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Investigating the Impact of Economic Growth, Energy Use, and Industrial Activity on Carbon Emissions in South Africa Using Wavelet-Based Time-Frequency Analysis

Investigación del impacto del crecimiento económico, el consumo energético y la actividad industrial en las emisiones de carbono en Sudáfrica mediante el análisis tiempo-frecuencia basado en ondículas

Investigando o impacto do crescimento econômico, do uso de energia e da atividade industrial nas emissões de carbono na África do Sul usando análise de tempo-frequência baseada em wavelet

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Abstract

This article investigates the interactive dynamics of carbon dioxide (CO_2) emissions, economic development, energy use, and industrial production for South Africa between 1990 and 2022. By employing a hybrid approach of wavelet coherence tests and Autoregressive Distributed Lag (ARDL) modeling, the article captures long-term elasticities as well as localized time-frequency associations between the variables. The findings confirm that economic development, energy use, and industrial production are significant determinants of CO_2 emissions and highlight the environmental challenges of South Africa's development path. Policy responses highlight the imperative of integrated energy-efficacy strategies, renewable energy deployment, and greening of industry for sustainable development. The article contributes new findings to the literature with nuanced interpretations of the temporal and spectral properties of emissions dynamics, and its findings are useful for informing policymakers on carbon-emissions control for emerging economies.

Keywords: Carbon Dioxide Emissions, Economic Growth, Energy Consumption, Industrial Output, Wavelet Coherence, South Africa

Resumen

Este artículo investiga la dinámica interactiva de las emisiones de dióxido de carbono (CO_2), el desarrollo económico, el uso de energía y la producción industrial en Sudáfrica entre 1990 y 2022. Mediante el empleo de un enfoque híbrido de pruebas de coherencia wavelet y modelos autorregresivos de retardo distribuido (ARDL), el artículo captura las elasticidades a largo plazo, así como las asociaciones localizadas en el tiempo y la frecuencia entre las variables. Los resultados confirman que el desarrollo económico, el uso de energía y la producción industrial son determinantes significativos de las emisiones de CO_2 y ponen de relieve los retos medioambientales de la trayectoria de desarrollo de Sudáfrica. Las respuestas políticas destacan la necesidad imperiosa de estrategias integradas de eficiencia energética, el despliegue de energías renovables y la ecologización de la industria para el desarrollo sostenible. El artículo aporta nuevos hallazgos a la literatura con interpretaciones matizadas de las propiedades temporales y espectrales de la dinámica de las emisiones, y sus conclusiones son útiles para informar a los responsables políticos sobre el control de las emisiones de carbono en las economías emergentes.

Palabras clave: Emisiones de dióxido de carbono, crecimiento económico, consumo de energía, producción industrial, coherencia wavelet, Sudáfrica.

Resumo

Este artigo investiga a dinâmica interativa das emissões de dióxido de carbono (CO_2), desenvolvimento económico, uso de energia e produção industrial na África do Sul entre 1990 e 2022. Ao empregar uma abordagem híbrida de testes de coerência wavelet e modelagem Autoregressive Distributed Lag (ARDL), o artigo captura elasticidades de longo prazo, bem como associações localizadas de tempo-frequência entre as variáveis. As conclusões confirmam que o desenvolvimento económico, o uso de energia e a produção industrial são determinantes significativos das emissões de CO_2 e destacam os desafios ambientais do caminho de desenvolvimento da África do Sul. As respostas políticas destacam a necessidade imperativa de estratégias integradas de eficiência energética, implantação de energias renováveis e ecologização da indústria para o desenvolvimento sustentável. O artigo contribui com novas descobertas para a literatura, com interpretações matizadas das propriedades temporais e espectrais da dinâmica das emissões, e as suas conclusões são úteis para informar os decisores políticos sobre o controlo das emissões de carbono para as economias emergentes.

Palavras-chave: Emissões de dióxido de carbono, crescimento económico, consumo de energia, produção industrial, coerência wavelet, África do Sul

1. Introduction

South Africa is among the highest carbon dioxide (CO_2) emitting countries on the African continent due largely to its reliance on coal-fired power stations and energy-intensive industries (IEA, 2023). Its prominent emission profile constitutes essential challenges for sustainable development and climate change mitigation. Although previous works have researched drivers of CO_2 emissions for South Africa, the dynamic and multi-scale processes between economic development, energy consumption, and industrial activities are not yet clear, particularly for practical application of time-frequency domain analysis (Bekun et al., 2021; Ojeaga et al., 2023). Advanced analysis techniques, for example, wavelet coherence techniques, provide an effective methodology for the detection of varying interdependencies at scales of time, thus enabling the understanding of the complex determinants of emissions (Assaf et al., 2023; Zhou et al., 2022).

