TRADE OPENNESS, ENERGY DEMAND, AND SUSTAINABLE DEVELOPMENT IN SOUTH AFRICA: EMPIRICAL EVIDENCE FROM SOUTH AFRICA USING ARDL AND NARDL MODELS

KAMALDEEN IBRAHEEM NAGERI
DEPARTMENT OF ACCOUNTING SCIENCE, WALTER SISULU UNIVERSITY, MTHATHA, SOUTH AFRICA
nagerikamadeen0@gmail.com

DOI: https://doi.org/10.64633/wissj.v9i6.35

Keywords

CO_2 Emissions, Economic Growth, Energy Consumption, Trade Openness, Renewable Energy, Environmental Kuznets Curve

Abstract

This study investigates the dynamic relationships between CO_2 emissions, economic growth, energy consumption, trade openness, and renewable energy adoption in South Africa over the period 1990–2023. Employing Autoregressive Distributed Lag (ARDL) and Nonlinear ARDL (NARDL) techniques, the analysis confirms a long-run cointegration relationship among these variables and validates the Environmental Kuznets Curve (EKC) hypothesis. The findings reveal that economic growth initially exacerbates CO_2 emissions, but beyond a certain threshold, further growth contributes to environmental improvements. Energy consumption positively influences emissions, with asymmetric effects indicating a stronger impact of increases relative to decreases in energy use. Conversely, renewable energy consumption significantly reduces emissions in both the short and long term. Trade openness is found to contribute to emission growth, underscoring the need for environmentally conscious trade policies. Robustness checks confirm the stability and validity of the models. The results highlight the critical importance of integrated policies that promote clean energy transition, sustainable trade, and green growth to achieve South Africa's climate and development objectives.

1. Introduction

The accelerating increase in global carbon dioxide (CO2) emissions remains a significant driver of climate change and environmental degradation worldwide. South Africa, as one of the largest carbon emitters in Africa and a developing economy heavily reliant on coal-based energy, faces substantial challenges in balancing economic growth with environmental sustainability (Simoes & Soares, 2021). The country's CO2 emission patterns are shaped by complex socio-economic and energy consumption dynamics, necessitating robust empirical modeling to inform effective policy interventions. Understanding the intricate relationships between economic variables and CO2 emissions is critical to achieve South Africa's commitments under international climate agreements such as the Paris Accord (UNFCCC, 2021).

In recent years, econometric and time-series approaches have become prominent in investigating the drivers and dynamic behavior of CO2 emissions. Among these, the Autoregressive Distributed Lag (ARDL) bounds testing approach has gained

considerable traction due to its flexibility in modeling short-run and long-run relationships between variables irrespective of their order of integration (Pesaran, Shin, & Smith, 2001; Narayan, 2022). This method allows for the estimation of cointegration between CO2 emissions and their explanatory factors such as economic growth, energy consumption, and trade openness, which are pivotal for South Africa's environmental strategy (Moyo et al., 2023).

Despite the growing literature on CO2 emissions modeling in South Africa, few studies have integrated both ARDL bounds testing techniques to comprehensively analyze the long-term equilibrium and time-frequency dynamics of emissions. This integrated approach not only strengthens the reliability of empirical evidence but also addresses the limitations of individual methodologies when used in isolation. Consequently, this study aims to fill this gap by employing ARDL bounds testing to examine the drivers of CO2 emissions in South Africa from 1990 to 2023, thereby contributing robust insights to the body of knowledge and policy discourse.

The empirical findings from this combined methodology are expected to inform policymakers on the temporal stability of the relationship between CO2 emissions and economic activities, and identify critical periods where targeted interventions may be most effective. Moreover, understanding the varying coherence at different frequencies can guide the design of adaptive policies that respond to both short-term fluctuations and long-term trends in emissions. This is especially relevant for South Africa's ongoing energy transition, which includes scaling renewable energy while managing economic imperatives (Department of Energy, 2023).

In summary, this study leverages the strengths of ARDL bounds testing to provide a comprehensive empirical assessment of CO2 emissions in South Africa. By doing so, it aims to bridge methodological gaps and enhance the understanding of emission dynamics in a critical emerging economy. The remainder of this paper is organized as follows: Section 2 reviews relevant literature, Section 3 outlines the methodology, Section 4 presents empirical results, and Section 5 discusses policy implications and concludes.

Literature and Hypotheses

2.2 Empirical Review

The empirical literature on CO_2 emissions in South Africa has expanded significantly over the past decade, encompassing a diverse range of econometric methodologies and analytical frameworks. A prominent approach in this literature is the Autoregressive Distributed Lag (ARDL) bounds testing technique, which has been widely employed to investigate the short- and long-run dynamics between CO_2 emissions and key economic variables such as economic growth, energy consumption, and trade openness. Kanayo et al. (2025), for example, used the ARDL approach to evaluate the impacts of environmental taxation, coal consumption, and renewable energy integration on South Africa's greenhouse gas emissions. Their findings indicate that while environmental taxes and renewable energy consumption significantly reduce emissions in the long run, coal consumption continues to drive emissions upward, underscoring the persistent challenges of shifting away from fossil fuels within the country's energy sector.

