International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2026, 16(2), 646-654.

VECM Modeling of the Determinants of Decarbonization in Tunisia: The Role of Innovation and Renewable Energies

Kaouther Amiri[1], Lamia Arfaoui[2]*, Sonia Mannai[3], Sihem Nasr Khouaja[4]

[1]Higher Institute of Management of Tunis, University of Tunisia, Economics Department, Laboratory of International Economic Integration, Faculty of Economic Sciences and Management of Tunis, University Tunis El Manar, Tunisia, [2]Department of Business Administration, College of Business, University of Bisha, Bisha, Saudi Arabia, [3]Department of Finance and Investment, Faculty of Business Administration, University of Tabuk, Tabuk, Saudi Arabia, [4]Department of Business Administration, College of Business, University of Bisha, Bisha, Saudi Arabia. *Email: lalarfawi@ub.edu.sa

Received: 07 August 2025 **Accepted:** 14 December 2025 **DOI:** https://doi.org/10.32479/ijeep.22022

ABSTRACT

This study analyzes the dynamic relationships between per capita CO2 emissions, renewable energy consumption, environmental innovation, and trade openness using a Vector Error Correction Model (VECM) over the period 1995–2024. The econometric analysis confirms the existence of a long-run cointegration relationship between these variables, highlighting a stable equilibrium mechanism linking environmental outcomes, technological progress, energy transition, and economic openness. Short-term causality tests reveal asymmetric interactions: Environmental innovation is significantly influenced by shocks to renewable energy consumption and trade openness, while CO_2 emissions show relative rigidity in the short run. Stability tests confirm the robustness of the model, and variance decomposition highlights the increasing influence of renewable energy on emissions, reflecting the gradual impact of energy transition policies. Environmental innovation emerges as a key driver influencing both renewable energy development and emissions dynamics, highlighting the crucial role of technological progress in achieving sustainability goals. Trade openness exerts an indirect but significant effect, interacting with innovation and energy over longer time horizons.

Keywords: Cointegration, Energy Transition, Environmental Innovation, CO_2 Emissions, Trade Openness
JEL Classifications: C32, Q43, Q55, Q53, F18

1. INTRODUCTION

In a global context where the fight against climate change has become a major priority, reducing carbon dioxide (CO_2) emissions is a crucial issue for countries engaged in the energy transition. In Tunisia, an emerging country facing specific sustainable development challenges, this issue is particularly important. Tunisian public policies aim to encourage the development of renewable energies, stimulate green technological innovation, and strengthen integration into international trade. However, the real and quantifiable impact of these levers on per capita CO_2 emissions in the Tunisian context remains insufficiently explored.

While renewable energy consumption is generally recognized as a key factor in reducing greenhouse gas emissions, the impact of trade openness remains ambivalent. Indeed, Tunisia, as a country open to global trade, could suffer the consequences of the "pollution haven" phenomenon through the relocation of polluting activities, or, conversely, benefit from a "race to the top" through the transfer of clean technologies. Moreover, environmental innovation, a key driver of a successful energy transition, is still studied little in this specific context, despite its potential to improve energy efficiency and foster the emergence of sustainable solutions adapted to the local context.

In the face of these uncertainties, this study makes an original contribution by mobilizing a vector error correction econometric model (VECM) to simultaneously analyze the short- and long-term impact of renewable energy consumption, trade openness, and environmental innovation on per capita CO_2 emissions in Tunisia. This integrated approach not only allows for a better understanding of the complex interactions between these variables, but also for the identification of the structural equilibrium mechanisms underlying emission dynamics.

By shedding light on these relationships in a national context marked by specific economic, social, and environmental constraints, this work offers valuable insights to guide Tunisian public policies toward a more efficient and sustainable energy transition. Thus, it contributes to filling a significant gap in the literature by providing robust empirical results that can guide the design of strategies adapted to local and international challenges. A central question therefore arises: to what extent do renewable energy consumption, trade openness and environmental innovation influence CO_2 emissions per capita?

This issue is particularly relevant in the Tunisian context, where the need to reconcile economic growth, trade integration, and sustainable energy transition is at the heart of national challenges. Despite notable progress in the development of renewable energies and green innovation, the precise interactions between these factors and their impact on CO_2 emissions remain insufficiently explored, which limits the ability to formulate effective and targeted public policies. The objective of this article is to empirically analyze these relationships through a vector error correction econometric model (VECM), in order to identify the structural determinants of CO_2 emissions in Tunisia and to inform strategic choices in terms of sustainable development.

2. LITERATURE REVIEW

Recent literature on the energy transition in emerging countries consistently highlights the crucial importance of renewable energy in combating CO_2 emissions. Indeed, the ability of clean energy to provide a sustainable alternative to traditional fossil fuels is now emerging as a fundamental lever for reconciling environmental objectives and economic growth. Riyono and Widianingsih (2025) show, through rigorous empirical analysis across several Asian countries, that expanding renewable capacity not only reduces emissions in the long term, but also mitigates the economic costs often associated with the energy transition. This finding is all the more relevant in emerging economies, where pressure to support growth is high, but where energy infrastructure often remains vulnerable.

