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# Assessing the Impact of Energy Sources and Macroeconomic Factors on Environmental Sustainability: Evidence from South Africa

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**ABSTRACT**

This study examines the role of energy sources and macroeconomic factors in environmental sustainability in South Africa, utilizing time series data from 1985 to 2024. The primary objective is to investigate the impact of different energy sources, electricity prices, economic growth, population growth, and inflation on $CO_2$ emissions and greenhouse gas emissions. The study employs Vector Error Correction Model (VECM) and Autoregressive Distributed Lag (ARDL) models to analyze the short-run and long-run relationships between energy consumption, energy generation, economic growth, and environmental sustainability. The key findings indicated that a negative statistically significant relationship exists between electricity prices and $CO_2$ emissions in the short run, but electricity prices increase greenhouse gas emissions in the long run. Renewable energy has a significant negative impact on $CO_2$ and greenhouse gas emissions, promoting environmental sustainability. Economic growth increases $CO_2$ and greenhouse gas emissions, supporting the Environmental Kuznets Curve hypothesis. Population growth increases $CO_2$ and greenhouse gas emissions in the long run. Nuclear power has a positive impact on $CO_2$ and greenhouse gas emissions, contradicting some previous studies. The study's policy recommendations include implementing pricing mechanisms that encourage energy conservation and reduce emissions. Investing in renewable energy sources like solar and wind power to reduce dependence on non-renewable energy. Promoting sustainable economic growth by investing in green technologies and implementing policies that balance economic development with environmental protection. Developing strategies to manage population growth and its impact on the environment. Implement policies to mitigate the impacts of climate change and promote a green economy.

**Keywords:** Environmental Sustainability, Energy Sources, Macroeconomic Factors, Climate Action, South Africa, SDGs 7, 8, and 13
**JEL Classifications:** C32, O44, P18, Q4, Q5

## 1. INTRODUCTION

Energy economics is a multidisciplinary field of study that examines the economic aspects of energy generation, consumption, and policy (Schmidt and Weigt, 2015). It involves analysing the interaction between energy systems, economic systems, and the environment. Environmental sustainability, nonetheless, refers to the ability of the environment to support economic development without compromising the ability of future generations to meet their own needs (Elsawy and Youssef, 2023). The concept of environmental sustainability has gained significant attention in recent years, as the globe grapples with the issues of climate change, biodiversity loss, and environmental degradation. South Africa remains one of the largest carbon emitters in Africa, largely due to its heavy reliance on fossil fuels for energy generation especially coal (Ayompe et al, 2021; Bekun et al, 2023). The relationship between energy sources, macroeconomic factors, and environmental sustainability is complex and multifaceted. Energy generation and consumption are significant contributors to environmental unsustainability, including greenhouse gas emissions, air pollution, and water pollution. However, energy is also essential for economic growth and poverty reduction. The purpose of this study is to investigate the role of energy sources and macroeconomic factors in environmental sustainability in South Africa.

The existing literature on the impact of energy sources and macroeconomic factors on $CO_2$ emissions presents conflicting results. In particular, studies by Adebayo et al. (2023), Baloch et al. (2019), Khattak et al. (2020), Liu et al. (2020), and Banday and Aneja (2020) found that renewable energy does not reduce $CO_2$ emissions in South Africa, using various econometric models. On the other hand, studies by Samour et al. (2022), Ekwueme et al. (2021), Matenda et al. (2024), and Udeagha and Ngepah (2022) found that renewable energy consumption reduces $CO_2$ emissions in South Africa. These conflicting results warrant further investigations into the relationships between energy sources and macroeconomic factors on environmental sustainability in South Africa. This study differentiates from existing studies by checking the impact of energy sources and macroeconomic factors on environmental sustainability in South Africa by using both $CO_2$ and greenhouse gas emissions as dependent variables.