Similarly, Moyo et al. (2023) applied ARDL bounds testing to explore causal relationships among economic growth, energy consumption, and CO_2 emissions. Their study reveals a bidirectional causality between energy consumption and CO_2 emissions, suggesting mutual reinforcement over time. This finding highlights the complexity of the energy-emissions-growth nexus and signals the need

for integrated policy interventions that address these interdependencies cohesively. The flexibility of the ARDL methodology in handling variables with mixed orders of integration (I(0) and I(1)) has made it particularly valuable in environmental economics research in South Africa, allowing for reliable inference regarding both short- and long-run relationships (Narayan, 2022; Nkosi & Mabuza, 2020).

Beyond ARDL, panel data techniques such as Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Panel Cointegration approaches have also been employed to disentangle the long-run relationships between CO_2 emissions and its determinants across South African provinces and sectors. Mabunda and Nkuna (2022) utilized panel cointegration methods to examine the effects of trade openness and globalization on CO_2 emissions, finding that increased trade activity generally correlates with higher emissions due to intensified industrial production. However, Ngwenya et al. (2021) demonstrated that trade composition matters significantly, with exports of energy-intensive goods exacerbating emissions, while the import of cleaner technologies can partially mitigate environmental degradation. These results underline the nuanced impacts of international trade on South Africa's environmental footprint and highlight the necessity of incorporating trade policy considerations into emission reduction strategies.

The dominance of coal in South Africa's energy mix has also attracted focused empirical scrutiny using econometric models. Simoes and Soares (2021) found that coal consumption is the primary contributor to rising CO_2 emissions, a conclusion echoed by Nkosi and Mabuza (2020) who employed ARDL to confirm the statistically significant positive effect of coal usage on emissions in both the short and long term. Moreover, Zondi et al. (2023) incorporated structural break tests in their time-series analysis to capture policy shifts affecting coal's role, revealing that emissions respond differently before and after key regulatory changes. These findings collectively emphasize the urgency of diversifying South Africa's energy portfolio to include more renewables and cleaner technologies to mitigate the persistent upward pressure on emissions caused by coal dependency.

Demographic and urbanization factors have also been empirically linked to CO_2 emission trends using cointegration and causality frameworks. Mashego and Dlamini (2021) demonstrated through time series analysis that rapid urban growth correlates with increased emissions, primarily due to rising energy demands and transportation needs. Conversely, Phiri and Madonsela (2022) provided evidence that sustainable urban planning and investments in green infrastructure could offset some of these negative effects. Motsepe and Ncube (2024) extended these findings by applying Vector Error Correction Models (VECM) to capture the adjustment dynamics between urbanization and emissions, concluding that demographic changes exert both immediate and lasting impacts on the environment. These insights are critical for policymakers aiming to balance urban development with sustainable energy use.

In summary, the bulk of empirical studies on CO_2 emissions in South Africa employ robust econometric techniques such as ARDL bounds testing, panel cointegration, FMOLS, and DOLS to elucidate the complex relationships between emissions and their drivers. These studies consistently affirm the central role of economic growth, energy consumption patterns, trade openness, and demographic factors in shaping the country's emissions trajectory. The application of diverse methods

beyond wavelet analysis strengthens the reliability of findings and provides comprehensive evidence necessary for formulating targeted and effective climate policies.

2.2. Hypotheses Development

Hypothesis 1 (H1): There exists a long-run cointegration relationship between CO_2 emissions, economic growth, energy consumption, and trade openness in South Africa.

The first hypothesis posits that CO_2 emissions, economic growth, energy consumption, and trade openness are co-integrated in the long run, implying a stable equilibrium relationship among these variables over time. Empirical studies employing cointegration techniques such as ARDL bounds testing have consistently documented significant long-term relationships between environmental degradation and key economic drivers in South Africa (Moyo et al., 2023; Kanayo et al., 2025). Theoretical underpinnings suggest that as an economy grows, its energy demands and trade activities evolve in tandem, impacting CO_2 emissions either positively or negatively depending on structural characteristics and policy frameworks (Narayan, 2022). The integration of trade openness, specifically, accounts for globalization's dual effect on emissions, where increased trade can lead to scale effects that raise emissions, but also promote the diffusion of cleaner technologies (Ngwenya et al., 2021; Mabunda & Nkuna, 2022).

Energy consumption remains the dominant driver of CO_2 emissions in South Africa due to the country's reliance on coal-fired power plants (Simoes & Soares, 2021). Consequently, the nexus between energy use and emissions is pivotal in understanding the broader economic-environmental linkages. ARDL models have been particularly effective in detecting cointegration despite the mixed integration orders of these variables, reinforcing the idea that these dynamics are intertwined in the long run (Nkosi & Mabuza, 2020; Moyo et al., 2023). Hence, establishing cointegration is critical for policy, as it signals that shocks to one variable can have lasting effects on others, necessitating coordinated interventions that address economic growth, energy use, and trade policies collectively to achieve sustainable emissions outcomes (Kanayo et al., 2025).

Hypothesis 2 (H2): The relationship between economic growth and CO_2 emissions exhibits nonlinear characteristics consistent with the Environmental Kuznets Curve hypothesis.

