Exploring Financial Contagion and the Energy Kuznets Curve in the context of Romania's Transitions to a Circular Economy

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Abstract. *This study discusses the renewable energy adoption and CO_2 emissions, dealing also with the intersection of financial contagion and Romania's transition to a Circular Economy (CE). Financial contagion is defined as the shocks transmission across markets and sectors. Especially in emerging economies like Romania, financial contagion brings about issues related to green investments and renewable energy stability. By means of the Energy Kuznets Curve (EKC), the non-linear relationship between economic growth, renewable energy production, and CO_2 emissions during 1990–2023. By means of econometric tools, including ARDL models and cointegration analysis, this study focuses on two issues: the impact of financial contagion on short- and long-term between renewable energy production and CO_2 emissions, and the influence of global financial shocks on the EKC trajectory. We obtain that financial contagion delays decarbonization, initially increasing CO_2 emissions due to inefficiencies in hybrid energy systems. Even if renewable energy adoption gradually reduces emissions, the absence of significant turning points in the EKC suggests Romania is in the early stages of its energy transition. Therefore, it arises the need to include financial stability mechanisms into CE strategies to counteract the negative effects of contagion and accelerate the shift to a low-carbon economy. The study makes a contribution the literature by showing the relationship between financial contagion, renewable energy, and emissions. Policymakers are provided with actionable recommendations to strengthen Romania's resilience and sustainability.*

Keywords: Energy Kuznets Curve, Financial Contagion, Renewable Energy, Circular Economy, Sustainable Development, Place-Based Policies.

Introduction

With regards to transitioning towards a Circular Economy (CE), financial contagion can slow down an economy's capacity to invest in green technologies and sustainable infrastructure. Financial crises may spread within sectors or economies and they often lead to reduced investments in renewable energy and a shift back to fossil fuels, even if temporarily. Financial volatility may slow down the decarbonization process, this especially happening in economies that prove to be emerging, such Romania's economy, where there is a limitation of financial resources.

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The European Union's Green Deal aims for its member states to achieve climate neutrality by 2050. This standpoint underscores the importance of CE principles in reducing CO2 emissions, taking care of natural resources and encouraging sustainable economic growth. For an economy like Romania, to achieve these goals is challenging due to limited financial capacities and high dependence on fossil fuels (European Commission 2019).

According to Ionescu et al. (2023), Gajurel and Dungey (2023), and (Nica et al. 2024) financial contagion means the transmission of shocks across financial markets, sectors, or economies, where disturbances or changes in one area trigger chain reactions in others. The implications for financial and economic stability are high, since they underscore the interconnectedness of global markets. Financial contagion is a chain reaction by which disruptions in one market or region spread rapidly to others. This way, the vulnerabilities across systems are amplified. Even if countries like Germany or France are more resilient to such shocks (Gugler and Haxhimusa 2019), Romania remains vulnerable to external shocks. This poses serious challenges to its transition to renewable energy.

As an emerging economy, Romania is a distinct case to examine the impact of financial contagion on the transition to a CE. The relationship between green technology investments, financial volatility, and CO_2 emissions can be examined by means of Energy Kuznets Curve (EKC). This hypothesis suggests a nonlinear relation between economic development and emissions reduction.

The main objective of this study is to analyze the interactions between financial contagion and the EKC during Romania's transition to a CE. Using ARDL models and EKC, the research reveals mechanisms through which financial volatility influences energy transitions and emission trends. This study addresses the following research questions (RQ):

- RQ1: How do short-term and long-term dynamics of financial contagion influence the non-linear relationship between renewable energy production and CO_2 emissions in Romania?
- RQ2: How is the EKC shaped by financial shocks and global market volatility?

The paper is structured as follows. The next section reviews the relevant literature, focusing on studies addressing financial contagion, the EKC, and renewable energy adoption. The Results and Discussion section showcases the empirical findings on the dynamic relationships that exist between economic growth, renewable energy, and CO2 emissions. The implications of financial contagion for energy transitions are studied. The paper ends with conclusions, policy implications and directions for future research.

Literature review

Since global energy markets become interconnected with financial systems, financial contagion becomes very important in influencing the dynamics of energy transition. Recent studies emphasize that financial contagion impacts not only the stability of energy markets but also the direction and scale of investments important for renewable energy adoption.

