The Nexus Between Carbon Dioxide Emissions, Economic Growth and Energy Transition: A South African Case Study

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Abstract

The nexus between carbon dioxide emissions (CO2), economic growth and energy transition is a crucial aspect in mitigating climate change in developing countries, including South Africa. However, with South Africa being highly dependent on fossil fuels and especially, coal generated energy, this relationship cannot be overlooked. Thus, the study investigated the nexus between CO2 emissions, economic growth and energy transition. The Autoregressive Distributed Lag (ARDL) methodology and Granger causality tests were applied on secondary time series data spanning the period 1991-2020 to meet the study's objectives. CO2 was regressed against economic growth and energy transition with trade openness and population growth added as control variables. The results showed a long-run relationship between the variables with CO2 emissions positively related to economic growth, trade openness and renewable energy consumption while being negatively related to population growth. The short-run results found CO2 emissions to be negatively related to trade openness and population growth while being positively related to economic growth and renewable energy consumption. The Error Correction Model (ECM) term was found to be 61.66% and highly significant at 1%, suggesting a reasonably high speed of adjustment. The Granger causality test proved causality between CO2 emissions, economic growth and energy transition. This results therefore proved the Environmental Kuznets Curve (EKC) hypothesis & supported the statement that South Africa is still a developing country, and that economic growth directly leads to environmental degradation through an increase in CO2 emissions. Stability test was used to check for the robustness of the time series model over time because an unstable model could produce spurious results. Therefore, to foster innovation in renewable energy technologies, increased funding for research and development is crucial. This can lead to breakthroughs that make renewable energy more accessible and affordable. Highlighting that policymakers should prioritize investments in renewable energy infrastructure to reduce reliance on coal and lower CO2 emissions, thereby promoting sustainable economic growth.

Keywords: CO2 Emissions, Economic Growth, ARDL, Environmental Sustainability, and Renewable Energy

INTRODUCTION AND BACKGROUND

The unpredictable fast-paced world changes rely mostly on accurate weather forecasts which is influenced by the stance of climate change, which in turn affects the economy. This paper draws from the energy and environmental economics literature which includes the studies by Odihiambo (2023), Udeagha and Muchapondwa (2022), and Akizu (2017) which studied the asymmetric impact of energy consumption on economic growth in South Africa as well as investigating the moderating role of economic policy uncertainty in the Environmental Kuznets curve for South Africa. The studies all highlight the impact of economic growth on carbon dioxide emissions, which exhibits different relationships because of different dynamics in each study.

In various regions, including the Association of Southeast Asian Nations (ASEAN) and selected African countries, findings suggest that energy consumption positively influences economic growth but can also lead to increased emissions unless managed through sustainable practices (Gershon, et al., 2024). The transition to low-carbon energy systems is essential for achieving a sustainable economic model that aligns with global climate goals, emphasizing the need for innovative policies and technologies to foster this shift (Susilowati, et al., 2023).

Developing countries such as South Africa, go through a series of challenges to balance CO2 emissions, economic growth, and energy transition. According to the (International Energy Agency, 2021), coal accounted for approximately 84% of South Africa's electricity generation and according to data from StatsSA (2023), for the period 2018-2023, there remained potential for increasing the economic growth rate from 0.2% to 0.6% in the proceeding decade, from the coal industry. However, those projections, as noted in (Odihiambo, 2023), show that the positive shocks in coal consumption will negatively affect the economic growth rate in the long run, highlighting the consequences of over-reliance on coal energy sources for economic growth in the country.

However, this study adds a different perspective compared to the previously conducted studies. Most of the studies focused on how economic growth and energy consumption impact carbon dioxide emissions. This study accounts for the issue of energy transition to augment existing models and contribute to the body of knowledge. Therefore, this study's uniqueness is the use of energy transition and how it impacts carbon dioxide emissions. The rest of this paper is structured as follows: literature review which for this study, will be based on, research methodology which focuses on data sources and methodological techniques applied, the study findings and discussions, and lastly the conclusion and policy implication(s).

LITERATURE REVIEW

This study is based mainly on the Environmental Kuznets Curve (EKC) economic theory. According to (Kuznets, 1995), the EKC theory suggests an inverted U-shaped relationship between environmental degradation and economic growth. As the country's income per capita increases, environmental degradation will be worse off at the initial stages before it can improve because the increase in the GDP per capita means the country can now implement strict environmental regulations and invest in cleaner energy. This is usually found in more developed countries than developing countries. The nexus between economic growth, energy transition and carbon dioxide (CO2) emissions in economies, differ in terms of the challenges the countries face, meaning that these challenges require an interdisciplinary approach that considers economic, environmental, and social factors (Akizu, et al., 2017). So, economic growth and environmental sustainability can have either a positive or negative relationship based on the Environmental Kuznets Curve (EKC) hypothesis (Kuznets, 1995).