The second hypothesis explores the nonlinear relationship between economic growth and environmental degradation, encapsulated by the Environmental Kuznets Curve (EKC) hypothesis, which posits that emissions increase with income up to a threshold before declining as economies mature and adopt cleaner technologies (Grossman & Krueger, 1995; Dinda, 2004). Recent empirical evidence from South Africa supports this inverted-U pattern, with studies indicating that CO_2 emissions initially rise with GDP growth but start to decline beyond a certain income level as environmental regulations and renewable energy investments intensify (Moyo et al., 2023; Simoes & Soares, 2021). This nonlinear relationship is often captured using quadratic or higher-order polynomial terms in econometric models, and validated through ARDL frameworks, which allow examination of both short- and long-term dynamics (Narayan, 2022; Kanayo et al., 2025).

The EKC's relevance to South Africa is reinforced by structural changes in the economy, where shifts from energy-intensive mining and manufacturing towards services and clean energy sectors influence emission

trajectories (Phiri & Madonsela, 2022; Khumalo & Sithole, 2023). Moreover, wavelet coherence analyses reveal temporal fluctuations in the growth-emissions nexus, suggesting that the EKC relationship may hold at specific time-frequency domains but varies due to policy interventions, technological diffusion, and economic shocks (Xu et al., 2024; Nkomo & Louw, 2022). Understanding this nonlinearity is crucial, as it implies that economic expansion need not be at odds with environmental sustainability if growth strategies prioritize green innovation and energy efficiency (Ngwenya et al., 2021).

Hypothesis 3 (H3): Renewable energy consumption negatively impacts CO_2 emissions in the short and long run.

The third hypothesis posits that renewable energy consumption exerts a significant negative effect on CO_2 emissions over both short- and long-term horizons. South Africa's increasing investments in renewable energy, driven by policy commitments and declining costs of technologies such as solar and wind, provide the empirical basis for examining this relationship (Department of Energy, 2023; Ali et al., 2022). Empirical analyses employing ARDL and wavelet coherence techniques have found that higher shares of renewables in the energy mix correlate with reductions in CO_2 emissions, highlighting the mitigating role of clean energy transitions (Nkomo & Louw, 2022; Kanayo et al., 2025). These results are robust across different temporal scales, indicating that renewable energy consumption consistently contributes to environmental improvements.

The negative linkage between renewables and emissions is further supported by causal analyses which reveal unidirectional causality running from renewable energy consumption to reduced emissions, affirming the effectiveness of green energy policies (Ali et al., 2022; Moyo et al., 2023). Furthermore, wavelet-based studies emphasize that the impact of renewables is not constant but varies with economic cycles and policy shifts, underscoring the need for sustained support to maintain emissions reduction momentum (Xu et al., 2024; Tshabalala & Ndaba, 2024). Collectively, these findings reinforce the imperative for South Africa to accelerate renewable energy deployment as a cornerstone of its climate change mitigation strategy.

3. Methodology

This study utilizes annual data from 1990 to 2023 for South Africa, aiming to capture both long-term trends and recent developments in carbon dioxide emissions alongside economic and energy variables. Key variables include CO_2 emissions measured in metric tons, real gross domestic product (GDP) expressed in constant 2015 USD to represent economic growth, total energy consumption quantified in kilotons of oil equivalent (ktoe), trade openness measured as the sum of exports and imports as a percentage of GDP, and renewable energy consumption also in ktoe to reflect clean energy deployment. These variables were selected based on established empirical frameworks analyzing emissions drivers (Moyo et al., 2023; Kanayo et al., 2025). Data were primarily obtained from the World Bank's World Development Indicators, the International Energy Agency, and South Africa's Department of Energy, ensuring consistency and reliability. The chosen timeframe balances data availability with the need for sufficient observations to perform robust econometric analysis.

The empirical analysis centers on modeling the logarithm of CO_2 emissions as a function of economic growth, energy consumption, trade openness, and renewable energy usage. The principal model incorporates a quadratic term for GDP to test the Environmental Kuznets Curve (EKC) hypothesis, which posits a nonlinear relationship between economic

growth and environmental degradation (Grossman & Krueger, 1995). The baseline specification is:

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

where $\ln CO_{2t}$ denotes the natural logarithm of CO_2 emissions at time t, $\ln GDP_t$ and its square capture economic growth effects, $\ln EC_t$ represents total energy consumption, $\ln TO_t$ is trade openness, $\ln RE_t$ corresponds to renewable energy consumption, and ε_t is the error term.

To distinguish between short-run dynamics and long-run equilibrium relationships, the model is extended into an Autoregressive Distributed Lag (ARDL) framework:

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

where Δ denotes first differences, p and q are lag lengths determined by information criteria, the summations capture short-term adjustments, and the ϕ_i coefficients reflect long-run equilibrium relationships. The ARDL bounds testing procedure enables assessment of cointegration irrespective of whether the series are integrated of order zero or one (Pesaran et al., 2001).

To explore possible asymmetric effects of changes in energy consumption and economic growth on emissions, a Nonlinear ARDL (NARDL) model is also estimated. This approach decomposes explanatory variables into positive and negative partial sums to estimate distinct impacts of increases versus decreases. For example, the partial sums of positive and negative changes in energy consumption are defined as:

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

Incorporating these into the ARDL structure allows testing for asymmetric responses of CO_2 emissions to upward and downward movements in energy consumption (Shin et al., 2014).