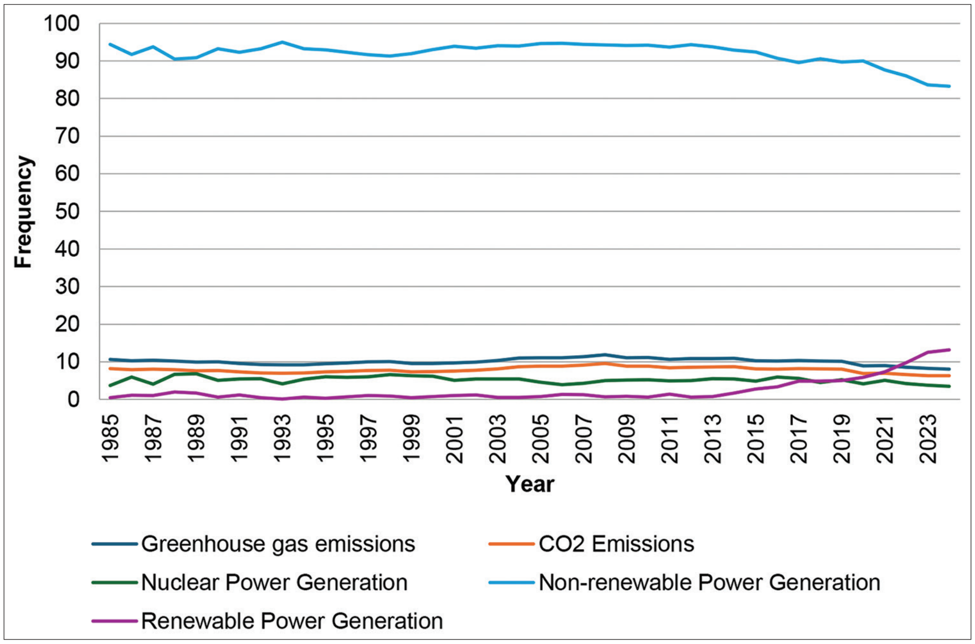
South Africa is one of the largest economies on the African continent, and its energy sector plays a pivotal role in driving economic growth and development. However, the country's reliance on fossil fuels has significant environmental implications, including high levels of greenhouse gas emissions and air pollution. Additionally, while this reliance has historically supported industrial growth and job creation, it has also made the country one of the top emitters of greenhouse gases (GHGs) on the African continent. As the world transitions to a low-carbon economy, it is crucial to comprehend the role of energy esources and macroeconomic factors in promoting environmental sustainability in South Africa (Kabeyi and Olanrewaju, 2022). Therefore, understanding the role of energy sources and macroeconomic factors in environmental sustainability is important for developing policies that balance economic growth with environmental protection. According to Xia et al. (2022), while energy is a vital input for economic development, its production and consumption often result in significant environmental externalities. According to Ntuli et al. (2024), the energy sector accounts for the bulk of South Africa's carbon dioxide emissions, raising serious concerns about the long-term sustainability of its development path. In the context of global efforts to reduce emissions and transition to cleaner energy systems, South Africa finds itself under increasing pressure to rethink its energy policy. Energy consumption and generation patterns, energy pricing structures, and the pace of economic growth are all deeply interconnected with environmental outcomes (Dilanchiev et al., 2024). For instance, Anser et al. (2024) state that rising energy consumption, often linked to expanding economic activity, may drive up emissions unless offset by cleaner energy sources or improved efficiency, and similarly, energy prices can influence consumer behaviour and industrial usage, potentially shaping the trajectory of emissions over time.

In the context of environmental sustainability, two important indicators are $CO_2$ emissions and greenhouse gas emissions. While they are often used interchangeably, these two indicators measure different aspects of environmental degradation. $CO_2$ emissions refer specifically to carbon dioxide emissions, which are a major contributor to global warming and climate change (Yoro and Daramola, 2020). On the other hand, greenhouse gas emissions refer to a broader range of gases, including $CO_2$ emissions, methane, nitrous oxide, and fluorinated gases, which contribute to global warming and climate change (Yoro and Daramola, 2020). Using these two indicators separately is important because it allows policymakers to target specific emissions reduction strategies. Recent developments in the field of environmental economics have highlighted the need to reduce $CO_2$ emissions by transitioning to renewable energy sources. However, reducing greenhouse gas emissions requires a broader approach that encompasses not only the reduction of emissions from these sources but also from agriculture, industry, and other sectors. By using both indicators separately, policymakers can develop more effective strategies for reducing environmental degradation and promoting sustainability.

