International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Research Article)

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Evaluating energy resilience and its greenhouse gas effect: A pathway towards sustainable energy transition in Morocco

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International Journal of Science and Research Archive, 2025, 16(03), 458–470

Publication history: Received on 01 August 2025; revised on 07 September 2025; accepted on 10 September 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.16.3.2524

Abstract

A robust and resilient energy infrastructure can efficiently ensure regular production and green RandD operations, which have an unpredictable Moroccan greenhouse effect. To accurately investigate the potential impact of energy resilience on carbon dioxide (CO_2) emissions, we first develop an energy resilience composite index based on three components (energy access, renewable energy, and energy efficiency) using cross-sectional data from Morocco in 2020. To investigate the internal impact mechanism in the energy resilience-CO_2 nexus, we divide the entire effect of energy resilience on CO_2 emissions into three categories: scale effect, technical effect, and composition effect. The key findings of this study indicate that: (1) enhanced energy resilience in Morocco correlates positively with CO_2 emissions, and three components of energy resilience namely energy access, renewable energy, and energy efficiency contribute to an increase in the greenhouse effect; (2) the relationship between strong energy resilience and CO_2 emissions exhibits significant asymmetric and heterogeneous characteristics; and (3) the positive link between energy resilience and CO_2 emissions arises because the negative technical and composition effects of energy resilience on emissions are entirely counterbalanced by a substantial positive scale effect. Based on these conclusions, we put forward several policy recommendations aimed at reinforcing energy resilience while mitigating the greenhouse effect.

Keywords: Energy Resilience; Greenhouse Effect; Quantile Regression; Simultaneous Equation Model; Morocco

1. Introduction

In recent years, industrialization and globalization have advanced steadily, fueled by substantial energy consumption. This has inevitably led to the release of significant environmental pollutants, particularly carbon dioxide (CO_2) (Feng et al., 2013; Wang et al., 2018a). Notably, Morocco has emerged as a leader in the energy transition, with targets set to reduce greenhouse gas emissions by 45.5% by 2030 and by 80–95% by 2050, as outlined by the Moroccan Agency for Sustainable Energy (Zhao et al., 2020). These climate changes have urged international organizations and institutions to seek solutions that support sustainable development. It is worth noting that modern societies contribute to greenhouse gas (GHG) emissions through multiple sources, with fossil fuel-based energy systems and industrial processes accounting for approximately 80% of total emissions.

In light of the growing severity of the greenhouse effect and its adverse impacts, governments worldwide have been actively promoting a shift toward green and low-carbon economic models (Dong et al., 2021; Dou et al., 2021; Khan et al., 2021b; Zhao et al., 2021a). Morocco, for instance, has demonstrated strong climate policy commitment since hosting the UNFCCC Conference (COP22) in 2016, which aligns closely with the objectives of the Paris Agreement. Furthermore, global cooperation frameworks such as the Kyoto Protocol and the Paris Agreement reflect a shared determination

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among nations to reduce carbon emissions (Soytas and Sari, 2009). A critical prerequisite for transitioning to a low-carbon economy is the shift toward green energy sources.

As a cornerstone of economic growth, social stability, and national defense, the energy system is a vital economic subsector in every society. It must reliably supply energy while remaining environmentally compatible to support sustainable development and economic restructuring. In recent years, climate change has made energy systems increasingly vulnerable to disruptions. Morocco's energy sector relies heavily on imported fossil fuels, contributing to climate uncertainties and posing risks to future economic and societal well-being. Safeguarding energy systems from such threats entails significant costs, making it more practical to build resilience—enabling systems to resist, absorb, adapt to, and rapidly recover from disruptions. This approach helps manage fluctuations in energy supply. In response, Morocco has implemented a new energy strategy focused on enhancing supply security, expanding access, promoting efficient consumption, and protecting the environment. This shock-absorbing capacity has strengthened Morocco's appeal for foreign investment and created an enabling environment for a resilient energy transition (Han et al., 2021).