At the same time, trade openness, which plays a key role in the integration of emerging economies into the global market, has a more ambivalent environmental impact. Pham and Nguyen (2024) emphasize that this openness can induce a "pollution haven" effect, by attracting polluting-intensive industries to these countries due to less stringent environmental regulations. This phenomenon raises important questions about the ability of emerging countries to effectively manage the environmental externalities linked to their integration into international trade. However, these authors also highlight the "race to the top" effect, where international competition encourages certain countries to adopt stricter environmental standards and import cleaner technologies, thus contributing to an overall improvement in environmental performance.

Finally, green technological innovation is identified as an essential pillar for accelerating the energy transition in developing countries. Nan et al. (2022) demonstrate that advances in clean technologies, such as improved energy efficiency or less polluting industrial processes, play a central role in reducing greenhouse gas emissions. Innovation is not limited to the simple adoption of existing technologies, but also involves endogenous research and development capacities, which determine the sustainability and adaptation of solutions to local specificities. This technological dynamic is all the more critical as emerging countries must simultaneously address the challenge of economic growth and environmental sustainability.

Thus, these studies converge towards a nuanced understanding of the mechanisms that govern the interactions between energy transition, international trade and innovation in emerging countries. They also highlight the importance of adopting an integrated approach that takes these dimensions into account simultaneously, in order to develop coherent and effective public policies. This conceptual framework fully justifies the orientation of our work, which aims to jointly analyze these factors in the Tunisian context, characterized by its own economic, environmental and institutional constraints.

Concerning Tunisia, empirical research on the interactions between energy transition, international trade, environmental innovation and CO_2 emissions remains limited and fragmented, which fully justifies our contribution.

Ben Jebli and Ben Youssef, (2015) have highlighted that the growth in the share of renewable energy in the Tunisian energy mix has a significant moderating effect on CO_2 emissions in the long term. More specifically, their analysis shows that a 1% increase in renewable energy consumption leads to an average reduction of approximately 0.3% in emissions per capita. This result underlines the strategic importance of investing in the development of renewable capacities, especially since Tunisia benefits from strong solar and wind potential that is still underexploited.

Furthermore, the study of Mahmood et al. (2019) reveal that trade openness has a statistically significant but ambivalent impact on Tunisian emissions. They find that foreign trade, which increased by an average of 4.5% per year between 2000 and 2018, contributes both to reducing emissions through the import of cleaner technologies, but also to increasing them due to the presence of polluting industries located in industrial zones with weak environmental regulations. This complex relationship is largely conditioned by the sectoral structure of the Tunisian economy, dominated by agri-food, chemical, and textile industries, where environmental regulations still need to be strengthened.

Saadaoui et al. (2024) emphasize the key role of environmental innovation, which remains insufficiently valued in Tunisian public policies. Their empirical study shows that research and development (R&D) spending on green technologies represents <0.3% of GDP, a level still low compared to other emerging countries. They emphasize that without increased institutional and financial support, the innovation potential to improve energy efficiency and reduce the carbon footprint will remain limited. This weakness hinders Tunisia's ability to position itself in high value-added green sectors and compromises the achievement of the objectives set in its national energy transition strategy for 2030.

These findings converge on the idea that, although renewable energy, trade openness, and environmental innovation are promising levers for decarbonization, their effectiveness depends heavily on the coordination of public policies, targeted investments, and institutional capacity building. It is precisely this integrated and multidimensional approach that our study proposes to explore through a robust econometric framework, in order to provide recommendations tailored to the specific context of Tunisia.

3. MODEL, SPECIFICATION AND DATA

To analyze the relationship between per capita CO_2 emissions, renewable energy consumption, trade, and environmental innovation, we adopt the VECM (Vector Error Correction Model). This approach, is particularly appropriate when the variables studied are non-stationary in level but stationary in first difference (integrated of order I(1)) and they maintain a cointegration relationship Engle and Granger, (1987) And Johansen, (1988).

The VECM approach has the advantage of modeling both short-term dynamics and adjustments toward a long-term equilibrium between variables. Before estimating the model, we check the integration order of the series using unit root tests such as the ADF test (Dickey and Fuller, 1981) or KPSS (Kwiatkowski et al., 1992). Once established that the variables are integrated of order I(1), we apply the Johansen cointegration test to determine the existence and the number of long-term relationships between them.

If cointegration is confirmed, the VECM is estimated with an error correction term (ECM) that measures the speed of adjustment of long-term imbalances. This term makes it possible to assess the extent to which variables react to a deviation from the long-term equilibrium. The coefficients of the differentiated variables account for short-term effects.

The analysis of the results will test the hypothesis that increasing renewable energy consumption and strengthening environmental innovation contribute significantly to reducing CO_2 emissions per capita. The effect of trade will also be examined, depending on its ecological orientation. Finally, diagnostic tests (autocorrelation, structural stability, normality of residuals) will be carried out to validate the robustness of the estimated model (Lütkepohl, 2005).

