Integrating Economic Growth, Energy Consumption, and Trade Openness in CO_2 Emissions Modeling: A Comprehensive Study of South Africa's Environmental Sustainability Challenges

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Abstract

This study investigates the dynamics of CO_2 emissions in South Africa by employing the Autoregressive Distributed Lag (ARDL) bounds testing approach combined with wavelet coherence analysis. The empirical results confirm the presence of a long-run cointegration relationship between CO_2 emissions, economic growth, energy consumption, trade openness, and renewable energy adoption. Consistent with the Environmental Kuznets Curve (EKC) hypothesis, economic growth initially increases emissions, but after reaching a threshold, further growth leads to a decline in emissions. Energy consumption and trade openness positively influence CO_2 emissions, whereas renewable energy consumption exerts a significant mitigating effect. The error correction term indicates a stable long-run equilibrium with a rapid adjustment speed. Wavelet coherence analysis reveals intricate time-frequency interdependencies among the variables, underscoring the temporal variability of their relationships. The findings highlight the necessity for integrated policies that promote sustainable economic growth, enhance renewable energy utilization, and incorporate environmental standards into trade frameworks. This study contributes to the literature by providing comprehensive temporal and frequency domain insights into South Africa's emissions trajectory, offering practical implications for achieving sustainable development goals.

Keywords: CO_2 Emissions, Economic Growth, Environmental Kuznets Curve, Renewable Energy, Trade Openness, ARDL Bounds Testing

1. Introduction

The persistent rise in global carbon dioxide (CO_2) emissions has become a critical challenge for environmental sustainability and climate change mitigation. South Africa, as one of the largest emerging economies on the African continent, significantly contributes to global CO_2 emissions

due to its heavy reliance on coal-based energy production and industrial activities (Hiraldo & Maroto-Valer, 2020). Understanding the dynamics and determinants of CO_2 emissions within the South African context is imperative for formulating effective environmental policies that align with global climate commitments such as the Paris Agreement (United Nations, 2015).

Recent empirical studies have increasingly employed advanced econometric techniques to capture the complex temporal relationships between economic growth, energy consumption, and environmental degradation. Among these, the Autoregressive Distributed Lag (ARDL) bounds testing analysis have gained prominence due to their robustness in examining both short- and long-run cointegration relationships and localized time-frequency dynamics (Akinwale et al., 2022; Mbatha & Adeleke, 2023). The ARDL method is particularly suitable for small sample sizes and mixed integration orders of variables.

Despite substantial research on CO_2 emissions globally, South Africa's unique economic structure, policy environment, and energy profile necessitate country-specific analysis. The literature suggests that economic growth in South Africa exhibits a nonlinear relationship with CO_2 emissions, potentially validating the Environmental Kuznets Curve (EKC) hypothesis in this setting (Ngaruko et al., 2019). Furthermore, renewable energy adoption remains low, and fossil fuel dependency remains high, complicating efforts to decouple economic development from environmental harm (Chala et al., 2021).

Accordingly, this study formulates and empirically tests the following hypotheses:
H1: There exists a long-run cointegration relationship between CO_2 emissions, economic growth, energy consumption, and trade openness in South Africa.
H2: The relationship between economic growth and CO_2 emissions exhibits nonlinear characteristics consistent with the Environmental Kuznets Curve hypothesis.
H3: Renewable energy consumption negatively impacts CO_2 emissions in the short and long run.

The study contributes to the extant literature by providing a comprehensive empirical examination of the temporal and frequency domain dynamics influencing CO_2 emissions in South Africa. The findings aim to inform policymakers on optimizing energy and environmental strategies to achieve sustainable development goals.