Given the context outlined above, three key research questions have emerged

- How can energy resilience be assessed more comprehensively and effectively?
- Does energy resilience actually influence the greenhouse effect, and if so, through what mechanisms?
- Is there a measurable impact of energy resilience and CO_2 emissions?

Exploring these questions is crucial for advancing the evaluation of energy resilience and understanding its implications for the greenhouse effect. Therefore, using cross-sectional data from Morocco in 2020, this study empirically examines the potential impact of energy resilience on CO_2 emissions in the country.

2. Literature review

In recent decades, resilience theory has expanded into the energy sector, with a growing body of literature devoted to studying energy resilience. As both a physical and systemic concept, the effective measurement of resilience has become an important topic within international development and sustainable development agendas, attracting active scholarly discussion. Key challenges remain in identifying practical strategies for building high resilience and in developing systematic methods to evaluate energy resilience—a problem facing many researchers. Several studies have sought to provide integrated views on energy security and resilience by clarifying terminology (Azzuni et al., 2018), concepts (Gholami et al., 2018), and perspectives (Molyneaux et al., 2016).

However, energy resilience is highly context-dependent, varying by type of threat and energy system, which complicates generalization and underscores the need for case-specific categorization. For example, Sharifi and Yamagata (2016) proposed a conceptual framework for assessing urban energy resilience and related planning criteria, linking resilience to sustainability principles such as availability, accessibility, affordability, and acceptability. Molyneaux et al. (2016) discussed assessment disciplines but focused mainly on evaluation criteria. Building on this, Erker et al. (2017) introduced a step-by-step resilience assessment method involving factual-level, value-level, and comparative analysis to support regional energy resilience. Shandiz et al. (2020) developed a multi-layered indicator framework to assess both short- and long-term impacts of disruptions, while Mutani et al. (2020) designed a dynamic urban energy model incorporating local climate conditions.

- H1: Energy resilience significantly contributes to achieving secure, sustainable, competitive, and affordable energy systems.
- H2: Energy resilience serves as a tool for reducing CO_2 emissions in Morocco.
- H3: Energy resilience is critical to the effective pursuit of sustainable development.

2.1. Research on the determinants of CO_2 emissions

In recent years, global warming has drawn significant attention from both academic and governmental sectors worldwide. Numerous studies have explored the driving factors of CO_2 emissions the primary component of the greenhouse effect focusing on economic growth, industrial structure, trade openness, labor dynamics, and urbanization.

A well-studied relationship is that between economic growth and CO_2 emissions, often analyzed through the Environmental Kuznets Curve (EKC) hypothesis. For example, Saboori et al. (2012) used ARDL methods on Malaysian data from 1980–2009 and identified an inverted U-shaped relationship, a conclusion supported by several other studies (Churchill et al., 2018; Pata and Caglar, 2021; Sinha and Shahbaz, 2018; Ulucak and Bilgili, 2018; Yilanci and Pata, 2020;

Zhang et al., 2019; Zhao et al., 2020). However, Arouri et al. (2012) and Baek (2015) found little evidence for the EKC in certain regional contexts.

Industrial structure adjustment also plays a critical role. An expansion of the pollution-intensive secondary industry tends to increase CO_2 emissions, whereas growth in the tertiary sector characterized by higher value-added and lower pollution facilitates emission reduction (Li et al., 2018; Mi et al., 2015; Tian et al., 2019; Yu et al., 2018; Zhou et al., 2013).

Urbanization is another major contributor to rising energy use and emissions, though empirical findings vary. Some studies report a positive correlation (Liu and Bae, 2018), others suggest a threshold effect (Martínez-Zarzoso and Maruotti, 2011), and some even show mixed outcomes across different dimensions of urbanization such as economic, spatial, demographic, and social aspects (Wang et al., 2018b).

