

The Dynamics of Energy Consumption, CO₂ Emissions and Economic Growth: Evidence from Ghana

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ABSTRACT

The relationship among energy consumption, carbon dioxide (CO₂) emissions, and economic growth has been the subject of extensive global debate, particularly in the context of sustainable development. This study investigates the dynamic interactions among these variables in Ghana using annual time-series data from 2000 to 2022. The analysis is guided by the endogenous growth theory and the Environmental Kuznets Curve (EKC) hypothesis, and employs econometric techniques including unit root tests, cointegration analysis, an error correction model (ECM), Granger causality tests, and impulse response functions (IRFs). Diagnostic tests ensured the robustness and reliability of the model. The unit root tests confirm that energy consumption, CO₂ emissions, and GDP per capita are integrated of order one, I (1). Johansen cointegration results confirm the existence of a long-run equilibrium relationship among the variables. The VECM estimates reveal that electricity consumption significantly drives economic growth in both the short run and long run, supporting the growth hypothesis. A joint short-run causality from energy consumption to GDP as well as from CO₂ emission to GDP were established. There was evidence of unidirectional causality from both energy and CO₂ to GDP. The findings imply that while energy consumption is critical to sustaining Ghana's economic growth, it also contributes significantly to environmental degradation. Policy measures should therefore focus on expanding renewable energy, enhancing energy efficiency, and aligning climate policies with national development strategies. By balancing growth objectives with environmental sustainability, Ghana can advance toward a low-carbon development pathway.

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Received: October 07, 2025; **Accepted:** November 14, 2025; **Published:** November 25, 2025

Keywords: Energy Consumption, CO₂ Emissions, Economic Growth, Cointegration, VECM, Ghana

Introduction

Energy plays a central role in driving economic growth and development, particularly in developing economies where industrialization, urbanization, and rising living standards are fueling increased energy demand. As economies expand, the consumption of energy resources intensifies, often resulting in higher levels of carbon dioxide (CO₂) emissions, which contribute significantly to global climate change [1,2]. The dynamic interaction among energy consumption, CO₂ emissions, and economic growth has, therefore, attracted extensive scholarly attention over the past few decades. While economic growth is desirable, its associated environmental costs present a challenge for achieving sustainable development [3].

In the context of Sub-Saharan Africa, energy consumption is highly dependent on fossil fuels and biomass, leading to growing concerns about environmental sustainability and climate vulnerability [4]. Ghana, like many developing economies, is experiencing rapid urbanization, industrial expansion, and population growth, which have intensified energy demand [5]. The country's energy mix

remains dominated by fossil fuels and hydroelectric power, but recent oil discoveries and natural gas utilization have further complicated the energy-growth-environment nexus [6]. Consequently, Ghana faces the dual challenge of meeting rising energy needs for economic transformation while minimizing CO₂ emissions and environmental degradation.

The debate on the relationship between energy consumption, economic growth, and environmental quality is often framed within the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between environmental degradation and income levels [7]. Empirical studies across different countries, however, have produced mixed and context-specific findings, underscoring the need for country-level investigations [8,9]. For Ghana, understanding this nexus is particularly important given the government's commitment to achieving the United Nations Sustainable Development Goals (SDGs), especially Goal 7 (affordable and clean energy) and Goal 13 (climate action).

Despite the growing body of research on energy, emissions, and growth across Africa, Ghana continues to be underrepresented in the literature. Existing studies either concentrate on aggregate

energy use without distinguishing between energy types or do not sufficiently address the dynamic causality among energy consumption, CO₂ emissions, and economic growth [10,11]. This gap in knowledge makes it challenging to design effective policies that balance the pursuit of economic growth with the need for environmental sustainability.

Against this backdrop, the present study aims to explore the interrelationships among energy consumption, CO₂ emissions, and economic growth in Ghana by employing robust econometric techniques and recent data, the research aims to provide empirical evidence on the causal linkages and long-run relationships among these variables. This study's findings will contribute meaningfully to the policy discourse on sustainable energy and climate mitigation in Ghana, and offer insights applicable to other developing economies facing comparable issues.

