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Article

Economic growth, renewable energy consumption patterns, and environmental sustainability in Ghana: Testing the Environmental Kuznets Curve

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Abstract: Global warming is mainly triggered by growing CO_2 emissions, significantly jeopardizing environmental sustainability, economic stability, and human well-being worldwide. Emphasizing the EKC hypothesis, this study, using data from 1993–2020, exposes the intricate network of connections between Ghana's energy use patterns, economic growth trajectories, and CO_2 emissions. This paper extensively investigates these dynamic relationships utilizing advanced econometric techniques like the Autoregressive Distributed Lag (ARDL) model, Vector Error Correction Model (VECM), and Autoregressive Integrated Moving Average (ARIMA) models. The findings show a solid positive long-term connection between economic development and CO_2 emissions, aligning with the EKC hypothesis's first stage. Notably, by showing a significant short-term effect on reducing CO_2 emissions, the study emphasizes the possibility of using renewable energy to shift towards a low-carbon economy. The VECM results corroborate the long-term equilibrium link between economic expansion and CO_2 emissions, even if the ARIMA models indicate a continuous increase in emissions, emphasizing the urgent need for mitigation efforts. Because they stress the importance of promoting clean technologies, accelerating the usage of renewable energy, and promoting sustainable urbanization, the study's results have substantial policy implications. Ghana can manage these intricate problems and support attaining the Sustainable Development Goals and a greener and more sustainable future using a comprehensive policy framework.

Keywords: clean energy; EKC theory; low carbon; sustainable development; Ghana

1. Introduction

Climate change has emerged as a critical global issue in the 21st century. The main reason for global warming and its associated effects is an increasing concentration of greenhouse gases, mainly CO_2 [1–3]. The implications of ecological alteration, such as escalating sea levels, more frequent and more substantial life-threatening meteorological conditions, and ecosystem degradation, pose severe global challenges to human well-being, economic stability, and environmental sustainability [4,5]. The international community has realized the necessity of tackling climate change and has taken initiatives to lessen its impacts. The Paris Agreement, enacted in 2015, intends to enhance the inclusive rejoinder to ecological disruption by keeping the overall temperature rise well below 2 °C, thus over pre-industrial points and pursuing efforts to limit the surge to 1.5 °C [6]. States have committed to lowering greenhouse gas emissions and moving towards low-carbon economies [3,4,7].

However, the route to a low-carbon future is complex and diverse since it includes the interaction of numerous economic, social, and environmental elements. Economic growth (ECG), usually stated by Gross Domestic Product per capita, has been historically connected to rising energy use and CO_2 emissions [8]. As countries aim to enhance the living conditions of their inhabitants, they confront the difficulty of splitting up economic growth from CO_2 emissions [9].

Trade openness, which shows the integration of a country's economy into the global market, may also impact CO_2 emissions. On the one hand, more trade may lead to the transfer of cleaner technology and support the acceptance of environmental norms [10]. Conversely, trade liberalization may result in the movement of CO_2-intensive businesses to countries with less rigorous ecological rules [11,12]. Renewable energy consumption (REC) has become crucial for lowering CO_2 emissions and mitigating climate change. Countries may drastically decrease their CO_2 footprint by transitioning away from fossil fuels and near RECs like wind, solar, and hydropower [13]. In 2020, REC accounted for 29% of global power inventions, and its proportion is predicted to expand to 45% by 2040 under existing policies. The need for energy, transportation, and infrastructure develops as the world's inhabitants increasingly occupy capitals. Urban regions account for roughly 75% of global CO_2 emissions, mainly owing to the concentration of economic activity and energy consumption [14]. However, cities also provide the potential for integrating sustainable practices and technology, such as energy-efficient structures, public transportation systems, and waste management solutions [15]. In Ghana, the issues of balancing economic growth, sustainable development, and climate change mitigation are especially significant. Ghana's GDP per capita has gradually expanded over the last three decades, from $481 in 1990 to $2329 in 2020 [16]. This ECG has been accompanied by a rise in CO_2 emissions, which grew from 0.25 in 1990 to 0.54 metric tons per capita in 2018 [17]. Ghana has made initiatives to fight ecological change and promote sustainable development. Extracting natural assets like oil, gas, and minerals may also contribute to CO_2 emissions. The extraction and handling of these resources generally require energy-intensive operations and may underwrite deforestation and land degradation [18].

The nation has accepted the Paris Agreement and filed its Nationally Determined Contribution (NDC), which sets its obligations to lessen greenhouse gas emissions according to Government of Ghana report. Ghana's NDC seeks a 45% drop in CO_2 emissions by 2030 compared to business-as-usual scenarios, conditioned on international cooperation. Ghana has concentrated on increasing the percentage of REC in its energy mix. In 2020, renewable energy accounted for 42.5% of Ghana's total electricity output, with hydropower being the dominant source [1]. The government has also adopted lineups to encourage energy adeptness, such as the National Energy Efficiency Action Plan, which seeks to lower energy intensity by 20% by 2030. However, Ghana confronts hurdles in its transition to a low-carbon economy. The country's natural resource rents, notably from oil and gas exploitation, contributed 5.7% of its GDP [19]. The earnings gained from these resources might provide economic and political incentives to maintain their exploitation, thus impeding the adoption of cleaner energy alternatives [20]. Urbanization also plays a vital role in Ghana's CO_2 emissions trajectory. The country's urban population has increased fast, from 33.9% of the total population in 1990 to 57.3% in 2020 [16]. The growth of cities like Accra and Kumasi has increased energy consumption, traffic congestion, and garbage creation, increasing CO_2 emissions [21].

This work intends to contribute to this endeavor by analyzing the linkage between CO_2 and numerous economic energies in Ghana using the Autoregressive Distributed Lag (ARDL) model, Vector Error Correction Model (VECM), and Autoregressive Integrated Moving Average (ARIMA) models. By understanding the sources of CO_2 emissions in Ghana, policymakers may devise targeted policies to stimulate sustainable ECG, boost the espousal of renewable energy, regulate natural resource exploitation, and support sustainable urbanization. The outcomes of this research guide the design and implementation of climate change mitigation policies to contribute to Ghana's attempts to accomplish its NDC objectives and the global battle against ecological change. The study of CO_2 emissions and their relationship with economics and energy has produced noteworthy courtesy in modern ages due to the pressing need to address climate change and its probable bearing on social welfare, economic stability, and environmental sustainability. Despite the increasing amount of research on this topic, there remains a need for a complete indulgence of the complex relationship between these elements, especially in developing states like Ghana [22]. This paper intends to address this gap by analyzing the link between CO_2 emissions and numerous economic energies in Ghana using the ARDL and ARIMA models, as well as forecasting and testing the Environmental Kuznets Curve (EKC) theory in the context of Ghana. The motivation for this study derives from the conflicting findings of prior exploration [23–25] on the determinants of CO_2 emissions and the limited attention on emerging countries, notably in sub-Saharan Africa. By concentrating on Ghana, which has witnessed consistent ECG and increased CO_2 emissions in recent decades, this study intends to give significant insights into the glitches and potential for balancing economic change and ecological change extenuation.