Contagion episodes stemming from financial crises or global shocks intensify the difficulty of shifting to a low-carbon economy. For example, Mahadeo et al. (2019) introduce the notion of energy contagion, where in crises in energy markets amplify energy-finance interconnections through co-moments (correlation, co-skewness, and co-volatility). These interdependencies become more pronounced during periods of extreme oil price volatility or crises, such as the COVID-19 pandemic (Ghorbel and Jeribi 2021). This interconnectedness highlights the vulnerability of energy markets to financial stability. This has consequences for the renewable energy sector. As noted by D'Ercole and Wagner (2023), environmentally responsible stocks underperformed during the 2023 banking crisis. This indicated that investors anticipated a slowdown in climate technology development amid financial distress. Gong et al. (2023) prove that traditional energy markets are net transmitters of risk. Clean energy markets are net recipients in the interconnected financial networks. The critical role of financial contagion is reinforced. In the short run, market disruptions driven by contagion amplify inefficiencies in renewable energy systems, fact suggested by the significant relationship between EPREN and CO_2 emissions. Wu et al. (2021) argue that main sources of systemic risk, e.g. volatility in the US stock market and shifts in financial sentiment have a significant impact on energy market risk. Even if these effects are short-term, they are significant obstacles to renewable energy transition. They constrain capital flows to green projects and reinforce dependence on hybrid energy systems. Ersin and Bildirici (2024) put an emphasize over the non-linear dynamics in these energy-finance interactions. This reveals bidirectional contagion between energy consumption and emissions and unidirectional casuality from energy consumption to CO_2 emissions**.** The feedback loops makes the transition to cleaner energy systems to be more difficult, especially during financial instability.

Mitigating the impact of financial contagion on energy transition requires the development of robust financial mechanisms. Instruments that shield renewable energy projects from the volatility of financial markets may be described by targeted fiscal incentives, green bonds or government-backed guarantees. Wu et al. (2021) proposed some systemic risk indices, like the Total Systemic Risk Index. Such systemic risk monitoring tools can provide information on shifting risk dynamics, enabling policymakers to create strategies for a stable energy transition.

As stated by not only this study, but also by the comprehensive literature, energy transition must take into account the dual role of financial contagion: both as a barrier to green investment and as a source of market volatility, which weakens the stability of the energy system.

The relationship between environmental quality and per capita income was first introduced by Grossman and Krueger (1991). They concluded that in the early stages of economic growth, environmental degradation tends to increase due to higher level of industrial activity. Further studies present mixed results. Holtz-Eakin and Selden (1995) identified a monotonic rising curve. Friedl and Getzner (2003) proved the existence of an N-shaped curve. However, empirical findings remain inconclusive. By Chowdhury and Moran (2012), some case studies support the EKC hypothesis, while others fail to prove it. Agras and Chapman (1999) and Richmond and Kaufmann (2006) stated that there is no significant relationship between economic growth and environmental pollutants.

Shahbaz et al. (2013) studied the dynamic relationship that exists between economic growth, energy consumption, and CO_2 emissions in Romania during 1980–2010 using the ARDL bounds testing approach. The presence of the EKC is confirmed for both the long and short run, with energy consumption as a major contributor to CO_2 emissions. Delcea et al. (2024) show that CE policies play a important role in reducing CO_2 emissions in Romania. Their ARDL analysis proves that renewable energy production lowers CO_2 emissions in the long term. Urbanization and patent applications increase emission levels. Similarly, Georgescu et al. (2024a) use a cybernetics systems approach to analyze Romania's CE framework. A conclusion of the study is that sustainable development strategies have decoupled economic growth from environmental sustainability. GDP per capita is negatively associated with CO_2 emissions. Municipal waste indicators show a positive impact on CO_2 emissions. By these studies, the multidimensional role of CE practices in emphasized in shaping Romania’s environmental outcomes.

Methodology and Data Collection

This study explores the relationship between financial contagion, renewable energy adoption and CO_2 emissions in an econometric structure based on the EKC. The EKC depicts a non-linear relationship between economic development and CO2 emissions, as an inverted U-shape. CO2 emissions follow an ascending trend with the economic growth but this trend declines as economies transition to technologies that are more eco-friendly (Adeleye et al. 2022; Georgescu et al. 2024b). The model captures the dynamic interplay between these elements in Romania's transition to a CE, by integrating renewable energy production and financial variables.

Figure 1 shows the flow for the ARDL analysis starting with raw data collection and preprocessing. The second step includes the use of Phillips-Perron unit root test to assess the stationarity of time series and to determine the integration order of variables. Then, the selection of lagged order is made based on the AIC, SC and HQ criteria for the further specification of the ARDL model.

The next step is the ARDL bounds cointegration test, which evaluates the long-term relationship among the variables. After confirming the cointegration, the ARDL regression is performed to determine both long-run and short-run coefficients as well as to formulate the ECM.

Finally, the diagnostic and stability checks are performed in order to confirm the adequacy of the chosen model. The presence of serial autocorrelation, heteroscedastic residuals, normality of the residuals, errors in model specification and stability of the parameters are checked. The process ends with the analysis of the results obtained and the formulation of recommendations on policy changes.