Similarly, trade openness has been identified as a significant determinant of CO_2 emissions, with studies showing both mitigating (Zhang et al., 2017; Shahbaz et al., 2013) and aggravating effects (Yan and Yang, 2010), often depending on a country's development level (Managi et al., 2009). Overall, any factor influencing production and commercial activities can substantially affect CO_2 emissions.

H4: Various forms of economic activity significantly increase CO_2 emissions, thereby exacerbating environmental damage.

2.2. Literature gaps

Based on the existing literature, numerous scholars have investigated the measurement of energy resilience, yet a lack of consistent standards persists. Establishing an effective and rational evaluation framework is therefore crucial for accurately assessing levels of energy resilience. Moreover, research on the environmental implications of energy resilience particularly its influence on the greenhouse effect remains limited. As an emerging field, energy resilience still encounters challenges in quantification and in identifying influencing factors, especially concerning ecological and intangible socioeconomic processes.

To the best of our knowledge, no study has specifically examined the relationship between energy resilience and CO_2 emissions in Morocco within the post-Arab Spring context (i.e., after 2011). This study aims to address this gap by analyzing the impact of energy resilience on CO_2 emissions through innovative channels. Furthermore, while energy resilience has been studied from multiple disciplinary perspectives, a comprehensive and economically informed evaluation is often overlooked. Similarly, the broader socio-economic consequences of energy resilience have not been sufficiently explored. These research gaps motivate the present study.

3. Evaluating the energy resilience index

3.1. Evaluation procedures for the energy resilience index

To empirically assess how energy resilience influences CO_2 emissions, this study develops a composite index using Morocco's 2020 cross-sectional data from the World Bank. Drawing on Gatto and Drago's (2020) framework, the index integrates three key dimensions, energy access, renewable energy, and energy efficiency, through 27 distinct indicators. A notable improvement over prior studies is the application of varying weights to each indicator, allowing for a more nuanced representation of their importance. The overall energy resilience index, along with three sub-indices for each dimension, is constructed using the Integrated Evaluation Method (IEM), following the approach outlined by Zhao et al. (2021b).

Table 1 Indicator system for evaluating China's energy resilience index

First-level indicator	Second-level indicator
Energy access	Utility creditworthiness The scope of the officially approved electrification plan Framework for grid electrification Framework for mini-grids Framework for stand-alone systems Consumer affordability of electricity Utility transparency and monitoring Utility creditworthiness
Energy efficiency	National Energy Efficiency Planning Energy Efficiency Institutions Consumer Information on Electricity Usage Incentives via Electricity Rate Structures Incentives and Mandates for Large-Scale Consumers Incentives and Mandates for the Public Sector Incentives and Mandates for Utilities Financing Mechanisms for Energy Efficiency Minimum Energy Performance Standards (MEPS) Energy Labeling Systems Building Energy Codes Carbon Pricing Mechanisms
Renewable energy	Legal Framework for Renewable Energy Renewable Energy Expansion Planning Incentives and Regulatory Support Design of Financial Incentives Grid Connection and Pricing Policies Counterparty Risk Management Carbon Pricing and Monitoring Systems

3.2. Estimation model and data sources

After calculating the composite energy resilience index, this study empirically assesses its causal effect on the greenhouse effect and tests the validity of the CO_2 Environmental Kuznets Curve (EKC) hypothesis. To ensure a robust analysis, several control variables are incorporated, including economic aggregate, trade openness, industrial structure adjustment, labor force, and urbanization level. The multivariate framework of the research is constructed as follows:

$$CO_2 = f(ERI_i, ISA_i, PGDP_i, TR_i, LF_i, URB_i) \qquad (1)$$

In the model, the subscript *i* denotes the cross-sectional unit (e.g., country), where CO_2 represents carbon dioxide emissions, ERI refers to the Energy Resilience Composite Index, Pgdp indicates economic growth, ISA captures industrial structure adjustment, GDP stands for economic aggregate, TR reflects trade openness, LF denotes labor force, and URB represents the level of urbanization.