The application of ARDL, which captures the relationship among the variables, and the ARIMA valuable model for forecasting approaches provide a greater understanding of the dynamic and diverse interactions between the variables of interest, which may guide the design and execution of targeted policies and interventions. This work adds to present-day works in various ways. It presents a detailed examination of the drivers of CO_2 emissions in Ghana, encompassing innumerable economic and energy factors. Second, applying sophisticated econometric approaches captures the dynamic and varied character of the interactions between these factors, which may give valuable insights for policymakers and scholars alike. The verdicts of this research may help implement climate change mitigation strategies in Ghana and other developing countries experiencing comparable difficulties, adding to the comprehensive efforts to fight ecological shifts and uphold sustainable development. This study establishes the basis for imminent research on the complicated interface among ECG, REC, and CO_2 emissions in developing nations. It underscores the significance of incorporating country-specific settings in studying these problems.

2. Review of related literature

2.1. Theoretical underpinning

EKC theory provides a framework for indulging the complicated interactions between ECG and ecological deterioration, especially in developing states like Ghana. The EKC hypothesis implies an inverted U-shaped link between ECG and environmental decline [26]. According to this theory, when a state's wealth level is nurtured, ecological degradation intensifies, but after reaching a specific threshold, continued ECG leads to decreased environmental deterioration. This is ascribed to causes such as growing demand for environmental quality, technological improvements, and the transition towards a more service-oriented economy [27]. The EKC theory has been widely explored in the context of CO_2 emissions, with varied findings [28,29]. We add to this discussion by reviewing the link between ECG and CO_2 emissions, considering developing economies, specifically Ghana. EKC theory offers a complete framework for understanding Ghana's CO_2 emissions bases. The outcomes of this research may guide the design and execution of policies aiming at promoting sustainable development and minimizing the concerns of ecological change in Ghana and other unindustrialized states experiencing comparable difficulties.

2.2. Hypothesis and empirical literature

2.2.1. Economic growth (ECG) and CO_2 emissions

ECG has been recognized as a primary generator of CO_2 emissions, and various research studies have studied the links between these factors [30]. The EKC theory recommends that as a state's wealth level grows, ecological deterioration, including CO_2 emissions, first increases but gradually reduces after reaching a specific threshold [31]. However, the empirical evidence supporting the EKC hypothesis is contradictory, with some research finding evidence of the inverted U-shaped association [32], while others deny the hypothesis [33]. The link between ECG and CO_2 emissions is complicated and may be impacted by several constructs, such as energy use, technological improvements, and governmental interventions. Zhou (2023) discovered that economic growth strongly influenced REC and CO_2 emissions, implying that as the economy develops, the request for energy increases, leading to increased emissions. Similarly, other studies discovered evidence of a unidirectional Granger causation flowing from GDP to REC and CO_2 emissions in Uganda, underscoring the significance of ECG in driving discharges [34].

The influence of ECG on CO_2 emissions might vary depending on the phase of economic development and the selected policies. The initiation that the bearing of ECG on CO_2 emissions is constructive for middle-income states but deleterious for high-income nations suggests that developed countries may have reached a point where further ECG can be decoupled from emissions through the espousal of cleaner technologies and policies [35]. The relevance of evaluating the energy mix and the percentage of REC in understanding the link between ECG and emissions [36]. Technological improvements and regulatory interventions may significantly minimize the upshot of ECG on CO_2 emissions. Energy innovation significantly deleteriously disturbs CO_2 emissions, indicating that investments in clean energy technology might help decouple economic growth from emissions [37]. Similarly, it was discovered that REC has a considerable deleterious effect on CO_2 emissions in the elongated term, showing the potential of clean energy to decrease emissions while sustaining economic growth [38].

Policy interventions, such as CO_2 pricing, renewable energy subsidies, and energy efficiency regulations, may also assist in minimizing the effect of ECG on emissions. CO_2 pricing may successfully cut emissions while having a modest impact on economic growth, mainly when the proceeds are recycled back into the economy [39]. Governmental support for REC is relevant in lowering emissions and reaching ecological ECG [40]. A few studies have studied the link between ECG and CO_2 emissions in Ghana. There is evidence of a long-run link among ECG, REC, and CO_2 emissions in Ghana, with economic growth having an enormous beneficial influence on emissions [41]. However, the report also underlines the effectiveness of renewable energy in minimizing the effect of economic growth on emissions. Although economic growth has a favorable impact on CO_2 emissions in Ghana, the bearing is different from other variables, such as energy use and trade openness [42]. To address the issues ECG presents on CO_2 emissions, Ghana has established several policies and programs to foster sustainable development and low-carbon growth. The National Climate Change Policy (NCCP) promotes a low-carbon economy by developing REC, energy adeptness, and ecological land use practices. Under the Paris Agreement, Ghana has also committed to decreasing its GHG by 15% from business-as-usual levels by 2030 [43]. However, the successful implementation of these regulations and the shift to a low-carbon economy would need substantial investments in clean energy technology, capacity development, and public awareness.

2.2.2. REC and CO_2 emissions

REC significantly minimizes CO_2 emissions and combats climate change [44]. As countries aim to switch to a low-carbon economy, using REC sources such as wind, solar, hydro, and biofuels has attracted significant attention [45]. Studies discovered the link between REC and CO_2 emissions, with the majority concluding that greater REC leads to decreased CO_2 emissions. The impact of REC on CO_2 emissions in 10 sub-Saharan African states was found to be a 1% surge in REC corresponds to a 0.11% reduction in CO_2 emissions [46]. REC had a substantial destructive effect on CO_2 emissions in 107 countries, with the impact being more considerable across low-income and lower-middle-income countries [47]. REC significantly affected CO_2 emissions in Algeria. The influence of REC use on CO_2 emissions may be ascribed to numerous variables [48]. First, renewable energy sources release little to no greenhouse gases during their operation, unlike fossil fuels, which are the principal source of CO_2 emissions [49]. Subsequently, using REC might lead to substituting fossil fuels in the energy mix, lowering total CO_2 [45]. Third, developing REC technology may lead to technical spillovers and the dissemination of clean technologies across industries and countries [50].

However, the link between REC and CO_2 emissions is not necessarily linear. It may be impacted by ECG, the amount of REC in the energy mix, and the availability of supporting laws and regulations. It is detected that the impact of REC on CO_2 emissions diverges between countries, with the effects being more significant in industrialized countries than in developing countries [51]. It is also observed that the outcome of REC on CO_2 emissions is contingent on the degree of wealth, with the impact being positive in low-income countries but deleterious in high-income countries [52]. To encourage the embracing of REC and decrease CO_2 emissions, countries have introduced different policies and measures such as feed-in tariffs, renewable portfolio requirements, and tax incentives [53]. In Ghana, the government has aimed to increase the REC percentage in the energy mix to 10% by 2030 [54]. The nation has also enacted various regulations to boost renewable energy production, such as the Renewable Energy Act and the Net Metering Scheme [55]. However, the adoption of REC in Ghana is still restricted, with renewable energy accounting for just 0.3% of the entire energy mix in 2018. REC has been demonstrated to have a considerable destructive influence on CO_2 emissions, with most research indicating that higher REC leads to decreased emissions [38]. However, the link between REC and CO_2 emissions is not necessarily linear. It may be impacted by variables such as the degree of ECG, the amount of renewable energy in the energy mix, and the availability of supporting laws and protocols. To hearten the adoption of REC and decrease CO_2 emissions, countries must enact inclusive plans and initiatives that remove the hurdles to REC and provide an enabling environment for investment and innovation.