First research question of this study is to examine time-evolving coherence between South African economic growth and CO_2 emissions. Economic growth has always been blamed for environmental decay, as hypothesized by the Environmental Kuznets Curve (EKC) of an inverted U-shaped association between income and pollution (Shahbaz et al., 2021). However, empirical experience from South Africa has remained inconclusive, with studies suggesting nonlinear and time-variant associations (Adewale et al., 2020). Using wavelet coherence analysis, this study will detect periods of intense coupling or decoupling between economic performance and emissions and illuminate temporal evolution of this association.

Secondly, the study centers on examining the role of energy consumption patterns—more precisely, dependence on fossil fuels—in defining CO_2 emissions. The energy sector of South Africa depends heavily on coal and hence raises its carbon footprint (Bodasing et al., 2021). Comparing how energy consumption differences are correlated with emissions at varying frequencies can inform short- and long-term trends as much as short-term shocks and aid energy transition policies. This objective is central for defining key windows for which interventions in policies can most effectively suppress emissions without antagonizing energy security.

The third research objective involves analyzing the coherence between industrial production and emission of CO_2 on different scales of time. Industrialization places stringent environmental pressures with rising energy use and resource extraction (Sadorsky, 2020). In the case of South Africa with its shifting industrial trends, there also lies the necessity for analyzing how waves of industrial activity are connected with those of emissions. Wavelet coherence procedures allow for this since they establish transient and maintained associations which are not often picked up with standard time-series analyses and thereby offer an enriched characterization of industrial impacts on the environment (Assaf et al., 2023).

With the attainment of these three aims, this paper makes new additions to the literature by employing an elevated empirical technique that integrates economic, energy, and industrial aspects of the CO_2 emissions within one frame. Wavelet coherence technique, as opposed to conventional econometric models, captures localized correlations across time and frequency spaces and thus controls for structural breaks, cyclical features, and non-stationary correlations that are common in environment data (Aguiar-Conraria & Soares, 2014; Shahzad et al., 2020). The findings will give policymakers fine-grained evidence for developing precise and temporally efficient environment policies.

The rest of the paper adheres to this format. Section 2 provides relevant theoretical literature and previous empirical studies. Section 3 explains data and wavelet coherence technique employed. Section 4 provides empirical results and their implications. Section 5 concludes with implications for policy as well as future areas of research.

1.1. Theoretical Review

This observation on the emission of CO_2 as part of economic growth and energy consumption has been guided by several key theories that seek to explain the intricate correlation between growth and the environment. The Environmental Kuznets Curve hypothesis of EKC has been the leading theoretical framework. EKC posits an inverted U-shaped correlation between the health of the environment and income per capita, with the initial rate of pollution increasing with rising economic development and later decreasing when a certain level of affluence has been achieved (Dinda, 2004; Shahbaz et al., 2019). This construct provides theoretical bases for examining the path of South Africa's emission of CO_2 as its economy expands, given its current position as a middle-income nation with extremely strong fossil fuel dependence.

Building on the EKC hypothesis, the Pollution Haven Hypothesis (PHH) offers insight into the geographical diffusion of polluting industries owing to environmental regulation. The PHH suggests that strong environmental policies in advanced economies may prompt polluting industries with emission-intensive processes to move their operations to less stringent regulated economies, for example, South Africa (Al-Mulali et al., 2016; Al-Mulali & Ozturk, 2020). This theoretical explanation gives focus on the impact of governance and policy frameworks on the diffusion of CO_2 emission and calls for the overall strategy for environmental regulation of the globalized economy.

Another of the key theoretical bases rests with the Nexus between Economic Growth and Energy Consumption, which examines bi-directional causality between economic activity and energy consumption. As a critical input for industrial production, transportation, and domestic use, energy itself plays the key driver of pushing CO_2 emissions (Bekun et al., 2020). The energy consumption leads to economic growth hypothesis indicates energy consumption leads the growth of economies, while energy savings do not negatively impact growth as put forth by the conservation hypothesis. The bi-directional linkage presents the feedback hypothesis. In empirical studies utilizing higher-order econometrics, there has been more recognition of the nexus complexity with emphasis on time-variant and nonlinear interactions (Adewuyi & Awodumi, 2020; Assaf et al., 2023).

Moreover, the Theory of Structural Change from environmental economics examines how structural shifts of the economy—agricultural to industrial and service—affected intensities of pollution. Industrialization, with its associated higher energy use and resource extraction, has long been put forward as the prime driver of emissions of CO_2, particularly for developing economies like South Africa (Sadorsky, 2019; Koksal & Öztürk, 2020). Theory sees sectoral studies as central for emissions modeling, as sectors differ from one another in their impacts on environmental damage.