Since South African has a comparative advantage in energy, the demand, supply, and trade of coal generated energy will have an impact on the energy market (Marques, et al., 2019). The nexus in South Africa shows that economic growth will therefore impact CO_2 emissions negatively while transitioning to cleaner energy (renewable sources) might slow down economic development.

A study by Ling, et al., (2022) shows that energy transition was found to be having varying impact on CO_2 emissions, but this transition depends on financial development and environment related technologies to reduce the emissions since renewable energy on its own cannot reduce the CO_2 emissions. So, South Africa's energy transition will therefore require funds and technological expertise to mitigate CO_2 emissions causing climate change and to avoid energy insecurities since irrational policy decisions might result in high unemployment, political instability, and the fall of vital sectors such as the energy and the agricultural sector. Therefore, the studies highlight how important it is to implement strategies that will balance South Africa's economic growth, energy transition and carbon dioxide emissions.

The relationship between economic growth and CO_2 emissions exhibits both short-run and long-run dynamics, influenced by various factors including energy consumption and policy decisions. Understanding these relationships is crucial for formulating effective environmental policies.

In the short run, economic growth often correlates with increased CO_2 emissions due to heightened energy consumption, particularly from fossil fuels (Febo, et al., 2023). Studies by Supron & Łącka (2023). indicate that while economic growth can drive emissions, the immediate effects vary by region, as seen in the Visegrad Group countries (Czech Republic, Hungary, Poland and Slovakia) where short-run relationships between economic growth and emissions were observed.

Long-term analyses reveal a more complex interaction. The Environmental Kuznets Curve (EKC) hypothesis posits that as economies develop, emissions initially rise but eventually decline; however, based it was shown in Kivedal (2023), that evidence supporting this is mixed, with some studies indicating that GDP primarily influences emissions in the short run and not necessarily in the long run.

Research by the University of Cape Town Energy Research Centre indicated a declining CO_2 emission as the economy grows, however, studies by Rahman, et al., (2022) along with Massagony and Budiono (2022) found a positive relationship between economic growth and environmental degradation in both the short run and the long run. The autoregressive distributed lag (ARDL) model shows that GDP growth positively correlates with CO_2 emissions, indicating that as the economy expands, emissions tend to rise (Bekun, et al., 2023).

A study by Begum, et al., (2015) supports the two studies because of the South African economy's heavy reliance on coal for energy generation. Despite these insights, South Africa faces significant challenges in achieving its climate goals due to its dependence on fossil fuels and limited resources for a comprehensive energy transition (Ignatov, 2023). According to Ngcobo and De Wet (2024), in the short run, economic growth and energy consumption are closely linked, with coal power generation being a major contributor to CO_2 emissions while the long run indicate that economic growth positively correlates with CO_2 emissions, primarily due to urbanization and industrial activities. Thus, transitioning to renewable energy is essential for sustainable growth, as financial development and economic growth positively impact renewable energy supply.

The relationship between energy transition and CO emissions is multifaceted, as evidenced by various studies. Energy transition, characterized by a shift towards cleaner energy sources, significantly contributes to reducing CO_2 emissions across different sectors. For instance, the use of renewable energy can mitigate CO_2 emissions despite economic growth, suggesting a potential decoupling of growth from emissions over time (Febo, et al., 2023).

In developed economies such as the USA, energy transition effectively curbs emissions in the building and transport sectors, although its impact is less pronounced in industrial and power sectors (Kartal, et al., 2024). Thus, clean energy consumption positively and significantly affects CO_2 emissions, indicating that as clean energy use increases, CO_2 emissions decline in the context of transition countries. Likewise, in OECD countries, a 1% increase in clean energy production correlates with a 0.33% reduction in CO_2 emissions in the short run (Zambrano-Monserrate, 2023).

In countries like China, which is still developing, the interplay between economic growth and energy consumption reveals that renewable energy utilization is crucial for mitigating emissions, emphasizing the need for robust energy transition programs (Xie & Bui, 2024). Technological change can reduce CO_2 emissions, while improved energy intensity leads to lower emissions, with structural changes acting as catalysts for green innovation and energy transition. Thus, the role of energy transition is to impact CO_2 emissions. The relationship between economic growth, energy transition, and CO_2 emissions in South Africa is complex and multifaceted. Research indicates that while economic growth can lead to increased CO_2 emissions, transitioning to renewable energy sources is essential for mitigating these emissions.

A study by Saba (2023) shows that there is a causal relationship between CO_2 emissions, energy consumption and economic growth in South Africa, with the emphasis on its defence, energy, growth, and environmental policies that promote environmental sustainability in both short-term and long-term. This backs-up the study by Espoir, et al., (2023), that South Africa's economic growth shows a negative impact on CO_2 emission in the long run, which supports the EKC hypothesis, emphasizing on the importance of integrated policy that is, energy transition. The integration of renewable energy strategies alongside economic development is essential for achieving long-term sustainability goals (Saba, 2023).
Udeagha and Muchapondwa (2022) proved a positive relationship between economic growth and energy transition in South Africa on the basis that its renewable energy expansion allows

them gain technological advancement and trade openness. Meaning that this highlights that South Africa it is on the final stage of the EKC which is the green stage, however, Begum, Sohag, Abdullah, and Mokhtar (2015) argues that there is a negative relationship between economic development and environmental sustainability. According to the International Energy Agency (2021), South Africa's large portion of electricity generation is coal based, contradiction the study by (Udeagha & Muchapondwa, 2022). Despite the potential for renewable energy to reduce emissions, studies reveal that renewable energy consumption has not significantly mitigated CO2 emissions in South Africa (Saba, 2023).