3. Methodology

3.1. Sources of data

The paper seeks to discuss and forecast the impacts of economic growth (ECG) and renewable energy consumption (REC) on CO_2 emissions in Ghana using time series data from 1993 to 2020. This particular time frame was carefully chosen because it is convenient to attain data on the essential indicators. Numerical data for this study is obtained from the World Development Indicators [16]. The data is, therefore, highly reliable, and the analysis generated from it is dependable.

3.2. Variable and measurement

CO_2 emissions, an integral aspect of every modern economy's macroeconomic policy since the climate change and green growth campaign, are the explained variable. The World Bank characterizes CO_2 emissions as burning fossil fuels and manufacturing cement. Among them are CO_2 produced by solid, liquid, and gas fuels and the usage of gas flaring. This variable is measured annually in metric tons per capita. REC is indispensable to a holistic approach to achieving and sustaining economic well-being and hence is included as one of our explanatory variables. It is proxies that represent a percentage of total final energy consumption. Finally, GDP, viewed as the total economic or market assessment of all the finished goods and services formed within a state's borders in a precise period, captures economic growth (ECG). This macroeconomic variable is a vital pointer to the presentation of any economy globally. The unit of measurement is billion US dollars in 2015 prices.

3.3. Empirical framework

3.3.1. Descriptive analysis

The analytical aspect of the methodology begins with the descriptive analysis, which provides information about the main features of the variables, such as their measures of central tendency, variability, and distribution. These statistics are paramount to understanding the rudiments and general patterns of the data.

3.3.2. Unit root test

The Augmented Dickey-Fuller (ADF) test is conducted to check the level of stationarity and establish the order of integration for the ARIMA model [56]. The test is essential to determining whether or not a series has a unit root and, hence, its reliability when used in the analysis. The null hypothesis for the ADF assessment is that the variables have a unit root, and the alternate hypothesis is that the variable has no unit root. The various equations for all three variables, CO_2 emissions, REC, and ECG are given by.

For CO_2 emissions:

$$\Delta CO2_t = \alpha + \beta t + \gamma CO2_{t-1} + \sum_{i=1}^{\rho} \delta_i \, \Delta CO2_{t-i} + \varepsilon_t \ldots\ldots\ldots\ldots \quad (1)$$

For economic growth:

$$\Delta ECG_t = \alpha + \beta t + \gamma ECG_{t-1} + \sum_{i=1}^{\rho} \delta_i \, \Delta ECG_{t-i} + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

For renewable energy consumption:

$$\Delta REC_t = \alpha + \beta t + \gamma REC_{t-1} + \sum_{i=1}^{\rho} \delta_i \, \Delta REC_{t-i} + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The disturbance term, denoted as ε_t, captures unobserved factors.

3.3.3. Cointegration analysis and VECM model

The primary essence of cointegration scrutiny is to explore the long-run correlation surrounding the constructs under consideration. The Johansen cointegration test is preferred to the Engle-Granger. This is due to the ability of the Johansen test to perform more than one cointegrating relationship [57]. The choice is also made based on the outcome of the unit root test. This test provides values for the eigenvalues, trace statistics, and maximum eigenvalue statistics whose interpretation tells whether or not there is cointegration. The cointegration or long-run link necessitates using the Vector Error Correction Model (VECM). The VECM is necessary to capture the short-run and long-run dynamics among the constructs. The VECM equation is given below:

$$\begin{aligned}
\Delta CO2_t &= \prod\nolimits_1 CO2_{t-1} + \prod\nolimits_2 ECG_{t-1} + \prod\nolimits_3 REC_{t-1} + \Gamma_1 \Delta CO2_{t-1} + \Gamma_2 \Delta ECG_{t-1} + \Gamma_3 \Delta REC_{t-1} + \varepsilon_{1t} \\
\Delta ECG_t &= \Phi_1 CO2_{t-1} + \Phi_2 ECG_{t-1} + \Phi_3 REC_{t-1} + \Theta_1 \Delta CO2_{t-1} + \Theta_2 \Delta ECG_{t-1} + \Theta_3 \Delta REC_{t-1} + \varepsilon_{2t} \quad (4) \\
\Delta REC_t &= \Omega_1 CO2_{t-1} + \Omega_2 ECG_{t-1} + \Omega_3 REC_{t-1} + \Delta_1 \Delta CO2_{t-1} + \Delta_2 \Delta ECG_{t-1} + \Delta_3 \Delta REC_{t-1} + \varepsilon_{3t}
\end{aligned}$$

$$\Delta Y_t = \Pi \Delta Y_{t-1} + \sum_{i=1}^{\rho-1} \Gamma_i \Delta Y_{t-i} + \sum_{i=1}^{q} \Lambda_i \Delta X_{t-i} + \varepsilon_t \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (5)$$

where the error term is ε_t, the matrix of cointegrating vectors is Π, the vector of the differenced variables is ΔY_t, and the parameter matrices are Γ_i and Λ_i. That two-pronged strategy provides information on how the constructs coevolve over the long term and accounts for short-run alterations to departures from equilibrium, deepening our study.

Time series models

The study adopts ARIMA as the primary time series model technique to forecast the future values of our variables. The model was preferred due to its competency and effectiveness in forecasting time series variables and because the selected variables are not stationary at the level but have an order of integration. The forecast period will be the next eight years, thus up to 2030.

$$CO2_t = \mu + \emptyset_1 CO2_{t-1} + \emptyset_2 CO2_{t-2} + \cdots + \emptyset_P CO2_{t-p} + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t \ldots \ldots \quad (6)$$

The ARIMA model's autoregressive (AR) and moving average parts are fully captured in the equation for CO_2 emissions above. The AR component regresses the variable on its earlier figures to forecast future values, while the MA component uses past stochastic terms. In a suitable order of the AR (p) and MA (q) processes, we conduct the Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) analyses known as the Box and Jenkins [58,59].

Econometric model—ARDL

The ARDL is the econometric tool deployed to analyze the cointegrating link between the variables in our single equation model [60,61]. One potent and practical econometric method for time series data analysis is the ARDL, especially when cointegrating correlations between the variables are present. It discovers the potential short-run and long-run links between the variables. This model is specified as follows:

$$\Delta CO2_t = \alpha_0 + \sum_{i=1}^{n} \alpha_i \Delta ECG_{t-i} + \sum_{i=1}^{n} \beta_i \Delta REC_{t-i} + \varepsilon_t \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (7)$$

where:

$\Delta CO2_t$ denotes change in CO_2 emissions in period *t*.

ΔECG_{t-i} and ΔREC_{t-i} represent the corresponding changes in ECG and REC over the period $t - i$.

αi and βi represent the coefficients.

The symbol ε_t represents the residual term or the error term.

The current study clarifies the complex connections in the dataset in a certain way. The basis is laid by descriptive analysis, the data is guaranteed stable by unit root tests, long-term relationships are investigated by cointegration analysis, and time series models predict future values. The choice of the ARDL model is to deliver an inclusive investigation of the interactions among variables in different time horizons. Moreover, as the ARDL model methodically handles the mutual effect of variables, its treatment of potential endogeneity is crucial. Our analysis is strengthened by this multi-model approach, which also gives us a thorough grasp of the energy-ecological-economic connection in Ghana.