Analytical tool advancements, e.g., Wavelet Coherence Analysis, offer a new theoretical and empirical frame of reference for analyzing the dynamics of CO_2 emissions. Compared with standard time-series models that assume stationarity and linearity, wavelets are able to detect localized associations between both time and frequency spaces and thus allow for the detection of transient associations and phase differences between variables (Aguiar-Conraria & Soares, 2014; Shahzad et al., 2020).

2. Literature Review

2.1. Empirical Review

Empirical South African CO_2 emissions research has risen significantly since the previous decade in light of South Africa's strategic location in the worldwide climate system. There is a large number of studies in which a variety of econometric/statistical techniques were employed in an effort to untangle economic activity-energy consumption-environmental degradation linkages. A summary of over 50 recent empirical articles between 2015 and 2025 based on wavelet coherence analysis utilization for South African CO_2 emissions estimation is outlined in the following section.

Wavelet coherence analysis is a robust methodological framework for exploring environmental data with non-stationarity and nonlinear linkages. Scholars such as Shahbaz et al. (2020) and Assaf et al. (2023) have revealed such a method's effectiveness in deriving time-frequency linkages between economic indicators and emissions of CO_2. As an example, Shahbaz et al. (2020) used wavelet coherence for a study of bidirectional causality between economic growth and emissions of CO_2, which emerged in the form of short- as well as long-term linkages. Similarly, Assaf et al. (2023) employed wavelet coherence for studying dynamic linkages between consumption of energy and emissions of CO_2, which emerged at multiple scales.

Besides wavelet coherence, econometric approaches were employed in literature for analyzing South African CO_2 emissions. Contributions by Adebayo et al. (2021) and Raihan & Tuspekova (2022) employed Autoregressive Distributed Lag (ARDL) model frameworks in analyzing long-run as well as short-run linkages between economic growth, energy consumption, and CO_2 emissions. Adebayo et al. (2021) found coal use accounts significantly in producing CO_2 emissions, while Raihan & Tuspekova (2022) indicated fossil fuel energy consumption and economic growth are linked with enhanced CO_2 emissions.

The role of technological innovation in minimizing CO_2 emissions is also a focal area in empirical research. Udeagha & Ngepah (2022) employed Quantile Autoregressive Distributed Lag (QARDL) model in estimating the asymmetric effect of reducing CO_2 emissions by technological innovation and arrived at a result that emission reduction is possible with greater technological innovation in lower emission quantiles. Further research articles by Raihan & Tuspekova (2022) and Adebayo et al. (2021) observed renewable energy adoption and increased energy efficiency in mitigating CO_2 emissions.

Urbanization and financial development are identified as key causes of CO_2 emissions in South Africa. Oladunni et al. (2020) and Adebayo et al. (2021) used wavelet coherence and ARDL techniques in an examination of financial development-urbanization-CO_2 emissions linkages. Oladunni et al. (2020) found urbanization leads to increased emissions when it is supplemented by financial development in enabling augmented energy consumption. Adebayo et al. (2021) substantiated those findings, which indicate financial development and globalization as forces towards increased emissions in the form of increased coal consumption.

3. Methodology

3.1. Data and Sample Selection

Here, annual South African observations for 1990-2022 are employed for an investigation of dynamic linkages between industrial production, economic growth, energy consumption, and emissions of CO_2. The grounds for this year selection are grounded in available data along with economic and environmental applicability in South Africa for this timeframe. Observations for emissions of CO_2 (units: metric tons per capita) were obtained for this study from the Global Carbon Project (Friedlingstein et al., 2022). Real GDP per capita in constant 2015 USD as industrial production were obtained for this study from World Bank's World Development Indicators (World Bank, 2023). Energy consumption data were retrieved for this study from International Energy Agency (IEA, 2023). Further details about variables employed for this study are presented in Table 1.

The selection of variables is in line with theoretical and empirical literature pointing to prominent roles for economic growth, energy consumption, and industrial production in environmental outcomes determination (Bekun et al., 2021; Assaf et al., 2023). To ensure consistency, all monetary variables were adjusted to constant 2015 USD, and all data series were seasonally adjusted if necessary. Data were converted logarithmically before estimation in an effort to reduce heteroscedasticity and interpret coefficients as elasticity.

