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Renewable Energy Adoption and Economic Resilience in Africa: A Case Study of Morocco

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Abstract

Morocco faces significant challenges in meeting its rapidly growing electricity demand, which is projected to increase by two to five times by 2030. In response, the country has set ambitious renewable energy targets—aiming for 42% of total installed capacity by 2020 and 52% by 2030. This study examines the relationship between renewable energy adoption and economic resilience in Morocco, in the context of increasing electricity needs and aggressive renewable targets. Employing a Structural Vector Autoregression model covering the period 1980–2024, the analysis reveals that renewable energy investments contribute positively to GDP growth, though their effects on emissions are mixed. While large-scale solar and wind projects have enhanced energy security and job creation, persistent infrastructure deficits and policy shortcomings limit their environmental impact. To ensure sustainable development, policymakers must complement renewable expansion with stricter energy efficiency standards, advanced clean technologies, and robust environmental regulations. Targeted subsidies and integrated planning will be essential to prevent economic growth from undermining environmental sustainability. Immediate action is needed to align Morocco's energy goals with its climate commitments.

1. Introduction

The adoption of renewable energy is seen as essential for sustainable development (United Nations, 2021; Sovacool & Dworkin, 2014). Renewable energy helps reduce climate change risks and promotes stronger economic systems. As governments worldwide confront climate change, energy security, and economic challenges, the transition to renewable energy has become even more important (IEA, 2020).

The Intergovernmental Panel on Climate Change (IPCC) stresses that reducing greenhouse gas emissions and cutting dependence on fossil fuels demands urgent action. Renewable energy, generated from natural sources like the sun, wind, water, and geothermal heat, offers a safer and more sustainable alternative (REN21, 2020). Falling technology costs, better energy

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storage, and improved grid integration have made renewable options increasingly competitive (IRENA, 2021). Countries are now more aware of the need to fight climate change and unlock the economic benefits of renewable energy. As a result, many are expanding efforts to shift toward low-carbon energy systems.

Economic resilience is the ability of an economy to withstand and recover from internal and external shocks while maintaining its core functions (Cherevatskyi, 2023; Ramli & Ithnin, 2022; Hynes et al., 2022). This concept has gained traction, especially after global disruptions like the COVID-19 pandemic (Filipenko, 2022). Resilience includes the capacity to adapt to adverse conditions and avoid business failures and production declines (Radic et al., 2022). It also covers natural, technological, economic, and political factors (Steen et al., 2024).

The link between renewable energy and economic resilience is increasingly evident. Countries with a more balanced and diverse energy supply recover faster from economic crises. When renewables make up a large share of the energy mix, recovery is even quicker (Donohue et al., 2023). In developing countries, innovations in renewable energy have improved efficiency and reduced harmful emissions (Aldieri et al., 2023). However, integrating renewables into electricity markets brings new uncertainties and risks, making it necessary to evaluate financial resilience (Sharma et al., 2024). Better connections between power and gas systems, enabled by renewables, offer critical economic benefits and help manage fluctuations in power supply (Sayed et al., 2023).

In response to these trends, many countries have launched programs to promote renewable energy use. Morocco has made notable efforts but still faces challenges in securing its future energy needs, particularly for electricity. Setting ambitious renewable energy goals: 42 per cent of total electricity generation capacity by 2020 and 52 per cent by 2030 (PMV, 2022). As global demand for energy rises, Morocco is giving more attention to renewable options that are accessible, affordable, and sustainable (Belakhdar et al., 2014).

Population growth and economic development are expected to drive Morocco's electricity demand to double relative to the North Mediterranean region (Kousksou et al., 2015; Ouammi et al., 2012). Projections suggest that annual electricity demand could climb from 35 TWh in 2016 to between 80 TWh and 170 TWh by 2030. Meeting this demand would require increasing generation capacities by four times by 2030 and more than ten times by 2050.

This study investigates the impact of renewable energy on Morocco’s economy through two key research objectives:

- Research Question 1: Evaluate the economic implications of renewable energy investments in Morocco.
- Research Question 2: Examine the dynamic interrelationships among renewable energy deployment, economic growth, and carbon emissions.

By addressing these questions, the study aims to bridge a critical gap in Morocco’s renewable energy strategy. The resulting insights will illuminate both the potential advantages and inherent constraints of expanding renewable energy initiatives. Moreover, the findings will inform the development of more resilient and sustainable energy policies tailored to Morocco’s long-term economic and environmental goals.

2. Theoretical Framework

2.1. Resilience and sustainable development theories

Sustainable development became a major global framework after the release of the Brundtland Report in 1987. The report defined it as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development [WCED], 1987). It responded to rising concerns about environmental degradation and the limits of traditional economic models that pursued growth without accounting for social and ecological costs.

However, the integration of resilience theory with sustainable development remains an underdeveloped area in the Brundtland framework, particularly regarding systemic shocks and long-term adaptability. While the WCED (1987) report established the triple-bottom-line approach, it did not fully account for how socio-ecological systems maintain functionality during disruptions–a gap later addressed by Folke et al. (2010) in their work on resilience thinking. Their research demonstrates that sustainable development requires not just balance among economic, environmental and social factors, but also the capacity to absorb disturbances and reorganise while undergoing change (Folke et al., 2010). This evolutionary perspective is critical for energy transitions, where lock-in effects and infrastructure inertia create vulnerability to climate shocks.