Therefore, while economic growth poses challenges for CO2 emissions, the path to a sustainable energy transition in South Africa requires overcoming significant barriers, emphasizing the need for comprehensive policy frameworks that support both economic and environmental objectives.

RESEARCH METHODOLOGY

The study employed the Autoregressive Distributed Lag (ARDL) and Granger causality approach to meet its objectives as well as answering the research questions that rose during the study. Thus, this section focuses on the econometrics steps ranging from the data type, model specification and the estimations techniques.

Data

The study employed annual time series secondary data from 1991 to 2020. The data was collected from the World Bank database, with in-depth details on Table 3.1. Carbon Dioxide Emission (CO2) is measured in units of metric tons per capita while GDP Growth (GDP), Population Growth (P), Trade (TR), and Renewable Energy Consumption (REC) are measured in percentages.

Table 1. Sources of Data

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Variables	Definition	Sources of data	Measurement
CO_2 Emissions (CO2)	Emissions stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	World Bank	Metric tons per capita
GDP Growth (GDP)	Annual percentage growth rate of GDP at market prices based on constant local currency.	World Bank	Percentages (%)
Population Growth (P)	Annual population growth rate for year t is the exponential rate of growth of midyear population from year t-1 to t, expressed as a percentage.	World Bank	Percentages (%)
Trade Openness (TR)	Trade is the sum of exports and imports of goods and services measured as a share of gross domestic product.	World Bank	Percentages (%)
Renewable Energy Consumption (REC)	Renewable energy consumption is the share of renewable energy in total final energy consumption.	World Bank	Percentages (%)

Dummy Variable (DUM)	A variable added to account for structural breaks	Author's computations	0 and 1
Source: Author's computations			

Source: Author's computations

Model Specification

This research focuses on the nexus between economic growth, energy transition and carbon dioxide emissions in the South African context for the period 1991 to 2020. The research is based on the conclusion intimated by Kuznets (1995) that economic growth and environmental sustainability can have either a positive or negative relationship based on the Environmental Kuznets Curve (EKC) hypothesis. This is given by the inverted U-shaped relationship between the economic development and environmental degradation. Therefore, this nexus revolves around the EKC theory.

The theoretical model which was suggested by the EKC theory is as follows:

$CO_2 = f\,(GDP_t, P_t, TR_t, REC_t, DUM_t)$.. 1

Where:

- CO_2 = Carbon Dioxide Emission
- GDP =GDP Growth
- P = Population Growth
- TR = Trade (% of GDP)
- REC = Renewable Energy Consumption
- DUM = Dummy variable

Table 2. Priori Expectations

Variables	Expectations	Author
CO_2 & GDP	Generally, economic growth tends to correlate with increased CO2 emissions, as evidenced by findings that show a positive correlation between GDP growth and emissions across different countries and time periods	(Fu, 2023)
CO_2 & P	The relationship between carbon dioxide emissions and population growth is complex, with several studies indicating that population dynamics significantly influence emissions levels.	(Casey & Galor, 2016)

CO_2 & TR	Prior expectations suggest that trade openness may initially lead to increased CO_2 emissions due to heightened economic activity and energy consumption, as indicated by the inverted U-shaped relationship found in some research.	(Dou, et al., 2020)
CO_2 & REC	The relationship between carbon dioxide emissions and renewable energy consumption is characterized by a priori expectations that increased renewable energy use will lead to a reduction in CO2 emissions	(Mukhtarov, et al., 2023)
Source: Author's computations		

Table 2 shows the priori expectations the study can expect to get after running tests, with relationships of the independent and dependent variables. By having these expectations, it makes it easier to evaluate the validity of the models and refine the economic phenomena.

And the linear representation of the model is as follows:

$CO_2 = \alpha_0 + \beta_1 GDP_t + \beta_2 P_t + \beta_3 TR_t + \beta_4 REC_t + DUM_t + \varepsilon_t$..2

Where:

- α_0 = Constant/intercept
- $\beta_1, \beta_2, \beta_3, \beta_4$ = Coefficients of the estimated model
- ε_t = Disturbance error term

Estimation Techniques

The study employed Autoregressive Distributed Lag (ARDL), and Granger causality techniques establish a model on the nexus between economic growth, energy transition and carbon dioxide emissions in South Africa. However, the stationarity (unit root) tests were conducted as step for appropriate selection model criteria.