To mitigate potential heteroscedasticity and reduce the influence of data fluctuations, all variables in Equation (1) are transformed using natural logarithms, resulting in the following revised specification:

$$lnCO_2 = \alpha_0 + \alpha_1 lnERI_i + \alpha_2 lnISA_i + \alpha_3 lnGDP_i + \alpha_4 lnTR_{i+}\alpha_5 lnLF_i + \alpha_6 lnURB_i + \varepsilon\_i \qquad (2)$$

In the model, α_0 is the constant and ε_i the error term, while α_2–α_6 are parameters to be estimated. A negative value is anticipated for α_1, the coefficient of the energy resilience composite index, implying that greater energy resilience may help reduce carbon emissions. To analyze the distinct effects of each component of energy resilience, the composite index can be replaced by its three sub-indices, energy access, renewable energy, and energy efficiency, for further empirical evaluation. Table 2 provides detailed variable descriptions and descriptive statistics, such as the number of observations, mean, standard deviation, minimum, and maximum values, after logarithmic transformation.

Table 2 Descriptions and statistics of all selected variables

Variable	Mean	Std. Dev.	Min
$LnCO_2$	10.103	2.177	4.988
LnERI	− 1.924	0.848	− 3.391
LnEAI	− 0.202	0.711	− 2.823
LnREI	− 1.633	0.846	− 3.591
LnEEI	− 1.107	1.193	− 4.695
LnPgdp	11.032	2.512	5.709
LnGDP	25.721	2.094	20.474
LnISA	3.209	0.395	1.724
LnTra	4.145	0.494	3.035
LnLab	16.510	1.362	11.686
LnUrb	3.143	0.492	2.516

Notes: Obs. stands for the observations of the variables, Mean refers to the average value of the variables, and Std. Dev. represents the standard deviation, Min and Max indicate

4. Estimation results

4.1. Correlation analysis of the energy resilience-CO_2 nexus

Prior to performing the main regression analysis on the relationship between energy resilience and CO_2 emissions, a correlation test was conducted between these core variables. As illustrated in Figure 1, both the composite energy resilience index and its three sub-indices exhibit a statistically significant positive correlation with CO_2 emissions. This suggests that, in the case of Morocco, higher energy resilience is associated with increased carbon emissions.

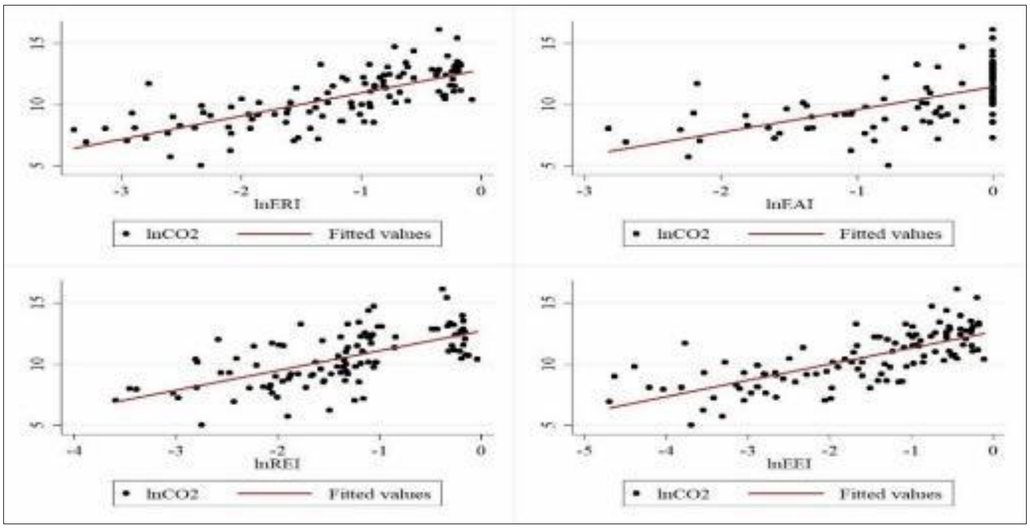


Figure 1 Trend chart of the correlation between energy resilience and CO_2 emissions