2. Methodology

This study employs annual time-series data covering the period from 1990 to 2022 for South Africa, chosen to capture long-term trends and recent dynamics in CO_2 emissions alongside economic and energy variables. The variables include CO_2 emissions (measured in metric tons), real gross domestic product (GDP) to represent economic growth, total energy consumption disaggregated by energy sources, and trade openness (measured as the sum of exports and imports as a percentage of GDP). Renewable energy consumption is included to capture the effect of clean energy deployment on emissions. The selection of these variables aligns with established literature investigating the drivers of emissions (Moyo et al., 2023; Kanayo et al., 2025). Data are sourced primarily from the World Bank's World Development Indicators (WDI), the International Energy Agency (IEA), and South Africa's Department of Energy publications, ensuring data reliability and comparability. The temporal coverage balances data availability with the need for sufficient observations to conduct robust econometric analyses.

The core of this study's empirical investigation relies on modeling the relationship between CO_2 emissions and key explanatory variables including economic growth, energy consumption, trade openness, and renewable energy use. The primary model is specified as:

$$\ln CO_{2t} = \alpha_0 + \alpha_1 \ln GDP_t + \alpha_2 (\ln GDP_t)^2 + \alpha_3 \ln EC_t + \alpha_4 \ln TO_t + \alpha_5 \ln RE_t + \varepsilon_t \quad (1)$$

where CO_{2t} denotes carbon dioxide emissions at time t, GDP_t is real GDP, EC_t is total energy consumption, TO_t represents trade openness, RE_t stands for renewable energy consumption, and ε_t is the error term. The inclusion of the quadratic term $(\ln GDP_t)^2$ allows for testing the Environmental Kuznets Curve (EKC) hypothesis, which suggests a nonlinear relationship between economic growth and emissions (Grossman & Krueger, 1995).

To capture potential short- and long-run dynamics and cointegration relationships, the Autoregressive Distributed Lag (ARDL) model is employed. The ARDL specification based on equation (1) is expressed as:

$$\Delta \ln CO_{2t} = \beta_0 + \sum_{i=1}^{p} \beta_{1i} \Delta \ln CO_{2,t-i} + \sum_{i=0}^{q} \beta_{2i} \Delta \ln GDP_{t-i} + \sum_{i=0}^{q} \beta_{3i} \Delta (\ln GDP_{t-i})^2 + \sum_{i=0}^{q} \beta_{4i} \Delta \ln EC_{t-i} + \sum_{i=0}^{q} \beta_{5i} \Delta \ln TO_{t-i} + \sum_{i=0}^{q} \beta_{6i} \Delta \ln RE_{t-i} + \phi_1 \ln CO_{2,t-1} + \phi_2 \ln GDP_{t-1} + \phi_3 (\ln GDP_{t-1})^2 + \phi_4 \ln EC_{t-1} + \phi_5 \ln TO_{t-1} + \phi_6 \ln RE_{t-1} + \varepsilon_t \quad (2)$$

Here, Δ denotes the first difference operator, p and q are optimal lag lengths selected based on information criteria, and the terms with summations capture short-run dynamics, while the

coefficients ϕ_i represent long-run relationships. The bounds testing procedure associated with the ARDL framework allows us to assess the existence of a long-run cointegration relationship among the variables, irrespective of their integration order (I(0) or I(1)) (Pesaran et al., 2001).

To test for potential asymmetric effects in energy consumption and economic growth on emissions, a Nonlinear ARDL (NARDL) model is estimated as a robustness check. This model decomposes explanatory variables into positive and negative partial sums, allowing separate estimation of their impacts (Shin et al., 2014). For instance, the positive and negative partial sums of energy consumption are defined as:

$$EC_t^+ = \sum_{j=1}^{t} \Delta EC_j^+ = \sum_{j=1}^{t} \max(\Delta EC_j, 0), \quad EC_t^- = \sum_{j=1}^{t} \Delta EC_j^- = \sum_{j=1}^{t} \min(\Delta EC_j, 0) \quad (3)$$

Incorporating these into the ARDL framework allows testing whether increases and decreases in energy consumption have asymmetric effects on CO_2 emissions.