Stationarity/Unit Root Tests

This study will employ the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) tests as formal tests, and the line graph and correlogram tests as informal tests for stationarity before testing for cointegration. It is because the order of integration amongst the series is important when deciding whether VECM, OLS, ARDL, Granger causality, and Johansen techniques should be employed. And two stationarity tests (ADF & PP) are run to reach the robustness of variety of serial correlation and time dependent heteroscedasticities.

Therefore, the formal unit root rest will use the following AR:

Y_t= α+ ∅Y_(t-1)+e_t -1≤p≤1 3

where e_t is the white noise term.

Cointegration Analysis

These techniques are used to test how valid is the long-run equilibrium relationship between the variables employed in the research. So, post stationarity testing when the order of integration is known, it becomes easier to know the technique which is appropriate to employ to understand the long-run relationship between variables.

Meaning that if the entire series is integrated of order zero (I0), the OLS model is applicable. But, if the entire series is integrated of order one (I1), then the Johansen and Juselius model is applicable. However, if the series is integrated at different order, then the ARDL model might be an appropriate application. For the purposes of this study, the study adopts the ARDL Bounds test for cointegration.

Autoregressive Distributed Lag (ARDL)

The ARDL is another type of time series model which can be used to test for cointegration between variables and it does so by modelling the long-run and short-run dynamics simultaneously. Meaning this can be used as an alternative to the VECM and the Granger causality test if variables are integrated at different orders. And besides testing for cointegration, it can be used to estimate the speed of adjustment to the long-run equilibrium between variables. Therefore, this study is employing ARDL because the variables are integrated at order zero (I0) and one (I1).

Granger Causality

Granger causality is a statistical concept used to determine whether one time series can predict another, with various methodologies enhancing its application across fields. It is based on the principle that if a variable-X granger-causes another variable-Y, then past values of X should provide information that helps predict future values of Y. The basic idea is to regress Y on its own past values and the past values of X. If the inclusion of past values of X significantly improves the prediction of Y compared to using only the past values of Y, then X is said to granger-cause Y.

Mathematically, it can be presented by the following two equations:

$$Y_t=\alpha_0+\alpha_1 Y_{t-1}+\alpha_2 Y_{t-2}+\cdots+e_t \quad 4$$

$$Y_t=\beta_0+\beta_1 Y_{t-1}+\beta_2 Y_{t-2}+\cdots+c_1 X_{t-1}+c_2 X_{t-2}+\cdots+e_t \quad 5$$

Where equation (4) is the equation for Y and equation (5) is the equation for Y including X. If the coefficients c1, c2, are statistically significant, we reject the null hypothesis that X does not granger-cause Y.

Granger causality does not imply true causation in a philosophical sense; it merely indicates a predictive relationship based on historical data. It is important to note that Granger causality can be one-way (unidirectional) or two-way (bidirectional), where both variables can predict each other.

Diagnostic Testing

Diagnostic tests are used to verify the reliability and efficiency of a time series model. These tests are crucial to see if the time series follows the assumption of the Ordinary Least Squares (OLS) techniques or it violates those assumption because according to Gujarati and Porter (2009), a time series model should suffice assumptions of the classical linear regression model. So, to make sure that the assumptions are met, a battery of diagnostic test which includes the Normality, Heteroscedasticity, Serial Correlation, and Misspecification tests must be ran.

The normality test is used in determining whether sample data are drawn from normal or non-normal residuals. Residuals with zero mean and variance are considered as normally distributed because if they are not distributed normally the estimators might not succumb to normal distribution, which can temper with their consistency along the tests. This test is conducted with a JARQUE BERA TEST by measuring the variable's difference of kurtosis and skewness. And according to the rule of thumb, we reject the null hypothesis (H0), that is Variable is normally distributed if its test-statistic (p-value) is less than the level of significance. Meaning the variable is normally distributed when the test-statistic if greater than the level of significance.

Heteroscedasticity is a violation of the OLS assumption that the error term must be homoscedastic, meaning it should have a constant variance for a variable to be normally distributed. So, heteroscedasticity might be due to over-differencing, the data has outliers or there is an improved technique to collect data. The test is conducted through Engle's Arch Lm Test, Harvey, Breusch Pagan Godfrey and The White's Heteroscedasticity Test. And the rule of thumb states that we reject the null hypothesis (H0), that is No heteroscedasticity when the test-statistic (p-value) is less than the level of significance. Meaning that the error term has a constant variance (homoscedastic).

Stability Testing

Stability test is used to check for the robustness of the time series model over time because an unstable model could produce spurious results. For this test the Cumulative Sum of Squared Residuals (CUSUM) and Cumulative Sum of Recursive Residuals (CUSUM of Squares) tests. So, when the plots of the CUSUM and CUSUM of Squares lies within the critical lines of 5% level of significance, the equation's parameters are stable to estimate the long-run relationships that exist in the model.

EMPIRICAL RESULTS AND DISCUSSION

In this section, all the econometric tests conducted, and their results will be discussed as the study has undertaken the ARDL techniques to achieve its objectives.