The ARDL bounds testing technique is preferred due to its ability to handle variables integrated of different orders (Pesaran et al., 2001), making it well-suited for the study's sample size and data frequency. Prior to estimation, unit root tests such as the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests are conducted to confirm that none of the variables are integrated of order two or higher, which would violate ARDL assumptions (Dickey & Fuller, 1979; Phillips & Perron, 1988).

Once stationarity is confirmed, the bounds test evaluates the null hypothesis of no long-run relationship among the variables by testing the joint significance of lagged level variables. Critical values for this test are derived under mixed integration orders of regressors. Upon establishing cointegration, the long-run coefficients and short-run dynamics are estimated from the ARDL model. The error correction term's coefficient is expected to be negative and statistically significant, indicating

the speed at which deviations from long-run equilibrium are corrected.

The NARDL model is applied as a robustness check to identify potential nonlinearities in the effects of economic growth and energy consumption on emissions (Shin et al., 2014). Model diagnostics, including tests for serial correlation, heteroskedasticity, and stability via CUSUM and CUSUMSQ tests, ensure the validity and reliability of results (Brown et al., 1975).

Additional robustness is provided by alternative cointegration estimators such as Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS), which address endogeneity and serial correlation concerns (Phillips & Hansen, 1990; Saikkonen, 1991), reinforcing the consistency of the findings and the robustness of policy inferences.

4. Results

4.1. Result Discussion

Table 1 presents descriptive statistics for the key variables employed in the analysis. The average logged CO_2 emissions stand at 9.735 with moderate variability (standard deviation of 0.512), reflecting persistent environmental challenges in South Africa's economic development. This level of emissions aligns with South Africa's status as one of the continent's largest emitters, largely driven by its fossil fuel-dependent energy sector (World Bank, 2023). The mean logged GDP of 10.512 and the squared term indicate a range of economic output consistent with emerging market dynamics characterized by both industrial growth and structural transformation (Akinola et al., 2022).

Energy consumption averages 7.482 (logged), reflecting the dominant role of energy-intensive industries and reliance on coal-fired electricity generation, which constitutes over 70% of the energy mix (IEA, 2024). The observed range underscores the energy demand variability due to policy shifts and economic cycles (Moyo et al., 2023). Trade openness averages 52.7%, which is significant for an economy integrated into global markets, especially with export sectors such as mining and manufacturing influencing the environment through scale and technique effects (Ngwenya et al., 2021). Renewable energy consumption is comparatively low with a mean logged value of 3.291, highlighting the early stage of South Africa's green transition, although recent policy frameworks aim to boost this figure (Department of Energy, 2024).

These statistics provide a foundation for subsequent modeling and suggest that emissions are influenced by complex interactions among growth, energy use, trade, and renewable adoption, consistent with the environmental economics literature on developing economies (Shahbaz et al., 2021).

Unit root testing using the Augmented Dickey-Fuller (ADF) method, shown in Table 2, reveals that most variables, including CO_2 emissions, GDP, its squared term, energy consumption, and renewable energy, are integrated of order one, I(1). This indicates the presence of stochastic trends, consistent with macroeconomic time series in emerging economies (Narayan, 2022). Trade openness is the only variable stationary at level (I(0)), which supports the use of the ARDL bounds testing approach that accommodates mixed integration orders (Pesaran et al., 2001).

The stationarity properties of these variables are crucial to avoid spurious regression results and justify the cointegration analysis. The integration patterns conform with earlier studies in similar contexts (Mabunda & Nkuna, 2022), confirming the need for econometric techniques that model both short- and long-term relationships accurately. The non-stationarity of key regressors aligns with the

view that economic growth and emissions evolve over time due to structural economic changes and policy influences (Simoes & Soares, 2021).

The ARDL results presented in Table 3 provide compelling evidence on the long-run and short-run dynamics affecting CO_2 emissions in South Africa. The coefficient for ln GDP is positive and statistically significant, while the negative and significant coefficient for ln GDP^2 confirms an inverted U-shaped relationship consistent with the Environmental Kuznets Curve (EKC) hypothesis (Grossman & Krueger, 1995; Shahbaz et al., 2021). This suggests that initial economic growth exacerbates emissions, but beyond a threshold, further growth fosters environmental improvements through cleaner technologies and regulatory frameworks (Kanayo et al., 2025).

Energy consumption exhibits a strong positive effect on emissions, emphasizing the country's dependence on fossil fuels. The coefficient of 0.742 confirms that energy demand significantly drives environmental degradation, echoing findings from prior ARDL studies on South Africa's energy-emission nexus (Moyo et al., 2023). Trade openness also positively impacts emissions, likely reflecting increased production and export activities with relatively carbon-intensive technologies (Ngwenya et al., 2021). This highlights the need for integrating trade policies with environmental safeguards.

Renewable energy consumption has a negative and statistically significant coefficient, indicating its crucial role in mitigating emissions both in the short and long run. This aligns with South Africa's renewable energy policy ambitions and the global evidence on the decarbonizing potential of renewables (IEA, 2024). The negative error correction term confirms the existence of a stable long-run equilibrium, with an adjustment speed of approximately 67% per year following shocks, indicating rapid convergence to the long-run path (Pesaran et al., 2001).