From Figure 1 above, South Africa's energy sector is dominated by fossil fuels, which contribute to high levels of $CO_2$ and greenhouse gas emissions. The country's energy consumption patterns have significant environmental implications, including climate change, air pollution, and water pollution. Despite the country's commitment to reducing greenhouse gas emissions, the energy sector remains a significant contributor to environmental degradation. Previous studies have examined the relationship between energy consumption and economic growth in South Africa. However, there is a need for a more comprehensive analysis of the role of energy sources and macroeconomic factors in environmental sustainability in the country. Specifically, there is a lack of research on the impact of different energy sources, such as nuclear, renewables, and non-renewable, on environmental sustainability.

The primary objective of this study is to investigate the role of energy sources and macroeconomic factors in environmental sustainability in South Africa. Specifically, the study aims to: Firstly, investigate the impact of different energy sources, such as nuclear, renewables, and non-renewable energy, on $CO_2$ emissions and greenhouse gas emissions in South Africa. Secondly, the study aims to examine the short-run and long-run relationships between energy consumption, energy generation, economic growth, and environmental sustainability in South Africa. To achieve these objectives, the study has formulated the following research questions: Firstly, what is the impact of different energy sources, such as nuclear, renewable, and non-renewable, on $CO_2$ emissions in South Africa? Secondly, what is the impact of different energy sources, such as nuclear, renewable, and non-renewable, on greenhouse gas emissions in South Africa? Thirdly, what is the impact of electricity prices, economic growth, population growth, and inflation on both $CO_2$ emissions and greenhouse gas emissions in South Africa? Lastly, what is the short-run and long-run relationship between energy consumption, economic growth, and environmental sustainability in South Africa? The rest of the study is organized as follows: Section 2 presents the

**Figure 1:** The relationship between energy sources and environmental sustainability in South Africa from 1985 to 2024




Source: Author's computation using data from the World Bank and Our World in Data (Oxford)

literature, followed by the methodology in Section 3. Results are presented in Section 4, followed by the discussion in Section 5 and the conclusion in Section 6.

## 2. LITERATURE REVIEW

### 2.1. Theoretical Literature

The study adopted the Environmental Kuznets Curve (EKC) framework to provide a lens through which to examine how energy-related economic variables affect environmental sustainability, particularly carbon dioxide, in South Africa. The Environmental Kuznets Curve (EKC) hypothesis, originating from the broader Kuznets Curve in economics, which links income inequality to economic development, serves as the theoretical foundation for this study. According to Grossman and Krueger (1995), the EKC proposes an inverted U-shaped relationship between environmental degradation and economic growth. In the early stages of development, as income and industrialization rise, environmental degradation tends to increase (Afzal et al., 2022). However, after reaching a certain income threshold or "turning point," further economic growth leads to environmental improvements as societies shift towards cleaner technologies, enforce stronger environmental regulations, and invest in sustainable practices.

Economic growth, energy consumption, energy generation methods, and energy prices are all key elements that interact with environmental outcomes, and their effects may change depending on the stage of economic development. In the early stages of growth, for instance, increased energy consumption (often from fossil fuels) drives up emissions. As income levels rise, cleaner technologies may become more accessible, public awareness of environmental issues may increase, and governments may impose stricter environmental regulations, all of which can reduce emissions. South Africa, with its upper-middle-income status and energy-intensive economy, provides a fitting context to test the EKC hypothesis. The country's high dependence on coal, frequent energy crises, and policy ambitions for a just energy transition make it crucial to assess whether the EKC relationship holds and, if so, where the country lies on the curve (Stern, 2017). Moreover, integrating energy prices into the EKC framework adds an important dimension. Dai et al. (2025) explain that energy pricing can influence both consumption patterns and investment in renewable alternatives. By including energy prices alongside energy generation and economic growth, this study expands traditional EKC applications and deepens the understanding of how market mechanisms interact with environmental sustainability. This theoretical framework also recognizes that economic growth alone does not automatically lead to environmental improvement. The "turning point" is not guaranteed, and its realization often depends on policy choices, technological innovation, and social factors such as population growth and inflation, which are included as control variables in this study. In summary, the EKC serves as a baseline theory by providing a structured approach to understanding the non-linear and evolving relationship between economic development and environmental degradation. It helps position this research within broader global debates while offering specific insights for South Africa's energy-environment nexus.