Literature Review

The nexus of energy consumption, economic growth, and carbon dioxide (CO₂) emissions has been the focus of environmental and development economics. Increased industrialization, urbanization and population increase in developing countries have compounded the problem of maintaining economic growth and reducing environmental degradation. The empirical research devoted to examining this nexus is still broad though uneven in terms of countries, techniques and time. The relationship among energy consumption, CO₂ emissions, and economic growth has been widely examined in empirical and theoretical literature. This section reviews relevant studies under three thematic areas: (i) theoretical underpinnings, (ii) empirical evidence from developed and emerging economies, and (iii) empirical studies on Ghana and Sub-Saharan Africa.

Theoretical Underpinnings

The energy-growth-environment dynamics discourse is based on a number of theoretical models. In neoclassical growth theory, capital, labour and technological advancements are the things that drive economic growth and in most cases energy is an input not a central factor [12]. Nevertheless, endogenous growth theory incorporates energy into the growth process, which emphasizes the importance of energy in the production, technological development, and productivity increase [13].

The second powerful paradigm is the Environmental Kuznets Curve (EKC) hypothesis, which assumes that there is an inverted U-shaped relationship between income and environmental degradation. The EKC predicts that the CO₂ emissions will increase at first but then fall as the economies switch to cleaner technologies and enforce strict environmental policies. Nevertheless, the universality of the EKC is debated, and empirical evidence is both positive and negative in various states and nations [14,15]. Indicatively, affirmed the presence of the EKC in Morocco, and the study revealed that although GDP deteriorates the quality of the environment, the level of income leads to a decrease in emissions [16]. Conversely, discovered that there was long-run cointegration between GDP, energy consumption and CO₂ emissions in the ASEAN countries but only confirmed that EKC in Myanmar and not Malaysia, Thailand and Philippines [17]. These disparities highlight the influence of factors like energy structure and capacity to develop technology on the environment.

Likewise, research in China and West Africa is incongruent. Reported the continuous growth of emissions with expansion, which proves that energy mix and industrial strength is still the major driver of emissions [18,19]. Also claimed that the inclusion

of innovation and policy variables into the EKC framework is more realistic in representing the growth-environment trade-off [20].

Moreover, the causality argument in the literature states four primary hypotheses namely the growth hypothesis (energy consumption causes growth), the conservation hypothesis (growth causes energy consumption), the feedback hypothesis (energy consumption causes growth) as well as the neutrality hypothesis (energy does not cause growth). These are the hypotheses on which empirical research on the energy-emissions-growth nexus can be built.

Evidence from Developed and Emerging Economies

Previous empirical studies have shown varied outcomes based on the country, methodology, and time frame of data study. Established the fundamental relationships between energy consumption, income, and CO₂ emissions, and found that the role of energy consumption is critical in promoting economic achievements and environmental results [21,22]. Follow-up research also generalised such analyses to regional and country-levels, with inconsistent findings on causality direction and policy implications [23].

Testing of causality assists in verifying the presence or absence of growth as a result of energy consumption (growth hypothesis) or as a result of economic expansion (conservation hypothesis). Conducted the analysis of Indonesia, Malaysia, the Philippines, and Thailand using the Johansen cointegration analysis and Granger causality, and discovered that the variables have a long-term relationship in all four countries [24]. The researchers found unidirectional causality of growth on energy consumption in Indonesia, Malaysia, and Thailand, thus confirming the conservative hypothesis, and vice versa in the Philippines, which confirmed the growth hypothesis.

Similarly, identified the heterogeneous patterns of causality by ASEAN countries, where unidirectional was found in certain countries, bidirectional or neutral in other countries, indicating that policy impacts are context-dependent.

Reported strong long-run cointegration in the relationship between energy consumption, GDP, and emissions in Africa, suggesting that clean energy transitions should be the priority in sustainable growths [25,26]. Likewise, established short- and long-run causality between these variables in South Africa and expressed their belief in the necessity of energy efficiency and diversification to minimize environmental stress and sustain the growth momentum [27]. The African situation is a special case of structural energy shortages, biomass dependability and susceptibility to climate change.

Examined the economy of Ghana and discovered that there is a long-run energy consumption and growth relationship where the causality is in energy to growth direction, thus confirming the hypothesis of growth.

Argued that Ghana's dependence on imported fossil fuels and limited renewable infrastructure constrain sustainable growth, emphasising the need for investments in energy efficiency and clean technologies. Likewise, both renewable and non-renewable energy use both impact the economic performance in Ghana; however, fossil fuels are a key contributor to CO₂ emission according to.

