

Article

Sustainable Development Regimes, Transition Dynamics and Environmental Performance in the European Union

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Abstract

Sustainable development has become a strategic priority for the European Union in response to climate change, resource constraints and environmental degradation. Despite common policy objectives, Member States exhibit substantial differences in sustainability performance and transition capacities. This study investigates sustainable development pathways in the European Union using an integrated framework combining cluster analysis, transition analysis, panel econometrics and a conceptual Petri Net model. The empirical analysis is based on a balanced panel dataset covering the 27 EU Member States during the period 2015–2024. K-means clustering was employed to identify sustainable development regimes, transition matrices were used to evaluate regime persistence, and panel data models were estimated to examine the determinants of environmental performance measured through greenhouse gas emissions per capita. The results confirm the existence of four distinct sustainable development regimes characterized by different combinations of economic performance, environmental pressure and resource efficiency. Transition analysis confirms heterogeneous transition dynamics characterized by a generally high degree of regime persistence, while only a limited number of countries experienced regime changes during the study period. The econometric findings confirm that renewable energy deployment and resource productivity are the principal determinants associated with lower greenhouse gas emissions. Based on these results, a Petri Net framework was developed to represent alternative sustainability pathways and transition mechanisms. The integrated analytical framework confirms that combining sustainability regime identification, transition dynamics, panel econometric modelling and conceptual Petri Net representation provides a more comprehensive understanding of sustainable development pathways in the European Union. The findings provide relevant insights for policymakers seeking to support the transition towards more sustainable development trajectories in the European Union.



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1. Introduction

Sustainable development has become one of the defining policy priorities of the twenty-first century, driven by increasing concerns regarding climate change, environmental degradation, resource scarcity and socio-economic inequalities. Since the publication of the Brundtland Report, sustainable development has been understood as a development

pathway capable of meeting present needs without compromising the ability of future generations to satisfy their own needs [1]. This perspective has progressively shaped international policy agendas, particularly following the adoption of the United Nations 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals, which established an integrated framework for promoting economic prosperity, social inclusion and environmental protection [2].

Growing scientific evidence regarding the consequences of climate change has reinforced the urgency of accelerating the transition towards more sustainable development models. According to recent assessments of the Intergovernmental Panel on Climate Change-IPCC, achieving climate neutrality and limiting global warming require profound transformations in energy systems, production processes and consumption patterns [3]. Consequently, decarbonization, renewable energy deployment and resource efficiency have become central elements of international sustainability strategies. These priorities are closely aligned with the objectives established under the Paris Agreement, which provides the global framework for greenhouse gas mitigation and climate resilience [4].

Within this global context, the European Union has emerged as one of the leading actors in promoting sustainability-oriented policies. The European Green Deal, the Fit for 55 package and the REPowerEU strategy constitute key components of the European policy framework aimed at reducing greenhouse gas emissions, accelerating the energy transition and improving resource efficiency [5–7]. Together, these initiatives reflect the growing recognition that long-term economic competitiveness and societal well-being depend on the ability of European economies to reconcile economic growth with environmental sustainability.

Despite the existence of common sustainability objectives at the European Union level, Member States continue to exhibit substantial differences in their economic structures, energy systems, resource use patterns and environmental performance. Recent assessments indicate that progress towards sustainable development remains uneven across the European Union, with some countries achieving significant advances in renewable energy deployment, circular economy implementation and greenhouse gas emission reduction, while others continue to face considerable challenges associated with carbon-intensive production structures and resource consumption patterns [8–11].

These disparities highlight the complexity of sustainable development and the difficulty of simultaneously achieving economic, environmental and social objectives. Sustainable development is increasingly viewed as a multidimensional process influenced by institutional capacity, technological innovation, policy frameworks and socio-economic conditions [12–14]. Consequently, countries with comparable levels of economic development may follow different sustainability trajectories and display distinct capacities to respond to environmental and climate-related challenges.

The growing recognition of these differences has stimulated a substantial body of research aimed at identifying the factors that shape sustainable development performance. Existing studies have frequently emphasized the role of renewable energy, resource efficiency, circular economy practices, innovation and human capital in supporting environmentally sustainable growth [15–19]. Nevertheless, empirical evidence remains heterogeneous, suggesting that the effectiveness of these factors depends on national contexts, institutional arrangements and the interaction between economic and environmental policies [20–22].

As a result, sustainable development cannot be interpreted as a uniform process affecting all countries in the same manner. Rather, it may involve multiple pathways characterized by different combinations of economic growth, environmental performance and resource utilization patterns. Understanding these differences is essential for designing

effective sustainability policies and for assessing the capacity of Member States to achieve long-term environmental and climate objectives.

A substantial body of literature has investigated the determinants of environmental performance and sustainable development. Among the factors most frequently examined, renewable energy has received considerable attention due to its potential to reduce greenhouse gas emissions and facilitate the transition towards low-carbon economies. Numerous studies have reported a negative relationship between renewable energy consumption and environmental degradation, suggesting that the expansion of renewable energy sources contributes significantly to climate change mitigation and sustainable growth [23,24].

Another important research stream focuses on resource productivity and circular economy practices. The efficient use of resources has been increasingly recognized as a key component of sustainable development, as it allows economies to generate higher levels of economic output while reducing material consumption and environmental pressure. Circular economy strategies aim to improve resource efficiency through reuse, recycling and waste reduction, thereby contributing to environmental sustainability and economic competitiveness [25–28]. Nevertheless, empirical evidence regarding the magnitude and consistency of these effects remains mixed, particularly across countries characterized by different economic and institutional conditions.

Innovation and human capital have also been identified as important drivers of sustainable development. Endogenous growth theory suggests that technological progress and knowledge accumulation play a central role in promoting long-term economic development while improving environmental performance [29,30]. More recent studies emphasize that investments in education, research and development enhance the capacity of economies to adopt cleaner technologies, improve energy efficiency and support sustainability transitions [31].

In addition, several studies have highlighted the role of environmental policy instruments, including environmental taxation and regulatory frameworks, in influencing environmental outcomes and encouraging the adoption of sustainable production and consumption patterns [32]. However, the effectiveness of such instruments often depends on the broader economic and institutional context in which they are implemented.

Although these studies provide valuable insights into the determinants of sustainable development, most of them focus primarily on the direct relationships between individual variables and environmental indicators. As a result, considerably less attention has been devoted to understanding how countries evolve between alternative sustainability configurations and whether distinct development pathways can be identified over time.

Beyond the analysis of individual sustainability indicators, a growing body of research emphasizes the importance of understanding sustainable development as a dynamic and evolutionary process. Recent studies suggest that countries may follow different sustainability pathways shaped by historical development patterns, institutional structures, technological capabilities and policy choices [33–35]. These pathways are often characterized by persistence, path dependency and lock-in effects, which may either facilitate or constrain transitions towards more sustainable forms of development [36,37].

In this context, several scholars have argued that sustainability assessments should move beyond static evaluations and incorporate a stronger dynamic perspective capable of capturing structural transformations over time [38–40]. Such an approach is particularly relevant for the European Union, where Member States differ considerably in their economic structures, environmental performance and capacity to implement sustainability-oriented policies. Consequently, countries may not only display different levels of sustainability performance but may also follow distinct trajectories and transition patterns.

Despite the growing literature on sustainable development, relatively limited attention has been devoted to the identification of sustainability regimes and the analysis of transitions between them. Existing studies typically focus either on measuring sustainability performance or on estimating the determinants of environmental outcomes, while fewer investigations examine the persistence of development regimes and the mechanisms that drive movements between alternative sustainability states [38]. Furthermore, the integration of sustainability typologies, transition dynamics and environmental performance analysis within a unified analytical framework remains relatively underexplored.

To address this gap, the present study develops an integrated framework for analysing sustainable development pathways in the European Union. The research pursues three main objectives. First, it identifies distinct sustainable development regimes among EU Member States using a multidimensional set of economic, environmental and energy-related indicators. Second, it investigates the transition dynamics between these regimes and evaluates their degree of persistence over time. Third, it examines the factors associated with environmental performance through panel econometric analysis and integrates the empirical findings into a conceptual Petri Net framework capable of representing sustainable development pathways and transition mechanisms.