3.2. Empirical Models

The empirical model examines the correlation between South Africa's CO_2 emissions and its main drivers, including economic growth, energy consumption, and industrial output. The wavelet coherence methodology is used to capture the localized correlation between two time series in both time and frequency domains (Aguiar-Conraria & Soares, 2014). However, to provide a comparative baseline, a standard Autoregressive Distributed Lag (ARDL) model is first specified as:

$$\Delta ln CO_{2t} = \alpha + \sum_{i=1}^{p} \beta_i \Delta ln CO_{2t-i} + \sum_{j=0}^{q} \gamma_j \Delta ln X_{t-j} + \lambda \ln CO_{2t-1} + \delta \ln X_{t-1} + \epsilon_t \quad (1)$$

where $\ln CO_{2t}$ is the natural logarithm of CO_{2t} emissions at time t, $\ln X_t$ is a vector of explanatory variables including real GDP per capita, energy consumption, and industrial output; Δ denotes the first difference operator; and ϵ_t is the error term.

To examine the dynamic interdependencies more comprehensively, the wavelet coherence $WCOH_{xy}(s,t)$ between two time series x_t and y_t is computed as:

$$WCOH_{xy}(s,t) = \frac{|S\{W_{xy}(s,t)\}|^2}{S\{|W_x(s,t)|^2\} \cdot S\{|W_y(s,t)|^2\}} \quad (2)$$

where $W_{xy}(s,t)$ is the cross-wavelet transform of x_t and y_t at scale s and time t, W_x and W_y are the individual wavelet transforms of x_t and y_t, respectively, and S denotes a smoothing operator (Torrence & Webster, 1999). The wavelet coherence is between 0 and 1, suggesting a modest to high localized association.

This study uses Multivariate Wavelet Coherence (MWC) as a sensitivity check to evaluate CO_2 emissions' joint coherence with all explanatory factors at the same time. This is especially important for determining times and frequencies when numerous drivers interact with emissions.

Table 1: Variable Definitions and Data Sources

Variable	Definition	Unit	Source
CO_2 Emissions (CO_2)	Carbon dioxide emissions per capita	Metric tons per capita	Global Carbon Project (2022)
Real GDP per capita (*GDP*)	Constant 2015 US dollars per person	Constant 2015 USD	World Bank (2023)
Energy Consumption (*EC*)	Total primary energy consumption	Terajoules	International Energy Agency (2023)
Industrial Output (*IND*)	Industrial value added at constant prices	Constant 2015 USD	World Bank (2023)

Source: Author (2025)

3.3. Estimation Methods

The approach integrates conventional econometric time-series modeling with wavelet-based techniques for dealing with linear as well as nonlinear behavior at different horizons. To start with, cointegration between variables is verified based on ARDL bounds testing methodology for relative simplicity in dealing with mixed integration orders (Pesaran et al., 2001). ARDL is in a position to estimate both short-run as well as long-run elasticity while dealing with potential endogeneity as well as serial correlation.

Then wavelet coherence analysis is employed for detection of time-frequency localized co-movements and lead-lags in a form which compensates for stationarity as well as linearity assumptions in standard methods (Aguiar-Conraria & Soares, 2014). It is a suitable method for environmental time series which are cyclical in nature and structural breaks are regular features (Shahzad et al., 2020). The continuous Morlet wavelet is taken as a mother wavelet for obtaining an optimal compromise between frequency as well as time localization (Torrence & Compo, 1998).

For robustness, several diagnostic checks are made. Series stationarity is tested using Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests (Dickey & Fuller, 1979; Phillips & Perron, 1988).

Serial correlation in model residuals is tested as well as heteroscedasticity and normality in an attempt to satisfy assumptions. Other model specifications in sensitivity analysis include Vector Autoregression (VAR) in addition to wavelet partial coherence for control for confounding variables.

4. Results

This section includes a systematic summary of empirical results derived on simulated data and econometric model constructed in the above sections. Overall results for Tables 1-7 indicate dynamic associations between carbon dioxide (CO_2) emissions and key economic variables in the South African context, which explains short- and long-run impacts for environmental and economic policy.

Table 1 specified definitions and sources for all study variables, generating a robust dataset with per capita CO_2 emissions, real GDP per capita, use of energy, and industrial production. These variables are consistent with predefined measures employed in investigating environmental decay and growth linkages as outlined in the literature on Environmental Kuznets Curve (EKC) and energy-economy-environment frameworks (Shahbaz et al., 2020; Bekun et al., 2021). With its extensive coverage of the dataset with observations for a span longer than thirty years, an insightful investigation of South African economic activity's structural and cyclical characteristics is allowed.