Analyzed the hypothesis of EKC in Ghana. Their evidence of the inverted U-shape was minimal, which indicates that Ghana

remains in the ascending portion of the curve and the economic growth is still worsening the emissions. These insights reinforce the importance of reassessing Ghana's energy-emissions-growth dynamics in the light of recent economic expansion, oil discoveries, and climate policy commitments. This study seeks to fill this gap by employing recent data and advanced econometric techniques to provide evidence-based insights for policy formulation.

A number of cross-country research studies have also been conducted to investigate the position of renewable energy as compared to non-renewable energy. Discovered that the use of renewable energy sources does not affect growth because it decreases CO₂ emissions and the use of fossil fuels contributes to environmental degradation. Recent research recognizes renewable energy adoption and technological progress as crucial mediators in the growth-emissions nexus. Introduced patent applications as a proxy for technological innovation in ASEAN countries and found that while technology enhances GDP in the short run, it may also temporarily raise emissions because many patents remain fossil-fuel oriented [28]. Similarly, demonstrated that improving energy efficiency and cross-border cooperation in China's Greater Bay Area effectively reduces emission intensity [29].

In South and Southeast Asia, confirmed that renewable energy has yet to achieve significant decoupling from emissions due to high implementation costs and technological barriers [30]. These findings align with and, who emphasized the need for financial incentives, technological transfer, and institutional reforms to support renewable energy deployment in developing economies.

These results indicate that the energy-growth-emissions nexus is greatly influenced by the energy composition.

Materials and Methods

The study adopts a quantitative research design grounded in time-series econometrics. This approach is suitable for examining the long-run and short-run interactions among macroeconomic and environmental variables, as established in prior empirical works. By applying cointegration and causality techniques, the study aims to capture both equilibrium relationships and directional causal linkages.

Data Source

The study relied on annual time-series data for Ghana covering the period 1980–2022. This period is selected to capture recent economic reforms, energy sector developments, and environmental policy changes. Data was obtained from reputable international source, the World Bank's World Development Indicators (WDI).

Variables and Measurement

The study considered three primary variables:

- **Economic Growth (GDP):** Real Gross Domestic Product per capita (constant 2015 US\$) is used as a proxy for economic growth.
- **Energy Consumption (EC):** Total primary energy consumption, measured in kilograms of oil equivalent per capita, is employed to capture the level of energy use.
- **Carbon Dioxide Emissions (CO₂):** Measured in metric tons per capita, representing environmental degradation arising from energy-related activities.

All variables are transformed into their natural logarithmic forms to stabilise variance, reduce heteroskedasticity, and allow interpretation of coefficients in terms of elasticities.

Econometric Framework

This is structured to provide both preliminary and advanced econometric insights. The purpose is to identify the long-run and short-run relationships among the variables and to assess the direction of causality within the energy-growth-emissions nexus. It begins with a descriptive analysis of the data, highlighting key trends and patterns in Ghana's energy use, economic growth, and CO₂ emissions over the study period.

The study applies unit root tests, specifically the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests, to determine the stationarity properties of the series. Establishing the order of integration is a crucial step in avoiding spurious regression and guiding the choice of cointegration techniques [31]. Following this, the Johansen cointegration test is employed to examine the presence of a long-run equilibrium relationship among the three variables. This approach is appropriate for multivariate analysis and has been widely used in energy-economy-environment studies [32]. Where cointegration is established, the Vector Error Correction Model (VECM) is estimated to capture both the long-run equilibrium dynamics and the short-run adjustments.

The Granger causality tests was performed within the VECM framework to establish the direction of causality. The robustness of the estimated models is verified through diagnostic and stability tests. All these helped to assess the compatibility of Ghana's economic growth with sustainable energy and environmental goals.

Data Analysis and Results

Descriptive Statistics and Preliminary Analysis

The descriptive statistics summaries the key features of the data for Ghana, covering 23 annual observations.