### 2.2. Empirical Literature

Given growing global environmental challenges, understanding the nexus between energy sources and macroeconomic factors in environmental sustainability has become increasingly critical. A growing body of research explores the intersection between energy sources and macroeconomic factors in environmental sustainability. For instance, Saidi and Omri (2020) investigated 15 leading renewable energy-consuming nations from 1990 to 2014 using FMOLS and VECM methods. Their study highlighted that renewable energy promotes economic growth while reducing carbon emissions. However, they found no long-run causality between $CO_2$ emissions and renewable energy, while a bidirectional causality exists between economic growth and $CO_2$ emissions. Similarly, Li et al. (2023) employed the ARDL model to examine five major carbon-emitting nations from 1965 to 2015. They found that economic expansion and consumption of energy exert a statistically significant positive influence on $CO_2$ emissions in the short and long term, irrespective of a country's level of development. Lee (2019) explored the temporal dynamics of renewable energy use, exports, and $CO_2$ emissions within the European Union from 1961 to 2012. The analysis indicated that renewable energy use contributes to lower emissions in both the short and long run, hence confirming the effectiveness of EU climate policies.

The findings of Abbasi et al. (2022) found that renewable energy sources lead to a short-term decrease in $CO_2$ emissions in China, whereas fossil fuel consumption drives emissions higher in both the short and long run. Furthermore, it was observed that economic growth leads to a decrease in emissions in the short run, yet results in an increase over the long term. In a similar context, Bekhet and Othman (2018) studied the role of renewable energy in Malaysia from 1971 to 2015 and found an inverted N-shaped association between GDP and $CO_2$ emissions. The results also confirmed that renewable energy consumption contributes to reducing emissions. Lastly, the carbon emissions had a unidirectional causality with renewable energy usage. Moreover, in the context of green innovation, Dogan and Turkekul (2016) found that renewable energy consumption and trade openness positively contribute to environmental sustainability in the United States. This highlights the importance of trade-environment-energy linkages in energy sources and environmental sustainability debates. Saint-Akadiri et al. (2019) found that while energy consumption weakly affects environmental quality in the short run in South Africa, it significantly harms it in the long run. Bekun and Sarkodie (2019) similarly validated the energy-led growth hypothesis, noting a unidirectional causality from energy use to economic growth and an associated rise in $CO_2$ emissions.

Adebayo et al. (2023), however, found that renewable energy in South Africa does not significantly mitigate emissions, likely due to its small share in the total energy mix. This contrasts with Achuo et al. (2022), who found globally that renewable energy reduces emissions. Similarly, Kirikkaleli and Adebayo (2021) emphasized that financial development and renewable energy enhance sustainability, but economic growth increases emissions. Studies from OECD and G7 countries, such as those by Khan et al. (2022) and Ahmed et al. (2022), confirm that governance and environmental policies improve ecological outcomes, while unchecked economic growth exacerbates environmental degradation. These findings often support the Environmental Kuznets Curve (EKC) hypothesis (Destek and Sarkodie, 2019).