4. Empirical results

This segment provides the conclusions of our pragmatic analyses. These results are geared toward providing ample insight into the diverse relationships existing among CO_2 emissions, REC, and ECG in Ghana. This section also gives forecast values for each variable and diagnostic tests to confirm the credibility of the values obtained.

4.1. Descriptive analysis

This section provides the descriptive statistics for each of the constructs under consideration. Ghana has a mean value of 0.34 for CO_2 emissions, indicating that the country emits relatively lower emissions than heavily industrialized Europe. The variability value of 0.1376 shows that the values are not widely spread from the mean, indicating the possible absence of outliers or “extreme cases” of CO_2 emissions. The average value for renewable energy consumption is 61.57613, with a variability value of 14.60556. This statistic depicts that renewable energy is not a standard option in Ghana. All three variables’ distributions show a symmetrical nature. The kurtosis values for all three variables are positive but less than 3, depicting a platykurtic nature, implying lower values below the sample mean. Economic growth has a mean value of 31,300,000,000 and a variability value of 16,000,000,000. **Table 1** shows a report of the summary statistics.

Table 1. Descriptive statistics.

Descriptive Statistics	CO_2	ECG	REC
Mean	0.340091	3.13×10^{10}	61.57613
Std. Dev.	0.137611	1.60×10^{10}	14.60556
Skewness	0.258527	0.663155	0.082371
Kurtosis	1.879463	2.061118	1.506953
Jarque-Bera	1.967141	3.410768	2.914427
P-value	0.373973	0.181703	0.232884

4.2. Unit root analysis

We conducted the ADF test to test the stationarity of the variables and ascertain whether there is a unit root or otherwise. The test reveals that all constructs are non-stationary at level; hence, analysis conducted with it will not be reliable. Nonetheless, all variables become stationary after the first difference is taken. This is evident as the *p*-values are non-significant at the 5% significance level before taking the first difference. However, all constructs depict *p*-values less than the 5% significance level at the first difference. **Table 2** shows a summary of the unit root test outcomes. After establishing a stationary time series, we proceed with further analysis.

Table 2. Unit root results.

Variable	**ADF Statistic**	***P*-value**	**Stationarity**
CO_2	−1.988019	0.5814	Non-stationary
ECG	−2.935873	0.1696	Non-stationary
REC	−1.15311	0.9009	Non-stationary
CO_{2diff1}	−6.673763	0.000	Stationary
ECG_{diff1}	−4.158498	0.015	Stationary
REC_{diff1}	−5.023815	0.0019	Stationary

4.3. Johansen cointegration test

Since all variables are stationary at the first difference, we proceed to conduct a Johansen cointegration test to explore the potential long-run relationships among our constructs. This test gives metric figures for the eigenvalues, trace, and maximum-eigenvalue statistics. It is worth mentioning that this test was conducted using an optimal lag of 4, and the preferred information criteria used was the Akaike Information Criteria (AIC). The null hypothesis for the test is that there is no cointegration, while the alternate hypothesis is that cointegration exists. Results show two cointegration relationships between the constructs since the trace statistic value is more excellent than the 5% critical value. **Table 3** gives the metric values and their respective figures obtained from the test.

Table 3. Johansen cointegration test result.

Metric	**1st**	**2nd**	**3rd**
Eigenvalues	0.831703	0.503314	0.053914
Trace Statistic	65.96839	19.63568	1.440962
Max-Eigen Statistic	46.3327	18.19472	1.440962

4.4. Vector error correction model (VECM)

The outcome of the VECM is shown in **Table 4**. The statistically significant and favorable error correction term coefficient for economic growth is the main conclusion that these variables have a long-term equilibrium connection. The statistically insignificant error correction term coefficients for CO_2 emissions and renewable energy consumption (REC) do not express long-term equilibrium linkages with the other variables. The fact that none of the coefficients describing the short-run dynamics are statistically significant implies that the variables do not have appreciable short-term effects on one another. The *R*-squared and modified *R*-squared values indicate that the model fits very well, explaining around 63.92% and 41.37% of the variance in the dependent variables, respectively. These findings clarify the long-term equilibrium connection; further diagnostic procedures and residual analysis guarantee the accuracy and reliability of the model’s estimations. The economic and policy ramifications of the conclusions are also carefully considered in light of Ghana’s environmental and energy regulations.

Table 4. VECM results.

Variable	**Coefficient**	***T*-Statistic**
CO_{2diff1}	−0.139956	−0.66906
ECG_{diff1}	2.92×10^{10}	4.98391
REC_{diff1}	−4.410853	−0.33243
C	−0.013675	0.54311
D(CO2d1)	−0.261484	0.87141
D(ECGd1)	8.55×10^{-12}	1.30542
D(RECd1)	−0.006349	1.01315
R-squared	*R*-squared for the error correction equations	0.639202
Adjusted *R*-squared	Adjusted *R*-squared for the error correction equations	0.413703

4.5. ARIMA model results

When conducting unit root tests and creating the order of integration, we define the suitable order of (p) for the AR process and (q) for the MA process. Hence, we conduct the ACF and PACF plots to help select our preferred forecasting model. The results generated for CO_2 emissions show a potential model of ARIMA (2, 1, 2). Conducting a Ljung-Box Q statistic for this model reveals that the residuals are white noise. ARMA shows both covariance stationarity and invertibility. Likewise, the ACF and PACF plots for economic growth (ECG) and renewable energy consumption (REC) suggest an ARIMA (1, 1, 1) model for both variables. The ACF and PACF results for renewable energy (REC) reveal an ARIMA (1, 1, 1) model. Conducting diagnostic tests for the variables reveals white noise, and the ARMA model is both covariance stationary and invertible. These results provide the basis for forecasting with the models. From 1990 to 2020, Ghana's economic development (ECG), CO_2 emissions, and use of renewable energy (REC) have all been shown historically. While economic growth is more erratic, with phases of expansion and recession, there is a rising tendency in CO_2 emissions over time. The use of renewable energy is steady, varying around a consistent amount, as shown in **Figure 1**. The stationarity of the data may be determined by observing the graphs in **Figure 1**. Should the initial difference show stationary characteristics (no trend and constant variance), the original series is likely integrated of order 1 or I (1).

With ARIMA modeling, where the data must be rendered stationary by differencing, this information establishes the proper differencing sequence. Orders of the autoregressive (AR) and moving average (MA) components in ARIMA models are determined by the autocorrelation function (ACF) and partial autocorrelation function (PACF) plots, as seen in **Figure 2**. Whereas the PACF plot, **Figure 2** illustrates the partial link between a time series and its lagged values after adjusting for the intervening delays, the ACF plot reveals the correlation between a time series and its lagged values. The ACF and PACF graphs show the existence of second-order autoregressive and moving average components after obtaining the initial difference in the data. The table proposes an ARIMA (2, 1, 2) model for CO_2 emissions. The future paths of Ghana's CO_2 emissions, economic progress, and use of renewable energy have been insightfully shown using the ARIMA modeling method. Using an extensive and exacting analytical procedure, we have discovered strong ARIMA models that successfully reflect the underlying dynamics in the historical data. We propose an ARIMA (2, 1, 2) formulation for Ghanaian CO_2 emissions forecasting. With the initial difference in the emissions data, this model accounts for moving average and second-order autoregressive components. The reliability of the predictions is supported by the diagnostic tests, which show that the residuals have white noise characteristics and that the ARMA process meets stationarity and inevitability requirements. An ARIMA (1, 1, 1) model is the best specification for economic development. Having first differenced the economic growth data, this model adds moving average and first-order autoregressive components.