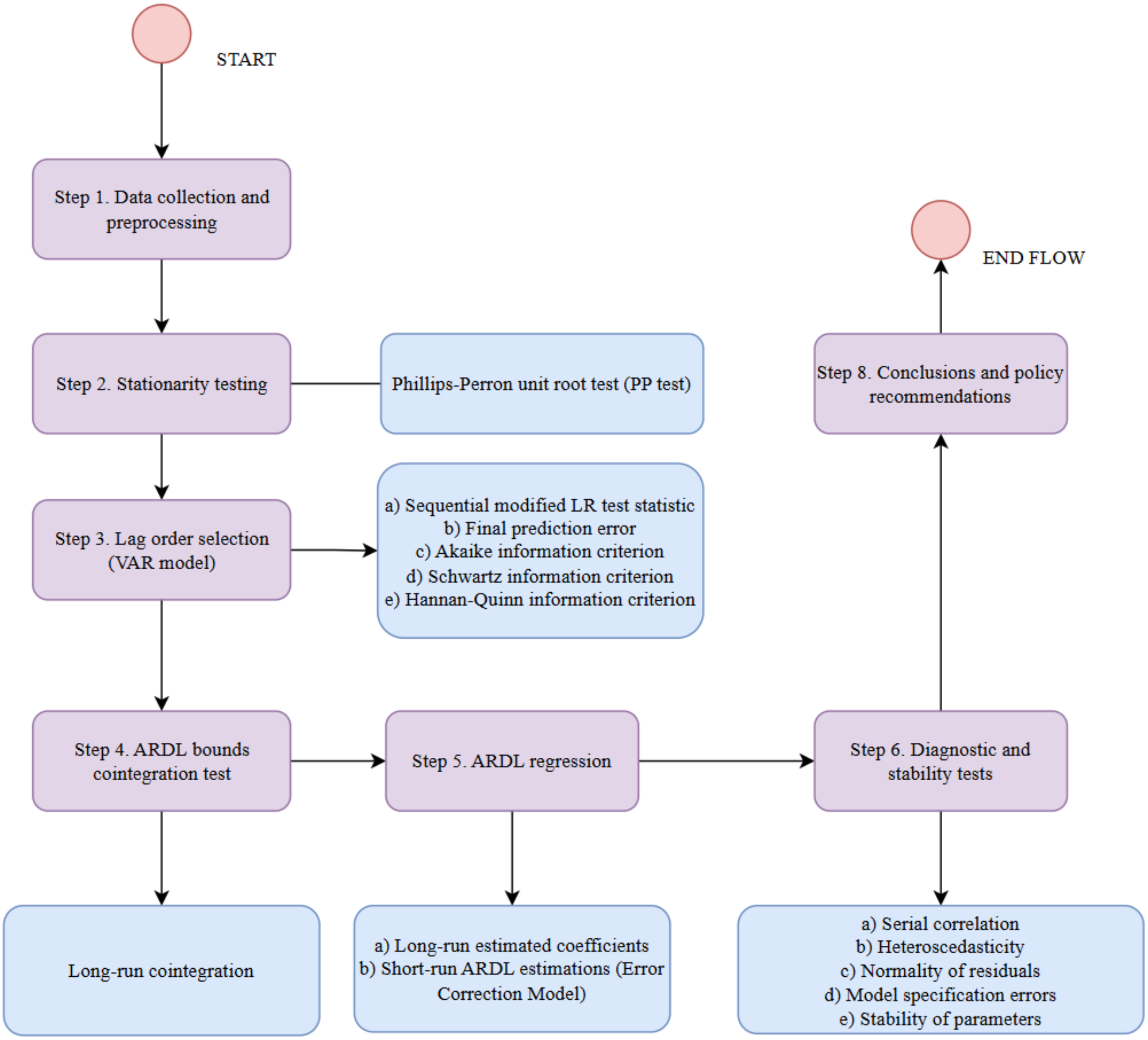

Figure 1. Methodological steps in ARDL analysis

Source: Authors' own research.

Table 1 contains annual observations for Romania, during 1990-2023, including research variables relevant to the EKC framework and the energy transition process. The dependent variable is CO_2 emissions per capita, measured in tonnes.

Table 1. Variable specifications

Variable	*Acronym*	*Measurement unit*	*Source*
CO_2 emissions per capita	CO_2	Tonnes	Our World in Data
Patent applications	PA	Number	World Bank
Gross domestic product	GDP	Constant 2015$	World Bank
Share of energy production from renewables	EPREN	%	Our World in Data
Urbanization	URB	%	World Bank

Source: Authors' own research.

Stationarity of the variables is checked with the Phillips-Perron (PP) unit root test in order to find the order of integration of the variables. The ARDL framework can take in variables of order I(0) or I(1), but not I(2) (Phillips and Perron 1988; Faisal et al. 2017). The dependence relationship is defined by equation (1):

$$CO_2 = f(GDP, EPREN, EPREN2, EPREN3, PA, URB) \quad (1)$$

where EPREN2 and EPREN3 represent the quadratic and cubic EPREN. Equation (1) becomes an ARDL (n, p, q, r, s, u, v) regression:

$$\Delta CO2_t = a_0 + \sum_{k=1}^{n} a_1 \Delta CO2_{t-k} + \sum_{k=1}^{p} a_2 \Delta GDP_{t-k} + \sum_{k=1}^{q} a_3 \Delta PA_{t-k} + \sum_{k=1}^{r} a_4 \Delta URB_{t-k} + \sum_{k=1}^{s} a_5 EPREN_{t-k} + \sum_{k=1}^{u} a_6 EPREN_{t-k}^2 + \sum_{k=1}^{v} a_7 EPREN_{t-k}^3 + \lambda_1 CO2_{t-1} + \lambda_2 GDP_{t-1} + \lambda_3 PA_{t-1} + \lambda_4 URB_{t-1} + \lambda_5 EPREN_{t-1} + \lambda_6 EPREN2_{t-1} + \lambda_7 EPREN3_{t-1} + \varepsilon_t \quad (2)$$

