

DETERMINANTS OF THE TRANSITION TOWARDS SUSTAINABLE ENERGY IN ROMANIA (2007–2024): A PRINCIPAL COMPONENT ANALYSIS APPROACH

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Abstract: *This study investigates the dynamics of sustainable resilience, green transition and energy challenges in Romania over the period 2007–2024. Using a set of key indicators related to renewable energy, greenhouse gas emissions, energy production, recycling, import dependency, energy intensity and economic development, the research applies Principal Component Analysis (PCA) to identify underlying dimensions. The results reveal two main components explaining 94.28% of total variance: a “Green Transition Performance” dimension and an “Economic Pressure” dimension. The findings highlight Romania’s progress in renewable energy adoption and energy efficiency; alongside persistent vulnerabilities related to energy imports. The study provides a synthetic perspective on sustainability dynamics and supports policy-oriented interpretations.*

Keywords: sustainable energy transition, principal component analysis (PCA), energy policy

1. Introduction

The transition toward sustainable energy systems represents a key challenge for European economies, particularly in the context of climate change, energy security and economic resilience. Romania, as an EU member state, has undergone significant structural transformations in its energy sector since 2007, driven by regulatory frameworks, technological advancements and market integration.

Within the European Union, this change is guided by major rules like the European Green Deal, which requires all member states to rethink how they produce and use energy. Romania, which joined the EU in 2007, has gone through a difficult process of changing its energy sector to meet these new standards while modernizing its older infrastructure.

Modern studies suggest that sustainability is far more than a single-issue goal. Instead, it functions as a synergy between protecting our natural ecosystems, maximizing the utility of our resources, and maintaining a stable, thriving economy. [1], [2]. Building on this interconnected view, the shift toward renewable energy adoption serves as a practical bridge between ecological preservation and industrial progress. A key topic in this area is represented by the idea of growing the economy without damaging the environment [3], [4]. In Romania, the path of economic development, measured by GDP per capita, shows two sides. On one hand, a stronger economy helps pay for new green technologies [5], [6]. On the other hand, it creates more demand for energy, which can make the transition harder [7], [8]. This balance is seen in the changing levels of

energy intensity and recycling rates across the country.

However, the transition faces serious risks. Romania still relies heavily on energy imports, which makes the national economy vulnerable to international prices and global supply problems [9]. This energy dependency creates a form of economic pressure that can slow down green progress, especially during times of fast growth or global instability [10]. Looking at the years between 2007 and 2024 is important to see both the improvements made after joining the EU and the structural problems that still exist. Furthermore, this long-term perspective helps isolate the recurring barriers to progress. It reveals that while policy frameworks have evolved significantly since EU accession, the physical infrastructure and investment patterns often struggle to keep pace with these ambitious regulatory shifts. In this context, it is needed to recognize the importance of policy reforms, financial instruments, and behavioral changes in supporting Romania's journey toward a low-carbon, resilient energy future [11]. Ultimately, this timeframe serves as a record of Romania's economic resilience. It documents how the nation manages the delicate task of maintaining growth while navigating the high costs associated with replacing fossil fuel legacies with cleaner, decentralized energy systems.

While many studies look at single issues like greenhouse gas emissions [12] or renewable energy alone [13], there are not many scientific articles that combine all these factors for Romania. Without a combined analysis, it is difficult to determine how success in one area, such as an increase in renewable capacity, might be offset by failures in another, like rising waste generation or energy poverty. A unified perspective is essential to understand if the country is achieving genuine decoupling or simply shifting its environmental burden elsewhere.

This paper aims to analyze the evolution of sustainable resilience, green transition and

energy challenges in Romania between 2007 and 2024. By employing a multivariate statistical approach, the study seeks to identify the main underlying dimensions shaping these processes and to provide a synthetic interpretation of their interactions.