The determinants of $CO_2$ emissions were investigated by Nawaz et al. (2020) in nine ASEAN countries from 2000 to 2018, using pooled mean group (PMG), dynamic OLS (DOLS), and fully modified OLS (FMOLS). They discovered that rising energy usage results in higher emissions. Similar conclusions were drawn by Osobajo et al. (2020), who performed a panel analysis across 70 nations from 1994 to 2013, demonstrating the strong positive relationship between energy consumption, economic growth, and carbon emissions. Destek and Sarkodie (2019) tested the Environmental Kuznets Curve (EKC) hypothesis utilising data from 11 newly industrialised countries covering the years 1977-2023. Their findings supported an inverted U-shaped relationship between economic growth and $CO_2$ emissions, demonstrating that environmental degradation tends to rise with increasing income levels before eventually decreasing. The findings also showed that energy consumption significantly exacerbates environmental impacts. The relationship between energy consumption, $CO_2$ emissions and output in the ASEAN region from 1971 to 2015 were assessed by Chontonawat (2020). The research identified a long-run equilibrium among these factors, indicating that conservation-focused energy policies may reduce emissions without compromising economic performance.

In South Africa, Akadiri et al. (2019) employed the ARDL and Toda-Yamamoto causality to evaluate the relationship between energy consumption, ecological footprint, and economic growth from 1973 to 2014. They found that environmental degradation in South Africa is primarily influenced by per capita energy use rather than economic output, highlighting the significance of energy efficiency measures. Similarly, Usman et al. (2020) analysed environmental degradation within the Environmental Kuznets Curve paradigm in South Africa from 1971 to 2014, incorporating the influences of democracy and globalisation. Their research validated the EKC hypothesis and demonstrated long-term bidirectional causality between energy use and environmental degradation. Additionally, energy consumption was strongly correlated with emissions. Multiple studies affirm that increased energy consumption is a major driver of carbon emissions. For instance, Esso and Keho (2016) used ARDL bounds testing in Sub-Saharan Africa and found that rising energy consumption and economic growth drive up $CO_2$ emissions. Sharif et al. (2019) confirmed a positive relationship between non-renewable energy consumption and emissions in 74 countries. Kirikkaleli et al. (2022) reported that in Chile, electricity consumption and economic growth contribute to emissions. Rauf et al. (2018) and Tan et al. (2023) examined China, finding that energy consumption, particularly in agriculture and non-renewable sources, degrades environmental quality. Hu and Man (2023) highlight China's growing literature linking energy use with emissions. These studies consistently advocate for the adoption of renewable energy and improved energy efficiency to mitigate fossil fuel-driven emissions. Voumik et al. (2023) performed a comprehensive evaluation of the effects of various energy sources used for electricity and heat generation on carbon emissions in G7 nations from 1971 to 2019. The findings revealed that electricity generation from coal and natural gas significantly increases $CO_2$ emissions, with coal-based energy recognised as the most harmful to environmental quality. In contrast, energy produced from hydroelectric and other renewable sources significantly decreases emissions, highlighting its importance in climate change prevention.

A study by Voumik et al. (2022) also found the same results, that electricity generation from fossil fuels, coal, oil, and gas, substantially increases $CO_2$ emissions, with coal identified as the most environmentally detrimental source. These findings advocate for the proliferation of clean energy technologies in developed nations. The effects of renewable energy implementation and expenditures in green technologies throughout G7 nations from 1990 to 2017 were explored by Usman (2023) and determined that both the utilisation of renewable energy and higher investments in green technologies correlated with a reduction in $CO_2$ emissions. Studies have also examined the methods of energy generation and their effects on emissions. Abbasi et al. (2022) found that in China, fossil fuel energy worsens emissions, while renewable sources mitigate them, albeit mainly in the short term. Tan et al. (2015) and Wang et al. (2022) explored waste-to-energy and microalgal biorefineries, respectively, promoting them as sustainable energy generation methods. Hysa et al. (2020) and Abe et al. (2019) argued for circular economy innovations and hydrogen energy as sustainable generation alternatives. In the South African context, Inglesi-Lotz (2016) showed that renewable energy supports economic growth, further reinforcing the need to shift the country's energy generation structure. These studies recommend diversifying the energy mix with low-carbon technologies and green innovations to reduce emissions from generation.