Table 1: Summary Statistics of CO₂, Electricity Consumption and GDP Per Capita

	CO ₂	Elect	GDP Per Capita
Mean	13.28025	65.04783	1379.156
Median	12.14040	65.10000	1507.436
Maximum	24.45300	86.30000	2445.501
Minimum	6.085900	41.30000	253.7469
Std. Dev.	5.835759	15.15384	764.4219
Skewness	0.479566	-0.034284	-0.218845
Kurtosis	2.031898	1.595867	1.595495
Jarque-Bera	1.779776	1.893945	2.074032
Probability	0.410702	0.387914	0.354511
Sum	305.4458	1496.100	31720.58
Sum Sq. Dev.	749.2338	5052.057	12855498
Observations	23	23	23

The mean value of CO₂ emissions is 13.28 metric tons per capita, with a minimum of 6.09 and a maximum of 24.45, suggesting a wide variation across the study period. Electricity consumption has an average of 65.05 kWh per capita, with values ranging from 41.30 to 86.30. GDP per capita on the other hand records a mean of 1379.16 (constant US\$), and with a minimum of 253.75 and a maximum of 2445.50, reflecting significant growth over the period. The variables exhibit considerable variability, especially in GDP per capita, reflecting Ghana's structural economic changes during the study period The Jarque-Bera test statistic indicate that

all the three variables are approximately normally distributed.

Unit Root Test Results

The stationarity of variables is a critical step in time-series econometrics, as non-stationary data may produce spurious regression results. The Augmented Dickey-Fuller (ADF) test is used to test the null hypothesis that a variable has a unit root (i.e., is non-stationary).

Table 2: Unit Root Test Results

Variable	ADF	Order	p-value	Conclusion
	Levels			
CO ₂	-0.295051	I(1)	0.0005	Stationary
ELECT	-0.967502	I(1)	0.0009	Stationary
GDP Per capita	-1.995470	I(1)	0.0005	Stationary

The Augmented Dickey-Fuller (ADF) test was applied to examine the stationarity of the series. The results are summarized in table 2. At level form, the ADF statistics -0.29, -0.9675 and -1.9955 for CO₂, EC, and GDPPC respectively were less negative than their critical values, and their p-values exceeded 0.05. This implies that the series are non-stationary at levels (I(0)). After first differencing, the ADF statistic for CO₂ (-5.22, p = 0.0005) was well below the critical values, confirming stationarity at first difference (I(1)). Similar results were found for ELEC and GDPPC. Thus, all variables are integrated of order one, I(1), consistent with findings in related energy–economy–environment studies [33].

Cointegration Analysis

Given that all variables are I(1), the Johansen cointegration test was applied to examine the existence of a long-run equilibrium relationship among CO₂ emissions, electricity consumption, and GDP per capita. The results in Table 4.8 indicate that both the trace statistic and the maximum eigenvalue statistic exceed the critical values at the 5% level for at least one cointegration equation.

This confirms the presence of a long-run relationship among the three variables. In other words, energy consumption, CO₂ emissions, and economic growth in Ghana move together over time, consistent with the environmental–economic development literature [34].

Table 3: Johansen Cointegration Tests

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**	Max-Eigen Statistic	0.05 Critical Value	Prob.**
None *	0.652038	35.15649	29.79707	0.0110	21.11322	21.13162	0.0503
At most 1 *	0.385387	14.04328	15.49471	0.0818	9.735249	14.26460	0.2299
At most 2 *	0.193782	4.308027	3.841465	0.0379	4.308027	3.841465	0.0379

The cointegration tests reveal there are at least two long run relationship among the variables, energy consumption, CO₂ emissions, and economic growth as indicated by both the Trace test and the Maximum Eigenvalue test. The rejection of the null hypothesis of no cointegration at the 5% significance level for both tests implies that changes in energy consumption, CO₂ emissions, and economic growth are jointly influenced by common stochastic trends over the long term. That is, any short-run imbalance between these variables will tend to be interim and the system will stabilize to equilibrium in the long run. This suggests the presence of a long-run equilibrium relationship among the variables in Ghana, consistent with studies. This discovery confirms the hypothesis that, Economic growth in the analyzed scenario is energy-dependent, and variations in the energy consumption are strictly correlated with the environmental performance in terms of CO₂ emissions.

Vector Error Correction Model (VECM) Results

Since cointegration exists, a VECM was estimated to capture how energy consumption (ELEC), carbon dioxide emissions (CO₂), and economic growth (GDP) interact both in the short and long run with the dependent variables ΔGDP, ΔELEC, and ΔCO₂ (first differences).