2. Research methodology

2.1 Data description and Variable selection

The empirical analysis is based on annual data for Romania covering the period 2007–2024, resulting in a sample of 18 observations. This timeframe was selected to capture Romania's evolution following its accession to the European Union in 2007, allowing for the assessment of structural changes associated with EU integration. The endpoint of the analysis, 2024, represents the most recent year for which complete data are available for all selected indicators. The dataset was extracted from the Eurostat database, ensuring consistency, reliability and comparability of the data. The dataset includes key indicators reflecting sustainable resilience, green transition and energy challenges. The selected variables capture three major dimensions: environmental sustainability, energy system performance and economic development:

- *Renewable energy share* (ren_share) – percentage of renewable energy in total final energy consumption;
- *Greenhouse gas emissions* (ghg_emiss) – environmental pressure indicator (index-based, tonnes per capita);
- *Energy productivity* (energy_prod) – the amount of economic output that is produced per unit of gross available energy (euro per kilogram);
- *Recycling rate* (recycle_rate) – percentage of recycled waste, reflecting circular economy practices;
- *Energy import dependency* (import_dep) – percentage of energy needs covered by imports;
- *Energy intensity* (energy_intens) – energy consumption per unit of GDP, proxy for energy efficiency (kilogram per thousands euro);

- *GDP per capita* (gdp_pps) – economic development indicator expressed in purchasing power standards (euro per capita).

The selection of these variables ensures a balanced representation of both sustainability and economic dimensions relevant to Romania's energy transition.

All statistical analyses were conducted using IBM SPSS Statistics software 26.

2.2 Descriptive analysis

Descriptive statistics were computed to provide an overview of the dataset and to assess variability, distributional properties and trends across variables.

Table 1 - Descriptive statistics of the selected variables (Romania, 2007–2024)

Descriptive Statistics										
	N	Minimum Statistic	Maximum Statistic	Mean		Std. Deviation Statistic	Skewness		Kurtosis	
				Statistic	Std. Error		Statistic	Std. Error	Statistic	Std. Error
ren_share	18	18.19500000	25.75800000	23.49105556	.4525786861	1.920128748	-1.521	.536	2.368	1.038
ghg_emiss	18	3.000000000	5.500000000	3.950000000	.1777216006	.7540088937	.904	.536	-.411	1.038
energy_prod	18	3.250000000	6.400000000	4.720000000	.2268064736	.9622583730	.274	.536	-.919	1.038
recycle_rate	18	.5000000000	14.80000000	10.74444444	1.094914633	4.645329371	-1.801	.536	1.727	1.038
import_dep	18	16.66300000	32.42300000	24.77266667	1.251024926	5.307649253	-.030	.536	-1.377	1.038
energy_intens	18	52.28000000	176.3300000	102.3072222	7.881734647	33.43936810	.450	.536	-.177	1.038
gdp_pps	18	6740	11220	8715.56	367.830	1560.570	.371	.536	-1.448	1.038
Valid N (listwise)	18									

The descriptive statistics provide an overview of the main indicators related to Romania's sustainable resilience and green transition over the period 2007–2024. The results indicate a relatively high variability across most variables, reflecting significant structural changes over time.

The share of renewable energy (mean = 23.49%) shows a steady upward tendency, with moderate dispersion, suggesting gradual progress in the adoption of clean energy sources. In contrast, greenhouse gas emissions display lower variability (mean = 3.95), indicating a relatively stable but declining trend.

Energy production and GDP per capita exhibit consistent increases over time, with mean values of 4.72 and 8715.56 respectively, reflecting economic growth and expansion in energy capacity. Similarly, the recycling rate shows considerable variability (mean = 10.74), indicating improvements in circular economy practices, although with fluctuations. Energy import dependency (mean = 24.77%) presents moderate dispersion, highlighting Romania's ongoing exposure to external energy sources. Meanwhile, energy intensity records a high standard deviation (33.44),

suggesting substantial improvements in energy efficiency over the analyzed period.

In terms of distributional characteristics, Skewness values indicate that variables such as renewable energy share and recycling rate are negatively skewed, reflecting upward trends over time. Other variables exhibit moderate deviations from normality, which is acceptable given the time-series nature of the data. The descriptive analysis confirms the presence of dynamic changes in sustainability and energy indicators, supporting the application of multivariate techniques such as PCA.

2.3 Methodological approach: Principal Component Analysis

To examine the underlying structure of the dataset and reduce dimensionality, this study applies Principal Component Analysis (PCA), which transforms the original set of correlated indicators into a reduced number of uncorrelated components that retain most of the variance in the data.

The suitability of the dataset for PCA is supported by the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (0.748), indicating a good level of adequacy, and by Bartlett's test of sphericity ($\chi^2 = 215.015$, $p < 0.001$), which confirms that the correlation matrix is appropriate for factor

extraction. The components were extracted based on the Kaiser criterion (eigenvalues greater than 1) and subsequently rotated using the Varimax method to improve interpretability. Only factor loadings above 0.40 are reported. Variables are assigned to components based on the highest absolute loading. These results confirm that the dataset is suitable for dimensionality reduction.