The "limits to growth" thesis (Meadows et al., 1972) implicitly acknowledged resilience concepts through its emphasis on system feedback loops, but contemporary scholars have strengthened this connection. Walker and Salt (2012) argue that resilience provides the missing operational framework for sustainable development, particularly through their concept of "transformability" –the capacity to create fundamentally new systems when ecological, economic or social conditions make the existing system untenable (Walker & Salt, 2012). In Morocco's energy transition, this manifests in the need to simultaneously phase out fossil fuel dependence while building renewable energy systems that can withstand climate variability and economic fluctuations, a challenge documented by Ouedraogo et al. (2017) in African energy systems.

Recent scholarship bridges this theoretical gap by framing sustainable development as inherently dependent on resilience capacities. According to Bahadur et al. (2015), the "resilience dividend" emerges when development initiatives combine WCED's intergenerational equity with capacities to anticipate, absorb and adapt to shocks (Bahadur et al., 2015). This fusion proves particularly relevant for Morocco's solar megaprojects, where Benatia et al., (2025) and Leichenko & O'Brien (2024) demonstrate that renewable energy infrastructure must be designed not just for low emissions, but also for climate resilience and equitable access–what they term "triple-win" sustainability (Benatia et al., 2025; Leichenko & O'Brien, 2024).

What sets sustainable development apart is its insistence on linking economic, environmental, and social objectives. This integration moves beyond sectoral approaches, encouraging development models that are more resilient, equitable, and sensitive to long-term needs. The framework stresses that true progress means balancing economic growth with environmental protection and social justice, making sure benefits are distributed fairly and that resource use does not undermine future well-being.

In the energy sector, sustainable development principles have played a crucial role in driving the shift from fossil fuels to renewable sources. This transition is necessary not only to curb greenhouse gas emissions and limit climate change but also to secure reliable energy access and promote social equity. Applying sustainable development thinking enables policymakers to design energy strategies that advance growth while protecting ecosystems and reducing inequalities. Recognizing the interconnectedness of economic, environmental, and social systems is central to achieving these goals and building a truly sustainable future.

2.2. Empirical evidence

Renewable energy adoption shows a positive relationship with economic resilience, as documented in several studies (Oraibi et al., 2023; Ahmad et al., 2022). Successful projects provide clean, reliable energy while supporting broader sustainable development goals (Shirley & Medhin, 2022; Onuoha et al., 2023). Systemic risk analysis frameworks for electricity markets have stressed the importance of accounting for the diversity and composition of energy sources in models of economic resilience.

Evidence from empirical studies proves that renewable energy adoption strengthens resilience in developing regions. Innovations in clean energy improve system efficiency and help countries withstand energy shocks and environmental risks (Aldieri et al., 2023). Distributed energy systems (DESs) based on clean technologies present a promising strategy for sustainable development and poverty reduction in rural and remote areas. These systems can raise living standards, boost local economies, and improve environmental outcomes (Ahmad et al., 2022).

Income distribution patterns also influence renewable energy consumption. Lower income inequality tends to encourage greater adoption of clean energy sources (Mehmood et al., 2022). These findings underline the role of renewable energy in advancing economic resilience and sustainable growth in low- and middle-income countries.

Integrating renewable sources such as hydro, wind, solar, and biomass offers a reliable and cost-effective solution to persistent electricity challenges (Lawal, 2023). Such projects can create jobs and stimulate economic activities, especially in rural areas with limited grid access (Adebayo et al., 2023). Renewable energy adoption also supports climate change mitigation by reducing carbon emissions (Ebhota & Tabakov, 2022).

However, several challenges remain. Developing sufficient technical capacity, securing adequate financing, and improving access to reliable energy data are critical (Onuoha et al., 2023). Building strong public-private partnerships and creating business models that support productive energy use can help lower costs and manage regulatory risks.

In conclusion, the empirical literature highlights the multifaceted benefits of renewable energy adoption, including enhanced economic resilience, improved environmental outcomes, and equitable development in low- and middle-income countries. However, challenges such as technical limitations, financing constraints, and data gaps underscore the need for targeted policy interventions. These findings provide a critical foundation for understanding the role of renewable energy in sustainable development and highlight gaps that the present study aims to address, particularly in the context of Morocco’s unique socioeconomic and environmental landscape. This review sets the stage for an in-depth analysis of how renewable energy adoption influences Morocco’s economic resilience and informs policy recommendations for overcoming identified barriers.

3. Methodology

3.1. Structural Vector Autoregression model

To address the objectives of this study, a Structural Vector Autoregression (SVAR) model was employed to analyze the dynamic relationships between renewable energy adoption, economic resilience, and carbon emissions in Morocco. The SVAR framework is well-suited for capturing the interdependencies among multiple time-series variables, as it models each variable as a function of its own lagged values and the lagged values of all other variables in the system (Khan et al., 2021). Unlike traditional VAR models, SVAR imposes structural restrictions to identify causal relationships, making it particularly effective for examining how shocks to one variable, such as renewable energy adoption, propagate through the system to affect economic growth and environmental outcomes.