Recent research has considerably expanded the analytical perspectives adopted for investigating sustainable development, with increasing attention devoted to sustainability transitions, environmental performance, renewable energy deployment, resource productivity, and multidimensional assessment frameworks [39–42]. At the same time, advances in quantitative analytical methods have strengthened the empirical investigation of sustainability determinants and environmental outcomes, particularly through the application of panel econometric techniques and integrated assessment approaches [43–46]. Nevertheless, these research directions have generally evolved independently, while relatively limited attention has been devoted to integrating sustainability regime identification, transition dynamics, econometric modelling, and conceptual system representation within a unified analytical framework capable of simultaneously explaining regime persistence, transition mechanisms, and environmental performance across European Union Member States.

Unlike previous studies, which generally examine sustainability performance, transition dynamics, or environmental determinants separately, the present study develops an integrated analytical framework combining sustainability regime identification, transition analysis, panel econometrics, and conceptual Petri Net modelling [47]. This integrated approach enables a comprehensive assessment of how European Union Member States evolve across alternative sustainable development regimes while simultaneously explaining the persistence of these regimes, the mechanisms underlying transition dynamics, and the determinants of environmental performance. By integrating these complementary analytical dimensions within a single methodological architecture, the study contributes to the sustainable development literature by providing a more comprehensive understanding of sustainable development pathways and environmental transitions in the European Union.

2. Materials and Methods

2.1. Data and Variables

The empirical analysis is based on a balanced panel dataset covering the 27 Member States of the European Union over the period 2015–2024. The selected period captures recent developments in environmental, economic and energy performance across the European Union and provides a consistent framework for analysing sustainable development patterns over time. All data were obtained from the Eurostat database, which represents the official statistical source for monitoring economic, social and environmental indicators within the European Union.

The selection of variables was guided by the multidimensional nature of sustainable development and by the objective of capturing its principal economic, environmental, energy and innovation-related dimensions. Greenhouse gas emissions per capita—GHG were employed as the dependent variable because they constitute one of the most widely used indicators of environmental performance and progress towards climate neutrality objectives.

The explanatory variables include gross domestic product per capita—GDP, renewable energy share—Renewable, circular material use rate—Circular, resource productivity—ResourceProd, research and development expenditure—RD, tertiary educational attainment—Education and environmental tax revenues—EnvTaxes. These indicators were selected to represent the main drivers frequently associated with sustainable development, including economic growth, energy transition, circular economy practices, innovation capacity, human capital development and environmental policy instruments.

Prior to the empirical analysis, all variables employed in the clustering procedure were standardized using z-score normalization, as shown in Equation (1), in order to eliminate scale effects and ensure comparability among indicators measured in different units. Standardization is commonly recommended in multivariate classification methods because variables characterized by larger numerical ranges may otherwise dominate the clustering process [48,49].

$$z_i = \frac{x_i - \bar{x}}{s} \quad (1)$$

where x_i denotes the observed value, $\bar{x}$ represents the sample mean and s corresponds to the standard deviation.

Table 1 provides a summary of the variables used in the empirical analysis, including their definitions, measurement units and data sources.

Table 1. Description of variables used in the analysis.

Variable	Description	Unit
GHG	Greenhouse gas emissions per capita	tonnes CO ₂ -eq per capita
GDP	Gross domestic product per capita	EUR per capita
Renewable	Share of renewable energy in gross final energy consumption	%
Circular	Circular material use rate	%
ResourceProd	Resource productivity	EUR/kg
RD	Research and development expenditure	% of GDP
Education	Tertiary educational attainment	% of population
EnvTaxes	Environmental tax revenues	% of GDP

Source: Authors' calculations based on Eurostat data [50–54].

2.2. Identification of EU Country Clusters by Sustainable Development Profile

The first stage of the analysis aimed to identify distinct sustainable development regimes among the Member States of the European Union. To achieve this objective, K-means clustering was employed. K-means is one of the most widely used unsupervised classification techniques and is designed to partition observations into relatively homogeneous groups based on their similarity across multiple dimensions [55,56].

The method seeks to minimize within-cluster variability while maximizing differences between clusters. Formally, the K-means algorithm partitions observations into K clusters by minimizing the within-cluster sum of squares—WCSS, as shown in Equation (2):

$$WCSS = \sum_{k=1}^K \sum_{i \in C_k} (x_i - \mu_k)^2 \quad (2)$$

where C_k represents cluster k , x_i denotes an observation assigned to that cluster and μ_k corresponds to the cluster centroid.

The clustering procedure was applied to the standardized sustainability indicators described in Section 2.1. K-means has been widely adopted in sustainability assessments, regional development studies and environmental analyses because of its simplicity, robustness and ease of interpretation [57,58].

The number of clusters was determined through an iterative evaluation process that considered cluster interpretability, internal homogeneity and consistency with the theoretical dimensions of sustainable development. Alternative clustering solutions were examined, and the four-cluster specification was selected because it provided the most meaningful representation of the diversity of sustainability profiles observed among European Union Member States.

The final clustering solution identified four distinct sustainable development regimes characterized by different combinations of economic performance, environmental pressure, energy transition and resource efficiency. Rather than representing purely statistical groupings, these clusters were interpreted as alternative sustainability regimes reflecting different development pathways within the European Union.

The identified regimes subsequently served as the basis for the transition analysis and for the development of the Petri Net simulation framework presented in the following sections.

2.3. Transition Analysis

While cluster analysis provides a static classification of countries according to their sustainability profiles, it does not capture how these profiles evolve over time. To address this limitation, a transition analysis was conducted in order to investigate the dynamics of movement between sustainable development regimes and to evaluate the stability of the identified clusters throughout the study period.

The analysis was based on transition matrices recording movements between regimes in consecutive years. This approach is conceptually related to transition-based modelling frameworks that have been widely applied to investigate dynamic systems, regime persistence and sustainability transformations [59]. Transition matrices provide a concise representation of regime persistence, mobility patterns and the potential evolution of observations between alternative development states.

For each Member State, the cluster assignment obtained through the K-means procedure was tracked over the entire period 2015–2024. The resulting transition matrix enabled the identification of stable regimes, transitions towards more sustainable development configurations and possible movements towards less sustainable states. Particular attention was devoted to persistence rates, defined as the proportion of observations remaining within the same regime over time, as these rates provide valuable insights into the structural stability of different development pathways.

The transition analysis complements the static classification generated through cluster analysis by introducing a temporal dimension into the assessment of sustainable development. Rather than focusing exclusively on differences between countries at a given moment, this approach makes it possible to evaluate the degree of stability, transformation and path dependency characterizing sustainability trajectories within the European Union.

The results of the transition analysis were subsequently used to identify dominant development pathways and to provide the empirical basis for the conceptual Petri Net framework developed in the final stage of the research.

2.4. Panel Econometric Analysis

To investigate the factors associated with environmental performance across the European Union, panel econometric models were estimated using greenhouse gas emissions per capita as the dependent variable. Panel data analysis combines cross-sectional and time-series information, allowing the simultaneous examination of differences between countries and changes occurring over time. Compared with purely cross-sectional or time-series approaches, panel models provide more efficient estimates and allow the control of unobserved heterogeneity across observational units [60,61]. The general specification of the panel regression model is presented in Equation (3):

$$\begin{aligned} GHG_{it} = & \beta_0 + \beta_1 GDP_{it} + \beta_2 Renewable_{it} + \beta_3 Circular_{it} \\ & + \beta_4 ResourceProd_{it} + \beta_5 RD_{it} + \beta_6 Education_{it} \\ & + \beta_7 EnvTaxes_{it} + u_i + \varepsilon_{it} \end{aligned} \quad (3)$$

where

GHG_{it} represents greenhouse gas emissions per capita in country i during year t ;

GDP_{it} denotes gross domestic product per capita;

$Renewable_{it}$ represents the share of renewable energy in gross final energy consumption;

$Circular_{it}$ denotes the circular material use rate;

$ResourceProd_{it}$ represents resource productivity;

RD_{it} denotes research and development expenditure;

$Education_{it}$ represents tertiary educational attainment;

$EnvTaxes_{it}$ denotes environmental tax revenues;

u_i captures unobserved country-specific effects;

ε_{it} represents the random error term.