The cointegrating equation extracted from the VECM output is:
 $GDP = -3.0737 \times ELEC + 2.3793 \times CO_2 + 6.0467$

The ELEC coefficient (-3.0737) indicates that, over the long term, increase in consumption of energy is correlated with decrease in economic growth, other things being unchanged. This negative sign is counterintuitive, potentially representing some form of inefficiency in energy use, reliance on non-productive energy sectors, or wastage of energy that fails to provide any productive benefit in the economic sphere [26,35].

The CO₂ emission coefficient (2.3793) is positive and significant (t = -1.958, almost 5% significance), which means that increased emission of CO₂ is be linked to increased levels of GDP in the long run. This is in favor of the growth-driven emission hypothesis where economic growth, which is usually driven by fossil fuel consumption, leads to increased CO₂ emission.

Table 4: Short-Run Dynamics (Error Correction Terms)

Dependent variable	Coefficient (CointEq1)	t-statistics
ΔGDP	-0.1089	-2.0258
ΔELEC	-0.0031	-0.0579
ΔCO ₂	0.0988	3.3897

Results in Table 4 reveal the error correction term (ECT) with a negative coefficient of -0.1089 and statistically significant, indicating that approximately 10.9% of any deviation from the long run equilibrium is corrected each period. This indicates a

moderate speed of adjustment. The positive and significant ECT for ΔCO_2 (0.0988) suggests that CO₂ emissions diverge temporarily from equilibrium following a shock but adjust dynamically in the subsequent period, reflecting environmental inertia or lagged responses to growth and energy fluctuations. The insignificant adjustment in ΔELEC implies that energy consumption is weakly exogenous—it does not respond to disequilibrium in the short run, meaning energy usage patterns change independently of deviations from the long-run equilibrium.

Short-run causality is inferred from the significance of the lagged first-differences of ELEC and CO₂. The results ($D(\text{ELEC}(-1)) = -1.0433, p = 0.0131$), indicate that a one-year lag of energy consumption significantly but negatively affects GDP growth in the short run. This suggests that increased energy consumption initially depresses economic growth, possibly due to inefficiencies, energy shortages, or high dependence on costly, non-renewable energy sources. The Wald test, ($\chi^2 = 10.156, p = 0.0062$) confirms joint short-run causality from energy consumption to GDP. The results also revealed that, CO₂ emissions from the preceding two years have a negative and marginally significant impact on GDP growth, ($D(\text{CO}_2(-2)) = -0.7739, p = 0.053$) at 10% significant level with the Wald test ($\chi^2 = 6.218, p = 0.0447$) confirming the joint short-run causality from CO₂ emissions to economic growth. This economically means that the cost of environmental degradation is harmful to growth, whether in terms of health expenses, farm destruction or inefficient energy usage. Although industrial growth and the consumption of energy lead to emission, the cost of the environment can be higher than the benefits of growth in the short-term. These results align with prior studies in developing economies, emphasizing the importance of energy as a driver of growth, but also highlight the environmental costs associated with rising emissions [37,38].

Table 5: Model Diagnostics

Test	Test-Statistics	Probability	Decision
Adjusted R-squared	0.7038	-	Approximately 70% of the variations in short-run GDP changes are explained by changes in energy consumption and CO ₂ emissions.
F-statistic	7.449	0.0014	It confirms the overall model significance
Standard error	0.043	-	The low standard error of regression (0.043) further supports a well-fitted model
Durbin–Watson statistic	2.18	-	No serial correlation in residuals, validating the robustness of the model.

These diagnostics reinforce the reliability of the estimated short-run relationships and long-run equilibrium correction mechanism.

Stability Tests

The inverse roots of the characteristic polynomial all lie within the unit circle, confirming that the VECM model is dynamically stable. The cumulative sum (CUSUM) was found to remain within the 5% critical boundaries throughout the sample period, indicating that there are no significant structural changes in the model parameters, and that the estimated coefficients are stable over time. The stability of the system further validates the robustness of the cointegration relationship and the reliability of the impulse response and variance decomposition analyses.