Table 2 - KMO and Bartlett's Test of sampling adequacy

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.748
Bartlett's Test of Sphericity	Approx. Chi-Square	215.015
	df	21
	Sig.	.000

The results regarding the total variance explained by the extracted components are presented in Table 3 and in the Scree Plot (Figure 1), both indicating the retention of two components.

Table 3 - Summary of variance explained by extracted components

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.002	71.458	71.458	5.002	71.458	71.458	4.287	61.245	61.245
2	1.597	22.820	94.278	1.597	22.820	94.278	2.312	33.034	94.278
3	.287	4.104	98.383						
4	.076	1.090	99.472						
5	.021	.296	99.768						
6	.012	.175	99.943						
7	.004	.057	100.000						

Extraction Method: Principal Component Analysis.

The first component has an eigenvalue of 5.002 and explains 71.46% of the total variance, while the second component has an eigenvalue of 1.597 and accounts for an additional 22.82% of the variance. Together, the two components explain 94.28% of the total variance, indicating a very high level of data representation.

The rotated solution further redistributes the explained variance between the components, with the first component accounting for 61.25% and the second component for 33.03% of the variance.

The Scree Plot confirms the retention of two components, as a clear break is observed after the second component.

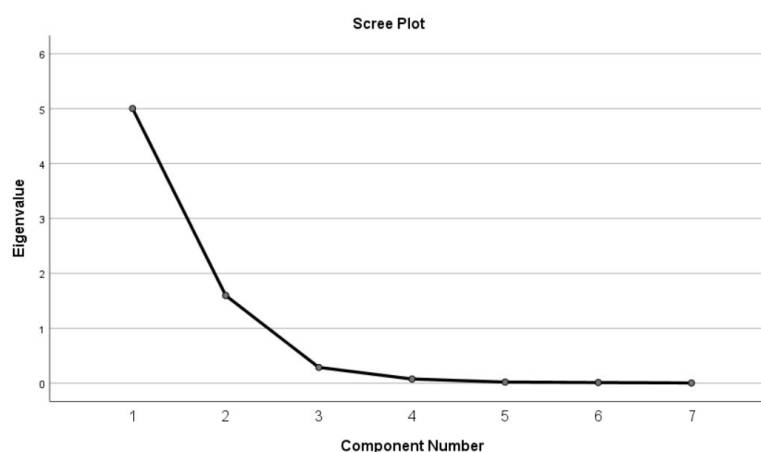


Figure 1 - Scree Plot for Principal Component Analysis

The high cumulative variance explained by the two components confirms that the PCA

model provides a robust and reliable representation of the underlying structure of

the dataset. Furthermore, the communalities indicate that all variables are well represented by the extracted components, with values ranging from 0.815 to 0.988.

Table 4 - Extracted Communalities of the Variables

Communalities		
	Initial	Extraction
ren_share	1.000	.963
ghg_emiss	1.000	.944
energy_prod	1.000	.972
recycle_rate	1.000	.815
import_dep	1.000	.932
energy_intens	1.000	.985
gdp_pps	1.000	.988

Extraction Method: Principal Component Analysis.

These high values suggest that the retained components capture a substantial proportion of the variance in each variable, confirming the robustness of the model.

3. Results and discussions

The PCA results indicate the presence of two principal components explaining 94.28% of the total variance. The results of the Varimax-rotated component matrix are presented in Table 5, highlighting the relationships between the selected variables and the extracted components.

Table 5 - Rotated Component Matrix and Factor Loadings

Rotated Component Matrix ^a		
	Component	
	1	2
ren_share	.979	
ghg_emiss	-.940	
recycle_rate	.889	
energy_intens	-.846	-.520
energy_prod	.734	.658
import_dep		.947
gdp_pps	.605	.789

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 3 iterations.

The first component, interpreted as “*Green Transition Performance*”, explains 71.46% of the total variance and reflects a sustainable development dimension, characterized by higher renewable energy

share, increased recycling rates and higher energy productivity, alongside lower greenhouse gas emissions and energy intensity. In contrast, the second component referred to as “*Economic Pressure*”, accounts for 22.82% of the total variance and captures the dimension of energy dependence and economic constraints, driven mainly by import dependency and economic activity indicators. The second component highlights Romania’s continued reliance on external energy sources and the structural challenges associated with energy demand.