In equation (2), D is the first difference, n, p, q, r, s, u, v are the lag orders. The optimal lag order will be determined by means of various criteria: Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan-Quinn Criterion (HQ). Further we apply the ARDL bounds testing approach developed by Pesaran et al. (2001) which indicates the presence of cointegration. In the presence of cointegration, the ECM model is described by equation (3):

$$\Delta CO2_t = a_0 + \sum_{k=1}^{n} a_1 \Delta CO2_{t-k} + \sum_{k=1}^{p} a_2 \Delta GDP_{t-k} + \sum_{k=1}^{q} a_3 \Delta PA_{t-k} + \sum_{k=1}^{r} a_4 \Delta URB_{t-k} + \sum_{k=1}^{s} a_5 EPREN_{t-k} + \sum_{k=1}^{u} a_6 EPREN_{t-k}^2 + \sum_{k=1}^{v} a_7 EPREN_{t-k}^3 + \Gamma ECM_{t-1} + \varepsilon_t \quad (3)$$

In the ARDL framework, once cointegration is confirmed, the Error Correction Term (ECT) measures the speed of adjustment of the dependent variable back to equilibrium after a disturbance. For validity, the ECT should be statistically significant and lie between -2 and 0 (Samargandi et al. 2015).

In the relationship between CO_2 emissions and economic development, the EKC follows an inverted U-shaped trajectory. Integrating renewable energy into this framework highlights its main role in reducing emissions and promoting sustainability (Adeleye et al. 2022; Georgescu et al. 2024b).

The model will be evaluated through diagnostic tests for serial correlation, heteroscedasticity, normality of residuals, model specification errors, and parameter stability using CUSUM and CUSUMSQ plots.

Results and discussions

In this section, the dynamic relationships that exist between multiple terms such as CO_2 emissions, EPREN, economic growth, innovation represented by PA, and URB is investigated within the EKC framework**.** Using the ARDL model and cointegration testing, we examine both short- and long-term effects. One studies how financial contagion and renewable energy transitions impact Romania's efforts toward sustainability. The analysis focuses on the causality between these variables, showing implications for policy and economic strategies in the context of the transition to a CE.

The violin plot for CO_2 emissions from Figure 2 indicates how these values are distributed across the datasets. A wider section of the plot corresponds to a greater concentration of CO_2 levels at that range, suggesting the most common emission levels.

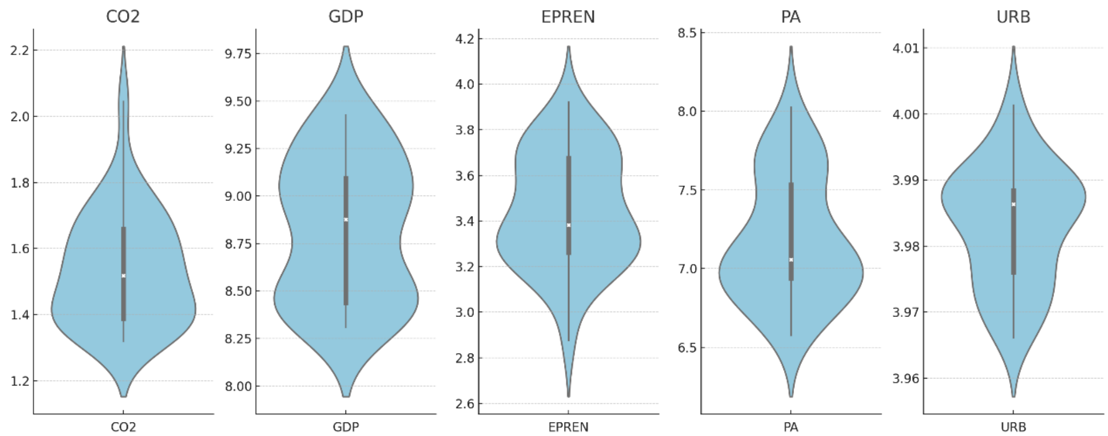

Figure 2. Violin plots of CO_2, GDP, EPREN, PA and URB (log variables)

Source: Authors' own research.