Empirical Results

Stationarity/Unit Root Tests

This study employs the Augmented Dickey-Fuller (ADF) in Table 3 and the Phillips-Perron (PP) tests in Table 4 as formal tests and according to Pesaran et al. (2001), these two stationarity tests are run to test the robustness of a variety of serial correlation and time dependent heteroscedasticities. So, post stationarity testing when the order of integration is known, it becomes easier to know the technique which is appropriate to employ to understand the long-run relationship between variables.

Table 3. Augmented Dickey Fuller (ADF)

VARIABLE	MODEL	LAG LENGTH	T STATISTIC	P – VALUE	ORDER OF INTEGRATION	DECISION
CO_2	Intercept	7	-1.4678	0.5349	I (0)	Not Stationary
	Intercept & Trend	7	-0.2414	0.9887	I (0)	
	None	7	0.2156	0.7417	I (0)	
D (CO_2)	Intercept	7	-4.7409	0.0007	I (1)	Stationary
	Intercept & Trend	7	-5.2435	0.0012	I (1)	
	None	7	-4.7830	0.0000	I (1)	
GDP	Intercept	7	-1.6748	0.4329	I (0)	Not Stationary
	Intercept & Trend	7	-1.7845	0.6861	I (0)	
	None	7	-1.4075	0.1449	I (0)	
D (GDP)	Intercept	7	-4.4490	0.0014	I (1)	Stationary
	Intercept & Trend	7	-5.0979	0.0016	I (1)	
	None	7	-4.5854	0.0000	I (1)	
P	Intercept	7	-3.5968	0.0122	I (0)	Noy Stationary
	Intercept & Trend	7	-2.9470	0.1640	I (0)	
	None	7	-1.4460	0.1352	I (0)	
D (P)	Intercept	7	-6.1775	0.0000	I (1)	Stationary
	Intercept & Trend	7	-6.5075	0.0001	I (1)	
	None	7	-6.1692	0.0000	I (1)	
TR	Intercept	7	-2.0990	0.2464	I (0)	Not Stationary
	Intercept & Trend	7	-2.4679	0.3402	I (0)	
	None	7	0.3156	0.7701	I (0)	
D (TR)	Intercept	7	-6.0320	0.0000	I (1)	Stationary

	Intercept & Trend	7	-5.2160	0.0017	I (1)	
	None	7	-6.0206	0.0000	I (1)	
REC	Intercept	7	-1.8503	0.3497	I (0)	Not Stationary
	Intercept & Trend	7	0.0937	0.9956	I (0)	
	None	7	-1.7776	0.0720	I (0)	
D (REC)	Intercept	7	-2.9107	0.0568	I (1)	Stationary
	Intercept & Trend	7	-3.2556	0.0945	I (1)	
	None	7	-2.6404	0.0102	I (1)	
DUM	Intercept	7	-5.9211	0.0000	I (0)	Stationary
	Intercept & Trend	7	-4.9174	0.0027	I (0)	
	None	7	-1.8490	0.0622	I (0)	
D (DUM)	Intercept	7	-5.9636	0.0000	I (1)	Stationary
	Intercept & Trend	7	-5.8236	0.0003	I (1)	
	None	7	-6.0179	0.0000	I (1)	
Source: Author's computations using EViews 12						

Source: Author's computations using EViews 12

Table 4. Phillips Perron (PP)

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VARIABLE	MODEL	T STATISTIC	P VALUE	ORDER OF INTEGRATION	DECISION
CO_2	Intercept	-1.4456	0.5462	I (0)	Not Stationary
	Intercept & Trend	0.3327	0.9979	I (0)	
	None	0.2342	0.7471	I (0)	
D (CO_2)	Intercept	-4.7414	0.0007	I (1)	Stationary
	Intercept & Trend	-5.2123	0.0012	I (1)	
	None	-4.7830	0.0000	I (1)	
GDP	Intercept	-1.7503	0.3952	I (0)	Not Stationary
	Intercept & Trend	-1.0105	0.9269	I (0)	
	None	-1.4340	0.1383	I (0)	
D (GDP)	Intercept	-4.3003	0.0023	I (1)	Stationary
	Intercept & Trend	-5.4072	0.0008	I (1)	
	None	-4.4605	0.0001	I (1)	