The ARDL bounds testing approach is chosen for its flexibility in handling variables integrated of order zero or one (Pesaran et al., 2001). This method is well-suited for small to moderate sample sizes, making it appropriate for annual data spanning 1990–2023. The initial step involves unit root tests using Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to ensure no variable is integrated of order two or higher, which would invalidate ARDL assumptions (Dickey & Fuller, 1979; Phillips & Perron, 1988).

Following stationarity verification, the bounds test assesses the existence of long-run cointegration among the variables by testing the joint significance of lagged level variables in the error correction form. The critical values for the bounds test account for the mixed integration orders of the regressors. Upon confirming cointegration, long-run and short-run coefficients are estimated from equation (2), with the error correction term's coefficient expected to be negative and significant, indicating the speed of adjustment toward equilibrium after shocks.

To address potential nonlinearities, the NARDL model is estimated as a sensitivity check to capture asymmetric impacts of positive and negative changes in key variables such as energy consumption and economic growth on CO_2 emissions (Shin et al., 2014). Model specification diagnostics, including tests for serial correlation, heteroskedasticity, and model stability using CUSUM and CUSUMSQ tests, are conducted to ensure robustness (Brown et al., 1975).

Additional robustness checks involve estimating the model using alternative cointegration techniques such as Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary

Least Squares (DOLS), which correct for endogeneity and serial correlation (Phillips & Hansen, 1990; Saikkonen, 1991). These confirm the consistency of the ARDL findings and reinforce the reliability of policy conclusions drawn from the study.

Table 1: Variable Definitions and Data Sources

Variable	Description	Unit / Measurement	Data Source
CO_2	Carbon dioxide emissions	Metric tons	World Bank WDI, IEA
GDP	Real Gross Domestic Product	Constant 2015 USD	World Bank WDI
EC	Total energy consumption	Kilotons of oil equivalent (ktoe)	International Energy Agency (IEA)
TO	Trade openness (exports + imports / GDP)	Percentage (%)	World Bank WDI
RE	Renewable energy consumption	Kilotons of oil equivalent (ktoe)	South Africa Department of Energy

Source: Author

3. Results

The empirical investigation begins with the examination of the correlation matrix presented in Table 2, which provides initial insights into the bivariate relationships among the variables under study. The matrix reveals a strong positive correlation between CO_2 emissions and GDP (0.802), indicating that economic growth in South Africa is closely associated with increased emissions. This relationship aligns with prior findings in emerging economies where growth often entails heightened industrial activity and energy consumption (Akinwale et al., 2022). Similarly, energy consumption exhibits a high positive correlation with CO_2 emissions (0.831), affirming the critical role of fossil fuel-based energy in driving environmental degradation (Mbatha & Adeleke, 2023). Notably, trade openness shows a moderate positive correlation with CO_2 emissions (0.458), suggesting that international trade activities may contribute to emissions, possibly due to export-oriented industries or transportation emissions (Chala et al., 2021). Conversely, renewable energy consumption is negatively correlated with CO_2 emissions (-0.521), which supports the hypothesis that renewable energy adoption can mitigate environmental harm by substituting fossil fuels (Hiraldo & Maroto-Valer, 2020).

Moving to Table 3, the ADF test results provide essential diagnostics on the stationarity properties of the series, a prerequisite for cointegration analysis using the ARDL framework. The findings indicate that most variables, including CO_2 emissions, GDP, GDP^2, energy consumption, and renewable energy, are non-stationary at levels but become stationary after first

differencing, thus classified as integrated of order one, I(1). Trade openness, however, is stationary at levels, I(0). This mixture of integration orders confirms the appropriateness of the ARDL bounds testing approach, which accommodates variables integrated at I(0) and I(1) without requiring uniform order of integration (Pesaran et al., 2001). The statistical significance of the ADF statistics for CO_2 emissions (-3.612, p=0.023) and renewable energy supports their stationarity after differencing.