Similarly, an ARIMA (1, 1, 1) model is the best option for estimating Ghana's renewable energy consumption. Significantly, Ghana's energy security and environmental sustainability could look better according to the projections produced by these ARIMA models. For the next five years, the estimates show a steady increase in CO_2 emissions, which might exacerbate the nation's contribution to global ecological change. Simultaneously, the forecast volatility of economic growth with phases of expansion and contraction emphasizes the need for strong measures to support sustained development. Though the use of REC is expected to follow a very steady trend, the levels are still too low to counteract the anticipated rises in CO_2 emissions significantly. This result emphasizes how urgently Ghana must use its enormous potential for renewable energy (REC) to hasten its shift to a more diverse and sustainable energy mix. We have skillfully combined domain knowledge, policy insights, and other contextual elements unique to Ghana's energy and environmental situation to improve our forecasts' precision and practical applicability. The study's projections are guaranteed to be statistically sound and based on the subtleties and complexity of the nation's economic, social, and policy context. Furthermore, we have tested the predicting performance of our models on holdout samples and fresh data using extensive out-of-sample validation activities. This validation procedure offers an unbiased evaluation of the prediction power of our models but also allows us to make the essential changes or consider other modeling strategies if needed. Finally, our ARIMA modeling study provides a thorough and trustworthy basis for estimating Ghana's CO_2 emissions, ECG, and REC. The results emphasize how urgently coordinated actions are needed to support sustainable economic growth, quicken the switch to REC, and implement efficient laws to lessen the adverse effects of CO_2 emissions on the atmosphere and human well-being. **Table 5** shows the ARIMA model coefficient and statistics and **Table 6** shows ARIMA forecasts.

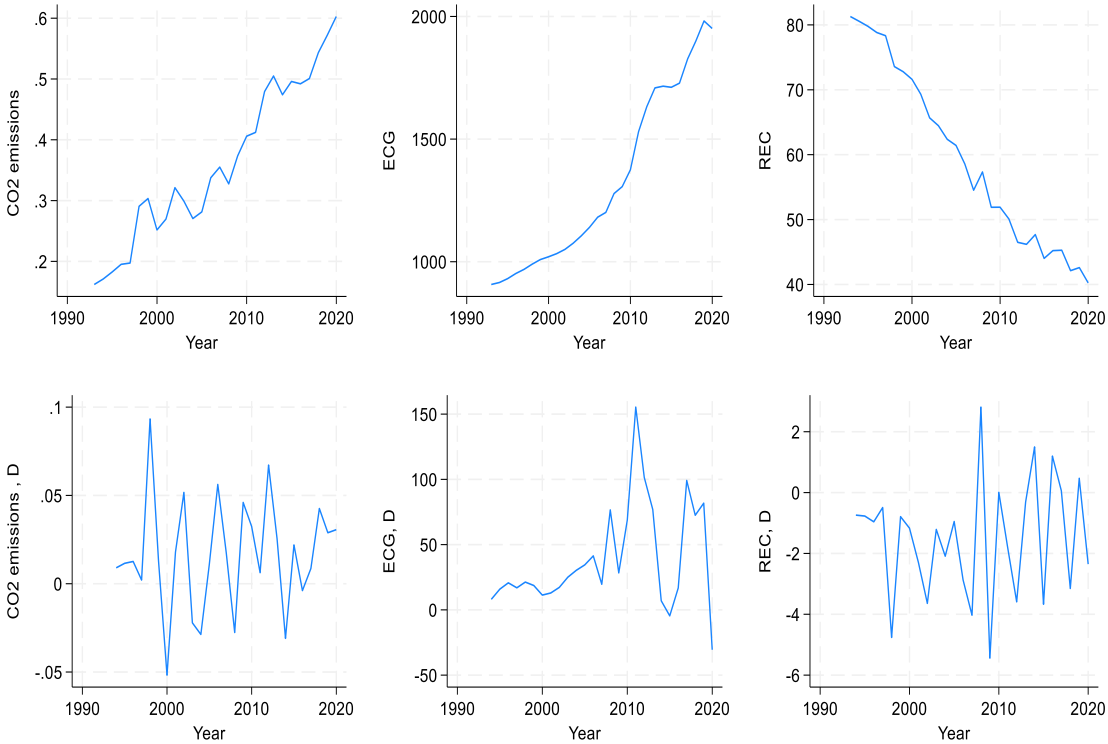

Figure 1. Stationary and non-stationary time series data.

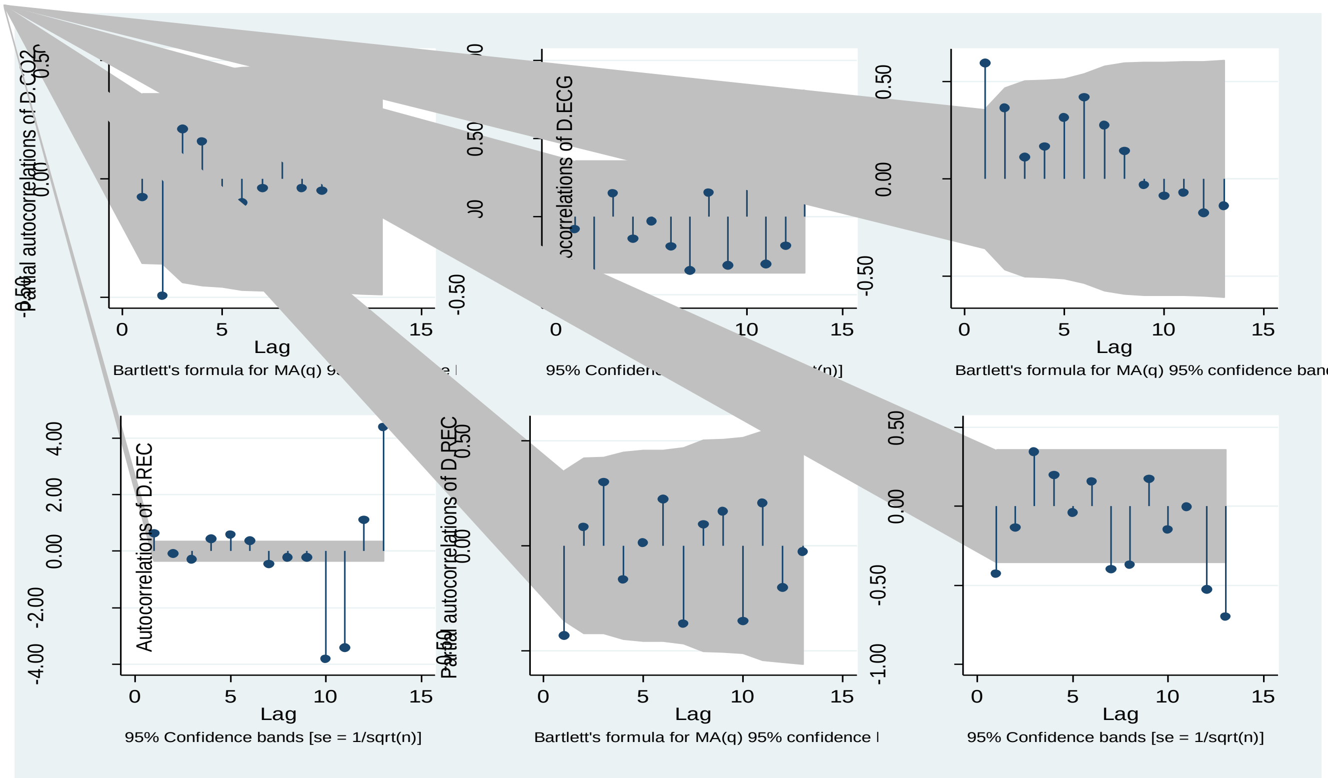

Figure 2. ACF and PACF analysis for differenced variables.