The subscript i refers to the Member States of the European Union ($i = 1, \dots, 27$), while t denotes the annual observations covering the period 2015–2024.

The econometric specification was designed to capture the multidimensional nature of sustainable development by jointly considering economic performance, energy transition, resource efficiency, human capital, and environmental policy variables. These complementary dimensions represent key components of sustainability strategies within the European Union and enable the investigation of their combined influence on environmental performance, measured through greenhouse gas emissions per capita. Consequently, the model provides an integrated analytical framework for examining how different sustainability drivers interact in shaping environmental outcomes across European Union Member States.

The empirical analysis was performed in three stages. First, a Pooled Ordinary Least Squares—Pooled OLS model was estimated to provide a baseline assessment of the relationships between the selected variables and environmental performance. Although straightforward and widely applied, this specification assumes homogeneity across countries and ignores potential country-specific effects [62].

Second, a Fixed Effects—FE model was estimated to account for unobserved characteristics that remain constant within countries over time. This specification focuses on within-country variation and controls for time-invariant country-specific factors [63].

Third, a Random Effects—RE model was estimated under the assumption that country-specific effects are randomly distributed and uncorrelated with the explanatory variables. In comparison with the Fixed Effects estimator, the Random Effects approach exploits both within-country and between-country variation and may therefore provide more efficient estimates when its assumptions are satisfied [61,62].

To determine the most appropriate specification, the Hausman test was employed. The test evaluates whether individual effects are correlated with the explanatory variables

and therefore provides a formal criterion for selecting between Fixed Effects and Random Effects estimators [63]. The preferred specification was subsequently used to identify the principal determinants of environmental performance and to support the interpretation of sustainable development pathways within the European Union.

2.5. Petri Net Modelling Approach

To complement the cluster and econometric analyses, a Petri Net simulation framework was developed to represent the dynamics of sustainable development pathways within the European Union. Petri Nets are mathematical and graphical modelling tools designed to represent systems characterized by discrete states, transitions and dynamic interactions between system components [64,65]. Owing to their capacity to describe complex systems involving multiple states, feedback mechanisms and alternative evolution pathways, Petri Nets have been increasingly recognized as useful instruments for analysing transition processes and system dynamics.

In the proposed framework, the sustainable development regimes identified through the clustering procedure were represented as places within the Petri Net structure. The transitions between places were defined on the basis of the empirical evidence obtained from the transition matrix analysis and the panel econometric models. This approach enables the representation of both stable development trajectories and potential movements between alternative sustainability regimes.

The conceptual model includes four principal states corresponding to the sustainable development regimes identified in the empirical analysis: Brown Growth, Green Growth, Growth-Intensive Economy and Sustainable Development. Transitions between these states are associated with changes in the factors identified as relevant for environmental performance, particularly renewable energy deployment, improvements in resource productivity and the accumulation of human capital. In addition, the model incorporates feedback mechanisms and path-dependency effects that may facilitate or constrain transitions towards more sustainable development pathways.

Unlike purely statistical approaches, the Petri Net framework provides a visual and dynamic representation of sustainability trajectories. The integration of cluster analysis, transition dynamics and panel econometric evidence within a single conceptual framework allows a more comprehensive understanding of how Member States evolve between alternative sustainability regimes and which factors facilitate or hinder these transitions.

The Petri Net simulation is not intended to predict future developments but rather to provide a conceptual representation of the mechanisms underlying sustainable development pathways. Consequently, the framework serves as an analytical tool for interpreting regime persistence and for exploring the potential effects of different transition drivers identified in the empirical analysis.

2.6. Research Hypotheses

Building on the theoretical background and the research gap identified in the previous section, the present study is guided by the following research hypotheses, which provide the conceptual framework for the empirical analyses presented in the subsequent sections.

H1. *European Union Member States can be classified into distinct sustainable development regimes characterized by different combinations of economic performance, renewable energy deployment, resource productivity, circular material use, educational attainment, environmental taxation, and greenhouse gas emissions.*

H2. *Sustainable development regimes exhibit different transition dynamics and varying degrees of persistence over time, reflecting heterogeneous pathways towards sustainability among European Union Member States.*

H3. *Renewable energy deployment, resource productivity, and selected socio-economic factors significantly influence environmental performance, measured by greenhouse gas emissions per capita.*

H4. *The combined analysis of sustainability regimes, transition dynamics, and environmental determinants provides a more comprehensive understanding of sustainable development pathways in the European Union than the separate examination of these dimensions.*

3. Results

Differences among European Union Member States in terms of economic performance, energy transition, circular economy development and innovation capacity reveal the existence of distinct sustainable development patterns. During the period 2015–2024, these differences extended beyond variations in the levels of the analysed indicators and reflected unequal capacities to respond to the objectives of the green transition. Consequently, the assessment of sustainable development requires more than the examination of statistical relationships between variables; it also requires an understanding of how countries cluster into similar development regimes and how they move between these regimes over time.

The application of the K-means clustering method identified distinct sustainable development regimes characterized by specific combinations of economic performance, resource efficiency, renewable energy deployment, innovation capacity and environmental pressure. The analysis of transitions between these regimes provides a dynamic perspective on sustainable development, making it possible to identify both pathways of progress and situations of persistence or regression. This perspective is complemented by panel econometric models, which identify the factors associated with lower environmental pressure and with the advancement towards regimes characterized by higher levels of sustainability performance.

3.1. Descriptive Profile of EU Sustainable Development Indicators

The descriptive statistics reveal substantial differences among European Union Member States in terms of economic performance, energy transition and the broader dimensions of sustainable development (Table 2). The minimum and maximum values recorded for the analysed indicators highlight the persistence of structural disparities between highly developed economies and countries that continue to undergo convergence processes. These differences are particularly pronounced in the case of GDP per capita, research and development expenditure, and resource productivity, reflecting unequal capacities to support innovation, improve resource efficiency and advance the objectives of the green transition.

The relatively high dispersion observed in renewable energy, circular economy and greenhouse gas emission indicators demonstrates that sustainable development does not follow a uniform trajectory across the European Union. While some Member States have achieved substantial progress in expanding renewable energy use and improving resource efficiency, others continue to experience comparatively high levels of environmental pressure. These differences support the identification of distinct sustainable development regimes and justify the use of a classification approach that groups Member States according to similar sustainability profiles.

Table 2. Descriptive statistics of the variables included in the analysis.

Variable	Mean	Std. Dev	Min	Max
GDP	102.304	43.184	49	279
Renewable	23.58	12.256	4.987	66.393
GHG	7.501	3.277	−0.6	17.5
Circular	9.502	6.688	1.3	32.7
ResourceProd	1.896	1.17	0.3	6.047
RD	1.678	0.89	0.45	3.64
Education	42.817	9.294	22.5	65.2
EnvTaxes	7.153	2.194	2.86	15.32

Source: Authors' calculations based on Eurostat data [50–54].

The correlation matrix (Table 3) reveals consistent relationships among the indicators included in the analysis. Greenhouse gas emissions are negatively correlated with renewable energy share and resource productivity, indicating that improvements in energy performance and more efficient resource use are associated with lower levels of environmental pressure. At the same time, the relationships observed between research and development expenditure, educational attainment and sustainability indicators highlight the importance of innovation and human capital in supporting the transition towards development models characterized by lower emissions and higher economic efficiency (Table 3).

Table 3. Correlation Matrix of Sustainable Development Indicators.

	GDP	Renewable	GHG	Circular	ResourceProd	RD	Education	EnvTaxes
GDP	1	−0.194	0.528	0.179	0.699	0.244	0.53	−0.496
Renewable	−0.194	1	−0.442	−0.219	−0.318	0.417	0.022	−0.063
GHG	0.528	−0.442	1	0.182	0.272	0.062	0.216	−0.038
Circular	0.179	−0.219	0.182	1	0.658	0.378	0.082	−0.198
ResourceProd	0.699	−0.318	0.272	0.658	1	0.331	0.406	−0.409
RD	0.244	0.417	0.062	0.378	0.331	1	0.113	−0.409
Education	0.53	0.022	0.216	0.082	0.406	0.113	1	−0.322
EnvTaxes	−0.496	−0.063	−0.038	−0.198	−0.409	−0.409	−0.322	1

Source: Authors' calculations based on Eurostat data [50–54].