Symmetry in the plot signifies a balanced spread. Any asymmetry or extended tails might indicate skewed data or the presence of outliers. The GDP distribution is represented by the height and density of the violin plot. The thickest part of the plot shows where GDP values are concentrated. It reveals the central tendency of the data. If the plot has long tails, it suggests variability or extreme GDP values. The EPREN violin plot highlights the spread and skewness of the data. Dense regions of the plot correspond to frequent values for EPREN generated from renewables. The PA violin plot illustrates patents variability over time. Symmetrical URB violin plot suggests consistent trends, while peaks or asymmetries indicate distinct clusters of URB levels or periods of rapid change.

Table 2 reports the Phillips and Perron unit root test (PP) (Phillips and Perron 1988). CO_2 is stationary at level I(0) and the other variables are integrated of order 1, I(1). Symbols like "*", "**", "***" indicate the significance of variables at 10%, 5%, and 1% levels, respectively.

Table 2. PP Unit Root Test Results

Variables	Level	First difference	Order of integration
	T-statistics	T-statistics	
CO_2	−3.28** (0.02)	−9.34*** (0.00)	I (0)
GDP	0.88 (0.99)	−4.76*** (0.00)	I (1)
PA	−1.66 (0.43)	−6.94*** (0.00)	I (1)
URB	−1.02 (0.73)	−4.45*** (0.00)	I (1)
EPREN	2.00 (0.78)	−11.75*** (0.00)	I (1)

Source: Authors' own research.

According to Table 3, the VAR model with 2 lags is the best choice for the ARDL analysis, according to all selection criteria. In Table 3, LR represent the sequential modified LR test statistic (each test at 5% level), FPE is final prediction error, AIC represents the Akaike information criterion, SC is Schwarz information criterion and HQ represent the Hannan-Quinn information criterion.

Table 3. VAR Lag order selection criteria

Lag	LogL	*LR*	FPE	AIC	SC	HQ
0	330.65	NA	3.87×10^{-18}	−20.22	−19.90	−20.12
1	512.78	273.19	1.02×10^{-21}	−28.54	−25.98	−27.69
2	607.94	101.10*	9.17×10^{-23}*	−31.43*	−26.62*	−29.83*

Source: Authors' own research.

The obtained model is ARDL (3,3,3,3,3). Table 4 presents the results of the ARDL cointegration bounds test.

Table 4. Results of ARDL (3,3,3,3,3) cointegration bounds test

Test statistic	*Value*	*K (number of regressors)*
F-statistic	6.75	6
Critical value bounds		
Significance	I (0)	I (1)
10%	2.33	3.51
5%	2.79	4.18
1%	3.97	5.69

Source: Authors' own research.

In Table 4, the calculated F-statistic of 6.75 is higher than the upper critical bound for I (1). This indicates the presence of cointegration among the variables. The estimated long-term ARDL coefficients are reported in Table 5.

Table 5. Long-run estimated results of ARDL (3,3,3,3,3) model

Variables	Coefficient	T-Statistics	Prob.
GDP	-0.26	-1.67	0.100*
EPREN	114.8	1.84	0.078*
EPREN2	-32.65	-1.85	0.077*
EPREN3	3.08	1.85	0.078*
PA	0.25	2.26	0.034**
URB	5.97	1.28	0.211
C	-155.97	-1.92	0.068*

Source: Authors' own research.

A 1% long-term increase in GDP leads a 0.26% long-run decrease in CO_2 emissions. This suggests a potential decoupling between economic growth and CO_2 emissions. This potential decoupling might be susceptible to financial contagion, since economic downturns driven by financial crises can disrupt renewable energy investments. During periods of financial instability, resources intended for green projects might be redirected toward short-term economic recovery. Thereby. the positive effects of GDP growth on CO_2 emissions are delayed.

A 1-unit increase in EPREN leads to a long-run increase in CO_2 emissions by 114.8 units. This suggests inefficiencies in renewable energy systems or reliance on hybrid systems that still use fossil fuels. This could also reflect the influence of financial contagion, which can amplify inefficiencies in renewable energy systems. Disruptions in renewable energy development are often caused by financial crises. This leads to delays in infrastructure upgrades, dependence on hybrid systems, ultimately leading to higher carbon intensity of EPREN.

The negative and significant quadratic term EPREN2 suggests a non-linear relationship between EPREN and CO_2 emissions. Initially, an increase in EPREN raises CO_2 emissions, but at higher levels, renewable energy production begins to reduce emissions.

The positive term EPREN3 indicates a more complex relationship between renewable energy and CO_2 emissions. This suggests the existence of possible thresholds or diminishing returns. The signs of EPREN, EPREN2, and EPREN3 point to an S-shaped curve, where EPREN has varying impacts on emissions over different phases of adoption. The S-shaped relationship may be further influenced by financial contagion. Financial instability can hinder the expansion of renewable energy, especially during the phase when CO_2 emissions are expected to level off. Financial shocks may raise the cost for renewable energy projects. CO_2 emissions associated with high levels of EPREN are postponed.