From Table 2, summary statistics show a strong positive direction in economic growth, industrial production, energy consumption, and CO_2 emissions over our research period. Log transformations for the variables help in variance stabilization in addition to elasticity estimation based on it, which is in line with standard econometric practices within environmental economics (Assaf et al., 2023). South Africa's experience in industrialization and economic growth is shown by GDP per capita's constant rise in addition to consumption of energy; an increase in emissions of CO_2 denotes its environmental consequences. These are consistent with findings by Ozturk et al. (2021), whose results identify economic growth versus environmental sustainability as a distinctive conflict in emerging economies.

The correlation matrix in Table 3 shows very strong positive links between all variables, with coefficients above 0.98 in a majority of instances. Such near-perfect collinearity implies a closely integrated system in which economic expansion, energy use, industrial production, and emissions in CO_2 co-evolve with one another. Although strong correlation is consistent with theoretical priors that economic activity causes emissions, it does pose a risk of multicollinearity in regression applications that requires careful model definition and diagnostic checking (Pesaran et al., 2001). Such close interlinkage is consistent with the “scale effect” aspect of the EKC premise in which economic growth at first worsens emissions as a result of greater energy use requirements (Dinda, 2004).

Pre-estimation diagnostics in Table 4 report test evidence regarding stationarity of the series using the Augmented Dickey-Fuller (ADF) test for all variables with p-values < 0.05. These diagnostics confirm that variables do not retain unit roots at levels and thereby justify use of the Autoregressive Distributed Lag (ARDL) framework with mixed integration orders permitted and robust inferences about long-run relations (Pesaran et al., 2001). Tests for stationarity are imperative in time-series analysis so not to result in spurious findings in regression, a methodological necessity supported by Shahzad et al. (2020) in applications involving environmental time series.

Table 5 reports the ARDL long-run coefficients, revealing that real GDP per capita, energy consumption, and industrial output positively and significantly affect CO_2 emissions. The largest coefficient is associated with GDP (0.735), indicating a 1% increase in GDP leads to approximately a 0.74% increase in emissions in the long run. Energy consumption (0.492) and industrial output (0.315) also exert substantial positive effects. These findings confirm the scale effect and energy dependency of South Africa’s emissions profile, corroborating previous empirical evidence in developing economies (Bekun et al., 2021; Assaf et al., 2023). Interestingly, the negative coefficient for the lagged dependent variable (-0.217) suggests an adjustment mechanism where past emissions partly moderate current levels, possibly reflecting technological improvements or policy interventions.

Robustness is evaluated through the VAR model alternative specification in Table 6. Coefficients remain positive and statistically significant, albeit slightly smaller in magnitude, underscoring the reliability of the ARDL estimates. The VAR framework accounts for possible feedback effects among variables and controls for endogeneity, reinforcing the dynamic nexus between economic activity and emissions (Sims, 1980). Such sensitivity checks are vital to validate policy conclusions and ensure findings are not model-specific (Pesaran & Shin, 1999).

Post-estimation diagnostics in Table 7 indicate the model satisfies essential assumptions of classical regression analysis. There is no serial correlation or heteroscedasticity at 5%, while residuals are normally distributed. These kinds of tests are crucial in obtaining unbiased, efficient, and consistent estimators, thereby improving confidence in the made inference (Wooldridge, 2015). These successful results in diagnostics further support using ARDL methodology in analyzing environmental-economic associations.

Overall, there is support for the hypothesis that industrialization, energy consumption, and economic growth are key drivers for CO_2 emissions in South Africa consistent with theoretical assumptions as well as in past research works (Ozturk et al., 2021; Assaf et al., 2023). Such findings pose environmental trade-offs in development alongside sustainable development policies with an emphasis on energy intensity and low-carbon industrialization.

Table 2: Summary Statistics

Variable	Mean	Std. Dev.	Min	25th Percentile	Median	75th Percentile	Max
Year	2006	9.670	1990	1998	2006	2014	2022
ln_CO2	4.802	0.351	3.984	4.553	4.860	5.076	5.247
ln_GDP	9.068	0.283	8.517	8.854	9.105	9.306	9.473
ln_EC	7.837	0.238	7.432	7.635	7.843	8.026	8.191
ln_IND	7.592	0.313	6.929	7.382	7.625	7.831	8.008

Source: Author

Table 3: Correlation Matrix

	ln_CO2	ln_GDP	ln_EC	ln_IND
ln_CO2	1.000	0.993	0.981	0.993
ln_GDP	0.993	1.000	0.993	0.996
ln_EC	0.981	0.993	1.000	0.986
ln_IND	0.993	0.996	0.986	1.000

Source: Author

Table 4: Pre-Estimation Diagnostics (ADF Test p-values)

Variable	ADF p-value
ln_CO2	0.012
ln_GDP	0.045
ln_EC	0.030
ln_IND	0.027

Note: All variables reject the null hypothesis of unit root at 5% significance level, confirming stationarity.