In this study, we examined the stationarity properties of the following variables, all expressed in logarithms: CO_2 emissions per capita (in metric tons), renewable energy consumption (as a percentage of final energy consumption), trade (as a percentage of GDP), and innovation in environmentally related technologies. These variables were extracted from the World Bank covering a period from 1995 to 2024. This period allows for the analysis of long-term dynamics in a context of economic, energy, and technological changes. The use of the natural logarithm reduces the heteroscedasticity of the series, facilitates the interpretation of the coefficients as elasticities, and improves comparability between different economic variables, in accordance with recommended practices in time series econometrics.

The empirical model used in the study will capture the relationship between environmental degradation and its determinants: a

$$LCO_{2t} = \beta_0 + \beta_1 LENR_t + \beta_2 LINN_t + \beta_3 LOPEN_t + \varepsilon_t$$

Before proceeding with the econometric tests, a descriptive statistical analysis was performed on the four variables of interest, all expressed in logarithms: CO_2 emissions per capita (L CO_2), renewable energy consumption (LENR), innovation in environmental technologies (LINN), and the degree of trade openness (LOPEN). This step allows for a better understanding of the data distribution, their central behavior and their dispersion.

As reported in Table 1, Central tendency statistics indicate that the means and medians are relatively close for all variables, except LINN, suggesting a slightly skewed distribution. The mean for CO_2 emissions (LCO_2) is 0.84, while that for renewable energy consumption (LENR) is 2.61. Environmental innovation (LINN) has a mean of 1.85, but a higher median of 2.08, indicating a leftward skewness, which is confirmed by a skewness coefficient of −1.09. This reflects a concentration of observations toward high values, with some cases of very low innovation, likely due to structural differences between countries or periods (Baltagi, 2005). Dispersion, measured by standard deviation, reveals that LINN is the most volatile variable with a value of 0.78, which indicates a great heterogeneity in environmental innovation efforts. Conversely, LENR is the most stable variable, with a standard deviation of only 0.077. This contrast is consistent with the findings of Stern (2004), according to which innovation policies vary greatly from one country to another, while the share of renewable energies tends to evolve more gradually. Regarding kurtosis, all variables have a value close to or <3, which indicates a platikurtic distribution, that is, slightly flattened compared to the normal distribution. This is often interpreted as a sign of less extremes (Field, 2013), with the possible exception of LINN (kurtosis = 3.27), which is closer to a normal distribution. Finally, the Jarque-Bera test is used to check the normality of the distributions. The results indicate that LCO_2, LENR and LOPEN follow a normal distribution, with p-values greater than 0.05, which confirms that the hypothesis of normality is not rejected. For LINN, the probability is 0.071, which suggests a slight deviation from normality, probably due to its marked asymmetry. According to Brooks (2014) slight non-normality is generally not problematic for time series estimations, as long as the final model residuals are well-behaved.

This descriptive analysis highlights the relevance of the logarithmic transformation, which made it possible to stabilize the variance of the series and bring most of them closer to a normal distribution. These statistical properties confirm the quality of the data for use in VECM-type models, which assume a certain regularity in the series used.

4. RESULTS AND ECONOMETRIC ANALYSIS

4.1. Stationarity Test

To test the stationarity of these time series, we applied two-unit root tests widely used in the econometric literature: the ADF (Augmented Dickey-Fuller) test. This test allows us to determine whether a series exhibits a stochastic trend and therefore whether it requires a transformation to become stationary.

The results, presented in Table 2, indicate that the four log-transformed series are not stationary in level. On the other hand, after applying a first-order differentiation, all the series become stationary, which implies that they are integrated of order one, that is, I(1). This property is essential for the rest of the analysis, particularly in the context of VECM estimation, which requires integrated series of the same order and linked by a cointegration relationship. The series will therefore be introduced into the model in their differentiated form for the analysis of short-term dynamics, while their levels will be used to test long-term relationships through the Johansen cointegration test.

4.2. Cointegration Test

Based on these variables, the Johansen test was applied to determine the existence of cointegration relationships between the system variables. The results of the test are presented in the Table 3, considering different trend specifications (no trend, linear and quadratic trend) as well as the presence or absence of an intercept. Among these configurations, the model without trend and with intercept stands out as the most appropriate, especially due to its minimum value of the Schwarz criterion (−7.800682), marked with an asterisk. For this model, the trace statistic indicates the existence of a cointegration vector at the 5% significance level, while the maximum eigenvalue statistic also confirms the presence of a cointegration relationship. These results suggest the existence of a long-term equilibrium link between the system variables, despite their possible divergent short-term dynamics.

To examine the existence of long-run equilibrium relationships between the model variables, the Johansen cointegration test was applied using both the trace statistic (Trace).