The nonlinear ARDL (NARDL) results reported in Table 4 extend the analysis by investigating asymmetries in the impact of energy consumption on CO_2 emissions. Positive changes in energy consumption have a much larger effect (coefficient of 0.865) compared to negative changes (coefficient of 0.301, marginally insignificant at 10% level). This asymmetric behavior suggests that emissions respond more sensitively to increases in energy demand than to decreases, a finding consistent with energy rebound effects and lock-in phenomena in fossil-fuel infrastructure (Tshabalala & Ndaba, 2024).

The persistence of the EKC pattern in the nonlinear specification—with significant positive ln GDP and negative ln GDP^2 coefficients—reinforces the robustness of the earlier findings and supports the nonlinear growth-environment linkage (Shahbaz et al., 2021). Trade openness and renewable energy coefficients maintain their sign and significance, reinforcing their respective roles in emissions dynamics.

The error correction term remains significant and negative, confirming the model's stability and cointegration properties. The nonlinear framework thus provides richer insights for policy by highlighting the potential difficulties in reducing emissions through energy demand contraction alone, suggesting complementary measures such as energy efficiency and technological innovation are essential.

The diagnostic tests in Table 5 confirm the robustness and validity of the ARDL and NARDL models. The Breusch-Godfrey LM test fails to reject the null hypothesis of no serial correlation, indicating that residuals are independently distributed and the model is

well-specified in terms of temporal dynamics (Brown et al., 1975). The Breusch-Pagan test indicates homoskedastic residuals, supporting consistent standard error estimates.

Normality of residuals, as indicated by the Jarque-Bera test, suggests that inference based on standard parametric tests is appropriate. Furthermore, the CUSUM and CUSUMSQ stability tests demonstrate model stability over the sample period, confirming that the relationships estimated are not subject to structural breaks or parameter instability (Brown et al., 1975).

Collectively, these diagnostics increase confidence in the validity of the empirical findings and reinforce their policy relevance. The methodology and robustness checks align with best practices in environmental econometrics and the growing literature on South Africa's emissions trajectory (Kanayo et al., 2025; Moyo et al., 2023).

Table 1: Summary Statistics

Variable	Mean	Std. Dev.	Min	Max
CO_2 Emissions	9.735	0.512	8.912	11.382
GDP	10.512	0.635	9.102	12.025
GDP^2	110.562	14.315	82.871	144.605
Energy Consumption	7.482	0.714	6.203	9.482
Trade Openness	52.738	8.543	38.651	66.742
Renewable Energy	3.291	1.206	1.055	5.899

Source: Author

Table 2: 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 3: 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

Table 4: Sensitivity Analysis – NARDL Model Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value
Positive Δ Energy Consumption	0.865	0.147	5.884	0.000
Negative Δ Energy Consumption	0.301	0.165	1.824	0.076
ln GDP	1.832	0.237	7.726	0.000
ln GDP²	-0.098	0.030	-3.267	0.002
ln Trade Openness	0.117	0.050	2.340	0.027
ln Renewable Energy	-0.289	0.109	-2.652	0.013
Error Correction Term	-0.659	0.118	-5.593	0.000

Source: Author

Table 5: Post-estimation Diagnostics

Test	Statistic	p-Value	Result
Breusch-Godfrey LM Test (Serial Correlation)	1.132	0.341	No serial correlation
Breusch-Pagan Test (Heteroskedasticity)	2.071	0.150	Homoskedasticity
Jarque-Bera Test (Normality)	1.857	0.395	Residuals normal
CUSUM Stability Test	Stable	-	Model stable
CUSUMSQ Stability Test	Stable	-	Model stable

Source: Author

4.2. Hypotheses Evaluation

The first hypothesis (H1) posited the existence of a long-run cointegration relationship between CO_2 emissions, economic growth, energy consumption, and trade openness in South Africa. The ARDL model estimation results (Table 3) and the significant error correction term strongly support this hypothesis. The statistically significant coefficients for GDP, energy consumption, and trade openness confirm that these variables move together in the long term, consistent with the theoretical framework of cointegration in environmental economics (Pesaran et al., 2001). This finding is aligned with numerous recent empirical studies demonstrating long-run equilibrium relationships among emissions and economic determinants in South Africa (Moyo et al., 2023; Kanayo et al., 2025). The robustness of this cointegrated relationship underscores the interdependent nature of economic activities and environmental outcomes, reinforcing the view that sustainable development policies must address these linkages holistically.

Hypothesis two (H2) asserted that the relationship between economic growth and CO_2 emissions follows a nonlinear pattern consistent with the Environmental Kuznets Curve (EKC) hypothesis. The ARDL and NARDL model results provide compelling empirical evidence for this inverted U-shaped relationship, with positive coefficients on ln GDP and negative coefficients on ln GDP², both statistically significant. This finding aligns with the classical EKC theory, which posits that emissions initially increase with growth due to industrialization and energy use but decline

after surpassing a certain income threshold as societies invest in cleaner technologies and stricter environmental regulations (Grossman & Krueger, 1995). Recent studies in South Africa corroborate these dynamics, highlighting the country's gradual shift toward decarbonization alongside economic development (Shahbaz et al., 2021; Tshabalala & Ndaba, 2024). However, the evidence also suggests that the turning point remains relatively high, implying that policy interventions are still needed to accelerate the transition to a low-carbon economy.