In this study, the SVAR model treats all variables—GDP, alternative energy (AENRGY), and CO_2 emissions—as endogenous, allowing for mutual interactions among them. This approach captures the dynamic feedback loops inherent in Morocco's energy-economic system, where renewable energy investments may influence GDP growth, which in turn affects emissions. The model's focus on stationary variables ensures robust econometric analysis, enabling the estimation of Impulse Response Functions (IRFs) and variance decompositions to assess the short- and long-term impacts of renewable energy shocks (Khan et al., 2021). By modeling these relationships, the SVAR framework provides insights into how Morocco's renewable energy policies contribute to economic resilience while addressing environmental sustainability.

Mathematically, the base of the SVAR model commences as:

$$Y_t = \beta_{10} - \beta_{12} Z_t + \gamma_{11} y_{t-1} + \gamma_{12} Z_{t-1} + \varepsilon_{yt} \tag{1}$$

$$Z_t = \beta_{20} - \beta_{21} Y_t + \gamma_{21} y_{t-1} + \gamma_{22} Z_{t-1} + \varepsilon_{zt} \tag{2}$$

Given that Y_t and Z_t are endogenous variables according to Equations (1) and (2), the contemporaneous effects of Z_t on Y_t and Y_t on Z_t, respectively, are captured by β_{12} and β_{21}. While the coefficients ε_{yt} and ε_{zt} represent structural flaws, the coefficients γ_i represent the lagged link between the variables.

Accordingly, Equations (3) to (10) below present the structural specification of the SVAR model:

$$\begin{aligned} \beta_0 Y_t &= \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + \cdots \ldots + \beta_p Y_p + \varepsilon_t \beta_0 Y_t \\ &= \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + \cdots \ldots + \beta_p Y_p + \varepsilon_t \end{aligned} \tag{3}$$

The reduced form of SVAR is specified as:

$$\begin{aligned} Y_t &= C + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots \ldots + \beta_p Y_p + \varepsilon_t Y_t \\ &= C + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + \beta_p Y_p + \varepsilon_t \end{aligned} \tag{4}$$

Therefore,

$$\begin{aligned} logRGDP_t = \alpha_{10} - \alpha_{12} logRENEW_t - \alpha_{13} logCO2_t + \sum_{t-1}^{p} \beta_{11}{}^{t} logRGDP_{t-1} \\ + \sum_{t-1}^{p} \beta_{12}{}^{t} logRENEW_{t-1} + \sum_{t-1}^{p} \beta_{13}{}^{t} logCO2_{t-1} + \mu_t^{RGDP} \end{aligned} \tag{5}$$

and

$$\begin{aligned} \beta_0 Y_t &= \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + \cdots \ldots + \beta_p Y_p + \varepsilon_t \beta_0 Y_t \\ &= \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + \cdots \ldots + \beta_p Y_p + \varepsilon_t \end{aligned} \tag{6}$$

The reduced form of SVAR is specified as:

$$\begin{aligned} Y_t &= C + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots \ldots + \beta_p Y_p + \varepsilon_t Y_t \\ &= C + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + \beta_p Y_p + \varepsilon_t \end{aligned} \tag{7}$$

Therefore, for the structural form of real GDP the proxy of growth, Equation (8) represents the SVAR as:

$$logRGDP_t = \alpha_{10} - \alpha_{12} logRENEW_t - \alpha_{13} logCO2_t + \sum_{t-1}^{p} \beta_{11}{}^{t} logRGDP_{t-1} + \sum_{t-1}^{p} \beta_{12}{}^{t} logRENEW_{t-1} + \sum_{t-1}^{p} \beta_{13}{}^{t} logCO2_{t-1} + \mu_t^{RGDP} \quad (8)$$

Likewise, renewable energy (Renew) and alternative energy (AEnergy)—used interchangeably in this study—are represented as follows:

$$logRENEW_t = \alpha_{20} - \alpha_{22} logRGDP_t - \alpha_{23} logCO2_t + \sum_{t-1}^{p} \beta_{21}{}^{t} logRENEW_{t-1} + \sum_{t-1}^{p} \beta_{22}{}^{t} logRGDP_{t-1} + \sum_{t-1}^{p} \beta_{23}{}^{t} logCO2_{t-1} + \mu_t^{GE} \quad (9)$$

Finally, the emission's SVAR equation represented by CO_2 is expressed as:

$$logCO2_t = \alpha_{30} - \alpha_{32} logRGDP_t - \alpha_{33} logRENEW_t + \sum_{t-1}^{p} \beta_{31}{}^{t} logCO2_{t-1} + \sum_{t-1}^{p} \beta_{32}{}^{t} logRENEW_{t-1} + \sum_{t-1}^{p} \beta_{33}{}^{t} logRGDP_{t-1} + \mu_t^{EG} \quad (10)$$