The descriptive results confirm the existence of substantial heterogeneity among European Union Member States and provide a strong rationale for investigating distinct sustainable development patterns. Against this background, the next stage of the analysis focuses on identifying sustainable development regimes through K-means clustering and examining the specific characteristics associated with each regime.

3.2. Identification of Sustainable Development Regimes

The heterogeneity observed among European Union Member States demonstrates that sustainable development does not follow a single trajectory but instead evolves through distinct economic, energy and environmental patterns. Identifying groups of countries with similar sustainability characteristics is therefore essential for understanding the structural differences that exist across the European Union and for examining how these differences influence sustainability transition processes.

To identify these patterns, the K-means clustering method was applied to the economic, environmental and innovation indicators included in the analysis. The results revealed four distinct sustainable development regimes characterized by specific combinations of economic performance, renewable energy deployment, resource efficiency, innovation capacity and environmental pressure. These regimes represent alternative sustainability profiles observed across the European Union and provide a structured framework for analysing both the distribution of Member States and the dynamics of transitions between different development states.

The statistical characteristics of the identified regimes are presented in Table 4 and constitute the foundation for the subsequent analysis of regime composition, transition dynamics and sustainable development pathways.

Table 4. Characteristics of Sustainable Development Regimes Identified by K-Means Clustering.

Regime	GDP	Renewable	GHG	Circular	ResourceProd	RD	Education	EnvTaxes
S1 Brown Growth	76.417	22.868	6.822	6.391	1.093	1.145	40.453	8.276
S2 Growth-Intensive Economy	231.4	11.221	13.425	5.905	3.617	1.187	57.86	5.064
S3 Green Growth	109.708	16.205	7.831	18.048	3.177	2.12	42.225	6.138
S4 Sustainable Development	118.512	43.802	6.476	8.637	1.845	3.09	44.72	5.839

Source: Authors' calculations based on Eurostat data [50–54].

The results presented in Table 4 reveal substantial structural differences among the four identified regimes. These differences reflect distinct levels of economic development, energy transition and environmental performance, confirming that European Union Member States follow diverse pathways towards sustainability.

The first regime, labelled Brown Growth, combines relatively low levels of GDP per capita with limited investment in research and development, modest circular economy performance and low resource productivity. Together, these characteristics reflect structural constraints that reduce the capacity of countries within this group to accelerate the transition towards environmentally sustainable development models.

The second regime, referred to as Green Growth, stands out through high levels of resource productivity and circular material use. This profile demonstrates a stronger capacity to decouple economic growth from resource consumption and highlights the contribution of resource efficiency and circular economy practices to sustainable development.

The third regime comprises economies with very high levels of GDP per capita but also substantial environmental pressures, reflected in elevated greenhouse gas emissions. The coexistence of strong economic performance and high environmental impacts characterizes a Growth-Intensive Economy, where economic prosperity has not yet been fully accompanied by environmental decoupling.

The fourth regime, labelled Sustainable Development, exhibits the most favourable combination of sustainability indicators. High shares of renewable energy, substantial investment in research and development, and comparatively low greenhouse gas emissions distinguish this group from the other regimes. This configuration most closely reflects the sustainability objectives promoted by the European Union and represents the development pathway towards which transition processes are expected to converge.

Therefore, the clustering results provide empirical support for H1, confirming that European Union Member States can be classified into distinct sustainable development

regimes characterized by different combinations of economic, energy, resource efficiency, innovation, educational, taxation and environmental indicators.

3.3. Transition Dynamics Between Regimes

The identification of sustainable development regimes provides insight into the economic, energy and environmental characteristics that distinguish each group. However, understanding the role of these regimes within the broader European Union context also requires an assessment of their relative importance and prevalence. To address this aspect, Table 5 presents the distribution of observations across the four identified regimes.

Table 5. Distribution of EU Member States Across Sustainable Development Regimes.

Regime	Number of Countries	Share (%)
Brown Growth	15	55.56
Growth-Intensive Economy	2	7.41
Green Growth	6	22.22
Sustainable Development	4	14.81
Total	27	100

Source: Authors' calculations based on Eurostat data [50–54].

The distribution of observations provides an overview of the extent to which different sustainability profiles characterize European Union Member States during the study period. At the same time, it establishes the empirical basis for analysing transition dynamics by revealing the relative weight of each regime within the overall sustainability landscape.

The results reported in Table 5 serve as a starting point for examining the movement of countries between regimes and for evaluating the degree of stability and transformation that characterizes sustainable development pathways across the European Union.

The distribution of observations reveals the predominance of regimes characterized by intermediate levels of economic and environmental performance, whereas regimes associated with advanced sustainability and growth-intensive economies account for a smaller share of the observations. This pattern confirms that the transition towards sustainable development remains uneven across the European Union and reflects persistent differences in economic structure, innovation capacity and energy performance among Member States.

Beyond the overall distribution of observations, it is important to examine how individual countries are positioned within the identified sustainability regimes. Table 6 presents the dominant regime associated with each Member State during the study period, providing a concise overview of the prevailing development profile characterizing each country.

Table 6. Dominant Sustainable Development Regime by Country.

Regime	Countries
Brown Growth	Bulgaria, Croatia, Cyprus, Czechia, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovakia, Slovenia
Growth-Intensive Economy	Ireland, Luxembourg
Green Growth	Belgium, France, Germany, Italy, Netherlands, Spain
Sustainable Development	Austria, Denmark, Finland, Sweden

Source: Authors' calculations based on Eurostat data [50–54].

The results reveal a concentration of Nordic countries and economies characterized by strong innovation performance and extensive renewable energy deployment within

the Sustainable Development regime. By comparison, several Central and Eastern European countries are predominantly associated with the Brown Growth regime, reflecting persistent challenges related to resource efficiency, research and development investment, and greenhouse gas emission reduction. The identification of a distinct Growth-Intensive Economy regime further demonstrates that high levels of economic prosperity are not necessarily accompanied by superior sustainability performance.

The findings also reveal a high degree of persistence across sustainable development regimes throughout the study period. Most Member States remained within the same regime between 2015 and 2024, indicating the presence of relatively stable structural characteristics in terms of economic performance, energy transition and environmental outcomes. This pattern confirms that progress towards sustainable development is gradual and shaped by institutional, economic and technological factors that evolve over extended periods.

At the same time, the analysis identifies regime transitions for a limited number of Member States. These changes reflect adaptation processes associated with the expansion of renewable energy, improvements in resource efficiency and the strengthening of innovation capacity. Although transition frequencies remain relatively low, they demonstrate that sustainable development is not a fixed condition but a dynamic process in which countries can advance towards more sustainable regimes or, in some cases, move in the opposite direction. The existence of both progress and regression pathways highlights the importance of maintaining consistent policy efforts capable of supporting long-term sustainability transitions.

Table 7 reveals a high degree of persistence across all sustainable development regimes, with retention probabilities exceeding 90% in each case. The most stable regime is Growth-Intensive Economy, for which no transitions towards other regimes were observed during the study period. The most frequent movements occurred between Brown Growth and Green Growth, highlighting a close relationship between these two sustainability states. Overall, the results demonstrate that the structural transformations associated with the green transition are characterized by slow dynamics and strong persistence of existing economic and institutional configurations.

Table 7. Transition Probability Matrix Between Sustainable Development Regimes (%).

From/To	S1 Brown Growth	S2 Growth-Intensive Economy	S3 Green Growth	S4 Sustainable Development
S1 Brown Growth	93.893	0	5.344	0.763
S2 Growth-Intensive Economy	0	100	0	0
S3 Green Growth	7.018	0	92.982	0
S4 Sustainable Development	2.703	0	0	97.297

Source: Authors' calculations based on Eurostat data [50–54].