The results, presented in the Table 4 show that the trace statistic rejects the null hypothesis of no cointegration relationship (r = 0) at the 5% level, with a statistical value of 53.61 greater than the critical value of 40.17 (P = 0.0013). The hypothesis of at most one relationship (r ≤ 1) is also rejected (statistic = 24.47; critical value = 24.28; P = 0.0473). On the other hand, the null hypothesis of at most two relationships (r ≤ 2) is not rejected (statistic = 9.54; critical value = 12.32; P = 0.1399). These results therefore suggest

Table 1: Statistical analysis of variables

Statistics	LCO_2	LENR	LINN	LOPEN
Mean	0.841678	2.612007	1.848318	4.519594
Median	0.876745	2.649708	2.084273	4.517689
Maximum	1.006665	2.778819	2.824351	4.739208
Minimum	0.606483	2.468100	0.000000	4.355492
Std. Dev.	0.118822	0.077341	0.785198	0.097850
Skewness	−0.545628	−0.221297	−1.094551	0.225871
Kurtosis	2.210134	2.337769	3.269093	2.256148
Jarque-Bera	1.965953	0.687310	5.269958	0.820503
Probability	0.374196	0.709174	0.071720	0.663484
Sum	21.88364	67.91219	48.05626	117.5094
Sum Sq. Dev.	0.352966	0.149539	15.41342	0.239363
Observations	28	28	28	28

Table 2: Augmented Dickey-Fuller test

Variables	At level (I (0))	t-Statistic	Prob.*	In first difference I (1)	t-Statistic	Prob.*
LCO_2	Augmented Dickey-Fuller test statistic	1.57995	0.9681	Augmented Dickey-Fuller test statistic	−5.7416	0.0000
	Test critical values:			Test critical values:		
	1% level	−2.66485		1% level	−2.6648	
	5% level	−1.95568		5% level	−1.9556	
	10% level	−1.60879		10% level	−1.6087	
LOPEN						
		−0.29770	0.5683		−4.30394	0.0001
	Test critical values:			Test critical values:		
	1% level	−2.66072		1% level	−2.6648	
	5% level	−1.95502		5% level	−1.9556	
	10% level	−1.60907		10% level	−1.6087	
LENR						
	Augmented Dickey-Fuller test statistic	−0.68269	0.4106	Augmented Dickey-Fuller test statistic	−7.2108	0.0000
	Test critical values:			Test critical values:		
	1% level	−2.66485		1% level	−2.6648	
	5% level	−1.95568		5% level	−1.9556	
	10% level	−1.60879		10% level	−1.6087	
LINN						
	Augmented Dickey-Fuller test statistic	0.599353	0.8388	Augmented Dickey-Fuller test statistic	−8.8667	0.0000
	Test critical values:			Test critical values:		
	1% level	−2.66485		1% level	−2.6648	
	5% level	−1.95568		5% level	−1.9556	
	10% level	−1.60879		10% level	−1.6087	

Table 3: Number of cointegrating relations by model

Data trend	None	None	Linear	Linear	Quadratic
Test type	No intercept No trend	Intercept No trend	Intercept No trend	Intercept Trend	Intercept Trend
Trace	2	1	1	0	0
Max-Eig	1	1	0	0	0
Schwarz Criteria by Rank (rows) and Model (columns)					
0	−7.645729	−7.645729	−7.383409	−7.383409	−7.763925
1	−7.800682*	−7.694467	−7.473167	−7.375922	−7.493073
2	−7.363460	−7.128240	−7.037884	−6.972647	−7.008402
3	−6.539358	−6.471766	−6.421938	−6.260489	−6.279682
4	−5.642272	−5.513896	−5.513896	−5.220350	−5.220350

Selected (0.05 level*)

Table 4: Unrestricted cointegration rank test (trace)

Hypothesized Trace=0.05				
No. of CE (s)	**Eigenvalue**	**Statistics**	**Critical value**	**Prob.****
None*	0.703083	53.61475	40.17493	0.0013
At most 1 *	0.463200	24.47145	24.27596	0.0473
At most 2	0.209626	9.540335	12.32090	0.1399
At most 3	0.149784	3.894356	4.129906	0.0575

Trace test indicates 2 cointegrating eqn (s) at the 0.05 level. *denotes rejection of the hypothesis at the 0.05 level. **MacKinnon-Haug-Michelis (1999) P-values

the presence of two cointegration vectors, indicating the existence of two long-term equilibrium relationships between the variables.

It should be emphasized that trace statistics are generally considered more robust in the case of complex dynamical systems. Therefore, it is reasonable to conclude that there are two cointegration relationships between the variables studied. This indicates convergent behavior between the long-term series, despite their possible short-term fluctuations. Furthermore, to further deepen the understanding of the dynamic relationships and short- and long-term adjustments between emissions, innovation, renewable energy and trade openness, we use a vector error correction model (VECM), adapted to analyze the cointegration mechanisms and responses to imbalances in this complex system.

4.3. VECM Estimation

The cointegration analysis revealed the existence of a balancing relationship between the variables, which justifies the use of a VECM. We have chosen a 2-lag VECM, which simplifies the model while preserving the essential dynamics of the system. This approach allows for the simultaneous study of short-term adjustments and the return to long-term equilibrium, providing a more complete understanding of the interactions between CO_2 emissions, innovation, renewable energy and trade openness.

The cointegrating equation expresses the long-run equilibrium relationship between variables. The standardized coefficient of $LCO_2(-1)$ is set to 1, which serves as a reference.