Inverse Roots of AR Characteristic Polynomial

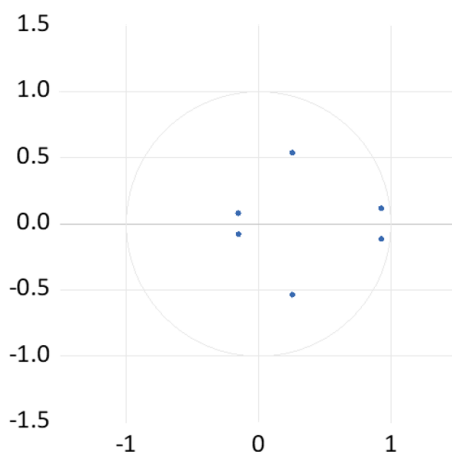


Figure 1: The Inverse Roots of the Autoregressive (AR) Characteristic Polynomial

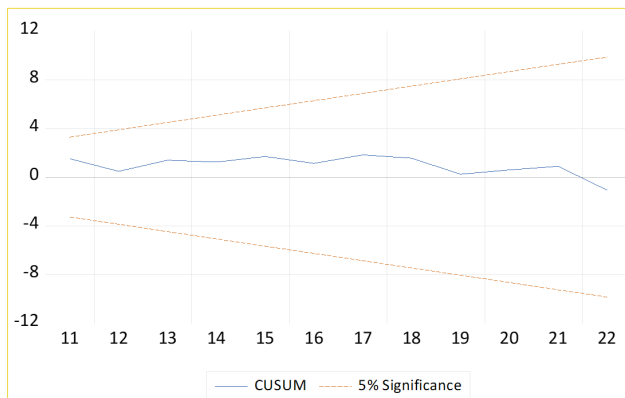


Figure 2: CUSUM Test

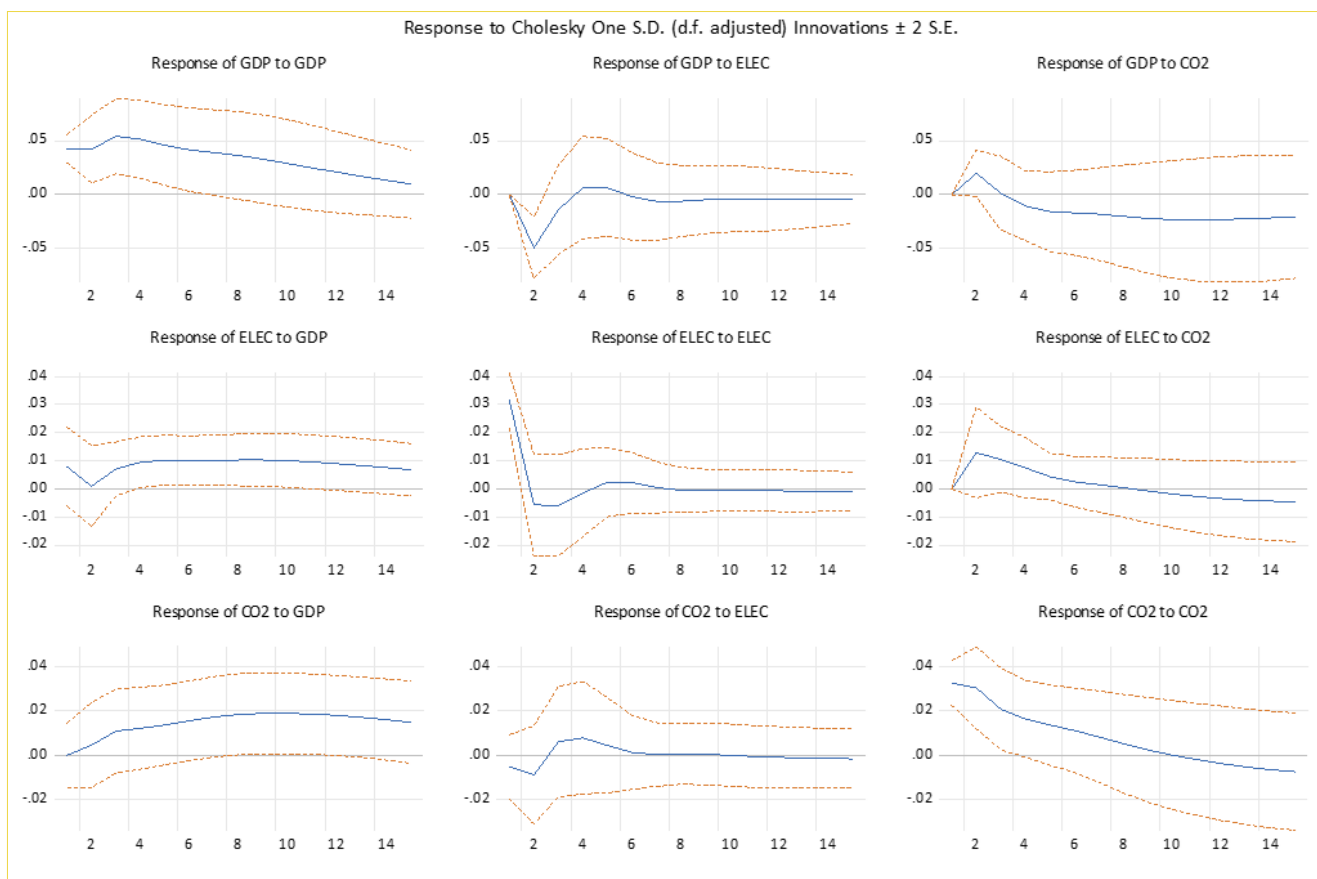


Figure 3: Impulse Response Graphs

The impulse response analysis reinforces the unidirectional short-run causality found in your VECM results: Energy \rightarrow GDP and CO₂ \rightarrow GDP.

It also reveals that energy consumption positively drives both growth and emissions, while CO₂ shocks slightly depress output. This dynamic pattern underscores the challenge of achieving sustainable economic growth in Ghana — balancing energy-driven expansion with environmental protection [39].

Conclusion and Recommendations

This study examined the dynamic relationship among energy consumption, CO₂ emissions, and economic growth in Ghana using annual time-series data from 2000 to 2022. Guided by the theoretical frameworks of the endogenous growth theory and the Environmental Kuznets Curve (EKC) hypothesis, and employing econometric techniques including unit root testing, Johansen cointegration, VECM, and Granger causality, the study arrived at several key conclusions.

The GDP, energy consumption, and CO₂ emission have a long-run equilibrium relationship, suggesting that Ghana's economic growth, energy use, and emissions are interconnected over time. The economic growth seems to be energy-dependent and at the expense of the environmental degradation implying a trade-off that exists between growth and sustainability. This finding suggests that Ghana remains

in the rising phase of the EKC curve, where economic growth is accompanied by worsening environmental quality. Overall, the study contributes to the empirical literature by providing updated, Ghana-specific evidence on the energy–growth–emissions nexus. It confirms that Ghana’s growth trajectory is energy-intensive and environmentally unsustainable unless deliberate interventions are implemented.