Table 5. ARIMA model coefficient and statistics.

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.
CO_2 emissions				
C	0.014651	0.00303	4.835939	0.0001
AR (2)	−0.241571	0.372548	−0.648428	0.5224
MA (2)	−0.377611	0.402238	−0.938776	0.3565
SIGMASQ	0.000672	0.000176	3.821172	0.0007
Economic growth				
C	1.55×10^9	8.92×10^8	1.733283	0.0949
AR (1)	0.574412	0.447962	1.282279	0.2111
MA (1)	0.066323	0.496557	0.133566	0.8948
SIGMASQ	9.72×10^{17}	2.96×10^{17}	3.287099	0.0029
Renewable energy consumption				
C	−1.380496	0.219423	−6.291491	0
AR (1)	−0.383339	0.460202	−0.832982	0.4124
MA (1)	−0.116343	0.513075	−0.226756	0.8224
SIGMASQ	3.095339	1.070934	2.890318	0.0077

Table 6. ARIMA forecasts.

Variables	Forecasted Values
	2021: 0.006205498
	2022: 0.000690593
CO_{2diff1}	2023: 0.016690792
	2024: 0.018023032
	2025: 0.014157851
	2021: 669361845.8
	2022: 1042371659
ECG_{diff1}	2023: 1256632831
	2024: 1379706939
	2025: 1450402137
	2021: 39.25698989
	2022: 37.72795563
REC_{diff1}	2023: 36.40440059
	2024: 35.00207726
	2025: 33.62994892

4.6. ARDL model

The econometric model provides an output on the link among the constructs. The ADF unit root test to check the stationarity level is the ARDL model's primal procedure, followed by an optimal lag selection and a cointegration test to define the long-run connection between variables. Ample diagnostic tests were conducted to check the dependability of the effects obtained. The ARCH test with a *p*-value of 0.9818 shows that the regression results are void of heteroscedasticity. Likewise, the

Breusch-Pagan test (0.3742) confirms that the output is homoscedastic. The Breusch-Godfrey LM test and the Correlogram of residuals test showed no serial correlation. Also, a Jarque-Bera normality test points out the normality of the results. The Ramsey RESET test shows values greater than 5% significance level, indicating that the model is well specified. The level of multicollinearity is negligible. The *R*-squared and Adjusted *R*-squared values, as depicted in the table, are 0.988642 and 0.986173, respectively, indicating that variations in CO_2 emissions are explained mainly by ECG and REC. The *F*-statistic is 400.4049, which shows the overall significance of the model. We show the results of the ARDL regression with output on the coefficients, standard error, *t*-statistic, and probability value, among others. **Table 7** shows ARDL model results.

Table 7. ARDL model results.

Variable	Coefficient	Std. Error	*t*-Statistic	Prob.*
CO_2 (−1)	0.375631	0.120667	3.11296	0.0049
ECG	5.22×10^{-12}	8.75×10^{-13}	5.966548	0.0000
REC	−0.013086	0.001769	−7.39763	0.0000
REC (−1)	0.004546	0.002016	2.255093	0.0339
REC (−2)	0.008334	0.001925	4.330378	0.0002
C	0.03913	0.082756	0.472836	0.6408
R-squared	0.988642	Mean dependent var	0.353014	
Adjusted *R*-squared	0.986173	S.D. dependent var	0.132668	
S.E. of regression	0.0156	Akaike info criterion	−5.301076	
Sum squared resid	0.005597	Schwarz criterion	−5.018188	
Log likelihood	82.86561	Hannan-Quinn criteria.	−5.212479	
F-statistic	400.4049	Durbin-Watson stat	1.917852	
Prob (*F*-statistic)	0.000			

* Shows < 1% Significant level.

Long- and short-term links among ECG, CO_2 emissions, and REC are explored using the ARDL model. This suggests a remarkable long-term beneficial association between CO_2 emissions and ECG. More specifically, the statistically significant coefficient of ECG (5.22×10^{-12}) shows that long-term faster economic development is supplementary with higher CO_2 emissions. In the future, the model demonstrates that utilizing renewable energy increases CO_2 emissions. Significant and negative coefficients of REC and its delayed values REC (−1) and REC (−2) show that increasing the utilization of renewable energy sources may short-term cut CO_2 emissions. Changes in emissions may take some time to emerge, as the positive and significant coefficient of CO_2 (−1) (0.375631) suggests that CO_2 emissions exhibit persistence or inertia in the short future. The model fits pretty well with an *R*-squared value of 0.988642; it explains around 98.86% of the dependent variable (CO_2) variation. The *F*-statistic (400.4049) and the probability (Prob(*F*-statistic) = 0.0000) that go along with it also demonstrate that the model is statistically significant overall. Furthermore, the residuals have no considerable autocorrelation within the permissible range, as evidenced by the Durbin-Watson statistic (1.917852). According to the

ARDL model results, increasing usage of REC may aid in cutting emissions in the short term, even if economic expansion eventually contributes positively to CO_2 emissions. Diagnostics of the model indicate a firm fit and adherence to essential assumptions. Assuming a nonlinear connection between ECG and environmental decline, the analysis of the EKC hypothesis in an era of more complex ARDL models. Environmental degradation may be experienced as countries' economies grow because they are driven by increasing industrial production and higher requirements for energy. On the contrary, it is viewed that after reaching a certain level in terms of per capita ECG, society starts paying more attention to environmental issues, and there are regulations or technologies aimed at mitigating the adverse impacts. These include social and economic aspects that occur simultaneously in all societies worldwide as people, among other things, earn an income and develop a system simultaneously. However, **Figure 3** below illustrates the EKC curve, which shows both phase's stationary and nonstationary on economic growth versus environmental quality dimensions. The EKC connection can be examined further through polynomial regression analysis or similar techniques. The research findings from the EKC theory are essential for reconciling economic growth with environmental sustainability in Ghana.