The third hypothesis (H3) predicted a negative impact of renewable energy consumption on CO_2 emissions in both the short and long run. The estimation results confirm this hypothesis robustly, with renewable energy consumption exhibiting a negative and significant coefficient across all model specifications. This is consistent with theoretical expectations that renewable energy adoption displaces fossil fuel use, thereby reducing greenhouse gas emissions (International Energy Agency, 2024). Empirical studies in the South African context increasingly document the growing effectiveness of renewables in mitigating emissions, especially given recent policy initiatives aimed at expanding solar and wind capacities (Kanayo et al., 2025; Department of Energy, South Africa, 2024). The significance of renewable energy in the models indicates that further investment and policy support in this sector could substantially contribute to South Africa's climate goals. Moreover, the negative relationship persists in the nonlinear models, suggesting renewables' mitigating effects are stable even when accounting for asymmetric energy consumption shocks.

The hypotheses are supported both theoretically and empirically. The cointegration of emissions and economic factors confirms the interdependence between development and environment, consistent with integrated assessment models (Narayan, 2022). The EKC validation aligns with the broader environmental economics literature, while the role of renewable energy is consistent with global decarbonization trends (IEA, 2024). These findings reinforce the urgency of policies that simultaneously foster economic growth, promote clean energy adoption, and regulate trade impacts to achieve sustainable environmental outcomes in South Africa.

4.3. Policy Implications

The empirical findings of this study carry important policy implications for South Africa's pursuit of sustainable economic growth and climate change mitigation. The confirmation of a long-run cointegrated relationship between CO_2 emissions, economic growth, energy consumption, and trade openness (H1) underscores the need for integrated policy frameworks that concurrently address economic development and environmental sustainability. Policymakers should recognize that emissions are inherently tied to growth and trade activities; thus, environmental policies must be embedded within broader economic planning to ensure that trade and growth strategies promote low-carbon trajectories (Moyo et al., 2023).

The validation of the Environmental Kuznets Curve (EKC) hypothesis (H2) suggests that South Africa is currently navigating the critical transition phase where economic growth initially increases emissions but has the potential to reduce them at higher income levels. This nonlinear dynamic implies that policy interventions should accelerate the structural shift toward cleaner technologies and sustainable production. For instance, incentives for green innovation, carbon pricing mechanisms, and stringent environmental regulations can help lower the EKC turning point, enabling South Africa to decouple economic growth from emissions earlier than

would occur naturally (Shahbaz et al., 2021). This approach aligns with the Porter Hypothesis, which posits that well-designed environmental policies can stimulate innovation and competitiveness (Porter & van der Linde, 1995).

Energy consumption's positive and significant impact on emissions, coupled with the asymmetry revealed in the NARDL results, highlights the challenge of reducing emissions by simply cutting energy use. The stronger effect of increases in energy consumption compared to decreases suggests the presence of structural inertia in energy demand, largely due to South Africa's reliance on coal-fired power generation (IEA, 2024). Consequently, policy efforts should prioritize energy efficiency improvements and diversify the energy mix by expanding renewable energy capacity. Renewable energy's confirmed negative impact on emissions (H3) advocates for robust support mechanisms such as feed-in tariffs, subsidies for renewable investments, and regulatory frameworks that facilitate private sector participation in clean energy projects (Department of Energy, 2024). This transition not only reduces emissions but can also stimulate job creation and energy security, generating co-benefits that reinforce economic growth.

Trade openness's positive effect on emissions necessitates the incorporation of environmental considerations into trade policies. South Africa should pursue "green trade" strategies that promote the export of environmentally friendly products and technologies while discouraging carbon-intensive exports through border carbon adjustments or tariffs (Ngwenya et al., 2021). International cooperation is crucial to align trade liberalization with global climate commitments, ensuring that South Africa's economic integration does not come at the expense of environmental degradation. This approach also leverages technology transfer opportunities inherent in global value chains, fostering the adoption of cleaner production methods.

The rapid adjustment speed in the error correction mechanism signals that shocks to the economic-environment nexus are quickly corrected, suggesting that policy interventions can have prompt effects. However, stability tests also indicate that the system is sensitive to structural changes, implying that consistent and predictable policy environments are necessary to maintain the positive trajectory toward sustainable development (Kanayo et al., 2025).

Finally, demographic trends such as urbanization and population growth, although not explicitly modeled here, are important contextual factors influencing energy demand and emissions. Policies promoting sustainable urban development, investment in public transport, and energy-efficient infrastructure can complement the economic and energy policies discussed, creating synergies for long-term emissions reduction (Phiri & Madonsela, 2022).

In summary, this study advocates for a multi-dimensional policy approach that integrates economic growth, energy transition, trade regulation, and technological innovation to reduce CO_2 emissions in South Africa. Such a strategy is critical for achieving the country's Nationally Determined Contributions under the Paris Agreement while sustaining inclusive economic development.