Table 4 summarizes the estimation results from the ARDL model, which quantifies the long-run elasticities of CO_2 emissions with respect to its determinants. The coefficient for the natural logarithm of GDP (ln GDP) is positive and statistically significant, while the coefficient for ln GDP^2 is negative, confirming the existence of an inverted U-shaped relationship consistent with the Environmental Kuznets Curve (EKC) hypothesis in the South African context (Ngaruko et al., 2019). This suggests that at initial stages of economic growth, CO_2 emissions increase, but beyond a certain income threshold, further growth leads to emissions reduction, potentially due to structural shifts and cleaner technologies.

Energy consumption (ln Energy Consumption) exerts a significant positive effect on CO_2 emissions, corroborating the earlier correlation results and emphasizing the central role of energy usage in environmental degradation. Trade openness also has a positive and significant coefficient, indicating that increased trade activities may exacerbate emissions, possibly through increased industrial production or transportation (Chala et al., 2021). Importantly, renewable energy consumption negatively impacts CO_2 emissions, providing robust empirical evidence that enhancing renewable energy adoption can effectively reduce emissions in both short and long run (Hiraldo & Maroto-Valer, 2020).

Finally, the error correction term (ECT) is negative and statistically significant, signifying the presence of a stable long-run equilibrium relationship among the variables. The magnitude of the ECT indicates a relatively fast adjustment speed, with approximately 67.1% of deviations from the equilibrium corrected each period. This reinforces the robustness of the model and the reliability of the long-run elasticities estimated.

Table 2: Correlation Matrix

	CO_2 Emissions	GDP	GDP^2	Energy Consumption	Trade Openness	Renewable Energy
CO_2 Emissions	1.000	0.802	0.756	0.831	0.458	-0.521
GDP	0.802	1.000	0.984	0.722	0.642	-0.412
GDP^2	0.756	0.984	1.000	0.684	0.608	-0.373
Energy Consumption	0.831	0.722	0.684	1.000	0.357	-0.497
Trade Openness	0.458	0.642	0.608	0.357	1.000	-0.206
Renewable Energy	-0.521	-0.412	-0.373	-0.497	-0.206	1.000

Source: Author

Table 3: Pre-estimation Diagnostics (ADF Unit Root Test)

Variable	ADF Statistic	p-value	Order of Integration
CO_2 Emissions	-3.612	0.023	I(1)
GDP	-2.981	0.098	I(1)
GDP^2	-3.005	0.087	I(1)
Energy Consumption	-2.832	0.112	I(1)
Trade Openness	-1.876	0.436	I(0)
Renewable Energy	-3.144	0.045	I(1)

Source: Author

Table 4: ARDL Model Estimation Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value
ln GDP	1.854	0.239	7.753	0.000
ln GDP^2	-0.102	0.034	-3.000	0.004
ln Energy Consumption	0.742	0.143	5.193	0.000
ln Trade Openness	0.121	0.052	2.327	0.028
ln Renewable Energy	-0.298	0.104	-2.866	0.007
Error Correction Term	-0.671	0.124	-5.408	0.000

Source: Author

The empirical findings of this study have significant implications for South Africa's environmental and economic policy framework. The confirmation of the Environmental Kuznets Curve (EKC) hypothesis suggests that economic growth initially exacerbates CO_2 emissions but can eventually lead to environmental improvements. However, the inverted U-shape does not imply that growth alone will solve environmental problems; rather, targeted policy interventions

are necessary to hasten the transition to the downward segment of the curve (Stern, 2017). Policymakers must, therefore, focus on accelerating structural transformation by promoting cleaner production technologies and shifting the economy towards less carbon-intensive sectors.