4.2. Benchmark regression

Before conducting the benchmark regression, tests for multicollinearity and heteroscedasticity were performed. The variance inflation factor (VIF) values confirmed the absence of multicollinearity among the variables, while the p-value indicated the presence of significant heteroscedasticity. To enhance estimation efficiency and accuracy, the comprehensive feasible generalized least squares (FGLS) method was employed, which accounts for inter-group heteroscedasticity, within-group autocorrelation, and contemporaneous correlation simultaneously. The results from estimating Equation (2) using FGLS are presented in the first column of Table 3.

Table 3 Results of the energy resilience-CO_2 nexus based on the FGLS method

Variable	Model (1)	Model (2)	Model (3)	Model (4)
	Full Resilience	Energy Access	Renewable Energy	Energy Efficiency
LnERI	0.428*** (3.10)			
LnEAI		0.381*** (3.45)		
LnREI			-0.025 (-0.22)	
LnEEI				0.205** (2.48)
LnPgdp	-0.402** (-2.31)	-0.378** (-2.18)	-0.421** (-2.35)	-0.370** (-2.12)
LnISA	0.491*** (2.95)	0.443*** (2.67)	0.472*** (2.71)	0.480*** (2.84)
LnGDP	0.634*** (6.88)	0.658*** (8.12)	0.781*** (8.70)	0.675*** (7.82)
LnTra	0.138 (0.90)	0.162 (1.08)	0.228 (1.44)	0.169 (1.10)
LnLab	0.412*** (4.15)	0.418*** (4.30)	0.328*** (3.28)	0.379*** (3.85)
LnUrb	0.647*** (3.02)	0.618*** (2.89)	0.561** (2.45)	0.592*** (2.71)
Constant	-13.525*** (-7.01)	-14.210*** (-8.45)	-16.482*** (-8.15)	-14.288*** (-7.65)

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate z-statistics.

Before performing the benchmark regression, diagnostic tests for multicollinearity and heteroscedasticity were conducted. Variance inflation factor (VIF) results indicated no multicollinearity among variables, while significant heteroscedasticity was detected. To address this and improve estimation robustness, the feasible generalized least squares (FGLS) method was applied, which corrects for cross-group heteroscedasticity, within-group autocorrelation, and contemporaneous correlation. The FGLS estimates of Equation (2) are reported in the first column of Table 3.

To further examine the influence of energy resilience components energy access (EAI), renewable energy (REI), and energy efficiency (EEI) on CO_2 emissions, Equation (2) was re-estimated by replacing the composite index with these three sub-indices. These results are shown in the last three columns of Table 3.

4.3. Robustness checks

To verify the robustness of the positive relationship between energy resilience and CO_2 emissions, a check was performed using the comprehensive FGLS method with per capita CO_2 emissions as an alternative dependent variable. The results are shown in Table 4.

A comparison of the signs and significance of coefficients in Tables 3 and 4 reveals general consistency across most variables. One notable exception is the relationship between trade openness and CO_2 emissions: while Table 3 suggests a positive association with total CO_2 emissions, Table 4 indicates a negative correlation with per capita CO_2 emissions. This implies that although international trade may increase total carbon emissions, it appears to reduce emissions on a per capita basis.