A study by Li et al. (2020) investigated the impact of energy price changes on $CO_2$ emissions in China from 2001 to 2016. The investigation applied spatial panel data models, and the findings revealed a strong inverse correlation between energy prices and emissions, suggesting that elevated energy costs correspond to reduced carbon outputs. Conversely, Mostafaeipour et al. (2020) studied the long-term trend of carbon emissions in Iran concerning the advancement of renewable energy. The study anticipated a persistent increase in emissions, mostly propelled by escalating electricity demand due to ongoing economic growth and population growth. Ghazouani (2021) focused on Tunisia between 1972 and 2016 to assess the symmetric and asymmetric effects of per capita GDP, FDI inflows, and crude oil prices on emissions. The study employed the ARDL and NARDL models, and the findings validated the EKC hypothesis. The symmetric results demonstrated that an increase in oil prices negatively affects $CO_2$ emissions, while asymmetric results revealed that an increase in crude oil prices worsens $CO_2$ emissions. A unidirectional causality between crude oil prices to $CO_2$ emissions. The same findings were obtained by Pang et al. (2023), who demonstrated that higher gasoline prices significantly reduce both traffic congestion and carbon emissions, suggesting a beneficial role of fuel price policy in environmental management.

Li et al. (2021) further analysed the environmental implications of vertical imbalances in Pakistan from 2000 to 2018. The findings showed that greater fiscal imbalances, characterised by centralised revenue authority and decentralised expenditure responsibilities, substantially contribute to increased $CO_2$ emissions. The results underscore the necessity for fiscal reorganisation and capacity enhancement within local government tiers to improve environmental governance. Li et al. (2018) examined the marginal influence of energy prices on carbon emissions and carbon intensity across eight economic regions by employing a spatial Geographically Weighted Regression (GWR) model. The structure of energy consumption and investment was found to be the primary driver of high carbon emissions. In another study, Balsalobre-Lorente et al. (2018) found that in EU countries, higher energy prices incentivize renewable energy adoption, which in turn lowers emissions over time. These studies suggest that pricing mechanisms can serve as effective tools for shaping sustainable energy demand. Though less frequently explored, some studies have linked energy prices to emissions outcomes. Dai et al. (2025), within the EKC framework, argue that energy prices influence consumption patterns and investments in clean energy. Higher prices may drive energy efficiency and shift demand toward renewables. Energy prices are implicitly discussed about market mechanisms affecting environmental outcomes, especially in countries transitioning to cleaner energy. While more empirical work is needed in this area, these findings suggest that policy-regulated energy pricing could serve as a tool to reduce emissions by influencing consumption behaviour.

The empirical literature examined the relationships among energy consumption, energy generation, energy price, and $CO_2$ emissions in different countries. Numerous studies affirm that fossil fuel usage, especially coal and natural gas, significantly contributes to increasing carbon emissions, whereas renewable energy sources, such as hydro, are essential for mitigating environmental damage. Mitigating $CO_2$ emissions are contingent not only on the shift from fossil fuels to renewable energy sources but also on proficient governance and strategic fiscal policies. Despite growing awareness of these links, empirical research that quantifies the role of energy sources and macroeconomic factors in environmental sustainability in South Africa remains limited. There is a need for evidence-based insights to guide decision-making, particularly in identifying which economic levers have the most significant impact on emissions reduction. This study aims to fill that gap by examining the relationship between energy consumption, energy generation, energy prices, and economic growth's impact on greenhouse gas emissions and $CO_2$ emissions, while controlling for inflation and population growth. The central problem addressed in this research is the lack of an integrated understanding of how energy sources and macroeconomic factors influence carbon emissions in South Africa. Without this knowledge, policy interventions may remain fragmented, failing to deliver meaningful reductions in environmental harm or support a just energy transition (Heffron and Sokołowski, 2024). By shedding light on these dynamics, the study seeks to contribute to the formulation of more sustainable energy and economic policies tailored to the South African context

## 3. METHODOLOGY

### 3.1. Research Design and Data Collection

The study's objective is to examine the role of energy sources and macroeconomic factors in environmental sustainability in South Africa using data from reputable secondary sources such as Eskom, the World Bank, and Our World In Data (Oxford), spanning from 1985 to 2024. The data for the variables given in Table 1 will be transformed into logarithms for variables such as $CO_2$ and greenhouse gas emissions, that is not in percentages.