The presence of GDP per capita in both components suggests its dual role: supporting sustainable development while also being linked to increased energy demand and structural pressure on the energy system. The results highlight a dual dynamic in Romania’s energy transition.

Figure 2 illustrates the evolution of the first principal component score, representing the *Green Transition Performance* in Romania over the period 2007–2024. The results indicate a general upward trend, suggesting continuous improvements in renewable energy adoption, energy efficiency and environmental performance.

The index records strongly negative values in the early years of the period, reflecting Romania’s initial structural gaps in terms of renewable energy adoption, energy efficiency and environmental performance at the time of EU accession. However, the sharp upward trend between 2007 and 2010 indicates a rapid adjustment process, likely driven by alignment with European environmental and energy policies.

Between 2011 and 2016, the index shows a consistent upward trajectory, reaching positive values and indicating significant improvements in green transition performance. This period reflects the expansion of renewable energy capacity, enhanced recycling rates and reductions in energy intensity, suggesting increased efficiency in resource use and gradual decarbonisation.

The period 2017–2021 is characterized by moderate fluctuations, suggesting a stabilization of the green transition process. While overall performance remains positive, the variability may reflect structural

adjustments, policy changes, or external shocks affecting the energy system, including market dynamics and evolving regulatory frameworks.

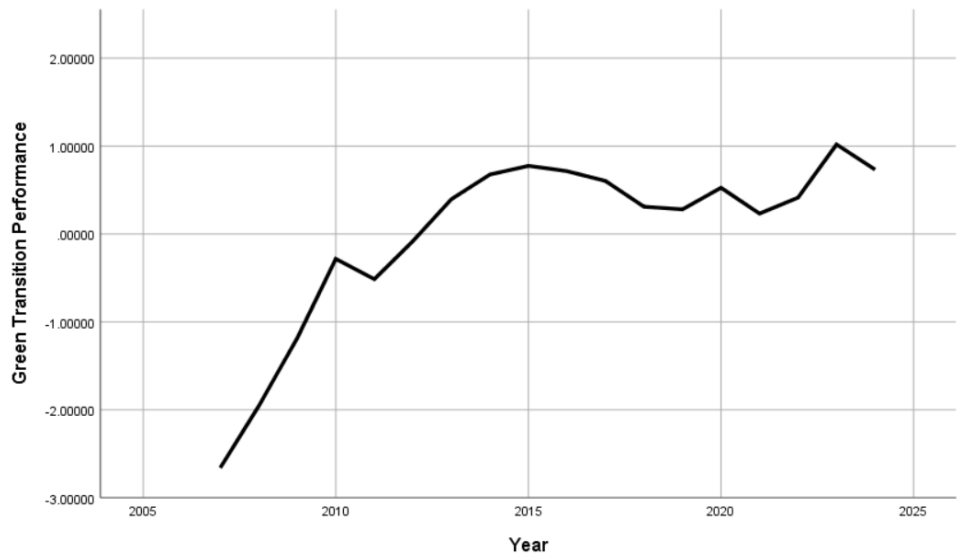


Figure 2 - Evolution of the **Green Transition Performance Index** in Romania (2007–2024)

In the most recent years, the index shows a renewed upward trend, reaching its highest values toward the end of the analysed period. This suggests an acceleration of Romania’s green transition, likely supported by EU-level initiatives such as the European Green

Deal and increased investments in renewable energy and energy efficiency.

The evolution of the second component reflects the dynamics of Romania’s energy dependence and associated economic pressures, primarily driven by energy import dependency and economic activity (Figure 3).