Table 4 Robust check: estimation by the alternative dependent variable

Dependent variable: LnPCO₂				
Variables	**Energy resilience**	**Energy access**	**Renewable energy**	**Energy efficiency**
LnERI	0.281*** (3.24)			
LnEAI		0.336*** (3.67)		
LnREI			0.074 (0.12)	
LnEEI				0.310** (2.50)
LnPgdp	− 0.419* (− 1.89)	− 0.178 (− 1.26)	− 0.212* (− 1.07)	− 0.310 (− 1.33)
LnISA	0.514*** (2.63)	0.289(2.35)	0.346** (2.39)	0.115** (2.48)
LnGDP	0.069*** (6.50)	0.62(7.97)	0.546*** (8.44)	0.521*** (7.54)
LnTra	− 0.185*** (− 5.81)	0.228** (2.21)	0.301** (2.46)	0.247** (2.19)
LnLab	− 0.514*** (2.77)	− 0.581*** (− 5.96)	− 0.188*** (− 6.62)	− 0.635*** (− 6.25)
LnUrb	0.273*** (2.85)	0.599*** (2.68)	0.519** (2.26)	0.227** (2.45)
Cons	−− 8.144*** (− 4.28)	− 9.573*** (− 5.61)	− 11.181*** (− 5.60)	− 9.401*** (− 4.94)

Note: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate z-statistics.

4.4. Heterogeneous analysis

To assess heterogeneous effects, we examine the asymmetric impact of energy resilience on CO_2 emissions using quantile regression (Coad and Rao, 2006). Following Tiwari's (2013) framework, we test whether the explanatory variables exert differential influences across various levels of CO_2 emissions. Equation (2) is estimated at multiple percentiles (10th, 25th, 50th, 75th, and 90th) of the conditional CO_2 distribution using a two-step quantile regression approach (Zhao et al., 2021). The results are presented in Table 5.

Energy resilience exhibits a significant effect on CO_2 emissions only at the 25th and 90th percentiles, with no notable impact at other quantiles. Economic growth and CO_2 emissions display a significant U-shaped relationship exclusively at the 25th quantile. The influence of economic aggregate and labor force remains relatively stable across emission levels. At medium to high emission quantiles (50th, 75th, and 90th), an increase in the secondary industry share aggravates the greenhouse effect, whereas urbanization contributes significantly to higher CO_2 emissions at the 10th, 25th, and 75th percentiles.

Table 5 Panel quantile regression results

Dependent variable: LnCO2					
Variable	**Quantiles**				
	10th	25th	50th	75th	90th
LnERI	0.122 (1.05)	0.303** (2.09)	0.068 (1.08)	0.124 (1.36)	0.318** (2.20)
LnPgdp	− 0.469 (− 1.36)	− 0.288** (− 2.20)	− 0.130 (− 1.62)	− 0.019 (− 0.98)	− 0.144 (− 0.55)
LnISA	0.205 (0.25)	0.445 (1.57)	0.651** (2.22)	0.393** (2.48)	0.221*** (3.25)
LnGDP	0.401*** (2.96)	0.256*** (3.46)	0.160*** (4.58)	0.162*** (4.18)	0.212*** (3.14)
LnTra	0.328 (0.94)	0.148 (0.61)	0.273 (1.42)	0.161 (0.81)	0.300 (1.12)
LnLab	0.639** (2.22)	0.445** (2.14)	0.339** (2.00)	0.389*** (2.61)	0.455*** (2.99)
_Cons	0.791** (2.09)	0.659** (1.99)	− 14.478*** (− 5.64)	− 14.287*** (− 5.62)	0.514 (1.30)
R-squared	0.7225	0.7269	0.7338	0.7266	0.7364

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate t-statistics.

5. Further discussion on the mechanism between energy resilience on CO_2 emissions

To systematically analyze how energy resilience influences CO_2 emissions, we decompose its total effect into three distinct components—scale effect, technical effect, and composition effect—following the approach of Copeland and Taylor (1994). This relationship is expressed as:

$$CO_2 = Scale \times Tech \times Com$$

Here, $\mathbf{CO_2}$ denotes carbon dioxide emissions; **Scale** refers to the scale effect, captured by total GDP; **Tech** represents the technical effect, measured as carbon emission intensity (CO_2 emissions per unit of GDP); and **Com** indicates the composition effect, proxied by the share of secondary industry output in GDP (Hao et al., 2020). Taking natural logarithms, the equation becomes:

$$LnCO_2 = LnScale + LnTech + LnCom$$

To account for the interdependent nature of CO_2 emissions and these three effects, a simultaneous equation model is developed for empirical estimation. The specific equations of the model are structured as follows:

$$lnScale_i = \beta_0 + \beta_1 lnERI_i + \beta_2 lnLab_i + \beta_3 lnTra_i + \beta_4 lnUrb_i + \beta_5 lnPgdp_i + \varepsilon_i$$

$$lnTech_i = \varphi_0 + \varphi_1 lnERI_i + \varphi_2 lnPgdp_i + \varphi_3 lnCom_i + \varepsilon_i$$

$$lnCom_i = n_o + n_1 lnERI_i + n_2 lnLab_i + n_3 lnTra_i + n_4 lnScale_i + \varepsilon_i$$

In the model, the subscript *i* denotes the cross-sectional unit (e.g., country). The terms β_0, φ_0, and η_0 represent constant terms, while ε_i signifies the random disturbance term. The coefficients β_1 to β_5, φ_1 to φ_4, and η_1 to η_4 are parameters to be estimated. It is anticipated that the coefficient of energy resilience in Equation (5) (β_1) will be positive, whereas in Equations (6) and (7), the corresponding coefficients (φ_1 and η_1) are expected to be negative.

5.1. Estimation of the energy resilience composite index.

Estimation of simultaneous equation models employs both single-equation (e.g., OLS, 2SLS, GMM) and system methods. Using a three-stage least squares (3SLS) approach, energy resilience is found to positively affect the scale of economic activity increasing CO_2 emissions by 0.854% for a 1% rise in resilience while negatively influencing technical and composition effects. This confirms that robust energy systems support economic growth by ensuring a stable energy supply, particularly during external shocks. Additional drivers, such as labor force expansion and urbanization, also contribute significantly to economic development.

Table 6 Results of the simultaneous equation model for the full sample

Variable	**Scale effect**	**Technical effect**	**Composition effect**
	LnScale	LnTech	LnCom
LnERI	0.854*** (8.38	− 0.029 (− 0.31)	− 0.159* (− 1.76)
LnLab	0.873*** (14.47)		− 0.028 (− 0.49)
LnTra	− 0.087 (− 0.56)		0.194** (2.15)
LnUrb	1.587*** (10.10)		
LnPgdp	− 0.003 (− 0.13)	− 0.360** (− 1.99)	
LnScale	0.142*** (2.58	6.416*** (3.78)	− 0.932 (− 0.82)

Notes: ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively; the values in parentheses indicate z-statistics.

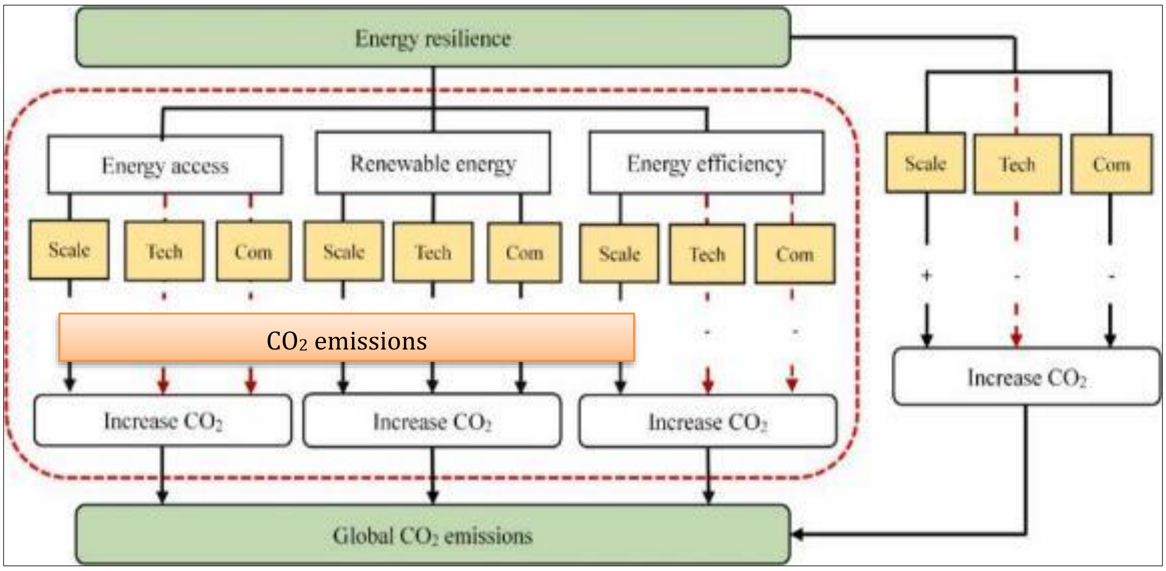
In the technical effect model (second column of Table 6), energy resilience shows an insignificant negative influence on carbon emission intensity. Enhancing the resilience of energy systems not only ensures a stable energy supply but also encourages technological research and development within the energy sector. Globally, efforts are underway to achieve breakthroughs in energy technology to raise utilization efficiency and support emission reduction goals. It should be noted, however, that energy technology innovation is a prolonged process with a considerable time lag. Additionally, a significant U-shaped relationship is observed between economic growth and CO_2 emissions.