P	Intercept	-3.7722	0.0080	I (0)	Stationary
	Intercept & Trend	-3.2281	0.0988	I (0)	
	None	-1.8721	0.0593	I (0)	
D (P)	Intercept	-6.2388	0.0000	I (1)	Stationary
	Intercept & Trend	-9.8889	0.0000	I (1)	
	None	-5.9459	0.0000	I (1)	
TR	Intercept	-2.0104	0.2810	I (0)	Not Stationary
	Intercept & Trend	-2.2382	0.4522	I (0)	
	None	0.8070	0.8812	I (0)	
D (TR)	Intercept	-7.4327	0.0000	I (1)	Stationary
	Intercept & Trend	-11.5156	0.0000	I (1)	
	None	-6.1177	0.0000	I (1)	
REC	Intercept	-1.0961	0.7036	I (0)	Not Stationary
	Intercept & Trend	-0.7973	0.9543	I (0)	
	None	-1.7039	0.0834	I (0)	
D (REC)	Intercept	-2.9107	0.0568	I (1)	Stationary
	Intercept & Trend	-3.1948	0.1000	I (1)	
	None	-2.5320	0.0134	I (1)	
DUM	Intercept	-5.8932	0.0000	I (0)	Stationary
	Intercept & Trend	-16.3553	0.0000	I (0)	
	None	-4.6719	0.0000	I (0)	
D (DUM)	Intercept	-30.0223	0.0001	I (1)	Stationary
	Intercept & Trend	-29.0465	0.0000	I (1)	
	None	-25.9966	0.0000	I (1)	
Source: Author's computations using EViews 12					

Source: Author's computations using EViews 12

The study could not be based only on informal unit root tests, hence the formal unit root tests such as ADF and PP were also performed. The summarized test results for each series are presented in the Table(s) 3. and 4. above and were solely tested on intercept and trend, none and intercept because the model with these parameters is the least restricted. The results of both tests shows that the variables are integrated at order I(0) and I(1). And according to Pesaran (1999) the unit root test becomes valid only if the results are stationary and are integrated of order I(0) and I(1) as per ARDL requirements. The ADF and PP test highlight that only the Population growth (P) is stationary at level whereas the Carbon dioxide emission (CO2), Economic growth (GDP), Trade openness (TR), and Renewable energy consumption (REC) are stationary at first difference. And they are statistically significant at 1%, 5%, and 10% levels of significance.

Autoregressive Distributed Lag (ARDL)

Cointegration bound test is simply a method that is used to determine whether a long run relationship exists between two or more variables in time series.

Table 5. ARDL Bound Test		
Test Statistic	**Value**	**K**
F-Statistic	25.63308	5
Critical Value Bounds		
Significance	I (0) Bound	I (1) Bound
10%	2.08	3.00
5%	2.39	3.38
2.5%	2.70	3.73
1%	3.06	4.15
Source: Author's computations using EViews 12		

In Table 5, the ARDL bound test on five variables was ran hence is k value is 5. These variables are presented in two sections, that is, integrated of order zero (lower bound) and one (upper bound). And according to the decision criteria of bound test, both Pesaran et al. (2001) and Narayan (2005), states that if the F-statistic is greater than the critical value of the upper bound I(1), we can conclude by saying there is cointegration.

And it was found that the F-statistics is higher than any of the critical values at 1%,2.5%,5%, and 10% respectively which means it is above the I (0) and I (1) orders of integration hence the rejection of the null hypothesis that there is no cointegration. Therefore, there is a long run relationship between the variable in the model.

Long run coefficient results

After establishing the existence of long run relationship using the bounds tests, the long run coefficient was then estimated on Table 6 below.

Table 6. Long run coefficients				
VARIABLE	**COEFFICIENT**	**STD.ERROR**	**T-STATISTIC**	**PROB.**
GDP	0.375218	0.060905	6.160723	0.0086
P	-0.090829	0.340838	-3.200435	0.0493
TR	0.208146	0.052002	4.002661	0.0280
REC	0.076844	0.071179	1.079595	0.3594
DUM	-2.955633	0.672615	-4.394245	0.0218
C	-2.510255	2.967263	-0.845963	0.4597

Source: Author's computations using EViews 12

Table 6. shows the long run relationship coefficients between the dependent variable (CO2) and the independent variables (GDP, P, TR, REC, and DUM). In the long run, a 1% increase of economic growth will lead to 0.38% increase in carbon dioxide emissions which meets the priori expectations based on the EKC theory as per the argument of (Kuznets, 1995). This is consistent with studies by (Rahman et al., 2022) and the stated priori expectations by (Fu, 2023). The stated studies used both VECM and ARDL to determine whether the EKC hypothesis was valid on carbon dioxide emissions.

Secondly, a 1% increase of trade openness will lead to a 0.21% increase in carbon dioxide emissions in the long run which meets the priori expectations of (Dou, et al., 2020). This is consistent with (Oğuz, 2024). The stated study proved that trade openness has a direct and significant on carbon dioxide emissions, thus suggesting a relationship were trade influences carbon dioxide emissions.

Thirdly, 1% increase of population growth will lead to a 0.09% decrease in carbon dioxide emissions in the long run which is not in line with the priori expectations based on the study by (Casey & Galor, 2016). It is in contradiction to Daramola (2021) which found a significant negative relationship between carbon dioxide emissions and population growth.

Also, in the long run 1% increase renewable energy consumption will lead to 0.08% increase in carbon dioxide emissions which is not in line with the priori expectations based on the study by Mukhtarov, et al., (2023). However, the study by Ofori-Sasu et al. (2023) shows that the relationship between carbon dioxide emissions and renewable energy consumption is U-shaped, with an initial increase in emissions with higher renewable energy use, then decrease beyond a certain threshold.