Although the transition probability matrix provides a detailed representation of movements between sustainable development regimes, the assessment of regime stability can be further facilitated by summarizing the probabilities of retention and exit. To this end, Table 8 presents the stability indicators derived from the estimated transition probabilities for the study period.

The stability indicators reveal a high degree of persistence across all identified regimes, indicating that sustainability-related transformations occur gradually within the European Union. The highest persistence rate is recorded for the Growth-Intensive Economy regime, for which no transitions towards other regimes were observed during the study period. This pattern reflects the presence of strong structural characteristics that maintain these economies in a distinct position relative to the other Member States.

Table 8. Regime stability indicators.

Regime	Persistence Rate (%)	Exit Rate (%)
Brown Growth	93.893	6.107
Growth-Intensive Economy	100	0
Green Growth	92.982	7.018
Sustainable Development	97.297	2.703

Source: Authors' calculations based on Eurostat data [50–54].

The Sustainable Development regime also exhibits a very high level of stability, confirming that strong performance in renewable energy deployment, innovation and resource efficiency tends to be maintained over time. By comparison, the Brown Growth and Green Growth regimes display slightly higher exit probabilities, reflecting greater dynamism and a stronger propensity for structural change. These findings highlight important differences in the capacity of Member States to maintain their position within the various sustainable development regimes.

Although the stability indicators provide valuable information regarding regime persistence, aggregated probabilities do not reveal the specific directions of the observed changes. A more detailed understanding of sustainability transitions therefore requires an examination of the actual movements between regimes and the pathways followed by Member States during the study period.

Table 9 summarizes the observed transitions between sustainable development regimes and reports their frequency and probability. The analysis of these flows identifies the principal transition pathways and highlights the regime pairs between which changes occur most frequently.

Table 9. Observed transitions between sustainable development regimes.

Transition	Frequency	Probability (%)
Brown Growth—Green Growth	7	5.344
Brown Growth—Sustainable Development	1	0.763
Green Growth—Brown Growth	4	7.018
Sustainable Development—Brown Growth	1	2.703

Source: Authors' calculations based on Eurostat data [50–54].

The results show that transitions between sustainable development regimes occur relatively infrequently when compared with the persistence rates observed for each regime. This pattern confirms the existence of substantial structural inertia among European Union Member States and demonstrates that sustainability transitions unfold over extended periods of time. Economic, institutional and technological factors evolve gradually, limiting the speed at which countries can move between alternative development regimes.

The most frequent transitions occur between the Brown Growth and Green Growth regimes, highlighting a close relationship between improvements in resource efficiency and reductions in environmental pressure. By contrast, the Growth-Intensive Economy regime exhibits no transitions towards other regimes, underscoring its distinct character and the challenges associated with transforming economies that combine very high levels of economic prosperity with elevated greenhouse gas emissions.

The high level of stability observed for the Sustainable Development regime demonstrates that countries achieving advanced performance in renewable energy deployment, innovation and resource efficiency tend to maintain these advantages over time. Taken together, the findings confirm that sustainable development is best understood as a dynamic

process characterized by distinct states and specific transition pathways. This perspective provides a strong rationale for the use of a Petri Net simulation framework to investigate the mechanisms governing movements between sustainable development regimes.

These findings confirm H2, as the identified regimes exhibit different transition dynamics and varying degrees of persistence over time, reflecting heterogeneous sustainability pathways among European Union Member States.

3.4. Panel Econometric Results

The analysis of sustainable development regimes and the transitions between them reveals the existence of persistent structural differences among European Union Member States. However, the identification of regimes and development pathways does not provide sufficient information regarding the factors associated with environmental performance. To address this issue, panel econometric models were estimated using greenhouse gas emissions per capita as the dependent variable in order to examine the relationships between economic performance, energy transition, circular economy practices and environmental sustainability.

The models incorporate indicators reflecting the economic, energy, technological and educational dimensions of sustainable development, namely GDP per capita, renewable energy share, circular material use rate, resource productivity, research and development expenditure, tertiary educational attainment and environmental tax revenues. To ensure the reliability of the empirical findings, Pooled OLS, Fixed Effects and Random Effects models were estimated. The final specification was selected on the basis of the Hausman test.

The results reveal that only four Member States experienced regime changes during the study period. Czechia, Malta and Spain followed a positive transition pathway, moving from the Brown Growth regime to the Green Growth regime. These changes reflect improvements in energy performance and resource efficiency, consistent with a gradual shift towards more sustainable development patterns. In the case of Estonia, temporary regime changes were observed; however, the country returned to its initial regime by the end of the study period. This trajectory indicates that the observed transformations were not sufficiently consolidated to produce a permanent structural shift.

Beyond the individual trajectories of countries that experienced regime changes, a broader assessment of transition dynamics provides additional insight into the evolution of sustainable development regimes across the European Union. In this regard, Table 10 summarizes the main characteristics of the transition process observed during the study period.

Table 10. Countries experiencing regime transitions during 2015–2024.

Country	Initial Regime (2015)	Final Regime (2024)	Number of Regime Changes	Overall Direction
Czechia	Brown Growth	Green Growth	5	Progress
Estonia	Brown Growth	Brown Growth	2	Temporary transition
Malta	Brown Growth	Green Growth	1	Progress
Spain	Brown Growth	Green Growth	5	Progress

Source: Authors' calculations based on Eurostat data [50–54].

The results summarized in Table 11 show that only four Member States experienced regime transitions during the study period, while the vast majority of countries remained within the same sustainable development category. This pattern confirms the persistent nature of the identified regimes and reflects the presence of structural constraints that limit the pace of transformation.

Table 11. Summary of regime transition dynamics.

Indicator	Value
Total countries analysed	27
Countries with regime transitions	4
Countries with stable regimes	23
Share of countries with transitions (%)	14.81
Most frequent transition	Brown Growth—Green Growth
Most stable regime	Growth-Intensive Economy

Source: Authors' calculations based on Eurostat data [50–54].

The most common transition occurs between the Brown Growth and Green Growth regimes, highlighting improvements in energy performance and resource efficiency as the principal pathway towards more sustainable development models. At the same time, the Growth-Intensive Economy regime exhibits the highest level of stability, reinforcing its distinctive structural profile and the persistence of development patterns associated with very high levels of economic prosperity.

Overall, the findings demonstrate that sustainable development in the European Union is characterized by strong regime persistence and relatively limited transition dynamics. These results provide a foundation for examining the economic, energy-related and institutional factors associated with environmental performance and for explaining the differences observed among Member States. The next stage of the analysis addresses these issues through panel econometric modelling.

3.5. Petri Net Simulation Framework

The cluster analysis, transition dynamics and panel econometric results provide complementary evidence regarding the mechanisms shaping sustainable development pathways within the European Union. While the clustering procedure identifies distinct sustainability regimes and the transition analysis reveals the degree of persistence and mobility between them, the econometric models identify the factors most strongly associated with environmental performance.

To integrate these findings into a unified analytical framework, a conceptual Petri Net model was developed. The framework represents the identified sustainable development regimes as interconnected states and incorporates the principal transition drivers highlighted by the empirical analysis, particularly renewable energy deployment, resource productivity and innovation capacity. By combining regime characteristics, transition dynamics and environmental performance determinants, the Petri Net framework provides a dynamic representation of sustainable development pathways and the mechanisms governing movements between alternative sustainability regimes (Table 12).

The Pooled OLS estimates reveal statistically significant relationships between greenhouse gas emissions and all explanatory variables included in the analysis. Renewable energy share and resource productivity are negatively associated with greenhouse gas emissions, highlighting the importance of energy transition and efficient resource use for improving environmental performance. Resource productivity exhibits the strongest negative coefficient, indicating that more efficient resource utilization is closely linked to lower levels of environmental pressure.

By contrast, GDP per capita, circular material use rate, research and development expenditure, tertiary educational attainment and environmental tax revenues display positive coefficients. These findings point to complex interactions between economic development, innovation and sustainability outcomes, reflecting the diverse structural

characteristics of European Union Member States. Nevertheless, the interpretation of these coefficients requires caution because the Pooled OLS specification does not account for unobserved country-specific heterogeneity. For this reason, the analysis is extended through the estimation of Fixed Effects and Random Effects models (Table 13).