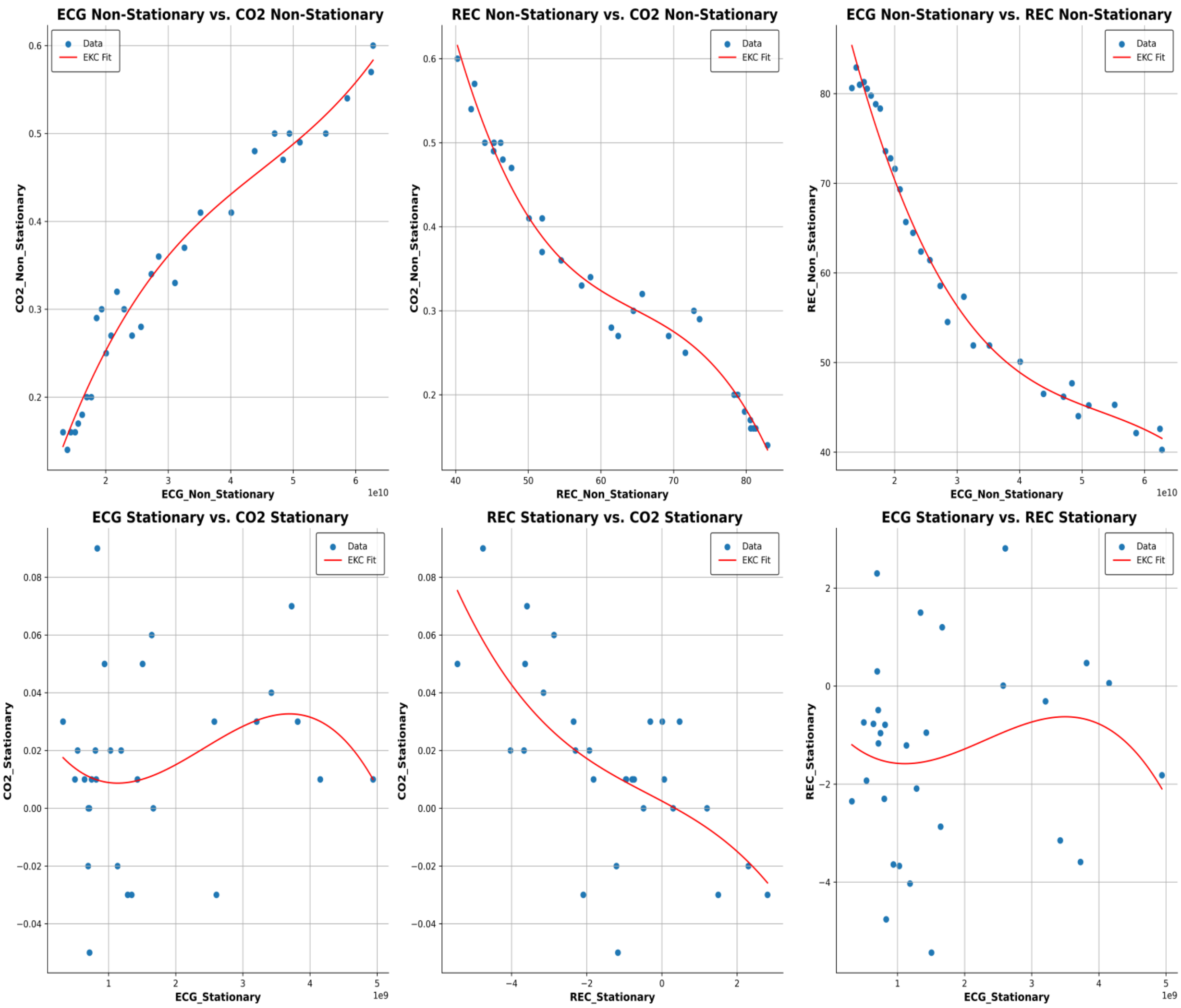

Figure 3. EKC curve stationary and non-stationary.

5. Discussion

The research findings provide substantial fresh perspectives into the complex interplay between ECG, REC, CO_2 emissions, and other pertinent aspects in Ghana's quest for sustainable development. Empirical analyses thoroughly comprehend these variables dynamic relationships and future trajectories using various econometric techniques, such as ARDL, VECM, and ARIMA models. One of the primary outcomes of the ARDL model is the noteworthy long-term positive link between CO_2 and ECG in Ghana [28,62,63]. This outcome aligns with the first stage of the EKC hypothesis, which holds that ecological degradation, in this case, CO_2 emissions, tends to increase before a country's GDP [26]. Particularly in developing countries like Ghana, this inclination is explicated by the proliferation of energy consumption and industrial activities accompanying economic expansion. However, the EKC hypothesis contends that, after a while, continuous economic growth results in the lessening of environmental degradation due to factors including growing public awareness, new technology, and legislative initiatives [37]. Furthermore, shown by the ARDL model, results show a significant short-term bearing of adopting REC on reducing CO_2 emissions in Ghana, aligning with prior studies by [64]. More REC may lower short-term CO_2 emissions, based on the lagged data and negative, statistically significant coefficients of REC. This conclusion underlines the viability of REC as a practical means of preserving economic growth while transitioning to a low-carbon economy. Nevertheless, the delayed CO_2 emissions variable's vivacious and significant coefficient suggests that CO_2 emissions are slow or persistent, which means that emission changes could not occur immediately.

Further evidence from the VECM results of the long-term equilibrium between ECG and CO_2 is the statistically significant error correction term coefficient for economic growth. Still, the small error correction term coefficients for CO_2 emissions and REC demonstrate that long-term equilibrium links with the other variables are absent. Moreover, from the lack of statistically significant coefficients describing the short-term dynamics, the variables have minimal short-term impact on one another. The ARIMA models provide Ghana with realistic estimates of its economic growth, CO_2 emissions, and utilization of REC. The predicted surges in CO_2 emissions throughout the following years highlight the urgent need for concerted action to lower emissions and address the bearings of ecological change [21,38]. Concurrently, the requirement for robust policies to support long-term economic development is highlighted by the anticipated unpredictable nature of economic growth, with phases of expansion and recession. Furthermore, even if the projected numbers for renewable energy consumption are somewhat modest, Ghana must take advantage of its enormous REC potential to accelerate the switch to a more diverse and viable energy mix. Stakeholders and decision-makers in Ghana's pursuit of sustainable development and climate change mitigation would find great value in the study findings. The affirmative long-term association between ECG and CO_2 emissions emphasizes the need for an all-encompassing strategy that balances economic objectives with environmental sustainability. Separating economic growth from increasingly poor environmental circumstances requires policies to uphold energy adeptness, the move to a low-carbon economy, and clean machinery. Moreover, the demonstration of the immediate bearing of utilizing REC on reducing CO_2 emissions highlights the need for Ghana to use REC sooner rather than later. Incentives, subsidies, and regulatory frameworks for renewable energy may help promote such technologies' development and use [48]. Moreover, reserves in the renewable energy sector's research and development and capacity building support Ghana's conversion to a more sustainable energy mix. Understanding the possible trials and concessions allied with pursuing sustainable development and slowing down climate change is critical.

The anticipated volatility of ECG shows the need to implement plans that stabilize environmental protection with economic stability. The goals of successful policies should include green development, job creation in sustainable industries, and resilience to economic shocks. The findings also stress the urgency of addressing the issue of natural resource exploitation and its potential impact on CO_2 emissions. While Ghana gains economically from its abundant natural resources, most notably gas and oil, the environmental effects, especially those associated with CO_2 emissions, must be appropriately managed. Policies promoting environmental control, sustainable natural resource management, and switching to Renewable Energy Consumption (REC) are necessary to lessen the destructive environmental consequences of resource exploitation [36,38]. Lastly, the study results emphasize how crucial urban planning and sustainable urbanization are to lowering CO_2 emissions. Reduced CO_2 footprint of cities and help overall efforts to decrease emissions as Ghana's urban population rises may be achieved by policies that promote energy-efficient infrastructure, compact and sustainable urban development, and sustainable mobility alternatives. The study's findings demonstrate how closely economic growth, energy use patterns, and Ghana's CO_2 emissions interact. Even as economic growth is a necessary component of development, a comprehensive legal framework that promotes using renewable energy, sustainable practices, and effective management of natural resources must strictly regulate its environmental consequences. Ghana can support global efforts to slow weather change and help conquer the SDGs by resolving these intricate problems.