A 1-unit increase in PA is associated with a 0.25% long-term increase in CO_2 emissions. Energy-intensive R&D processes or innovations in non-sustainable industries can contribute to this relation. Increasing URB is associated with higher CO_2 emissions, but the relationship is statistically insignificant. Financial contagion can intensity the carbon intensity of R&D activities. Companies under financial stress may prioritize cost-cutting innovations over environmentally sustainable solutions.

From Table 5, one can deduce the cubic equation between CO_2 emissions and EPREN:

$$CO_2 = 114.8 \times EPREN - 32.65 \times EPREN2 + 3.08 \times EPREN3 - 155.97 \quad (4)$$

The turning points occur where the derivative of CO_2 with respect to EPREN equals zero. Thus, a quadratic equation is obtained:

$$9.24 \times EPREN2 - 65.3 \times EPREN + 114.8 = 0 \quad (5)$$

The turning points of equation (5) are complex numbers. Hence the cubic relationship does not have real maxima or minima for the range of plausible EPREN values. The cubic equation represents the Energy Kuznets Curve, and its shape is shown in Figure 3.

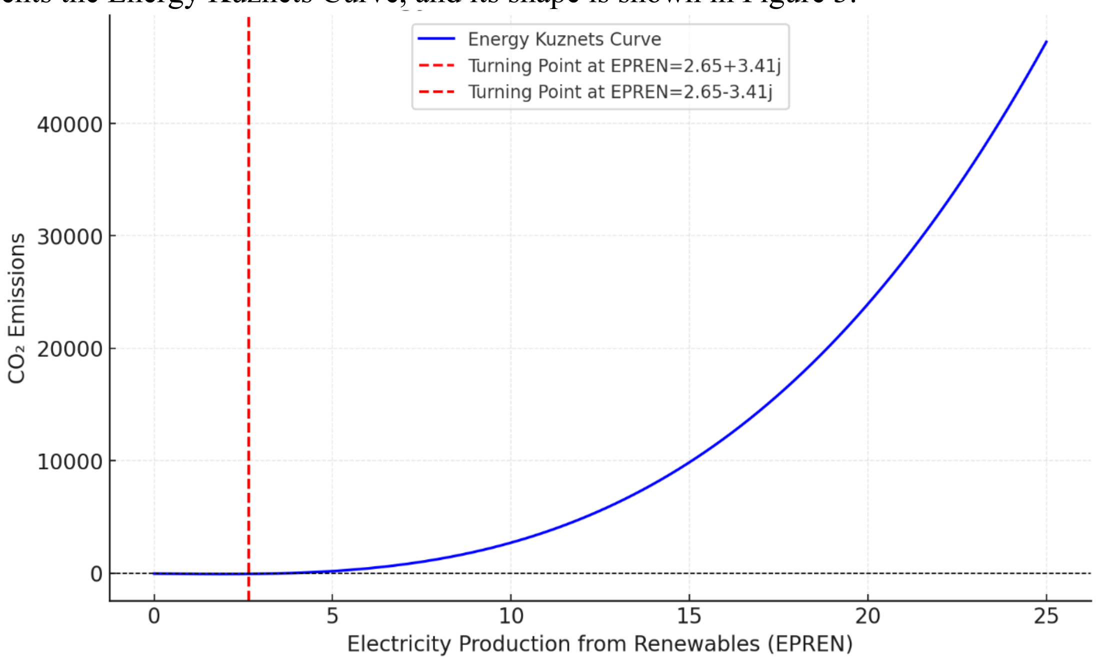

Figure 3. Energy Kuznets Curve for Romania

Source: Authors' own research.

Figure 3 suggests that EPREN influences CO_2 emissions in a non-linear but continuous manner, without a distinct turning point. At lower levels of renewable electricity production, CO_2 emissions increase as EPREN grows. This describes the early phases of renewable energy adoption, where s fossil-fuel-based infrastructure is still in use. The renewable energy production process involves energy-intensive processes with a high carbon footprint.

In the transitional phase, in the mid-range EPREN values, the rise in CO_2 emissions slows down. As renewable energy expands, cleaner technologies become dominant. Dependency on fossil fuels starts to decline.

At very high EPREN values, CO_2 emissions may fall. Renewables dominate the energy mix, the energy efficiency improves and older, high-emission energy systems are gradually replaced.

Table 6 presents ARDL-ECM short-run estimated results.

Table 6. ARDL-ECM model for short-run estimated results

Variable	Coefficient	*T-statistics*	Prob.
D(GDP)	0.95	8.67	0.00***
D(EPREN)	44.33	8.17	0.00***
D(EPREN2)	−12.96	−8.36	0.00***
D(URB)	14.65	5.50	0.00***
CointEq (-1)	−0.40	−8.48	0.00***
R-squared			0.84
Adjusted R-squared			0.82

Source: Authors' own research.

A 1% increase in GDP leads to a 0.95% increase in CO_2 emissions in the short run. This shows that economic growth remains carbon intensive. During financial contagion, this relationship may become stronger. Geen funding may be disrupted, increasing reliance on fossil fuels.