The matrix form of Equations (8)–(10) is also provided below for clarity:

$$\begin{vmatrix} RGDP \\ RENEW \\ CO2 \end{vmatrix} = \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} \begin{bmatrix} 1 & + & + \\ + & 1 & + \\ + & + & 1 \end{bmatrix} \begin{vmatrix} \mu_t^{RGDP} \\ \mu_t^{GE} \\ \mu_t^{EG} \end{vmatrix} \quad (11)$$

where

$$A = \begin{vmatrix} 1 & A_{12} & A_{13} \\ A_{21} & 1 & A_{23} \\ A_{31} & A_{32} & 1 \end{vmatrix}, \quad C = \begin{vmatrix} C_1 \\ C_2 \\ C_3 \end{vmatrix}, \quad Z = \begin{vmatrix} EXTRATE \\ GE \\ GDP \end{vmatrix},$$
$$Z_{t-1} = \begin{vmatrix} EXTRATE_{t-} \\ GE_{t-1} \\ GDP_{t-1} \end{vmatrix}, \quad U_t = \begin{vmatrix} \mu_t^{RGDP} \\ \mu_t^{GE} \\ \mu_t^{EG} \end{vmatrix} \quad (12)$$

and

$$a = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \text{ such that } U_t \sim iid\ (0\sigma^2) \quad (13)$$

Z and Z_{t-1} are 3×1 vectors of dependent variables; Z_{t-1} is a vector of lagged variables; A is a 3×3 matrix of the parameters to be estimated and identified with as a diagonal element; C is a 3×1 vector of constants, a is a 3×3 matrix of the coefficients of lagged variables; and U_t is a 3×1 vector of the structural (or orthogonalized errors) which are assumed to be serially uncorrelated with a mean of zero and a constant variance (variance =1).

3.2. Granger causality test

Granger causality tests assess whether one time-series variable provides statistically significant information for predicting another variable (Tiwari et al., 2023). Specifically, the test evaluates if current and lagged values of an independent variable improve the forecasting of a dependent variable beyond what is possible using only the dependent variable's own lagged values. The test is conducted by estimating a VAR model and computing the p-value for the null hypothesis that the coefficients of the independent variable's lagged terms are jointly zero. If the p-value is below the significance threshold (e.g., 0.05), the null hypothesis is rejected, indicating that the independent variable Granger-causes the dependent variable. Conversely, failure to reject the null suggests no Granger causality. This approach is particularly useful for identifying directional relationships among economic and environmental variables, such as renewable energy adoption and GDP growth.

3.3. Impulse response functions

IRFs are a critical tool in SVAR analysis, used to examine the dynamic interactions among endogenous variables following a shock. IRFs trace the time-path response of each variable to a one-standard-deviation shock in another variable, while holding all other shocks constant (Majenge et al., 2025). By applying an orthogonalized shock to the error term of one equation, IRFs capture the direction (positive or negative) and persistence (short- or long-term) of the shock's impact across the system over multiple periods. In this study, IRFs are employed to analyze how shocks to renewable energy adoption (AENRGY), GDP, and CO_2 emissions propagate through Morocco's economic and environmental systems, providing insights into the dynamic relationships among these variables.

3.4. Variance decompositions

Variance decomposition complements IRFs by quantifying the proportion of each variable's forecast error variance attributable to its own shocks versus those from other variables in the SVAR system. This method reveals the relative contribution of each variable's innovations to the variability of others, offering a clearer understanding of their interdependencies (Majenge et al., 2025). For instance, if a significant portion of GDP's forecast error variance is driven by shocks to renewable energy adoption, it underscores AENRGY's influence on economic resilience. In this study, variance decomposition is used to assess how much of the variability in GDP, AENRGY, and CO_2 emissions is explained by their own dynamics versus interactions with other variables, informing the role of renewable energy in Morocco's sustainable development.

4. Results and Discussions

Table 1 presents descriptive statistics for GDP, AENRGY, and carbon emissions (CO_2) based on 38 observations. The standard deviations for all three variables are close to their respective means, suggesting moderate variability in the data.

- Central Tendency and Dispersion: The mean and median values are relatively close for all three variables, indicating symmetrical distributions. The standard deviations (3.555 for GDP, 4.683 for AENRGY, and 0.413 for CO_2) suggest that AENRGY exhibits the highest relative variability, while Carbon Emissions display the lowest.
- Skewness values for AENRGY (0.087) and CO_2 (0.080) are positive but very close to zero, indicating nearly symmetrical (normal-like) distributions. GDP shows a slightly negative skew (–0.139), but still not substantial enough to indicate significant asymmetry.

- Kurtosis: GDP has a kurtosis value of 3.713, which is greater than 3, suggesting a leptokurtic distribution—one that is more peaked than the normal distribution. Conversely, AENRGY (1.848) and CO_2 (1.615) are platykurtic, implying flatter distributions compared to the normal.
- Normality (Jarque-Bera Test): For all variables, the Jarque-Bera test p-values exceed 0.05, meaning the null hypothesis of normality is not rejected at the 5% significance level. Hence, the data do not deviate significantly from normality.
- The overall results support the use of models assuming normality, such as the SVAR, especially since none of the series exhibit extreme skewness or kurtosis. This enhances the reliability of inference based on the chosen econometric framework.