**Table 1: Data sources and variable descriptions**

| Variable | Description | Unit | Source |
|---|---|---|---|
| LEG | GDP per capita growth (annual) | Percentage | World Bank |
| LNUC | Nuclear power | % of electricity | Our World in Data (Oxford) |
| LNRE | Non-renewable energy from fossil fuels | % of electricity | Our World in Data (Oxford) |
| LRE | Renewable energy | % of electricity | Our World in Data (Oxford) |
| LEC | Electric power consumption | kWh/capita | World Bank |
| LINF | Inflation, GDP deflator | Annual % | World Bank |
| LPG | Population growth | Annual % | World Bank |
| $LCO_2$ | Carbon dioxide ($CO_2$) emissions, excluding LULUC, per capita | ($tCO_2e$/capita) | World Bank |
| LGHG | Total greenhouse gas emissions excluding LULUC per capita | ($tCO_2e$/capita) | World Bank |
| LEP | Electricity real price increase | Percentage | Eskom |

Source: Author's compilation

This is a quantitative study that will make use of EViews 10 and Stata 18 computational statistical software for the estimation of the relationships among variables.

## 3.2. Methodology and Data Analysis

### 3.2.1. Theory and model specification

The study is grounded in the Environmental Kuznets Curve theory, which posits that there is an inverted U-shaped relationship between economic growth and environmental degradation. The EKC theory suggests that as economies grow, environmental degradation initially increases but eventually decreases as the economy reaches a certain level of development. The study also draws on the literature on energy sources, macroeconomic factors, and environmental sustainability, including the impact of different energy sources on environmental degradation. The study deploys two models to examine the role of energy sources and macroeconomic factors in environmental sustainability in South Africa, as given below.

Model 1: Carbon Dioxide ($CO_2$) Emissions

$CO_2$ emissions = f(electricity consumption, nuclear power generation, non-renewable energy generation, renewable energy generation, electricity prices, economic growth, inflation, population growth) (1)

Model 2: Greenhouse Gas (GHG) Emissions

Greenhouse gas emissions = f(electricity consumption, nuclear power generation, non-renewable energy generation, renewable energy generation, electricity prices, economic growth, inflation, population growth) (2)

These models are transformed into logarithms to form two multivariate empirical models in econometric form as given below:

$$LCO_{2t} = \alpha_1 + \alpha_{LEC} LEC_t + \alpha_{LNUC} LNUC_t + \alpha_{LNRE} LNRE_t + \alpha_{LRE} LRE_t + \alpha_{LEP} LEP_t + \alpha_{LEG} LEG_t + \alpha_{LINF} LINF_t + \alpha_{LPG} LPG_t + \varepsilon_t \quad (3)$$

$$LGHG_t = \alpha_1 + \alpha_{LEC} LEC_t + \alpha_{LNUC} LNUC_t + \alpha_{LNRE} LNRE_t + \alpha_{LRE} LRE_t + \alpha_{LEP} LEP_t + \alpha_{LEG} LEG_t + \alpha_{LINF} LINF_t + \alpha_{LPG} LPG_t + \varepsilon_t \quad (4)$$

Where $LCO_{2t}$ represents $CO_2$ emissions in logarithms, $LGHG_t$ represents greenhouse gas emissions in logarithms, $LEC_t$ represents electric power consumption in logarithms, $LNUC_t$ represents nuclear power generation in logarithms, $LNRE_t$ represents non-renewable energy generation in logarithms, $LRE_t$ represents renewable energy generation in logarithms, $LEP_t$ represents electricity prices in logarithms, $LEG_t$ represents economic growth in logarithms, $LINF_t$ represents inflation in logarithms, $LPG_t$ represents population growth in logarithms, $\alpha_1$ is the constant, and $\varepsilon_t$ is the error term.

