant of renewable energy consumption, a 1% increase can raise its share in gross final energy consumption by 0.52% – 0.97%. The effects of GDP per capita on the recycling and circularity rates are 0.15% and 0.34%, respectively. Research and development expenditure as a share of GDP generates significant impacts on all indicators. A 1% increase in R&D expenditure can increase the recycling rate, circularity rate and renewable energy consumption by 0.60%, 0.39%, and 0.52 – 0.75%, respectively. Resource productivity, in turn, positively influences the recycling and circularity rates by 0.27% and 0.36%, respectively. With the help of these three indicators and their common determinants, four circular economy transition models can be outlined in the European Union. They differ in terms of economic progress and priorities in the field of the circular economy. However, both strengths and weaknesses have the potential to play a positive role in the transition.

A few recommendations can be made considering the main results and conclusions:

1) It is recommended that the EU Circular Economy Monitoring Framework incorporate more energy and environmental aspects.
2) It is recommended that more incentives for circular design be provided. This is a key prerequisite for waste prevention, rather than focusing on the subsequent treatment of generated waste.

3) It is recommended that investments in research and development be further encouraged when they are not sufficiently prioritised. This should improve resource productivity and energy efficiency, as well as technologies related to material recovery and renewable energy.
4) To increase the recycling and circularity rates, a wide range of tools can be implemented, including subsidies, preferential financing of technological innovations, regulatory measures related to eco–design, environmental taxation and raising awareness among businesses and the public. It is also important to introduce landfill bans on certain waste streams so that municipalities undertake measures for separate collection and treatment.
5) To promote the renewable energy sector, various tools can be used, such as guaranteed purchase of the renewable energy, feed–in tariffs, tax incentives and subsidies, or green finance for projects related to renewable energy sources. Sustainability concepts should be integrated into all educational programmes and professional development courses. To support the energy transition, governments can introduce specific urban planning regulations, offer financial incentives to increase energy efficiency, and raise awareness to engage communities. Meanwhile, actions to slow down urbanisation can be undertaken, such as providing incentives to live and work in rural areas.

The results reported in this dissertation should be considered in light of certain limitations. First, not all the important circular indicators or all potentially significant determinants were considered. Second, the sample was limited in space and time, due to its focus on the European Union and time–series data availability. However, these limitations present an opportunity for future research. Consequent studies can examine other circular indicators and identify and evaluate different economic, social and environmental factors. Other countries can be included as well to expand the sample or provide ground for comparisons between the European Union and the rest of the world. Further research on the topic can also take into account the consequences of the COVID–19 pandemic, the economic crisis, the Russia–Ukraine war and revised priorities related to the European Green Deal.

Considering the abovementioned limitations, this dissertation attempts to overcome the fragmentation of knowledge on the topic of the circular economy by distinguishing it from sustainable development, providing a more precise definition, suggesting improvements to the EU monitoring framework, and, most importantly, highlighting key determinants, the collective impact of which can significantly influence the transformation. The information provided can benefit various stakeholders in science, business, and politics who are conducting similar research, considering a transformation of their business models, or developing policies and legislation related to the circular economy.

The dissertation **contributes** to theory and practice in the field of circular economy in the following ways:

1) In consideration of the key aspects of the circular economy concept, including its essence, main principles, practical measures, objectives and benefits, a new definition of the circular economy was formulated to enhance its interpretation.
2) In consideration of some shortcomings of the EU monitoring framework on the circular economy, appropriate energy, environmental and product–life indicators were identified to address gaps and provide a more comprehensive assessment of the circular economy in the European Union.
3) The analysis of two commonly used circular economy metrics related to materials, namely the recycling rate of municipal waste and the circular material use rate, confirmed the positive influence of factors, such as economic development, research and development and resource productivity. Additionally, it was found that landfill bans increase the recycling rate, while increased resource productivity and environmental tax revenues enhance circularity.
4) One of the most suitable circular metrics from an energy perspective is the share of renewable energy consumption in gross final energy consumption. The analysis confirmed the positive impact of factors, such as economic development, research and development and population density, along with the negative impact of trade openness and urbanisation. Furthermore, determinants, such as the share of people with secondary, post–secondary or higher education, a more frequent internet use, facilitating information sharing, potential increases in the energy poverty, and long–term increases in the population growth rate were found to exert a positive influence. However, greenhouse gas emissions per capita were found to reduce the consumption of renewable energy.
5) Four circular economy transition models in the EU were identified through cluster analysis based on the three circular indicators and their determinants.

Publications Related to the Topic of the Dissertation

1. **Pantcheva, R., & Mengov, G.** (2022). Recycling Rate in Europe: Econometric modeling and dART clustering analysis. *2022 International Conference Automatics and Informatics (ICAI)*, 179–182. doi:10.1109/icai55857.2022.9960075. Indexed in **SCOPUS**.
2. **Pantcheva, R.** (2023). Circular Use of Materials: Drivers of the Circularity Rate in the European Union. *Economic Studies (Ikonomicheski Izsledvania)*, *32*(3), 148–161. Indexed in **SCOPUS**.
3. **Pantcheva, R.** (2023). Circular Economy Awareness in Bulgaria. *Yearbook of the Faculty of Economics and Business Administration*, *22*(1), 109–124.
4. **Pantcheva, R.** (2024). Economic and Social Drivers of Renewable Energy Consumption in the European Union: An Econometric Analysis. *Economic Studies (Ikonomicheski Izsledvania), in press*. Indexed in **SCOPUS**.

Other publications:

Gerunov, A., Atanasov, I., Yanchev, M., Shalvardjiev, D., Mengov, G., Egbert, H., Dineva, L., Pantcheva, R., & Korcheva, A. (2024). Drivers of perceptions towards euro adoption among the young: evidence from Bulgaria. *Access*, *5*(2), 185–206. doi: 10.46656/access.2024.5.2(1). Indexed in **Web of Science**.

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