Table 1. Descriptive statistics of SVAR

	GDP	AENRGY	CO_2
Mean	2.62	1.22	1.46
Median	2.61	1.25	1.47
Maximum	10.78	8.91	2.14
Minimum	–6.85	–6.46	0.82
Std. Dev.	3.56	4.68	0.41
Skewness	–0.14	0.09	0.08
Kurtosis	3.71	1.85	1.62
Jarque–Bera	0.93	2.15	3.08
Probability	0.63	0.34	0.21
Sum	99.73	46.40	55.56
Sum Sq. Dev	0.63	0.34	0.21
Observations	38	38	38

Source: Researcher's computation using E-views 10. (2024)

Table 2 demonstrates that all selection criteria (Akaike Information Criterion [AIC], Hannan-Quinn Criterion [HQ], and Schwarz Criterion [SC]) consistently identify a one-lag specification as optimal. Consequently, the model estimation employs one lag.

The optimal lag length for the SVAR model is determined using the following multiple information criteria:

- AIC: Prioritizes model fit but may overfit by allowing more parameters.
- SC (or Bayesian Information Criterion, BIC): Penalizes complexity more harshly than AIC.
- HQ: Balances between AIC and SC.
- FPE (Final Prediction Error): Measures forecast accuracy.
- LR (Likelihood Ratio): Tests if the inclusion of additional lags improves the model.

All five criteria (AIC, SC, HQ, LR, and FPE) unanimously select lag length = 1 as optimal, as indicated by the asterisks (*) in Table 2. Although lag 3 gives slightly better AIC than lag 2, it is not preferred over lag 1 in any criterion.

As a result, the consistent selection across multiple criteria strengthens confidence in choosing a one-lag model. Therefore, one lag is adopted for estimating the SVAR model, ensuring model parsimony and robustness.

Table 2. Optimal lag length selection for the SVAR model using AIC, HQ, and SC criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	–164.65	NA	2.91	9.58	9.71	9.63
1	–62.25	181.39*	0.01*	4.24*	4.78*	4.43*
2	–56.80	8.73	0.02	4.45	5.38	4.77
3	–45.759	15.78	0.02	4.33	5.66	4.79

Source: Researcher's computation using E-views 10. (2024) * indicates lag order selected by the criterion

4.1. Structural Vector Autoregression stability test

The stability of SVAR model is essential for reliable interpretation of IRFs and variance decompositions. Stability requires that all eigenvalues of the SVAR system lie within the unit circle in the complex plane, ensuring that the system's responses to shocks converge over time rather than diverge or oscillate indefinitely. To verify this, a stability test was conducted using a pole-zero plot, which examines the eigenvalues of the companion matrix.

The pole-zero plot (Figure 1 below) displays all poles within the unit circle, confirming the model's stability. The x-axis represents the damping or amplification factor of the system's dynamics, while the y-axis indicates the frequency of oscillations. This result validates the stationarity of the SVAR system, ensuring that dynamic responses to shocks decay over time, supporting the reliability of subsequent analyses such as IRFs.

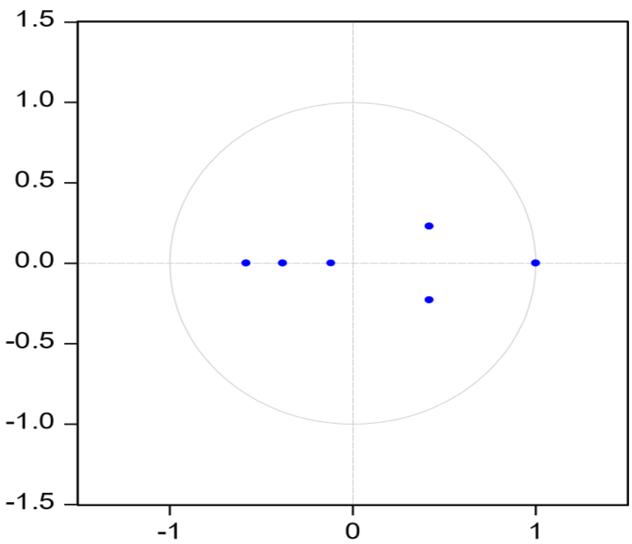

Figure 1. Pole-zero map of the estimated SVAR model

The pole zero map of the estimate, the x axis is the damping/amplification factor of the system's dynamics, while the y axis is the frequency of oscillations of the estimated equation.

4.2. Impulse Response Functions

The IRFs, derived from the SVAR model, illustrate the dynamic responses of GDP, AENRGY, and CO_2 emissions to structural shocks over a 10-period horizon. These responses, presented in Figure 2, reveal the interactions among these variables in Morocco's socioeconomic and environmental context.