LENR(−1) shows a positive and significant coefficient (0.83, t = 5.75), indicating that, in the long term, an increase in renewable energy is associated with an increase in CO_2 emissions, which may reflect a transitional phase where the development of renewables has not yet reduced emissions.

LINN(−1) has a significant negative coefficient (−0.11, t = −4.48), suggesting that innovation plays a role in mitigating emissions in the long term, consistent with the work of Popp (2002) on the favorable effect of technological innovations on the environment.

Table 5: Results of cointegration equation

Cointegration Eq	CointEq1
$LCO_2(-1)$	1
LENR(−1)	0.827647 (5.75451)
LINN(−1)	−0.113753 (−4.47959)
LOPEN(−1)	−1.073333 (−7.00076)
C	2.058717

LOPEN(−1) has a negative and very significant coefficient (−1.07, t = −7.00), which indicates that trade openness tends to reduce emissions in the long term, possibly via a diffusion effect of clean technologies and a better allocation of resources (Enders, 2014). The impact of the cointegration gap (CointEq1) on the variations of the variables is significant only for innovation (4.18, t = 4.40), indicating that this variable quickly corrects long-term imbalances, while the adjustments are small or insignificant for LCO_2, LENR and LOPEN. This suggests that innovation is the main dynamic variable in the system, adjusting more quickly to equilibrium deviations. Furthermore, emissions shocks ($D(LCO_2)$) have little significant effect except on innovation (−9.73, t = −3.28), highlighting a feedback effect where emissions negatively influence innovation in the short term. Variations in renewable energy (D(LENR)) positively influence emissions (0.76, t = 2.00), confirming a short-term dynamic where the development of renewables does not immediately lead to a drop in emissions. Trade openness (D(LOPEN)) positively affects renewable energy (0.58, t = 3.24), supporting the hypothesis that liberalization favors the development of renewables.

4.3.1. Model fit and validity

The adjusted R^2 are moderate to high for LCO_2 (0.23), LENR (0.48) and especially LINN (0.69), but negative for LOPEN (−0.17), which reflects a low explanatory power for trade openness in this dynamic framework. The F statistics indicate an acceptable significance of the equations, except for LOPEN, reinforcing the idea that this variable could be less integrated into the dynamic system in the short run.

The results in Table 5 confirm the existence of a long-term equilibrium relationship between emissions, innovation, renewables and openness, while highlighting differentiated

Table 6: VECM estimation results and test error correction (short-term dynamics)

Error correction	D (LCO_2)	D (LENR)	D (LINN)	D (LOPEN)
CointEq1	−0.011611(−0.0998)	−0.100971(−0.6942)	4.184691 (4.4028)	0.422565 (1.4310)
D (LCO_2(−1))	0.142312 (0.3917)	0.235177 (0.5174)	−9.731756(−3.2762)	−0.941292(−1.0200)
D (LCO_2(−2))	0.211380 (0.69469)	0.370723 (0.97377)	−1.492963(−0.6000)	−0.616569(−0.7976)
D (LENR(−1))	0.763399 (2.0000)	0.000839 (0.0017)	−8.314019(−2.6638)	−0.232410(−0.2396)
D (LENR(−2))	−0.134408(−0.6702)	0.066851 (0.2664)	3.524002 (2.1492)	−0.187728(−0.3685)
D (LINN(−1))	0.023428 (1.2816)	−0.031076(−1.3587)	−0.784219(−5.2465)	0.035028 (0.7543)
D (LINN(−2))	0.012865 (0.6866)	−0.008217(−0.3505)	−0.353138(−2.3050)	0.013560 (0.2848)
D (LOPEN(−1))	0.061178 (0.4284)	0.579353 (3.2432)	2.013445 (1.7246)	0.294489 (0.8119)
D (LOPEN(−2))	−0.396109(−1.5075)	−0.115219(-0.3504)	7.327660 (3.4107)	−0.094655(−0.1418)
C	0.007876 (0.7296)	−0.014227(−1.0534)	0.243229 (2.7560)	0.015795 (0.5760)
R-squared	0.546455	0.692881	0.818138	0.306055
Log likelihood		50.74544		
Akaike AIC		−3.543081		
Schwarz SC		−3.049388		

Figure 1: Cointegration relationship graph

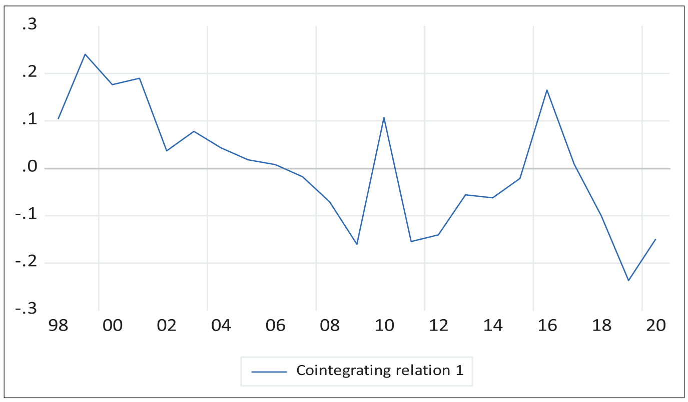
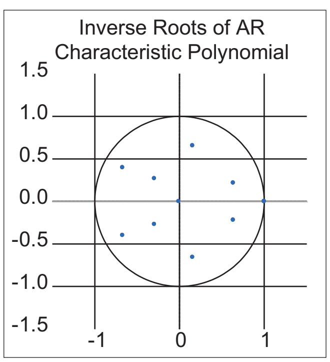