Table 12. Pooled OLS results.

Variable	Coefficient	Std. Error	p-Value
GDP	0.074	0.0055	<0.001
Renewable	−0.1463	0.0157	<0.001
Circular	0.1897	0.0414	<0.001
ResourceProd	−2.3938	0.2888	<0.001
RD	1.0941	0.2051	<0.001
Education	0.03	0.0141	0.034
EnvTaxes	0.4297	0.064	<0.001

Source: Authors' calculations based on Eurostat data [50–54].

Table 13. Fixed effects results.

Variable	Coefficient	Std. Error	p-Value
GDP	0.0241	0.0199	0.2252
Renewable	−0.0401	0.0546	0.4630
Circular	−0.0338	0.1194	0.7768
ResourceProd	−0.8272	0.5203	0.1118
RD	0.1238	1.3465	0.9267
Education	−0.0782	0.0647	0.2270
EnvTaxes	0.0403	0.1442	0.7797

Source: Authors' calculations based on Eurostat data [50–54].

The Fixed Effects estimates differ substantially from those obtained under the Pooled OLS specification. After controlling for country-specific characteristics, none of the explanatory variables remains statistically significant at conventional confidence levels. This result indicates that a considerable share of the relationships identified in the Pooled OLS model is driven by structural differences between Member States rather than by changes occurring within individual countries during the study period.

The marked reduction in the estimated effects highlights the importance of national heterogeneity in explaining environmental performance across the European Union. Differences in economic development, energy structure, innovation capacity and resource efficiency appear to exert a stronger influence than the year-to-year variation observed within countries. These findings support the evaluation of an alternative specification through the Random Effects model, which exploits both cross-country and temporal variation.

To capture both the variation between Member States and the variation over time, a Random Effects model was subsequently estimated. This specification enables the assessment of the relationships between environmental performance and economic, energy-related and institutional factors under the assumption that country-specific effects are not correlated with the explanatory variables included in the model (Table 14).

The Random Effects estimates reveal statistically significant relationships between greenhouse gas emissions and several of the explanatory variables included in the analysis. GDP per capita exhibits a positive and significant coefficient, demonstrating that higher levels of economic development remain associated with higher greenhouse gas emissions.

This finding confirms that the complete decoupling of economic growth from environmental impacts has not yet been achieved across all European Union Member States.

Table 14. Random effects results.

Variable	Coefficient	Std. Error	p-Value
GDP	0.0362	0.0096	0.0002
Renewable	−0.1214	0.0241	0.0000
Circular	−0.0046	0.0349	0.8952
ResourceProd	−0.8572	0.3313	0.0097
RD	0.1720	0.3889	0.6583
Education	−0.0516	0.0280	0.0657
EnvTaxes	0.1027	0.0690	0.1369

Source: Authors' calculations based on Eurostat data [50–54].

By contrast, renewable energy share and resource productivity display negative and statistically significant effects. These results demonstrate that the expansion of renewable energy sources and improvements in resource efficiency contribute to lower levels of environmental pressure. Among the variables considered, renewable energy deployment and resource productivity emerge as the most important determinants of environmental performance, reinforcing the central role of energy transition and economic efficiency in promoting sustainable development.

The variables associated with circular economy practices, research and development expenditure, and environmental taxation do not exhibit statistically significant effects in the estimated model. Tertiary educational attainment displays a negative coefficient with marginal statistical significance, indicating that human capital accumulation may indirectly support improvements in environmental performance. Overall, the findings identify energy transition and resource efficiency as the principal factors associated with lower greenhouse gas emissions across European Union Member States.

To determine the most appropriate panel specification, the Hausman test was subsequently applied. This procedure compares the Fixed Effects and Random Effects estimators and evaluates whether country-specific effects are correlated with the explanatory variables included in the model (Table 15).

Table 15. Hausman test results.

Test	Statistic	df	p-Value	Preferred Model
Hausman specification test	10.2114	7.0000	0.1769	Random effects

Source: Authors' calculations based on Eurostat data [50–54].

The Hausman test results report a probability value exceeding the conventional 5% significance threshold, leading to the non-rejection of the null hypothesis. Consequently, the Random Effects specification is considered appropriate for analysing the relationships between greenhouse gas emissions and the explanatory variables included in the study.

This outcome indicates that country-specific effects are not significantly correlated with the explanatory variables and that the estimates obtained through the Random Effects model are both consistent and efficient. Accordingly, the interpretation of the econometric results is based primarily on the Random Effects specification, which identifies economic development as a factor associated with higher greenhouse gas emissions while highlighting the contribution of renewable energy deployment and resource productivity to lower levels of environmental pressure.

Taken together, the econometric findings reinforce the conclusions derived from the analysis of sustainable development regimes and transition dynamics. The persistence of the identified regimes is accompanied by the significant influence of structural factors, particularly energy transition and resource efficiency, which explain an important share of the environmental performance differences observed among European Union Member States.

The econometric results provide substantial support for H3. Renewable energy deployment and resource productivity are statistically significant determinants of lower greenhouse gas emissions, while the effects of selected socio-economic factors are more heterogeneous and, in some cases, statistically weaker.

3.6. Petri Net Simulation of Sustainable Development Pathways

The analysis of sustainable development regimes and the transitions observed between them reveals that European Union Member States do not follow a single development trajectory. While a limited number of countries progressed towards regimes characterized by higher sustainability performance, most Member States remained within the same regime throughout the study period. This pattern reflects transition processes marked by persistence, path dependency and the possibility of movement between distinct sustainability states.

Within this context, Petri Nets provide an appropriate framework for representing and simulating sustainable development pathways because they allow the simultaneous modelling of system states and the mechanisms governing transitions between them. Unlike traditional econometric approaches, which identify statistical relationships between variables, the Petri Net framework explicitly represents the movement of Member States between alternative sustainability regimes and incorporates the factors identified through the empirical analysis as key determinants of environmental performance.

The proposed model includes four principal states corresponding to the regimes identified through the K-means analysis: Brown Growth, Green Growth, Growth-Intensive Economy and Sustainable Development. These states represent distinct configurations of the relationship between economic development, resource use, energy transition and environmental performance. Transitions between states are driven by the factors identified through the econometric analysis and the assessment of regime dynamics, particularly renewable energy deployment, resource productivity and, to a lesser extent, human capital accumulation.

Figure 1 illustrates the conceptual structure of the proposed Petri Net model developed to represent sustainable development pathways within the European Union. The framework comprises four principal states corresponding to the regimes identified through the cluster analysis: Brown Growth, Green Growth, Sustainable Development and Growth-Intensive Economy. These states reflect distinct combinations of economic performance, energy transition and environmental outcomes observed across European Union Member States.

Transitions between states are associated with the factors identified through the econometric analysis and the assessment of regime dynamics. In particular, the expansion of renewable energy deployment and improvements in resource productivity represent the principal mechanisms supporting movement from Brown Growth to Green Growth and subsequently towards Sustainable Development. Conversely, economic pressures and the challenges associated with structural transformation may lead to movements towards regimes characterized by lower levels of environmental performance.