A 1-unit increase in EPREN increases CO_2 emissions by 44.33 units in the short run. This points to financial inefficiencies and carbon costs to build renewable energy infrastructure. The negative coefficient for EPREN2 term shows diminishing returns. As renewable energy grows, the impact on CO_2 emissions lessens. Financial contagion can worsen these short-run inefficiencies. Instability causes delays in green projects, funding cuts and reliance on hybrid systems.

A 1% increase in URB leads to a 14.65 unit increase in CO_2 emissions in the short term. This is likely due to urban expansion, construction, transportation and other energy-intensive activities. Financial contagion may influence this relationship. Crises cause delays or cuts in urban development funding, leading to an inefficient use of resources and higher CO_2 emissions. Patents reflect slow, structural changes.

CointEq (-1) is negative and statistically significant, confirming the validity of the ECM model. 40% of the gap between short-run and long-run CO_2 emissions levels is corrected each period. This indicates a moderate speed of adjustment to equilibrium. The model explains 84% of the variability in CO_2 emissions. After adjusting for the number of regressors, 82% of the variability is still explained, indicating a good fit. 40% adjustment speed may indicate external pressures like financial contagion. Short-term shocks in global markets can delay the return to equilibrium. Financial crises can slow down decarbonization and increase energy market uncertainty.

The diagnostic and stability tests in Table 7 validate the reliability and robustness of the estimated ARDL model.

Table 7. Results of diagnostic and stability tests

Diagnostic test	H_0	**Decision Statistics [p-value]**
Serial Correlation	There is no serial correlation in the residuals.	Accept H_0 1.66 [0.21]
Heteroscedasticity (GLEJSER)	There is no autoregressive conditional heteroscedasticity	Accept H_0 1.33 [0.27]
Jarque Bera	Normal distribution	Accept H_0 0.92 [0.62]
Ramsey Reset	Absence of model misspecification	Accept H_0 2.53 [0.11]

Source: Authors' own research.

The CUSUM and CUSUMSQ plots in Figures 4 and 5 show that the cumulative sum of recursive residuals lies within the 5% critical bounds, confirming the stability and reliability of the model's parameters (Brown et al. 1975) over the studied period.

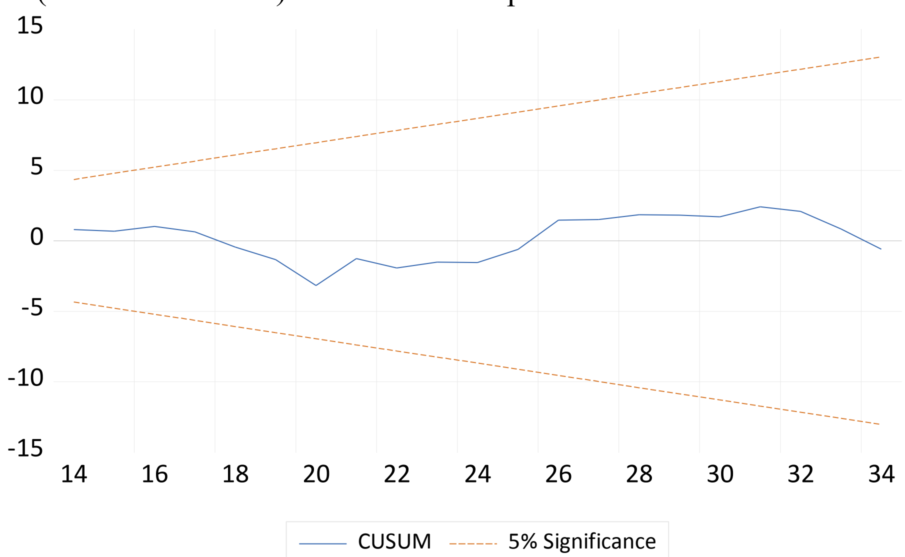

Figure 4. Plot of CUSUM at 5% level of significance

Source: Authors' own research.

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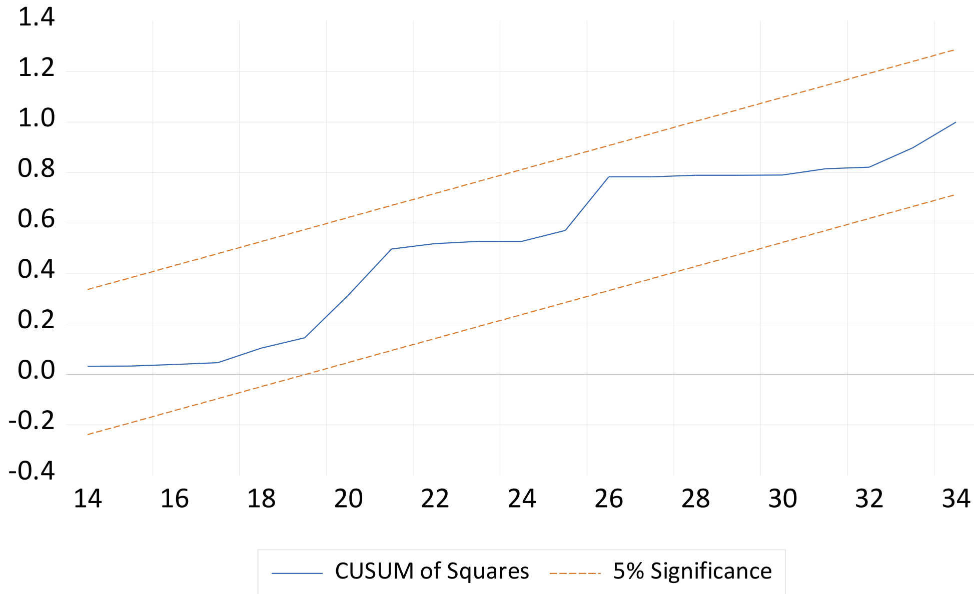