Lastly, the presence of structural breaks, represented by the dummy variable, indicates that significant events (like the COVID-19 pandemic) can lead to a 2.96% decrease in emissions. This highlights the impact of external shocks on emission levels and suggests the need for policies that consider such structural changes. Thus, going back to the introduction of the study, statistics from StatsSA (2023) revealed that carbon dioxide emissions dropped from 476.4 million metric tons in 2019 to 455.6 million metric tons in 2020, which was because of the Covid-19 pandemic.

Short run coefficients

Table 7. Short run coefficients

VARIABLE	COEFFICIENT	STD.ERROR	T-STATISTIC	PROB.

D(GDP)	0.091714	0.008572	10.69894	0.0017
D(P)	-0.552034	0.035805	-15.41781	0.0006
D(TR)	-0.000777	0.002555	-0.303904	0.7811
D(REC)	0.149222	0.022464	6.642698	0.0070
D(DUMMY)	-0.683488	0.035753	-19.11671	0.0003
CointEq (-1)	-0.616623	0.026577	-23.20118	0.0002
Source: Author's computations using EViews 12				

Table 7 shows that there is a significant short run positive relationship between GDP growth and carbon dioxide emissions. This meets the priori expectations by (Fu, 2023), meaning at the early stages of development we can expect significant rise in both the growth rate and environmental degradation as stipulated by the inverted U-shape.

Also, there is a significant negative relationship in the short run since a 1% increase in population growth will decrease carbon dioxide emissions by 0.55%. This relationship assumes that more human capital is necessary to mitigate the carbon dioxide emissions. There is also an insignificant negative relationship in the short run between trade openness and carbon dioxide emissions because a 1% increase in trade openness will result in a 0.00078% decrease in carbon dioxide emissions. This contradicts the relationship that the two variables are set to have in the long run and the impact is very negligible.

Also, a 1% increase renewable energy consumption will lead to a 0. 15% increase carbon dioxide emissions which is not in line with the priori expectations based on the study by Mukhtarov, et al., (2023). However, the short run relationship is significant. The presence of structural breaks within the economy will results in a 0.68% decrease in carbon dioxide emissions in a significant short run relationship.

The error correction term is negative as expected, highly significant at 1% and is reported at -0.62%. This means that the estimated model can adjust fast and converges towards equilibrium at a speed of approximately 62%.

Granger Causality

Table 8. Granger Causality Results		
Null Hypothesis	Probability value	Conclusion
GDP does not Granger Cause CO2	0.0484	Reject H_0

CO2 does not Granger Cause GDP	0.3512	Do not reject H_0
DUM does not Granger Cause CO2 CO2 does not Granger Cause DUM	0.3217 0.1375	Do not reject H_0 Do not reject H_0
P does not Granger Cause CO2 CO2 does not Granger Cause P	0.1486 0.4537	Do not reject H_0 Do not reject H0
REC does not Granger Cause CO2 CO2 does not Granger Cause REC	0.0003 0.3637	Reject H_0 Do not reject H0
TR does not Granger Cause CO2 CO2 does not Granger Cause TR	0.7303 0.2154	Do not reject H0 Do not reject H0
DUM does not Granger Cause GDP GDP does not Granger Cause DUM	0.2251 0.1426	Do not reject H0 Do not reject H0
P does not Granger Cause GDP GDP does not Granger Cause P	0.5992 0.7596	Do not reject H0 Do not reject H0
REC does not Granger Cause GDP GDP does not Granger Cause REC	0.0186 0.3812	Reject H_0 Do not reject H0
TR does not Granger Cause GDP GDP does not Granger Cause TR	0.0042 0.0473	Reject H_0 Reject H_0
P does not Granger Cause DUM DUM does not Granger Cause P	0.8567 0.9763	Do not reject H0 Do not reject H0
REC does not Granger Cause DUM DUM does not Granger Cause REC	0.0197 0.6390	Reject H_0 Do not reject H0
TR does not Granger Cause DUM DUM does not Granger Cause TR	0.0133 0.3569	Reject H_0 Do not reject H0
REC does not Granger Cause P P does not Granger Cause REC	0.7997 0.3557	Do not reject H0 Do not reject H0
TR does not Granger Cause P	0.8359	Do not reject H0

P does not Granger Cause TR	0.4912	Do not reject H0
TR does not Granger Cause REC REC does not Granger Cause TR	0.4431 0.0053	Do not reject H0 Reject H_0
Source: Author's computations using EViews 12		

Table 8 was used to achieve the second objective, that is the causality between economic growth, energy transition and carbon dioxide emissions. This study rejects the null hypothesis of GDP not granger causing CO2, meaning that is the basis of accepting the alternative hypothesis that GDP does granger cause CO2 in a unidirectional relationship. This simply shows that any attempt of growing the GDP will have an impact on the dynamics of the CO2, whereas vice versa the GDP cannot be impacted by CO2 changes.