Regarding the composition effect, a 1% increase in energy resilience leads to a 0.159% decrease in the share of secondary industry in GDP, indicating a negative influence. Fossil fuels such as coal and oil are not only finite but also highly polluting. To strengthen energy resilience, countries are increasingly shifting toward cleaner and more sustainable energy sources—such as solar, wind, and tidal power—as well as improving energy efficiency (Lin and Moubarak, 2014). This transition supports the transformation of traditional secondary industries and promotes the growth of the tertiary sector, thereby helping mitigate the greenhouse effect.

In summary, although energy resilience exerts negative technical and composition effects on CO_2 emissions, these are outweighed by its strong positive scale effect. The net impact of energy resilience on emissions is therefore significantly positive, indicating that it contributes to higher CO_2 levels primarily through economic expansion, despite partially offsetting influences from improved technology and industrial restructuring.

5.2. Estimation for the sub-indexes of energy resilience

To sum up, the net effects of three components of energy resilience (i.e., energy access, renewable energy, and energy efficiency) on CO_2 emissions are significantly positive. The technical and composition effects are offset by the positive impact of the scale effect on CO_2 emissions to a certain extent. To clearly identify the specific impact channels, we further draw the internal mechanism between energy resilience and CO_2 emissions, which is presented in Fig. 5.



Notes: the red dotted line indicates that the effect is not significant, while the black solid line represents that the effect is significant.

Figure 5 The internal impact mechanism between energy resilience and CO_2 emissions

6. Conclusion and policy implications

This study examines the causal relationship between energy resilience and CO_2 emissions by constructing a composite index of energy resilience and analyzing cross-sectional data from Morocco in 2020. Heterogeneity among variables is also investigated, and the overall impact is decomposed into three distinct effects: scale, technical, and composition effects. The main findings are as follows:

- Energy resilience contributes significantly to increased CO_2 emissions. Each of its component's energy access, renewable energy, and energy efficiency also exhibits a positive relationship with the greenhouse effect.
- The net positive impact of energy resilience on emissions is driven by its strong scale effect, which outweighs the negative contributions of the technical and composition effects.

Based on these results, the following policy recommendations are proposed

- Governments should enhance energy technology innovation to effectively reduce carbon emissions.
- Countries should reduce dependence on fossil fuels by restructuring their industries, promoting high-value and low-pollution tertiary sectors, and modernizing traditional high-emission industries.
- Efforts should be made to transition from extensive to intensive economic development models, ensuring that economic growth aligns with green and low-carbon objectives. Building efficient, clean, secure, and sustainable energy systems should be prioritized as a key direction for future development.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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