Figure 5. Plot of CUSUMSQ at 5% level of significance

Source: Authors' own research.

Conclusion

This study shows that financial contagion can slow Romania's shift towards a CE, especially in adopting renewables and cutting CO_2 emissions. The results highlight the need to address financial risks to support a sustainable EKC. Policymakers should include financial stability in CE strategies to reduce the impact of external shocks. EU-level cooperation to stabilize markets can boost Romania's resilience and speed up its decarbonization efforts.

In the short term, financial contagion weakens renewable infrastructure, causing CO_2 emissions to rise due to delays and reliance on hybrid systems. Long-term effects are non-linear, as renewables eventually reduce CO_2 emissions. Financial shocks slow this progress by limiting clean energy investments (RQ1).

The EKC shows a complex path, with no real turning points. This suggests that Romania is in the early or middle stage of its energy transition. Financial contagion and market volatility slow progress. They disrupt main structural changes needed for renewables to cut CO_2 emissions (RQ2).

In the initial stages of renewable energy adoption, the EKC might reveals a positive relationship between EPREN and CO_2 emissions. This counterintuitive finding highlights the potential carbon-intensive nature of renewable energy system development, including the manufacturing of components, transportation, installation, and hybrid systems partially reliant on fossil fuels. Policies in this phase should prioritize greening the supply chain for renewable technologies. For example, incentivizing the use of recycled or low-carbon materials in manufacturing and promoting local production to reduce transportation emissions can mitigate the carbon footprint. Moreover, introducing stricter environmental standards for renewable energy projects and investing in green innovations during the infrastructure setup phase could prevent CO_2 emissions from rising during this critical transition period.

As renewable energy systems expand, the relationship between EPREN and CO_2 emissions begins to plateau, signaling a transition phase where renewables start displacing fossil fuels. Policies in this phase should focus on accelerating this transition by decommissioning aging fossil-fuel-based power plants and replacing them with renewable alternatives. Governments should provide fiscal incentives such as tax breaks or subsidies for renewable energy adoption and storage solutions to ensure grid reliability and efficiency. Additionally, investments in upgrading the national energy grid to accommodate higher renewable energy penetration can reduce energy loss and improve the carbon efficiency of the overall system. Educational campaigns to raise awareness and encourage businesses and households to adopt renewable energy solutions would also support this phase.

In the long term, when renewable energy production potentially surpasses critical thresholds, CO_2 emissions are expected to decline as cleaner energy sources dominate the grid. Policies should aim to maintain this trajectory by ensuring a balance between energy demand, supply, and sustainability. Investment in energy storage technologies, such as advanced batteries or hydrogen systems, is essential to address the intermittency of renewables like solar and wind. Policymakers should consider implementing carbon pricing mechanisms, such as emissions trading schemes or carbon taxes, to disincentivize any lingering fossil fuel use and generate revenue to fund further renewable energy projects. Finally, international collaboration for technology transfer and financing, along with strong domestic governance, can ensure that Romania meets its long-term decarbonization goals under global climate commitments.

As in any scientific study, this research has some limitations. In our case, for Romania, the analysis is at the annual level, which makes it difficult to grasp certain aspects of emissions or energy consumption that might occur over a shorter time frame or during a particular season. More available data could enable us to paint a more comprehensive picture. Furthermore, the model does not consider other variables such as government intervention, energy costs or the structure of the economy, which could be responsible for the relationships evidenced above. This is an important limitation that can be addressed in future research avenues to have a more comprehensive and well substantiated understanding of the explored dynamics. Also, specific financial indicators (market volatility, credit spreads, etc.) could be exploited to assess financial contagion effects on the renewable energy transition process in the future.

Continuous monitoring of renewables impact on CO_2 emissions is essential. Policymakers should track CO_2 emission cut and adapt strategies as data and technologies evolve. A dedicated renewable energy fund can reduce the risks of financial contagion. This fund should be protected from global shocks. It could be partly financed through international climate funds. Its goal is to keep renewable projects on track, even during economic crises.

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