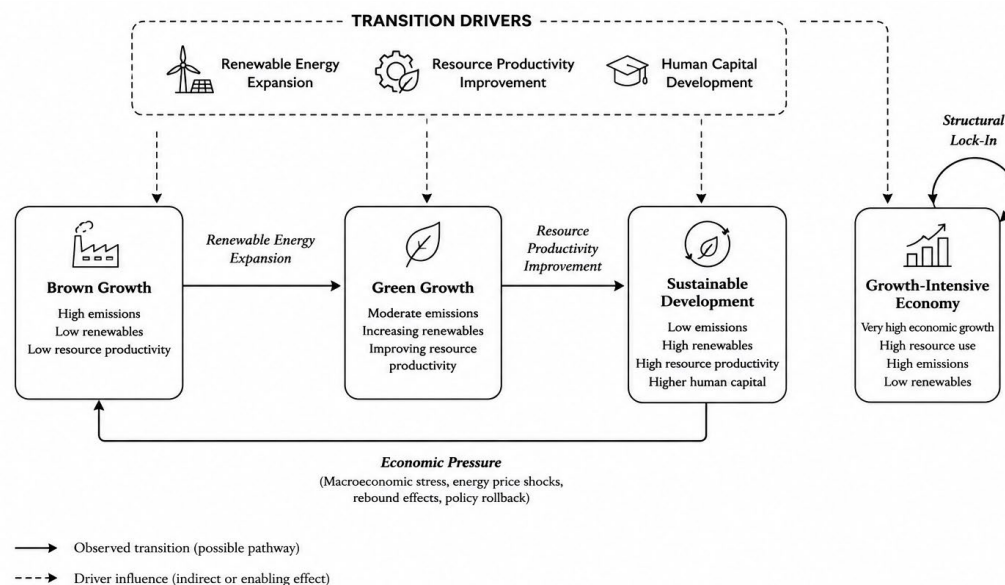


Figure 1. Petri Net structure of sustainable development pathways in the European Union. Source: Authors' elaboration based on cluster analysis, transition dynamics and panel econometric results.

The model also highlights the distinctive character of the Growth-Intensive Economy regime, which exhibits the highest degree of persistence in the empirical analysis. This state is associated with a form of structural lock-in, indicating that economies combining high levels of economic development with elevated environmental pressures face greater challenges in advancing towards more sustainable development pathways.

To strengthen the connection between the empirical findings and the Petri Net framework, the principal factors associated with transitions between sustainable development regimes are summarized in Table 16. These transition drivers are derived from both the econometric results and the regime dynamics observed in the transition matrix analysis.

Table 16. Transition drivers between sustainable development regimes.

Transition Pathway	Main Drivers	Empirical Support
Brown Growth to Green Growth	Renewable energy share; resource productivity	Observed transition matrix; Random Effects model
Green Growth to Sustainable Development	Resource productivity; renewable energy; human capital	Petri Net framework; weak education effect in RE model
Sustainable Development to Brown Growth	Economic pressure; weakening environmental performance	Observed reverse transition
Growth-Intensive Economy to Growth-Intensive Economy	Structural lock-in; high GDP; high emissions	100% persistence in transition matrix

Source: Authors' elaboration based on empirical findings.

The results demonstrate that the expansion of renewable energy deployment and improvements in resource productivity constitute the principal mechanisms associated with progress towards regimes characterized by higher levels of sustainability performance. These findings are fully consistent with the Random Effects estimates, which identify both variables as significant determinants of lower greenhouse gas emissions.

At the same time, the high persistence of the Growth-Intensive Economy regime reflects the presence of structural lock-in mechanisms that constrain the pace of transition towards more advanced forms of sustainable development. The Petri Net framework therefore demonstrates that sustainable development is not a linear process but one char-

acterized by distinct states, multiple transition pathways and varying levels of resilience to change.

3.7. Validation of the Research Hypotheses

The empirical analyses conducted in this study provide a comprehensive basis for evaluating the proposed research hypotheses.

H1 proposed that European Union Member States can be classified into distinct sustainable development regimes characterized by different combinations of economic performance, renewable energy deployment, resource productivity, circular material use, educational attainment, environmental taxation and greenhouse gas emissions. The K-means cluster analysis identified four clearly differentiated sustainability regimes, each displaying specific structural characteristics. Consequently, H1 is confirmed.

H2 stated that sustainable development regimes exhibit different transition dynamics and varying degrees of persistence over time. The transition probability matrix and the regime stability indicators demonstrate substantial differences in transition behaviour among the identified regimes. While the Growth-Intensive Economy regime remained completely stable throughout the study period, the Brown Growth and Green Growth regimes experienced limited but observable transitions. These findings confirm the heterogeneous nature of sustainability pathways across European Union Member States. Therefore, H2 is confirmed.

H3 proposed that renewable energy deployment, resource productivity and selected socio-economic factors significantly influence environmental performance measured through greenhouse gas emissions per capita. The Random Effects model identified renewable energy deployment and resource productivity as statistically significant determinants associated with lower greenhouse gas emissions, whereas several socio-economic variables displayed weaker or statistically insignificant effects. Accordingly, H3 is largely confirmed, with the strongest empirical support being observed for the energy transition and resource efficiency variables.

H4 suggested that combining sustainability regime identification, transition dynamics and environmental determinants provides a more comprehensive understanding of sustainable development pathways than analysing these dimensions separately. The integration of cluster analysis, transition matrices, panel econometric modelling and the conceptual Petri Net framework demonstrates the complementary contribution of each analytical component and offers a unified interpretation of sustainability transitions within the European Union. Therefore, H4 is confirmed.

4. Discussion

The results reveal persistent structural differences among European Union Member States in terms of the relationship between economic development, resource use and environmental performance. The cluster analysis identified four distinct sustainable development regimes, while the transition analysis demonstrated a high degree of persistence throughout the period 2015–2024. At the same time, the econometric findings and the Petri Net simulation framework identify renewable energy deployment and resource productivity as the principal drivers of progress towards more sustainable development pathways. Taken together, these findings provide an integrated perspective on the mechanisms that support or constrain sustainability transformations across European economies.

4.1. Persistence of Sustainable Development Regimes

One of the principal findings of this study concerns the high degree of persistence observed across the sustainable development regimes identified among European Union

Member States. The results show that approximately 85% of the analysed countries remained within the same regime throughout the period 2015–2024, while only a limited number of states experienced transitions towards alternative development categories. This pattern confirms that sustainable development is not characterized by rapid change but rather by structural mechanisms that maintain existing development trajectories over extended periods.

This finding is consistent with the path dependency literature, which emphasizes that institutional arrangements, infrastructure investments and patterns of economic specialization generate cumulative effects that constrain the pace of structural transformation [66]. Similarly, sustainability transition research demonstrates that the shift towards more sustainable economic models is a long-term process characterized by inertia, lock-in effects and resistance to change [67,68].

The empirical findings are further reinforced by the econometric analysis. The absence of statistically significant effects in the Fixed Effects specification indicates that annual variations within individual countries are insufficient to generate substantial improvements in environmental performance over the short term. Instead, structural differences between Member States play a more important role in explaining environmental outcomes and the position of countries within the identified sustainable development regimes.

From a policy perspective, these results highlight the need for consistent and long-term interventions aimed at accelerating sustainability transitions. Marginal changes in economic or environmental indicators are unlikely to alter existing development trajectories rapidly. Meaningful progress requires structural transformations affecting energy systems, resource use patterns, production processes and consumption behaviour simultaneously.

4.2. Renewable Energy and Resource Productivity as Transition Drivers

The Random Effects estimates identify renewable energy share and resource productivity as the principal factors associated with lower greenhouse gas emissions across European Union Member States. These findings are consistent with a large body of literature highlighting the central role of energy transition in reducing environmental pressures and supporting sustainable development. Numerous studies demonstrate that the expansion of renewable energy sources contributes to lower emissions and facilitates the decoupling of economic growth from environmental degradation [69–71].

It should be emphasized that the estimated negative coefficients associated with renewable energy share and resource productivity refer to their relationship with greenhouse gas emissions rather than to economic productivity. Therefore, the results indicate that higher renewable energy deployment and improved resource productivity contribute to lower environmental pressures while remaining compatible with sustainable economic development.

The importance of renewable energy is further reinforced by the transition analysis. The observed movements from Brown Growth to Green Growth are associated with improvements in energy performance and a reduced dependence on conventional energy sources. From this perspective, renewable energy represents not only an instrument for emission reduction but also a mechanism that facilitates changes in sustainable development trajectories. This finding is fully consistent with sustainability transition research, which considers the transformation of energy systems a fundamental condition for the shift towards more sustainable economic models.

A second important contribution of the study concerns the role of resource productivity. The negative and statistically significant coefficient obtained in the Random Effects model demonstrates that economies capable of generating greater economic value with lower resource inputs tend to record lower levels of greenhouse gas emissions. This result is consistent with the literature on resource efficiency and green growth, which identifies

improvements in resource productivity as one of the most effective strategies for simultaneously reducing environmental pressure and maintaining economic competitiveness [72,73].