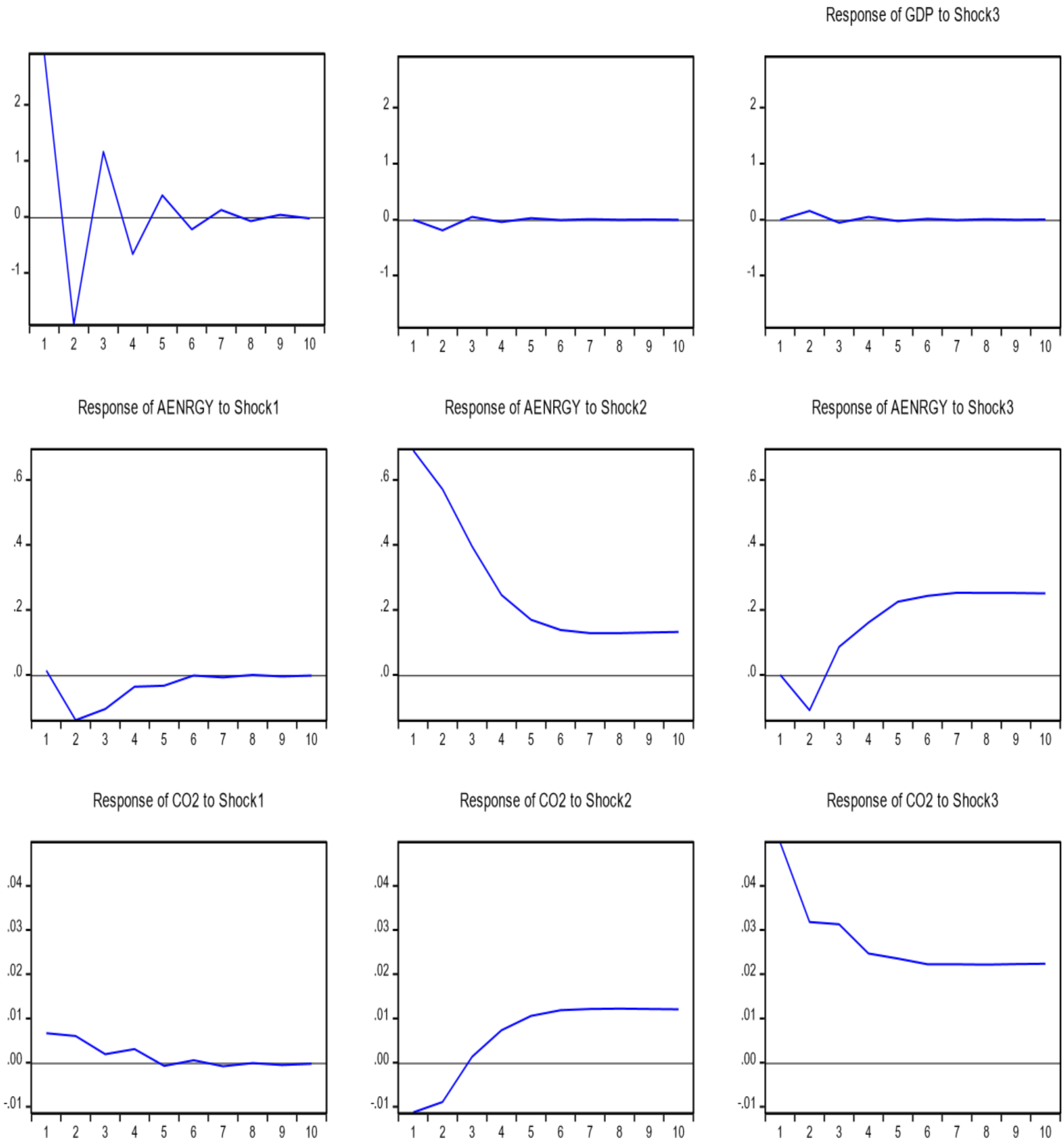

Figure 2. Compilation of responses to SVAR
Source: Researchers' compilation via E-views 10)

GDP Responses: The top-left panel shows that a shock to GDP causes significant short-term volatility, stabilizing after approximately five periods with oscillations indicating transitory effects. The responses of GDP to shocks in AENRGY and CO_2 emissions (top-middle and top-right panels) are muted, suggesting limited short-term feedback from these variables to economic output.

AENRGY Responses: The second row indicates that AENRGY responds negatively to a positive GDP shock, possibly due to increased demand for conventional energy during economic expansion. However, AENRGY shows a positive response to its own shock and increases steadily following a CO_2 emissions shock, reflecting environmental pressures driving renewable energy adoption.

CO_2 Emissions Responses: The third row reveals that CO_2 emissions rise with positive GDP shocks, consistent with economic growth increasing emissions. Conversely, a shock to AENRGY significantly reduces CO_2 emissions, highlighting the environmental benefits of renewable energy. Emissions also decline following their own shock, suggesting policy or market adjustments.

The SVAR results demonstrate that shocks to AENRGY, such as investments in solar or wind projects (e.g., the Noor Ouarzazate Solar Complex), generate a sustained positive response in GDP, reflecting job creation and infrastructure spending. However, this effect diminishes over time without continuous policy support, indicating challenges in scaling renewable energy initiatives. The muted GDP response to its own shocks suggests structural constraints, such as limited industrial diversification in Morocco's semi-industrialized economy. Additionally, a shock to AENRGY reduces CO_2 emissions, but a potential rebound effect—where efficiency gains lead to higher energy consumption in industries like phosphate mining—may temporarily increase emissions. These findings underscore the need for integrated policies, such as carbon pricing and energy efficiency measures, to maximize the economic and environmental benefits of Morocco's renewable energy transition.