In conclusion, the study underscores the central role of energy in Ghana’s growth trajectory, while also highlighting the environmental trade-offs that accompany this dependence. Sustainable economic growth in Ghana will depend on the country’s ability to restructure its energy sector, embrace renewable technologies, and integrate environmental concerns into economic planning. By doing so, Ghana can achieve a balanced path toward industrialization, prosperity, and environmental sustainability.

The findings generate practical insights for policymakers on the energy–growth–environment trade-off, offering guidance for balancing development and sustainability. This is an indication that the policies which are designed to stimulate economic growth without considering the energy efficiency or environmental sustainability might be reflected in long-term consequences of the environmental quality. On the other hand, a sustainable economic growth can be achieved through increasing energy efficiency and adopting renewable energy sources to reduce the emission of CO₂.

Recommendations

- Ghana must expand and modernize its energy infrastructure to meet rising demand while reducing system losses.
- The heavy reliance on fossil fuels should be reduced through investment in renewable energy sources such as solar, wind, biomass, and mini-hydro.
- Policies promoting energy efficiency in industries, households, and transport should be enforced through standards, labeling, and public awareness campaigns.
- Adoption of smart-grid technologies can optimize energy use and reduce waste. Investments in low-carbon technologies should be supported to decouple growth from emissions.

Suggestions for Future Research

While this study has provided useful insights, it is not without limitations. Future research could:

- Disaggregate energy consumption into renewable and non-renewable sources to provide more detailed policy insights.
- Extend the analysis using sectoral data (e.g., industry, transport, households) to identify sector-specific dynamics.
- Explore the role of institutional quality, foreign direct investment, and technological innovation in shaping the energy–growth–emissions nexus in Ghana.

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