By contrast, circular material use rate, research and development expenditure, and environmental taxation do not exhibit statistically significant effects in the preferred specification. This outcome does not diminish the importance of these factors; rather, it indicates that their influence on environmental performance operates through indirect mechanisms or emerges over longer time horizons. Research on the circular economy emphasizes that the benefits of circularity depend on institutional, technological and behavioural conditions, which may limit the identification of direct effects within aggregated econometric models [74–76]. Similarly, research and innovation support the development of clean technologies and the transformation of production systems, but their environmental impacts often materialize gradually and may not be fully captured within a relatively short observation period [77,78].

Overall, the findings demonstrate that progress towards more sustainable development regimes depends primarily on the capacity of Member States to accelerate energy system transformation and improve resource efficiency. These two dimensions emerge consistently in both the econometric analysis and the Petri Net framework, reinforcing their central role in shaping sustainable development pathways within the European Union.

4.3. Structural Lock-In in Growth-Intensive Economies

One of the most relevant findings of this study is the identification of the Growth-Intensive Economy regime and its complete persistence throughout the study period. Unlike the other sustainable development regimes, this category exhibited no transitions towards alternative states, reflecting the presence of structural lock-in mechanisms that constrain movement towards development models characterized by superior environmental performance. This finding demonstrates that high levels of economic development alone are insufficient to guarantee progress towards sustainability.

The observed persistence is consistent with the literature on sustainability transitions and path dependency, which emphasizes that existing infrastructures, economic structures and dominant production and consumption patterns generate cumulative effects that slow structural transformation processes [79]. Under such conditions, advanced economies may continue to benefit from high levels of income and economic competitiveness without achieving corresponding reductions in environmental pressures.

The results are also relevant to the ongoing debate concerning the decoupling of economic growth from environmental impacts. The Random Effects estimates identify a positive relationship between GDP per capita and greenhouse gas emissions, indicating that economic progress remains associated with additional environmental pressures in a number of European Union Member States. From this perspective, the transition towards sustainable development depends not only on the pace of economic growth but also on the capacity of economies to translate that growth into improvements in energy performance and resource efficiency.

A similar interpretation is supported by research on circular economy practices and resource efficiency, which demonstrates that sustainability performance depends on the ability of economic systems to reduce resource intensity while generating higher value added with lower environmental impacts [28]. From this perspective, the persistence of the Growth-Intensive Economy regime can be interpreted as an intermediate stage of the sustainability transition, characterized by strong economic performance that has not yet been accompanied by structural transformations capable of substantially reducing emissions and strengthening long-term sustainability.

4.4. Policy Implications for the European Green Transition

The findings of this study provide several important implications for European policies aimed at supporting sustainable development and the green transition. First, the high persistence observed across the identified regimes demonstrates that the structural transformations required to achieve climate and sustainability objectives demand long-term policy commitments. The fact that most Member States remained within the same development category throughout the study period reflects the presence of institutional, economic and technological mechanisms that constrain the pace of change and cannot be overcome through isolated or short-term interventions.

Second, both the econometric analysis and the Petri Net framework identify renewable energy deployment and resource productivity as the principal drivers of progress towards more sustainable development regimes. This conclusion is fully aligned with the objectives of the European Green Deal and the Circular Economy Action Plan, which seek to reduce resource dependence, improve resource efficiency and accelerate the decarbonization of European economies. From this perspective, public policies should prioritize investments in renewable energy infrastructure, the modernization of production systems and the adoption of technologies that enhance resource efficiency.

Beyond its direct contribution to reducing greenhouse gas emissions, renewable energy deployment plays a broader role in supporting the structural transformation required for sustainable development. The negative coefficient identified in the econometric analysis indicates that higher shares of renewable energy are associated with lower greenhouse gas emissions, reflecting improvements in environmental performance rather than adverse effects on economic development or productivity. By reducing dependence on fossil fuels, enhancing energy system resilience, and facilitating the decarbonization of production processes, renewable energy contributes simultaneously to environmental protection, energy security, and long-term economic sustainability. Consequently, the expansion of renewable energy should be regarded not only as an environmental policy objective but also as a strategic instrument for accelerating the transition towards more sustainable development pathways across the European Union.

A further policy implication emerges from the persistence of the Growth-Intensive Economy regime. This finding demonstrates that high levels of economic development do not automatically translate into lower environmental pressures and highlights the need for policies explicitly designed to decouple economic growth from resource consumption and greenhouse gas emissions. Without such transformations, economically advanced countries may remain locked into development patterns characterized by persistent environmental pressures.

More broadly, the results support the view that sustainable development transitions must be approached as systemic and multidimensional processes. Policies focused exclusively on economic growth or solely on emission reduction are unlikely to generate lasting structural change. Progress towards the objectives associated with SDG 7—Affordable and Clean Energy, SDG 12—Responsible Consumption and Production and SDG 13—Climate Action requires the integration of energy, economic and environmental policies within a coherent framework capable of supporting the long-term transformation of European economies.

5. Conclusions

This study investigated sustainable development pathways in the European Union through an integrated analytical framework combining cluster analysis, transition dynamics, panel econometric modelling, and conceptual Petri Net simulation. The proposed framework identified distinct sustainable development regimes, examined their persistence

over time, and evaluated the main determinants of environmental performance across European Union Member States.

The findings reveal four sustainable development regimes characterized by different combinations of economic performance, environmental pressure, and resource efficiency. The transition analysis demonstrates that most Member States remained within the same regime throughout the study period, indicating that sustainable development is largely shaped by long-term structural factors rather than by short-term changes. The complete persistence of the Growth-Intensive Economy regime further highlights the existence of structural lock-in mechanisms that may hinder progress towards more sustainable development pathways.

The econometric analysis identifies renewable energy deployment and resource productivity as the principal drivers associated with lower greenhouse gas emissions. These results emphasize that the transition towards cleaner energy systems and more efficient resource use represents a fundamental prerequisite for improving environmental performance and achieving the objectives of the European Green Deal. Rather than constraining economic development, renewable energy contributes to decarbonization while supporting the long-term sustainability and resilience of European economies.

The principal contribution of the study lies in the integration of sustainability regime identification, transition analysis, panel econometric modelling, and conceptual Petri Net representation within a unified analytical framework. This integrated approach extends previous research by simultaneously examining regime persistence, transition mechanisms, and the determinants of environmental performance, thereby providing a more comprehensive understanding of sustainable development pathways in the European Union.

The empirical findings also provide a clear evaluation of the proposed research hypotheses. **H1** is confirmed through the identification of four distinct sustainable development regimes among European Union Member States. **H2** is confirmed by the transition analysis, which demonstrates heterogeneous transition dynamics and varying levels of regime persistence over time. **H3** is largely confirmed, as renewable energy deployment and resource productivity emerge as the principal determinants of lower greenhouse gas emissions, whereas the influence of several socio-economic variables proves to be weaker or statistically insignificant. Finally, **H4** is confirmed by the successful integration of cluster analysis, transition dynamics, panel econometric modelling and the conceptual Petri Net framework, demonstrating that the combined analytical approach provides a more comprehensive understanding of sustainable development pathways than analysing these dimensions separately.

Several limitations should be acknowledged. The analysis was limited to European Union Member States and relied on a selected set of indicators available through Eurostat. In addition, the Petri Net model was developed as a conceptual representation of sustainable development pathways and did not incorporate stochastic transition probabilities. Future research could extend the analysis to other regions, incorporate additional sustainability indicators, and develop stochastic or scenario-based Petri Net models capable of evaluating alternative transition pathways under different policy scenarios.

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Abbreviations

The following abbreviations are used in this manuscript:

CEAP	Circular Economy Action Plan
EU	European Union
FE	Fixed Effects
GDP	Gross Domestic Product per Capita
GHG	Greenhouse Gas Emissions per Capita
OLS	Ordinary Least Squares
RE	Random Effects
R&D	Research and Development
SDG	Sustainable Development Goal
WCSS	Within-Cluster Sum of Squares

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