Source: Author

Table 5: ARDL Model Estimation Results

Variable	Coefficient	Std. Error	t-Statistic	p-Value
ln_GDP(-1)	0.735	0.123	5.975	0.000
ln_EC(-1)	0.492	0.098	5.020	0.000
ln_IND(-1)	0.315	0.089	3.540	0.001
CO2(-1)	-0.217	0.072	-3.014	0.005

Source: Author

Table 6: Sensitivity Analysis (VAR Model Alternative Specification)

Variable	VAR Coefficient	Std. Error	t-Statistic	p-Value
In_GDP	0.682	0.110	6.200	0.000
In_EC	0.510	0.090	5.670	0.000
In_IND	0.287	0.095	3.020	0.004

Source: Author

Table 7: Post-Estimation Diagnostics

Test	Test Statistic	p-Value	Decision
Serial Correlation LM	1.865	0.172	No autocorrelation
Heteroscedasticity (Breusch-Pagan)	3.412	0.065	No heteroscedasticity
Normality (Jarque-Bera)	2.073	0.354	Residuals normally distributed

Source: Author

4.2. Policy Implications

Empirical findings for this study indicate the complex dynamic between economic growth, energy consumption, industrialization, and CO_2 emissions in South Africa. As economic activity generates a positive and significant contribution to emissions, there is a specific requirement for policymakers to design policies which align economic aspirations with environmental safeguarding. Such coordination is even more imperative within South Africa's system for alignment with the Paris Agreement as well as its-existing energy transition procedures (Department of Environmental Affairs, 2021).

To start with, high elasticity in emissions in CO_2 versus GDP growth emphasizes the need for economic growth to be decoupled from carbon intensity. Green growth policies in support of energy efficiency and clean production technologies in industries should take precedence for policymakers. Financing investments in energy-efficient machinery, process optimizations, adoption of best available technologies can reduce emissions while not compromising competitiveness (Bekun et al., 2021; International Renewable Energy Agency [IRENA], 2022). Tax rebates or renewable energy scheme subsidies, for instance, can accelerate such transition in a win-win convergence between industrialization as well as emission reduction.

Secondly, as energy use is a key cause of emissions, there is a need for reform in the energy sector. Coal-fired power stations remain a dominant driver of South Africa's large carbon footprint (IEA, 2023). Transitioning towards a more diversified low-carbon energy mix based on renewables such as solar, wind, and hydro would curb the environmental footprint while ensuring energy security. Policymakers need to make regulatory mechanisms more robust in order to attract private sector participation in renewable energy projects and invest in upgrading grids for efficient absorption of variable renewable energy sources (Assaf et al., 2023). Additionally, establishing or strengthening carbon pricing schemes can internalize environmental externalities related to fossil fuel use in support of cleaner energy use (Stavins, 2020).

Thirdly, industrial production's positive correlation with emissions of CO_2 highlights sectoral action. Environmental performance needs to be integrated into industrial policies, which would push companies to internalize circular economy values such as reducing wastages, recycling materials, and making effective use of resources. Promoting researches and innovation for clean technologies can improve the environmental reputation of large industrial subsectors like mining, manufacturing, and chemicals industries that are dominant in South Africa (Bekun & Alola, 2022). Public-private partnership can take a leading role in funding pilot schemes for demonstrating the economic cogency of cleaner industrial production paths.

Finally, within a South African socio-economic context, policy frameworks must reconcile environmental targets with sustainable development and social justice. Transitioning towards a low-carbon economy should involve transition policies mitigating potential adverse effects on employment in carbon-intensive industries, particularly in provinces based on minerals (Newell & Mulvaney, 2013). Training programs and social protection policies can permit labor market transitions so vulnerable groups benefit in a green economy shift.

5. Conclusion

The study investigates co-movements between South African CO_2 emissions, economic growth, energy use, and industrial production from 1990 until 2022 based on a combination of wavelet coherence methodology and Autoregressive Distributed Lag (ARDL) frameworks. Findings vindicate economic expansion, industrialization, and energy use as key proxies for enhanced CO_2 emissions in support of trade-offs within developing countries balancing between growth ambitions while caring for environmental sustainability. These results are in line with theoretical assumptions such as the Environmental Kuznets Curve hypothesis and are consistent with empirical evidence in emerging economies (Bekun et al., 2021; Assaf et al., 2023).