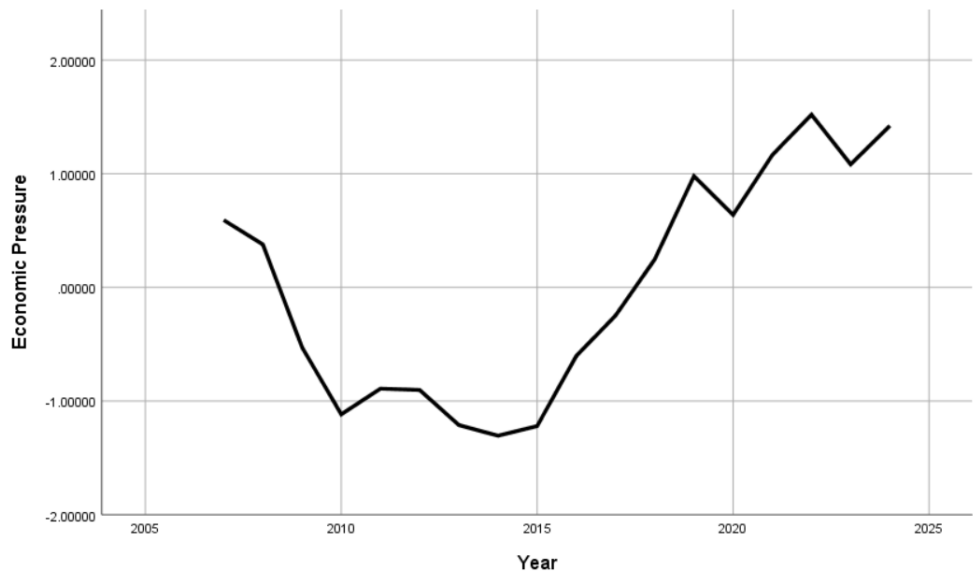


Figure 3 - Evolution of **Economic Pressure Index** in Romania (2007–2024)

Given the structure of the component, higher values of the index indicate increased economic pressure and stronger reliance on external energy sources, while lower values reflect reduced pressure and a more balanced energy structure.

In the early years following EU accession, the index shows a downward trend, reaching negative values around 2010–2014. This indicates a period of relatively lower economic pressure and reduced dependence on external energy sources, likely associated with lower economic activity and energy demand following the global financial crisis. Between 2011 and 2015, the index remains at low levels, suggesting a continuation of relatively moderate economic pressure and a more contained energy demand.

Starting with 2016, the index exhibits a clear upward trend, indicating a gradual increase in economic pressure and energy dependence. This evolution is consistent with economic growth, which typically leads to higher energy consumption and, implicitly, increased reliance on energy imports.

In the most recent period (2020–2024), the index reaches its highest values, reflecting intensified economic pressure and heightened exposure to external energy shocks. These dynamics are likely influenced by energy market volatility, geopolitical tensions and rising energy costs, which have amplified Romania's sensitivity to external energy dependencies.

4. Conclusions

The results of this study provide a comprehensive and synthetic perspective on the dynamics of Romania's green transition, highlighting both significant progress and persistent structural challenges. The empirical analysis, based on Principal Component Analysis (PCA), reveals that Romania has achieved substantial improvements in environmental performance, renewable energy adoption, and energy efficiency over the period 2007–2024.

The evolution of the **Green Transition Performance index** confirms a clear long-term upward trend, indicating that the

transition process is both progressive and path-dependent, reflecting cumulative policy efforts and structural transformations associated with European Union integration. The strong contribution of energy intensity and the negative association with greenhouse gas emissions suggest that improvements in energy efficiency and the decoupling of economic growth from environmental degradation represent key drivers of sustainability.

At the same time, the analysis highlights the persistence of structural vulnerabilities within the energy system. The **Economic Pressure index** reveals that, despite progress in sustainability, Romania continues to face significant challenges related to energy dependence and exposure to external shocks. The joint interpretation of the two indices emphasizes a dual dynamic: while sustainability performance has improved steadily, economic pressures associated with energy dependence have not been fully mitigated.

From a policy perspective, these findings underline the need for balanced and integrated strategies. On the one hand, continued support for renewable energy expansion, circular economy practices, and energy efficiency is essential to sustain the positive trajectory of the green transition. On the other hand, reducing energy import dependency through diversification of energy sources and increased domestic production remains a critical priority for enhancing energy security and economic resilience. Ensuring stability and consistency in policy frameworks is also necessary to avoid potential reversals and to support long-term progress.

The main contribution of this study lies in the development of a synthetic analytical framework that integrates multiple sustainability and energy indicators into two interpretable dimensions, providing a clearer understanding of the complex interactions between environmental performance and energy system constraints. By combining dimensionality reduction techniques with a dynamic analysis of component scores, the

research offers a policy-relevant perspective on Romania's energy transition. Finally, it should be noted that the relatively small sample size (18 observations) represents a limitation of the study. However, given the time-series nature of the data and the high

explanatory power of the model (over 90% of total variance explained), the results remain robust for exploratory and interpretative purposes and provide a solid basis for future research.

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