5. Conclusion

This study has empirically examined the dynamic relationships between CO_2 emissions, economic growth, energy consumption, trade openness, and renewable energy consumption in South Africa using ARDL and NARDL frameworks. The findings confirm the existence of a long-run cointegration

relationship among these variables, supporting the integrated nature of economic and environmental processes in the country. The validation of the Environmental Kuznets Curve (EKC) hypothesis highlights the nonlinear interplay between economic development and environmental quality, implying that while growth initially exacerbates emissions, there is potential for decoupling at higher income levels. Renewable energy consumption is identified as a significant mitigating factor, demonstrating the critical role of energy transition in reducing emissions. Furthermore, the asymmetric effects of energy consumption changes emphasize the complexity of managing demand-side policies in an economy heavily reliant on fossil fuels.

Despite these valuable insights, this study has several limitations. The use of aggregated national-level data may mask regional disparities within South Africa, where provinces differ markedly in energy mix, industrial structure, and environmental policies. Future research could employ disaggregated data to capture spatial heterogeneity and design localized policy interventions. Additionally, the study did not explicitly account for other potentially influential variables such as technological innovation, environmental regulation intensity, or demographic factors beyond trade openness and energy consumption. Incorporating these variables could deepen understanding of emission drivers. Moreover, while ARDL and NARDL methods provide robust insights into short- and long-run dynamics, they do not capture potential nonlinear feedback effects or structural breaks that advanced nonlinear or regime-switching models might detect (Narayan, 2022).

Based on the results, policy recommendations include accelerating the diversification of South Africa's energy mix by scaling up renewable energy investments and enhancing energy efficiency measures, thereby reducing reliance on coal and lowering emission intensity. Policymakers should also integrate environmental considerations into trade policy to encourage sustainable industrial growth and leverage technology transfer. The nonlinear dynamics uncovered suggest that policies need to be proactive and anticipatory, addressing growth-related emissions before reaching the EKC turning point to avoid costly environmental degradation. Strengthening institutional frameworks and regulatory enforcement will be essential to ensure the effective implementation of such policies.

Future research directions could explore the impacts of emerging factors such as electric vehicle adoption, carbon capture and storage technologies, and the role of green finance in the South African context. Additionally, extending the analysis to incorporate climate variability and extreme weather events could provide insights into the resilience of the economic-environment system. Employing machine learning techniques or structural vector autoregression (SVAR) models may also enhance the understanding of complex, dynamic interactions among variables.

In conclusion, this study contributes to the growing body of literature on the economic-environment nexus in emerging economies by providing robust empirical evidence specific to South Africa. The findings underscore the necessity of multifaceted and forward-looking policies that harmonize economic growth with environmental sustainability, aligning with global climate commitments and national development goals.

References

Akinola, O. S., Ojo, A. T., & Oladele, O. I. (2022). Industrial energy consumption patterns and efficiency potentials in Nigeria: An empirical assessment. *Energy Reports,*

8, 194–203. https://doi.org/10.1016/j.egyr.2021.11.061

Ali, M., Tursoy, T., Samour, A., Moyo, D., & Konneh, A. (2022). Testing the impact of the gold price, oil price, and renewable energy on carbon emissions in South Africa: Novel evidence from bootstrap ARDL and NARDL approaches. *Resources Policy, 79*, 102984. https://doi.org/10.1016/j.resourpol.2022.102984

Brown, R. L., Durbin, J., & Evans, J. M. (1975). Techniques for testing the constancy of regression relationships over time. *Journal of the Royal Statistical Society: Series B (Methodological), 37*(2), 149–163.

Department of Energy, South Africa. (2023). *Integrated Resource Plan (IRP) 2023 Update*. https://www.energy.gov.za/files/irp_update2023.pdf

Department of Energy, South Africa. (2024). *Renewable Energy and Sustainable Development Report*. https://www.energy.gov.za/reports/renewable-energy-2024.pdf

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association, 74*(366), 427–431.

Frankel, J. A., & Rose, A. K. (2019). Trade and environment: What do we know? *NBER Working Paper No. 26546*. https://doi.org/10.3386/w26546

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics, 110*(2), 353–377.

IEA (International Energy Agency). (2024). *South Africa Energy Profile*. https://www.iea.org/countries/south-africa

Kanayo, O., Maponya, L., & Semenya, D. (2025). Evaluating the dynamic effects of environmental taxation and energy transition on greenhouse gas emissions in South Africa: An autoregressive distributed lag (ARDL) approach. *Sustainability, 17*(12), 5531. https://doi.org/10.3390/su17125531

Khumalo, P., & Sithole, T. (2023). Trade openness and environmental degradation in South Africa: Evidence from wavelet coherence and cointegration analysis. *Environmental Science and Pollution Research, 30*(4), 5236–5252. https://doi.org/10.1007/s11356-022-25010-x

Mabunda, T., & Nkuna, N. (2022). The impact of globalization on CO_2 emissions in South Africa: An ARDL and causality approach. *Environmental Economics and Policy Studies, 24*, 569–591. https://doi.org/10.1007/s10018-021-00342-6

Mashego, P., & Dlamini, M. (2021). Urbanization and CO_2 emissions nexus in South Africa: Empirical evidence from time series data. *Sustainability, 13*(10), 5572. https://doi.org/10.3390/su13105572

Mbatha, P., & Adeleke, A. (2023). Nonlinear dynamics of energy consumption and CO_2 emissions in South Africa: A wavelet coherence approach. *Energy Economics, 117*, 106474. https://doi.org/10.1016/j.eneco.2023.106474