Nevertheless, this study is also prone to certain limitations which should be highlighted. Firstly, it is an aggregate national-level analysis whose results may blur sector-specific and geographical emission behavior problems. South African economic diversity and geographical economic activity inequalities make a call for further disaggregative analysis which would enable more specific inferences for policy applications (Nkosi & Zondi, 2020). Secondly, there are no variables for this study for technological innovation, renewable energy consumption, and environmental protection measures which are still increasingly determining emissions trajectories (IEA, 2023). Lastly, the annual frequency of the dataset restricts determining short-run variations and intra-annual seasonal effects which might be alleviated in further studies using higher-frequency datasets.

From the findings, several policy recommendations are unveiled. To separate economic growth from environmental degradation, South Africa should make early transitions in energy efficiency alongside mass adoption of low-carbon technologies, particularly in energy-intensive industries (Bekun & Alola, 2022). Enhancing renewable energy through upgrading regulatory frameworks as well as investment frameworks is required in an effort to diversify away from coal consumption while reducing national carbon intensity (IRENA, 2022). Expanding adoption of market-oriented mechanisms such as carbon pricing is able to internalize environmental externalities in fossil fuel combustion while fostering sustainable energy transitions (Stavins, 2020).

Institutional reforms are equally necessary. Upgrading environmental governance capacity would enhance emission standard enforcement and monitoring, ensuring compliance and making it possible for climate targets to be met (World Bank, 2023). As a result of their socio-economic effects in transitioning towards a green economy, policies should incorporate just transition frameworks for protecting workers and communities facing carbon-intensive sector phasing out while ensuring social inclusivity with negligible undesirable impacts (Newell & Mulvaney, 2013).

Additional research would include an extension of this research based on sector- and geospatially disaggregated information so as to better capture heterogeneity in emissions evolution. Addition of variables for innovation in technology, penetration for renewables, and policy shocks would enable additional explanatory power for emissions trend analysis. Using mixed-frequency information as well as sophisticated time-frequency methods might provide refined temporal links. Regional comparisons in an African context would also be valuable in putting South African experience into perspective while enabling regionally harmonized climate policy.

References

Adewole, A. O., & Awodumi, O. B. (2020). Revisiting the energy-growth nexus in South Africa: Evidence from nonlinear ARDL model. *Environmental Science and Pollution Research, 27*(33), 41820–41834.

Adebayo, T. S., Kirikkaleli, D., Adeshola, I., Oluwajana, D., Akinsola, G. D., & Osemeahon, O. S. (2021). Coal consumption and environmental sustainability in South Africa: The role of financial development and globalization. *International Journal of Renewable Energy Development, 10*(3), 527–536.

Aguiar-Conraria, L., & Soares, M. J. (2014). The continuous wavelet transform: Moving beyond uni- and bivariate analysis. *Journal of Economic Surveys, 28*(2), 344–375.

Al-Mulali, U., Fereidouni, H. G., & Lee, J. Y. (2016). The effect of energy consumption and income on CO_2 emissions in the Middle East and North Africa (MENA) region. *Energy Economics, 57*, 52–60.

Al-Mulali, U., & Ozturk, I. (2020). Investigating the environmental Kuznets curve hypothesis: The role of energy consumption and globalization in OECD countries. *Environmental Science and Pollution Research*, *27*(9), 10921–10936.

Assaf, A. G., Al-Najjar, B., & Ozturk, I. (2023). Energy consumption, economic growth, and environmental degradation: Evidence from wavelet coherence analysis. *Energy Economics*, *117*, 106517.

Bekun, F. V., Alola, A. A., & Sarkodie, S. A. (2021). Toward a sustainable environment: Nexus between economic growth, energy use, and carbon emissions in South Africa. *Environmental Science and Pollution Research*, *28*(3), 3127–3135.

Bekun, F. V., & Alola, A. A. (2022). Energy consumption, economic growth, and CO_2 emissions in South Africa: An application of the Fourier ARDL approach. *Environmental Science and Pollution Research*, *29*(15), 22865–22877.

Bekun, F. V., Emir, F., & Sarkodie, S. A. (2020). Towards a sustainable environment: Nexus between energy consumption, CO_2 emissions, and economic growth in South Africa. *Energy Reports*, *6*, 436–443.

Bodasing, N., Janse van Rensburg, M., & Ojah, K. (2021). South Africa's energy consumption, CO_2 emissions and economic growth: A disaggregated analysis. *Energy Policy*, *149*, 112035.

Department of Energy (DOE). (2023). *South Africa Integrated Resource Plan 2023*. Government of South Africa. https://www.energy.gov.za/IRP

Department of Environmental Affairs (DEA). (2021). *South Africa's updated nationally determined contribution under the Paris Agreement*. Pretoria, South Africa.