6. Conclusion

This paper focused on the EKC hypothesis to understand an intricate connections network between Ghana's CO_2 emissions, ECG trajectories, and REC patterns. The research thoroughly examines the dynamic interactions among these variables using advanced econometric techniques, including the ARDL, VECM, and ARIMA models. The findings confirm a notable positive long-term link between economic growth and CO_2 emissions in Ghana, which aligns with the first stage of the EKC theory. Often, as the country's economy expands, so do industrial activity, energy use, and CO_2 emissions. However, the EKC hypothesis argues that, outside a limit, additional ECG may, driven by factors like increased public awareness, new technology, and legislative acts, slow down the degradation of the environment. Notably, the study indicates a significant immediate impact of Ghana's use of REC on reducing CO_2 emissions. The deleterious and statistically momentous coefficients associated with REC and its lagged values recommend that utilizing more REC sources may lower short-term CO_2 emissions. This conclusion underlines the viability of renewable energy as a practical means of preserving economic growth while shifting to a low-carbon economy. Although the VECM results further validate the long-term symmetry link between ECG and CO_2 emissions, the ARIMA models provide insightful predictions for these variables. The expected data highlights how urgently concerted actions to lower emissions and address the effects of ecological change are required since CO_2 emissions will probably increase significantly in the coming years. Simultaneously, Ghana's need to fully exploit its enormous potential for renewable energy is highlighted by the projected values for renewable energy consumption, which, although exhibiting a steady trend, are relatively low, and the projected volatility of economic growth emphasizes the need for strong policies to support long-term economic growth.

The findings will affect Ghana's policy pursuit of sustainable change and climate change extenuation. A strategy harmonizing economic objectives with environmental sustainability requires policy measures to assist clean technologies, energy efficiency, and a shift to a low-carbon society. Furthermore, using REC technologies must be accelerated using subsidies, incentives, and regulatory frameworks. Successful initiatives should also promote green growth, employment creation in sustainable industries, and resilience to economic downturns while addressing the potential trade-offs between environmental preservation and economic stability. The issue of natural resource mining and its consequences on CO_2 emissions has to be carefully managed via legislation that promotes environmental regulation, sustainable natural resource management, and the conversion to greener energy sources. Finally, the paper emphasizes the significance of urban planning and sustainable urbanization in lowering CO_2 emissions. Reducing the CO_2 footprint of cities and promoting general efforts to cut emissions as Ghana's urban population increases may be achieved mainly by policies that promote energy-efficient infrastructure, compact and sustainable urban development, and sustainable mobility alternatives. Ultimately, this report provides a thorough understanding of the complex relationships among Ghana's ECG, REC patterns, and CO_2 emissions for policymakers and other interested parties. Ghana can handle complicated difficulties and assist the world in lowering ecological change and realizing SDGs by utilizing a comprehensive policy framework that promotes renewable energy, sustainable behaviors, and effective management of natural resources.

6.1. Policy direction

There must be a multifaceted approach to the intricate network of problems linked to economic growth, CO_2 emissions, and energy usage problems. Starting with this, promoting sustainable and clean economic growth options is essential. Policies should separate overly high CO_2 emissions and environmental harm from ECG. Encouraging all sectors to use clean technologies, energy efficiency measures, and sustainable industrial practices is crucial. Moreover, encouraging environmentally friendly businesses, generating employment in sustainable industries, and providing funds for clean infrastructure might facilitate a smooth shift to a low-carbon future. Secondly, expediting the transition to REC must be one of the top policy goals. Enhancing regulation and incentive schemes is essential to encourage the usage of renewable energy sources like solar, wind, and hydropower. To further incentivize individuals, businesses, and utilities to move to renewable energy sources are tax cuts, subsidies, and preferential financing options. Financing research and development may also upsurge the effectiveness and cost of REC systems, encouraging innovation and technological advancement. Thirdly, better management of natural resources and environmental legislation is necessary. Comprehensive laws ensuring that environmental aspects are considered in resource exploitation activities are essential for the sustainable extraction of natural resources. As such, strengthening environmental regulations and enforcement processes might minimize the bearing of resource extraction on CO_2 and ecological deprivation. Concurrently, it is equally important to look at substitutes to fossil fuels for energy and promote the change in resource extraction techniques to more environmentally friendly ones.

Fourth, a key policy strategy is to promote sustainable urbanization and urban planning. Urban planning regulations that give energy-efficient buildings, sustainable transportation alternatives, and the priority of compact and sustainable urban development must be developed and implemented. Funding the development of bus rapid transit systems and other public transportation infrastructure, as well as promoting the usage of electric and hybrid vehicles, may also help to lower urban emissions. Promoting the use of green spaces, urban trees, and sustainable urban drainage systems may help reduce the urban heat island effect and boost CO_2 sequestration. Fifthly, it is essential to increase international collaboration and technology transfer. Encouraging sustainable development and limiting climate change may be simpler by participating in global cooperation and knowledge-sharing initiatives. Ghana may also benefit from facilitating programs for technology transfer and capacity building. Furthermore, aligning national policies with international commitments and objectives and participating in inclusive determinations to halt ecological change, such as the Paris Agreement, is essential. Sixthly, public awareness and stakeholder participation must be increased. Putting public awareness and education programs into place to promote sustainable lifestyles, responsible resource use, and energy conservation may contribute to developing a sustainable mindset among people. Promoted public-private partnerships and stakeholder engagement may encourage collaboration and collaborative efforts toward sustainable development objectives. Moreover, it is essential to include local people, civil society organizations, and indigenous groups in the policymaking processes related to environmental legislation and sustainable development initiatives. Ultimately, improving institutional capacity and governance is an essential policy option. Enhancing the capacities of relevant government agencies and groups in charge of implementing and monitoring environmental legislation and sustainable development initiatives is critical. As such, it is vital to ensure transparency, accountability, and effective collaboration across different governmental levels and interested parties throughout the formulation and implementation of policies. Moreover, investing in data collection, monitoring, and evaluation tools enables one to monitor changes, assess policies, and make well-informed decisions backed by accurate data. Ghana can effectively handle the intricate web of problems related to energy use, CO_2 emissions, and economic development if these broad policy recommendations are coordinated and long-term. This will facilitate a low-carbon, sustainable future and back global initiatives to relax ecological change and accomplish the SDGs.

6.2. Limitations and suggestions for future studies

The critical limitation of this study is that it deals only with macroeconomic indicators and the test of the EKC in the Ghanaian context, thus allowing further research in environmental sustainability and quantitative dimensions. While the findings shed light on the economic resilience of Ghana's sustainability issues, the investigation could be extended to other developing countries or variables of interest to foster generalization and depth of understanding. Future research may want to consider the long-term implications of pandemic-induced policies to make strategic recommendations toward sustainable development and ecological progress.

Author contributions: Conceptualization, MPF; methodology, GMS and MPF; software, SAB and KDM; validation, JW, MPF and KDM; formal analysis, MPF; investigation, SAB; resources, JW; data curation, MPF; writing—original draft preparation, KDM and MPF; writing—review and editing, JW and SAW; visualization, GMS; supervision, JW; project administration, KDM. All authors have read and agreed to the published version of the manuscript.

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