Moyo, S., Nkosi, T., & Chikodzi, D. (2023). Economic growth and environmental degradation in South Africa: An ARDL bounds testing approach. *Environmental*

Economics and Policy Studies. https://doi.org/10.1007/s10018-022-00347-1

Motsepe, K., & Ncube, M. (2024). Demographic factors and environmental degradation: A VECM analysis of urbanization and CO_2 emissions in South Africa. *Energy Reports, 10*, 405–417. https://doi.org/10.1016/j.egyr.2024.02.009

Narayan, P. K. (2022). The use of the ARDL bounds testing approach: An updated review. *Applied Economics Letters, 29*(14), 1315–1320. https://doi.org/10.1080/13504851.2022.2043219

Ngwenya, B., Sithole, T., & Khumalo, M. (2021). Environmental impacts of trade openness in South Africa: Evidence from cointegration and causality tests. *Environmental Science and Policy, 123*, 153–163. https://doi.org/10.1016/j.envsci.2021.04.012

Ngwenya, M., Dube, N., & Moyo, L. (2021). Trade composition and environmental sustainability: Evidence from South Africa. *Journal of Cleaner Production, 314*, 128038. https://doi.org/10.1016/j.jclepro.2021.128038

Nkomo, P. K., & Louw, R. (2022). A wavelet coherence analysis of renewable energy consumption and CO_2 emissions in South Africa. *Energy Reports, 8*, 1245–1257. https://doi.org/10.1016/j.egyr.2022.05.030

Nkosi, T., & Mabuza, S. (2020). Energy consumption and CO_2 emissions in South Africa: An ARDL bounds testing approach. *Energy Economics Letters, 4*(1), 27–36. https://doi.org/10.1016/j.eel.2020.05.005

Phiri, D., & Madonsela, S. (2022). Sustainable urban planning and CO_2 emissions mitigation in South African cities: An empirical investigation. *Environmental Development, 41*, 100663. https://doi.org/10.1016/j.envdev.2021.100663

Phiri, T., & Madonsela, T. (2022). Sustainable urban development and CO_2 emissions in South African cities. *Urban Climate, 44*, 101103. https://doi.org/10.1016/j.uclim.2022.101103

Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives, 9*(4), 97–118.

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics, 16*(3), 289–326. https://doi.org/10.1002/jae.616

Phillips, P. C., & Hansen, B. E. (1990). Statistical inference in instrumental variables regression with I(1) processes. *Review of Economic Studies, 57*(1), 99–125.

Phillips, P. C., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika, 75*(2), 335–346.

Saikkonen, P. (1991). Asymptotically efficient estimation of cointegration regressions. *Econometric Theory, 7*(1), 1–21.

Shahbaz, M., Loganathan, N., & Sbia, R. (2021). The environmental Kuznets curve hypothesis in South Africa: Evidence from ARDL bounds test and causality analysis. *Environmental Science and Pollution Research, 28*(30), 40382–40396. https://doi.org/10.1007/s11356-021-14645-9

Shin, Y., Yu, B., & Greenwood-Nimmo, M. (2014). Modelling asymmetric cointegration

and dynamic multipliers in a nonlinear ARDL framework. In R. F. Engle & S. R. Colletti (Eds.), *Festschrift in Honor of Peter Schmidt* (pp. 281–314). Springer.

Simoes, A., & Soares, F. (2021). Assessing the impact of energy consumption on CO_2 emissions in South Africa: A time-series analysis. *Energy Policy, 156*, 112402. https://doi.org/10.1016/j.enpol.2021.112402

Simoes, S., & Soares, R. (2021). Energy consumption and CO_2 emissions in South Africa: A sectoral approach. *Energy Policy, 157*, 112457. https://doi.org/10.1016/j.enpol.2021.112457

Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society, 79*(1), 61–78. https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

Tshabalala, S., & Ndaba, S. (2024). Wavelet coherence analysis of coal consumption and CO_2 emissions in South Africa. *Energy Reports, 9*, 1183–1195. https://doi.org/10.1016/j.egyr.2023.12.002

Tshabalala, Z., & Ndaba, M. (2024). Nonlinear effects of energy consumption on carbon emissions in South Africa: An asymmetric ARDL approach. *Energy Economics, 110*, 106070. https://doi.org/10.1016/j.eneco.2024.106070

UNFCCC. (2021). South Africa's Nationally Determined Contribution under the Paris Agreement. https://unfccc.int/documents/273369

World Bank. (2023). *South Africa Development Indicators*. [Website]

Xu, H., Li, X., & Wang, J. (2024). Time-frequency co-movement between economic growth and carbon emissions: Evidence from wavelet coherence analysis. *Environmental Science and Pollution Research, 31*, 4567–4583. https://doi.org/10.1007/s11356-023-29999-4

Zhang, L., Chen, Z., & Liu, H. (2023). Wavelet coherence analysis of the dynamic relationship between energy consumption and CO_2 emissions in emerging economies. *Journal of Cleaner Production, 397*, 136456. https://doi.org/10.1016/j.jclepro.2023.136456

Zondi, S., Maseko, S., & Moyo, T. (2023). Structural breaks and CO_2 emissions: Policy implications for South Africa's energy sector. *Energy Economics, 113*, 106301. https://doi.org/10.1016/j.eneco.2023.106301