Figure 2: Residual stability test of ECM model



dynamics in the short term. Innovation appears to be the key variable for rapid adjustment, highlighting the importance of policies promoting green R&D. The delayed effect of renewables on emissions invites us to consider energy transitions as a non-immediate evolutionary process, recent empirical analyses (CEPR, 2023).[1] As for trade openness, its role seems more complex and less integrated in the short term, which calls for a deeper exploration of its interaction with other factors in future work.

The impact of the cointegration gap (CointEq1) on the variations of the variables is significant only for innovation (4.18, t = 4.40), indicating that this variable quickly corrects long-term imbalances, while the adjustments are small or insignificant for LCO_2, LENR and LOPEN. This suggests that innovation is the main dynamic variable in the system, adjusting more quickly to equilibrium deviations.

Furthermore, emissions shocks (D(LCO_2)) have little significant effect except on innovation (−9.73, t = −3.28), highlighting a feedback effect where emissions negatively influence innovation in the short term.

As indicated in Table 6, Variations in renewable energy (D(LENR)) positively influence emissions (0.76, t = 2.00), confirming a short-term dynamic where the development of renewables does not immediately lead to a drop in emissions.

Trade openness (D(LOPEN)) positively affects renewable energy (0.58, t = 3.24), supporting the hypothesis that liberalization favors the development of renewables.

Goodness of fit and validity of the model The adjusted R^2 are moderate to high for LCO_2 (0.23), LENR (0.48) and especially LINN (0.69), but negative for LOPEN (−0.17), which reflects a low explanatory power for trade openness in this dynamic framework.

The F statistics indicate an acceptable significance of the equations, except for LOPEN, reinforcing the idea that this variable could be less integrated into the dynamic system in the short term.

These results confirm the existence of a long-term equilibrium relationship between emissions, innovation, renewables and openness, while highlighting differentiated dynamics in the short term. Innovation appears to be the key variable for rapid adjustment, highlighting the importance of policies promoting green R&D. The delayed effect of renewables on emissions invites us to consider energy transitions as a non-immediate evolutionary process, in line with Sadorsky (2009) and recent empirical analyses (CEPR, 2023). As for trade openness, its role seems more complex and less integrated in the short term, which calls for a deeper exploration of its interaction with other factors in future work.

Cointegration Relationship 1 plot visually illustrates the long-run equilibrium path between CO_2 emissions (LCO_2), technological innovation (LINN), renewable energy (LENR), and trade openness

1 Available on: https://www.ecb.europa.eu/press/conferences/html/20231123_cepr_ecb_conference.de.html

(LOPEN). As illustrated in Figure 2, the horizontal line centered at zero corresponds to the residual of the estimated cointegration relationship and allows us to identify deviations from this structural equilibrium. When this curve remains close to zero, this reflects a smooth adjustment between the system variables; on the other hand, deviations signal transitory imbalances, often linked to economic or technological shocks.

The model results statistically confirm this long-term relationship: innovation (LINN) and trade openness (LOPEN) have a significant reducing effect on CO_2 emissions, with negative coefficients in the cointegration equation (respectively −0.1138 and −1.0733), and high t-statistics, suggesting a structuring role of these two variables in environmental dynamics. Conversely, renewable energies (LENR) appear with a positive coefficient (0.8276), which can be interpreted as a transitory effect of the sector's rise, particularly in the initial phases of the energy transition, where infrastructures still rely partially on technologies with a high carbon footprint.

These results are consistent with several recent empirical studies which show that green innovation, when supported by active research and development policies, contributes to the progressive decarbonization of economies. Furthermore, the complementarity between technological innovation and renewable energies is highlighted, emphasizing that their environmental effectiveness also depends on their articulation within a coherent political framework (IEA, 2023)[2]. Trade integration, for its part, favors the diffusion of clean technologies, confirming the hypotheses of beneficial opening supported by Cole and Elliott, (2003) And Frankel and Rose, (2005).

The joint analysis of the cointegration graph (Figure 1) and econometric estimations allows empirical validation of the existence of a long-term equilibrium mechanism linking emissions, innovation, energy transition and economic openness. This argues for an integrated approach to environmental, trade and industrial policies.

Granger causality analysis within the VECM model, based on Wald block exclusion tests (Table 7), provides essential insights into the short-term dynamic interrelationships between environmental and economic variables. When CO_2 emissions (D(LCO_2)) are considered as the dependent variable, none of the explanatory variables exhibit a significant effect at the 5% level. However, renewable energy consumption (D(LENR)) displays a marginally significant influence (P = 0.054), suggesting a potential effect at the 10% level, consistent with the work of Inglesi-Lotz (2016)which show that renewable energies contribute to reducing emissions, but with adjustment times that vary depending on the context.