The positive and substantial impact of energy consumption on CO_2 emissions reinforces the urgency of transforming South Africa's energy mix. Given the country's heavy dependence on coal, energy policies should prioritize the expansion of renewable energy infrastructure, which the results show significantly reduces emissions. Investments in solar, wind, and hydroelectric power not only reduce the environmental footprint but also create green jobs and enhance energy security, fostering sustainable economic development (IEA, 2023). Furthermore, implementing carbon pricing mechanisms or taxes can internalize the environmental externalities of fossil fuel consumption, incentivizing firms to innovate and adopt cleaner technologies (Parry et al., 2018).

Trade openness's positive association with emissions signals the need for integrating environmental standards into trade policies. South Africa should consider adopting "green trade" measures that encourage sustainable practices in export and import activities. This may involve supporting the export of low-carbon products and enforcing environmental compliance among firms engaged in international trade (Frankel & Rose, 2019). Such measures can align trade expansion with environmental sustainability goals, mitigating the carbon leakage risks associated with globalization.

The negative coefficient of renewable energy consumption underlines the effectiveness of policies that support renewable energy adoption. Governments should remove barriers to renewable energy investments by offering fiscal incentives, subsidies, and streamlined regulatory frameworks. Additionally, public-private partnerships can mobilize the necessary capital for large-scale renewable projects, bridging the investment gap in the energy sector (Bhattacharyya & Timilsina, 2020).

Finally, the significant error correction term highlights the responsiveness of the CO_2 emissions system to policy shocks and economic adjustments. This suggests that timely and well-designed policies can rapidly influence emissions trajectories, emphasizing the importance of continuous monitoring and adaptive policy management.

In conclusion, the findings advocate for an integrated policy approach that simultaneously promotes economic growth, energy transition, and environmental protection. Such policies will

enable South Africa to meet its international climate commitments while sustaining socio-economic development.

4. Conclusion

This study comprehensively examined the dynamics of CO_2 emissions in South Africa using robust econometric techniques, specifically the ARDL bounds testing and wavelet coherence analysis. The empirical results affirm the validity of the Environmental Kuznets Curve (EKC) hypothesis, revealing an inverted U-shaped relationship between economic growth and environmental degradation. This indicates that while early stages of economic development intensify CO_2 emissions, further growth, combined with structural changes and technological advancements, can contribute to emission reductions (Ngaruko et al., 2019). The positive relationship between energy consumption and emissions underscores the continued reliance on fossil fuels, particularly coal, as a significant contributor to environmental pollution (Mbatha & Adeleke, 2023). Additionally, the study found that trade openness, although vital for economic integration, tends to increase emissions, highlighting the necessity for environmentally conscious trade policies (Chala et al., 2021). Conversely, renewable energy consumption demonstrates a clear mitigating effect on CO_2 emissions, supporting the imperative for green energy transition policies (Hiraldo & Maroto-Valer, 2020).

The findings emphasize that economic growth alone cannot guarantee environmental sustainability; proactive policies targeting energy diversification, renewable adoption, and green trade are essential. The significant error correction term also reveals the system's responsiveness to policy and economic changes, suggesting that timely interventions can effectively steer emission trajectories. These insights are critical for policymakers striving to reconcile South Africa’s economic ambitions with global climate commitments.

Despite its contributions, this study has limitations that pave the way for future research. First, the analysis is constrained by data availability up to the most recent period, and incorporating more granular sectoral data could deepen the understanding of emission drivers. Future studies could also explore nonlinear and asymmetric impacts of policy shocks using advanced time-series techniques such as nonlinear ARDL or regime-switching models. Furthermore, integrating social factors, such as population dynamics and urbanization, with environmental variables could

provide a more holistic perspective on emission trends. The application of machine learning algorithms to forecast emissions and evaluate policy scenarios also represents a promising direction for enhancing predictive accuracy and policy relevance.

In conclusion, South Africa's pathway toward sustainable development requires multifaceted strategies that align economic growth with environmental stewardship. Continuous empirical assessment and adaptive policy frameworks will be pivotal in achieving these dual objectives, ensuring South Africa contributes meaningfully to global climate change mitigation efforts.

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