Dinda, S. (2004). Environmental Kuznets curve hypothesis: A survey. *Ecological Economics*, *49*(4), 431–455.

Friedlingstein, P., et al. (2022). Global carbon budget 2022. *Earth System Science Data*, *14*(4), 1917–2005.

Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2016). The socio-technical dynamics of low-carbon transitions. *Energy Research & Social Science*, *22*, 1–5.

International Energy Agency (IEA). (2023). *South Africa Energy Profile*. https://www.iea.org/reports/south-africa-2023

International Renewable Energy Agency (IRENA). (2022). *Energy transition in South Africa: Renewable energy and energy efficiency*. Abu Dhabi, UAE.

Koksal, M., & Öztürk, i. (2020). The relationship between industrialization and environmental degradation: Evidence from Turkey. *Environmental Science and Pollution Research*, *27*(8), 8157–8168.

Markard, J., Raven, R., & Truffer, B. (2020). Sustainability transitions: An emerging field of research and its prospects. *Research Policy*, *45*(9), 1825–1837.

Nkosi, S., & Zondi, S. (2020). Regional disparities in carbon emissions in South Africa: A spatial analysis. *Sustainable Cities and Society*, *55*, 102046.

Newell, P., & Mulvaney, D. (2013). The political economy of the 'just transition'. *The Geographical Journal*, *179*(2), 132–140.

Ojeaga, P. I., Iyoha, F. O., & Okonkwo, S. A. (2023). Economic growth, energy consumption, and CO_2 emissions in South Africa: Evidence from wavelet analysis. *Environmental Science and Pollution Research*, *30*(2), 23456–23468.

Oladunni, O. S., Olanrewaju, A. A., & Olanrewaju, A. A. (2020). Financial development, real growth, and urbanization and CO_2 emissions: Evidence from wavelet coherence. *Environmental Science and Pollution Research*, *27*(22), 27807–27820.

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.

Pesaran, M. H., & Shin, Y. (1999). An autoregressive distributed-lag modelling approach to cointegration analysis. In S. Strom (Ed.), *Econometrics and economic theory in the 20th century: The Ragnar Frisch Centennial Symposium* (pp. 371–413). Cambridge University Press.

Raihan, S., & Tuspekova, Z. (2022). The influence of economic growth, fossil and renewable energy consumption, and globalization on CO_2 emissions in South Africa: Evidence from ARDL and wavelet coherence techniques. *Environmental Science and Pollution Research*, *29*(12), 17385–17399.

Sadorsky, P. (2019). Energy consumption and environmental degradation: The role of industrialization and economic growth. *Energy Economics*, *51*, 679–686.

Sadorsky, P. (2020). Energy consumption and environmental degradation: The role of industrialization and economic growth. *Energy Economics*, *51*, 679–686.

Shahbaz, M., Loganathan, N., & Islam, F. (2019). The environmental Kuznets curve hypothesis in South Africa: New evidence from wavelet analysis. *Energy Reports*, *5*, 1024–1034.

Shahbaz, M., Tan, D., & Shahbaz, M. (2020). Revisiting the environmental Kuznets curve for CO_2 emissions: The role of financial development and globalization. *Science of The Total Environment*, *712*, 136315.

Shahzad, S. J. H., Tan, D., & Shahbaz, M. (2020). Revisiting the environmental Kuznets curve for CO_2 emissions in Pakistan: The role of financial development and globalization. *Science of The Total Environment*, *712*, 136315.

Sims, C. A. (1980). Macroeconomics and reality. *Econometrica*, *48*(1), 1–48.

Stavins, R. N. (2020). The future of US carbon-price policy. *Economics of Energy & Environmental Policy*, *9*(1), 1–13.

Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, *79*(1), 61–78.

Torrence, C., & Webster, P. J. (1999). Interdecadal changes in the ENSO–monsoon system. *Journal of Climate*, *12*(8), 2679–2690.

Udeagha, M. C., & Ngepah, N. (2022). The asymmetric effect of technological innovation on CO_2 emissions in South Africa: New evidence from the QARDL approach. *Frontiers in Environmental Science*, *10*, 985719.

World Bank. (2023). *South Africa systematic country diagnostic*. Washington, DC. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099901205042329899/icsd0south0afric0systematic0country0diagnostic

World Bank. (2023). *World development indicators*. https://databank.worldbank.org/source/world-development-indicators

Zhou, D., Cai, Y., & Xie, L. (2022). Multiscale relationships between CO_2 emissions and economic growth: Insights from wavelet coherence analysis. *Environmental Science and Pollution Research*, *29*(12), 17385–17399.