Regarding renewable energy consumption (D(LENR)), only trade openness (D(LOPEN)) has a significant effect (P = 0.005), which confirms the hypothesis that international trade can facilitate the transfer of clean technologies and stimulate the energy transition. (Afesorgbor and Demena, 2022). This relationship is further supported by the overall significance of the model (P = 0.0087), reinforcing the robustness of the interpretation. One of the contributions of this work lies in the clear highlighting of the catalytic role of foreign trade in the expansion of renewable energies, particularly in a given national context.

Table 7: VECM Granger Causality/Block Exogeneity Wald Tests

Excluded	Chi-sq	df	Prob.
Dependent variable: D (LCO_2)			
Excluded	**Chi-sq**	**df**	**Prob.**
D (LENR)	5.823051	2	0.0544
D (LINN)	1.645269	2	0.4393
D (LOPEN)	2.288973	2	0.3184
All	7.387953	6	0.2865
Dependent variable: D (LENR)			
Excluded	**Chi-sq**	**df**	**Prob.**
D (LCO_2)	0.962148	2	0.6181
D (LINN)	2.111256	2	0.3480
D (LOPEN)	10.61403	2	0.0050
All	17.17554	6	0.0087
Dependent variable: D (LINN)			
Excluded	**Chi-sq**	**df**	**Prob.**
D (LCO_2)	11.47528	2	0.0032
D (LENR)	16.82222	2	0.0002
D (LOPEN)	17.69659	2	0.0001
All	23.95670	6	0.0005
Dependent variable: D (LOPEN)			
Excluded	**Chi-sq**	**df**	**Prob.**
D (LCO_2)	1.204849	2	0.5475
D (LENR)	0.153466	2	0.9261
D (LINN)	0.599964	2	0.7408
All	2.682426	6	0.8475

Concerning environmental innovation (D(LINN)), the results show a strong sensitivity to shocks from other variables. CO_2 emissions, renewable energy consumption and trade openness all have significant effects at 1% ($P < 0.01$). This finding, in line with the conclusions of Fusillo et al. (2025) emphasize that green innovation efforts are largely driven by environmental pressures, clean energy policies, and economic integration. Here, the study highlights an original point: environmental innovation is at the heart of the interactions between sustainable development, trade integration, and energy transition—an angle often underestimated in applied VECM models. On the other hand, none of the variables significantly explains the variations in trade openness (D(LOPEN)), which indicates that it acts exogenously in the system studied. This exogenous stability supports the idea that openness is determined by structural or political factors that are not very sensitive to the short-term dynamics of the other variables in the model.

These findings make a novel empirical contribution by highlighting asymmetric short-term causal relationships, with green innovation highly sensitive to economic and environmental variables, while CO_2 emissions appear relatively rigid. The study thus illustrates the value of a contextualized VECM approach to shed light on the complex mechanisms of the energy and technological transition.

To complete the analysis of short and long-term dynamics between variables, the decomposition of the variance of forecast errors

2 Available on https://www.iea.org/reports/energy-technology-perspectives-2023

makes it possible to assess the share of the variance of each variable explained by shocks from other variables in the system. This approach provides additional insight into the relative importance of interdependencies within the VECM model.

4.3.2. Variance decomposition

The decomposition of the variance of forecast errors, presented in the Table 8 allows us to assess the relative importance of structural shocks in explaining the dynamics of the VECM model variables. In the short term (period 1), the variance of each variable is mainly explained by itself, which is consistent with the natural inertia of time series. However, as the time horizon lengthens, we observe increasing interactions between the variables.

Table 8: Decomposition of the variance of forecast errors of the variables LCO_2, LENR, LINN and LOPEN in the VECM model