Similarly, the causal relationship between REC and CO2 is also unidirectional. Even when looking at the priori expectations, it would not make sense that changes in REC will be entirely dependent on CO2. However, the results show that any change in REC will be the one significantly impacting CO2. Therefore, the overall results suggests that GDP and REC have significant impact on CO2 whereas the same cannot be assumed about CO2 on GDP and REC.

Diagnostic Testing

Table 9. Diagnostic Tests

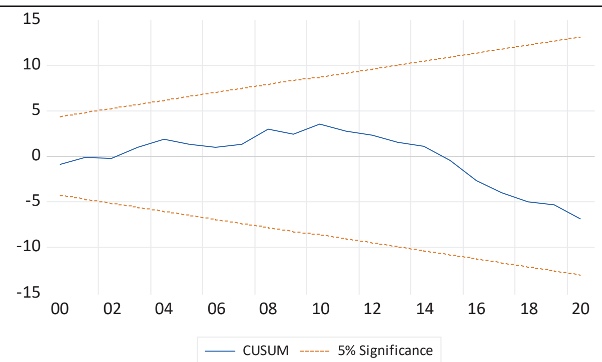
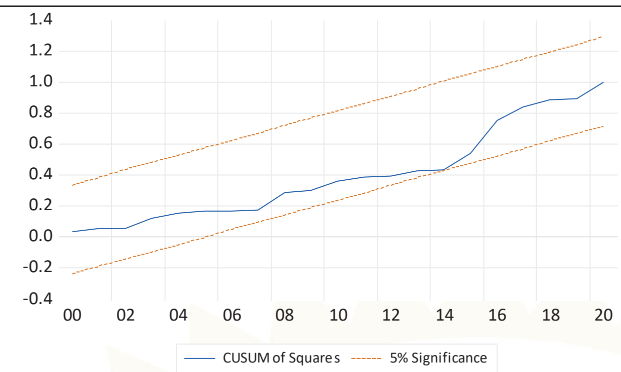
Test	**Null hypothesis**	**T statistic**	**P-value**	**Decision**
Jarque-Bera	Variables are normally distributed	0.8729	0.6463	Do not reject the null hypothesis at all significance levels
Engle's Arch LM	No Arch heteroscedasticity	0.4679	0.4822	Do not reject the null hypothesis at all significance levels
White's Heteroscedasticity	No heteroscedasticity	0.8432	0.4912	Do not reject the null hypothesis at all significance levels
Breusch Pagan Godfrey	No heteroscedasticity	0.5661	0.6746	Do not reject the null hypothesis at all significance levels
Harvey	No heteroscedasticity	0.6431	0.6167	Do not reject the null hypothesis at all significance levels
Breusch Godfrey LM	No serial correlation	1.9370	0.1058	Do not reject the null hypothesis at all significance levels

Source: Author's computations using EViews 12

In Table 9, a battery of diagnostic tests was run. Firstly, the normality test was run using the Jarque-Bera test, and the results led to the acceptance of the null hypothesis that the variables are normally distributed. The model also surpassed any traces of heteroscedasticity as all the results from the four tests has led to also accepting the null hypothesis that there is no heteroscedasticity in the model. There were also no traces of serial correlation and misspecification as the results also led to the acceptance of the null hypotheses. indicate the model meets the assumptions of the Ordinary Least Squares (OLS) method.

Stability Testing

Table 10. Stability Tests

Table 10. Stability Tests	
CUSUM	CUSUM of SQUARES
	

In Table 10, the CUSUM and the CUSUM of squares, both represented by the blue lines lies between the 5% significance boundaries, represented by the red dotted lines, implying that the model is stable.

CONCLUSION

The aim of this study was to investigate the nexus between economic growth, energy transition and CO2 emission in South Africa for the period 1991 to 2020. This analysis proved that economic growth directly leads to environmental degradation through an increase in CO2 emission through a significant long run relationship. To get to this analysis, the study employed the ARDL approach since when the running the unit root tests, both formal and informal, the variables were said to be integrated at different orders, thus a justification of selecting the ARDL (Pesaran, et al., 1999). The ARDL bound test has found cointegration in the model, making it now possible to determine the long and short run relationship between economic growth and energy transitions.

Thus, shows South Africa needs to mitigate its emissions, hence, the emphasis on energy transition by the study which will foster the SGD no.13 that is, Climate action. These findings will have significant implications for policymakers and environmentalists, emphasizing the need for balanced strategies that promote environmental preservation and sustainable economic growth. Therefore, the study recommends that the policymakers should prioritize investments in renewable energy infrastructure to reduce reliance on coal and lower CO2 emissions, thereby promoting sustainable economic growth. Given the mixed results regarding the relationship between economic growth and environmental degradation, tailored policies that balance economic development with environmental sustainability are essential. This might include regulations that incentivize green technologies and penalize high-emission practices. These recommendations aim to create a framework that encourages sustainable economic practices while addressing the environmental concerns highlighted in the study.

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