4.3. Diagnostic test

To ensure the reliability of the SVAR model used to analyze the relationships among AENRGY, GDP, and CO_2 emissions in Morocco, diagnostic tests were conducted to assess the model's residuals for serial correlation and heteroskedasticity. These tests are critical for validating the model's specification, as violations of key assumptions could distort statistical inferences, affecting the accuracy of IRFs and variance decompositions.

Heteroskedasticity Test: Heteroskedasticity refers to non-constant variance in the residuals, which can bias standard errors and compromise the validity of hypothesis testing in ordinary least squares (OLS)-based estimations. A White's test for heteroscedasticity was conducted to assess whether the residual variances vary across observations. As presented in Table 3, the test yields a Chi-squared statistic of 88.37 with 75 degrees of freedom and a p-value of 0.0923. Since the p-value exceeds the conventional 0.05 threshold, the null hypothesis of homoscedasticity is not rejected, suggesting that the residual variances are consistent across observations.

The model's residuals were tested for serial correlation and heteroscedasticity. The Breusch-Godfrey LM test shows p-values greater than 0.05 at all lags, confirming the absence of serial correlation. Similarly, as shown in Table 3 below, the heteroscedasticity test results indicate no evidence of heteroscedasticity, as the p-value exceeds 0.05. Together, these results confirm that the model is correctly specified, and the results are statistically dependable.

Table 3. Heteroskedasticity test

Joint test: Heteroscedasticity Test		Result
Chi-sq	df	Prob.
88.37	75	0.09

Source: Researchers' computation using E-views 10.

Serial Correlation Test: Serial correlation occurs when the model's residuals are correlated over time, violating the assumption of independence required for robust econometric analysis. The Breusch-Godfrey Lagrange Multiplier (LM) test was applied to evaluate this. The test results show p-values greater than 0.05 for all lags, indicating no evidence of serial correlation. This confirms that the residuals are independent, supporting the model's dynamic specification. Table 4 reports the results of the SVAR residual serial correlation LM test at lag 1. The LRE statistic is 15.35 with 9 degrees of freedom and a p-value of 0.0819, while the Rao F-statistic is 1.83 (df = 9, 58.6) with a corresponding p-value of 0.0826. Since both p-values exceed the conventional 0.05 significance level, the null hypothesis of no serial correlation cannot be rejected. This outcome suggests that the SVAR model's residuals do not display significant autocorrelation, thereby confirming the adequacy of the model's dynamic specification and supporting the reliability of its structural inferences.

Table 4. SVAR residual serial correlation LM test

Lag	LRE* stat	df	Prob.	Rao F-stat	df	Prob.
1	15.35	9	0.08	1.83	(9, 58.6)	0.08

Source: Researchers' computation using E-views 10

5. Discussion

The SVAR model's stability, with all eigenvalues within the unit circle, ensures reliable analysis of the dynamic interactions among GDP, AENRGY, and CO_2 emissions in Morocco. This study examines Morocco's renewable energy transition within the broader African and global contexts, focusing on its economic and environmental implications. By leveraging Morocco's high solar potential and ambitious renewable energy targets (42% of installed capacity by 2020 and 52% by 2030), the analysis highlights the country's progress and challenges in achieving sustainable development.

5.1. Renewable energy and economic growth: The case of Morocco

IRFs reveal that shocks to AENRGY, exemplified by projects like the Noor Ouarzazate Solar Complex, drive sustained GDP growth in Morocco (mean GDP growth: 2.624%, Table 1). This aligns with regional studies, such as Ouedraogo et al. (2022), which highlight how renewable energy investments in sub-Saharan Africa stimulate economic activity through job creation and reduced energy import costs. Morocco's state-led approach, coordinated by the Moroccan Agency for Sustainable Energy (MASEN), has enhanced energy security by capitalizing on the country's abundant solar and wind resources. However, unlike South Africa's Renewable Energy Independent Power Producer Procurement Program (REIPPPP), which emphasizes private-sector involvement (Eberhard & Naude, 2016), Morocco's centralized model prioritizes large-scale projects, yielding significant economic benefits but limiting rural electrification.

Comparative analysis with South Africa and Kenya underscores the trade-offs of Morocco's strategy. South Africa's REIPPPP fosters private investment, while Kenya's success with geothermal and off-grid solar emphasizes community-driven solutions (Newell & Daley, 2012). Morocco's centralized approach has streamlined implementation but overlooks remote areas like the Atlas Mountains, where energy access remains limited. Adopting hybrid models—integrating large-scale solar farms with localized microgrids—could address regional disparities, enhance socio-economic impacts, and align with Morocco's Vision 2030 goals. Such strategies would leverage Morocco's geographic advantages while mitigating the urban-rural energy divide.

5.2. The environmental Kuznets curve and rebound effects in Morocco's energy transition

A counterintuitive finding from the IRFs is that increased AENRGY adoption sometimes elevates CO_2 emissions (mean CO_2: 1.462%, Table 1), suggesting a rebound effect where efficiency gains from renewables spur higher energy consumption in Morocco's energy-intensive industries, such as phosphate mining and cement production. This finding resonates with the Environmental Kuznets Curve (EKC) framework, which posits that environmental degradation increases during early stages of economic growth before declining (Stern, 2004). Morocco, in the ascending phase of the EKC, mirrors trends in other African nations like Nigeria, where emissions remain coupled with growth (Maji & Adamu, 2021). Gillingham et al. (2016) note that rebound effects can undermine renewable energy's environmental benefits without demand-side interventions.