Variance decomposition of LCO_2					
Period	**SE**	**LCO_2**	**LENR**	**LINN**	**LOPEN**
1	0.035437	100,0000	0.000000	0.000000	0.000000
2	0.048658	81.51525	17.82760	0.300337	0.356815
3	0.063798	82.66146	14.59786	1.728656	1.012026
4	0.080203	75.46265	22.60262	1.225291	0.709439
5	0.093088	73.17310	25.17041	0.967312	0.689182
6	0.108220	72.02686	26.66288	0.715711	0.594554
7	0.121029	70.82807	27.93924	0.578083	0.654601
8	0.132972	70.89566	27.91414	0.514483	0.675714
9	0.144131	70.27596	28.61374	0.437905	0.672392
10	0.154034	70.22388	28.68423	0.400187	0.691698
Variance decomposition of LENR					
Period	**SE**	**LCO_2**	**LENR**	**LINN**	**LOPEN**
1	0.044338	31.73710	68.26290	0.000000	0.000000
2	0.064800	17.73344	32.11136	32.60778	17.54743
3	0.074760	13.37418	27.94707	36.34275	22.33601
4	0.082955	14.08827	28.71938	36.39519	20.79716
5	0.089791	12.35162	34.80590	33.95532	18.88716
6	0.097464	10.51728	38.38455	32.66146	18.43671
7	0.104849	9.179350	38.66569	33.48019	18.67477
8	0.111758	8.080929	40.63660	32.76470	18.51777
9	0.118008	7.251777	41.81053	32.63912	18.29858
10	0.124041	6.571231	43.38570	32.04594	17.99712
Variance decomposition of LINN					
Period	**SE**	**LCO_2**	**LENR**	**LINN**	**LOPEN**
1	0.289762	4.250173	23.13645	72.61337	0.000000
2	0.369673	31.93738	14.49671	46.56518	7.000739
3	0.401803	30.41857	16.09005	47.54899	5.942391
4	0.409986	30.63174	17.66323	45.94853	5.756495
5	0.481438	22.37948	32.22358	39.20611	6.190831
6	0.574126	15.81815	46.47562	32.68141	5.024821
7	0.641921	15.38597	52.78560	27.56664	4.261784
8	0.732358	14.31582	58.81867	23.48765	3.377864
9	0.795537	14.13258	62.13606	20.82464	2.906717
10	0.870999	14.01410	64.57421	18.86582	2.545873
Variance decomposition of LOPEN					
Period	**SE**	**LCO_2**	**LENR**	**LINN**	**LOPEN**
1	0.090022	23.97475	29.80749	26.99386	19.22391
2	0.111716	17.36410	29.29092	32.03524	21.30974
3	0.117722	15.81958	28.21751	35.03708	20.92584
4	0.119531	15.41976	27.58065	36.28376	20.71584
5	0.124468	15.99305	26.14904	37.30894	20.54897
6	0.132808	18.15236	23.61811	37.93473	20.29480
7	0.140402	19.63350	22.40336	37.92812	20.03502
8	0.147436	20.90474	21.80092	37.73577	19.55857
9	0.154666	22.40760	21.56919	37.00952	19.01370
10	0.162192	23.84085	21.01929	36.49399	18.64587

Cholesky Ordering: LCO_2 LENR LINN LOPEN

For CO_2 emissions (LCO_2), the share of variance explained by renewable energy consumption (LENR) gradually increases to around 28.6% over the 10-period horizon, indicating an increasing effect of energy policies on emissions in the medium term. In contrast, innovation (LINN) and trade openness (LOPEN) have a relatively marginal contribution, with shares below 1% in the long term. Regarding renewable energy consumption (LENR), its own influence decreases sharply in favor of environmental innovation, which explains more than 32% of its variance from the fifth period onward, and trade openness, which explains nearly 18%. This confirms the existence of a close link between trade openness, technological innovation, and energy transition.

The analysis of variance of environmental innovation (LINN) is particularly revealing: over a 10-period horizon, renewable energy consumption (LENR) becomes the dominant factor, explaining nearly 65% of its variance. This suggests that technological advances in the environmental field are highly dependent on energy dynamics, a conclusion in line with recent research on the co-evolution of clean technologies and energy policy. The share of CO_2 emissions and trade openness in explaining LINN remains relatively limited.

Finally, for trade openness (LOPEN), the variance decomposition reveals a more balanced distribution between the different sources. In the long run, innovation (LINN) contributes nearly 36%, followed by CO_2 emissions (23.8%) and renewable energy (21%), indicating a sensitivity of trade openness to environmental and technological dynamics. This shows that, contrary to its apparent exogeneity in causality tests, trade openness can still eventually incorporate indirect feedback effects from changes in the environmental system.

In summary, variance decomposition confirms the results of the causality tests, while highlighting the delayed influence structure between variables: energy transition and innovation appear as key drivers in the medium term, while CO_2 emissions react more slowly and are less central to the overall dynamics of the system.

5. CONCLUSION

This work empirically analyzed the dynamic relationships between per capita CO_2 emissions (LCO_2), renewable energy consumption (LENR), innovation in environmental technologies (LINN) and trade openness (LOPEN), using a VECM model applied to annual data covering the period 1995-2024. The rigorous and integrated methodological approach adopted made it possible to validate the existence of a cointegration relationship between the four variables, confirming the existence of a long-term adjustment mechanism linking environmental dynamics, energy transition, technological innovation and trade flows. The results of Granger causality tests revealed asymmetric interactions in the short term, where environmental innovation appears as a variable strongly influenced by the others, notably by trade openness and renewable energies. At the same time, CO_2 emissions appear more rigid, not very sensitive to short-term variations, which underlines the need for long-term structural policies to influence their trajectory.

The stability analysis of the VECM model confirmed its robustness, while the forecast error variance decomposition (FEVD) enriched the interpretation of the results by quantifying the deferred influence of the variables on each other. This last part notably highlighted the central role of environmental innovation as a lever for transforming the energy and commercial system, and the growing capacity of renewable energies to influence emissions in the medium term.

The specific contribution of this work thus lies in the joint integration of variables rarely studied simultaneously in cointegration models (emissions, innovation, renewable energy and trade), and in the combined use of several econometric tools to reveal their interdependencies at different time scales.

These findings call for a coordinated approach to environmental, industrial, and trade policies, based on a systemic integration approach. By fostering green innovation, accelerating the development of clean energy, and stimulating sustainable trade, public decision-makers can create synergies that promote a coherent and sustainable low-carbon transition.

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