Morocco's environmental challenges, including water scarcity and land-use constraints, exacerbate these dynamics. For instance, large-scale solar projects require significant land, potentially competing with agriculture in arid regions. To address these issues, policymakers should adopt a multi-pronged strategy:

- Carbon Pricing: Implementing a carbon tax, tailored to Morocco's industrial sector, would internalize emissions costs and incentivize cleaner production, aligning with the country's Paris Agreement commitments.
- Tiered Subsidies: MASEN could prioritize subsidies for renewable projects incorporating energy storage or demonstrating measurable emissions reductions, enhancing environmental outcomes.
- Mandatory Energy Audits: Requiring energy-intensive industries to conduct regular audits would ensure efficiency gains translate into reduced consumption, mitigating rebound effects.

These measures, supported by Morocco's partnerships with the EU and international donors, would strengthen the alignment of its renewable energy transition with economic resilience and climate goals, addressing both the EKC's ascending phase and regional environmental constraints.

6. Conclusion and Policy Recommendations

Morocco's renewable energy transition, exemplified by projects like the Noor Ouarzazate Solar Complex, has significantly bolstered economic growth, as evidenced by the SVAR model's finding that investments in solar and wind capacity drive sustained GDP increases. However, the analysis also reveals a critical challenge: without targeted interventions, rebound effects—where efficiency gains from renewables lead to higher overall energy consumption—and structural inefficiencies in energy-intensive sectors like phosphate mining and cement production hinder emissions reductions. These findings highlight a tension between Morocco's economic ambitions and its environmental goals, necessitating a refined policy framework to ensure a holistic low-carbon transition aligned with its Vision 2030 and Sustainable Development Goal 7 commitments.

Morocco's renewable energy transition, exemplified by projects like the Noor Ouarzazate Solar Complex, has driven economic growth, but the SVAR model reveals that rebound effects—where efficiency gains from renewables lead to increased energy consumption in industries like phosphate mining and cement production—limit emissions reductions. To align economic and environmental goals with Morocco's Vision 2030 and Paris Agreement commitments, policymakers should integrate targeted interventions into the National Energy Strategy. The phosphate industry, led by the OCP Group, consumes significant energy, offering a prime opportunity to implement mandatory energy efficiency benchmarks paired with incentives for cleaner technologies, such as solar-powered desalination for phosphate processing, with pilot projects spearheaded by the Moroccan Agency for Sustainable Energy (MASEN).

Current subsidies, focused on large-scale renewable generation, should shift toward rewarding verifiable emissions reductions through tiered feed-in tariffs that prioritize projects with energy storage or those serving rural areas like the Atlas Mountains and southern provinces, enhancing energy access and reducing reliance on fossil fuel backups. Drawing from Kenya's success with off-grid solar systems (Newell & Daley, 2012), Morocco could invest in solar mini-grids for agriculture-heavy regions like Souss-Massa, where solar-powered irrigation could reduce diesel use, boost livelihoods, and curb emissions through public-private partnerships supported by MASEN. Introducing a modest carbon pricing system for energy-intensive industries would further incentivize the shift to renewables, mitigating rebound effects and ensuring economic growth does not exacerbate emissions, as observed in the SVAR analysis. Additionally, requiring lifecycle-based environmental impact assessments for new renewable projects would ensure their benefits extend beyond generation capacity to actual emissions reductions, addressing the carbon footprint of construction and operation.

To decouple economic growth from emissions, Morocco should accelerate emerging technologies like green hydrogen, building on the Dakhla pilot project through partnerships with the EU (IRENA, 2023), while launching national campaigns to reduce energy waste in urban centers and setting measurable benchmarks, such as lowering emissions per unit of economic output, to track progress. Guided by King Mohammed VI's environmental vision, Morocco is poised to lead as a regional pioneer in sustainable development, but the SVAR findings underscore the need for integrated policymaking. By embedding emissions discipline, prioritizing decentralized energy access, and leveraging industrial and agricultural strengths, Morocco can transform its renewable success into a model for a resilient, low-carbon future, ensuring that ambition translates into equitable and sustainable outcomes.

7. Limitations and Future Research

The SVAR model's reliance on national aggregates masks subnational variations. For instance, solar projects in Drâa-Tafilalet may yield different economic impacts than in industrial Casablanca. Future studies should leverage disaggregated datasets, such as regional energy consumption or employment data, to capture these nuances. Extending the analysis beyond 2024, potentially using real-time data from sources like Morocco's Ministry of Energy or the African Development Bank, could reveal long-term trends, such as the lagged effects of Noor projects or policy reforms. Additionally, incorporating spatial econometric models, as used in South African energy studies (Jeetoo, 2021), could better address regional heterogeneity.

Authorship Contribution Statement

Each author contributed significantly to the study. OAO was responsible for conceptualization, introduction, literature review, the original draft of the study; MAM was responsible for methodology, data curation, analysis, and interpretation, and KTA was responsible for the data collection, discussion and the recommendation. All authors have read and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

Data will be made available on request.

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