### 3.2.2. Unit root test

The study relies on the two-unit root tests, namely the Augmented Dickey-Fuller (ADF) developed by Said and Dickey (1984) and the Phillips-Perron unit root test developed by Phillips and Perron (1988). The ADF unit root test is an extended version of the initially Dickey-Fuller test, which includes lagged terms of the dependent variable to eliminate autocorrelation. The three possible forms of the ADF test are specified as given below.

$$\Delta y_t = \gamma y_{t-1} + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \mu_t \quad (5)$$

$$\Delta y_t = \alpha_0 + \gamma y_{t-1} + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \mu_t \quad (6)$$

$$\Delta y_t = a_0 + \gamma y_{t-1} + a_2 t + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \mu_t \quad (7)$$

The difference between the three regressions again concerns the presence of the deterministic elements $\alpha_0$ and $\alpha_2$t. The focus of all three equations is to test if $\gamma = 0$. If the ADF statistical value is smaller than the critical value of the *t-statistic* critical value, then we reject the null hypothesis and conclude that $\gamma_t$ is a stationary process. On the other hand, the PP unit root test the regression if it is an AR(1) process as given below.

$$\Delta y_{t-1} = \alpha_0 + \gamma y_{t-1} + e_t \quad (8)$$

The PP corrects the t-statistic of the coefficient $\gamma$ from AR(1) regression to account for the serial correlation in $e_t$. If the PP statistical value is smaller than the critical value of the *t-statistic* critical value, then we reject the null hypothesis and conclude that is a stationary process.

### 3.2.3. Cointegration test

The study relies on the ARDL bounds test for cointegration developed by Pesaran et al. (2001) to determine if a long-run relationship exists between variables. It is particularly useful when dealing with time series data where the order of integration, whether the variable is stationary or needs differencing to become stationary, is unknown or mixed, meaning that integrated of I(0) or I(1) or both. Unlike Johansen's cointegration, the bounds test does not require pre-testing for the order of integration of each variable, and it uses an F-statistic to test for the significance of lagged levels of variables in an ARDL model (Sam et al., 2019). To test the bounds test for cointegration, the conditional ARDL ($p,q_{1-8}$) model hypotheses with 9 variables are specified as given below.

$$H_0 = b_{1i} = b_{2i} = b_{3i} = b_{4i} = b_{5i} = b_{6i} = b_{7i} = b_{8i} = b_{9i} = 0 \qquad (where\ i = 1,..9)$$

$$H_1 \neq b_{1i} \neq b_{2i} \neq b_{3i} \neq b_{4i} \neq b_{5i} \neq b_{6i} \neq b_{7i} \neq b_{8i} \neq b_{9i} \neq 0$$

*3.2.4. Estimation technique*

The study relies on the Vector Error Correction Model (VECM) proposed by Engle and Granger (1987). The VECM model builds upon the concept of cointegration, which they also formalized, and is used to analyse the long-run equilibrium relationships and short-run dynamics of multiple time series variables, which improves forecast accuracy. The study chose the VECM since it is underutilized in the literature review provided in Section 2. The conventional VECM used in this study can be specified as given in the equations below.

$$\Delta Y_t = \sigma + \sum_{i=1}^{k-1} \gamma_i \Delta Y_{t-i} + \sum_{j=1}^{k-1} \eta_j \Delta X_{t-j} + \sum_{m=1}^{k-1} \xi_m \Delta R_{t-m} + \lambda ECT_{t-1} + \mu_t \qquad (9)$$

Where $\lambda$ is the coefficient of the ECT and the speed of adjustment that measures the speed at which returns to equilibrium after changes in $X$ and $R$. $ECT_{t-1}$ is the lagged OLS residual obtained from the long run cointegrating equation: $Y_t = \sigma + \eta j X_t + \xi_m R_t + \mu_t$ and can be expressed as $ECT_{t-1} = [Y_{t-1} - \eta_j X_{t-1} - \xi_m R_{t-1}]$, the cointegrating equation. The ECT explains that deviations from previous periods from the long-run equilibrium (which is the error) affect short-run changes in the dependent variable. $\mu_t$ represents the residuals, usually referred to as stochastic error terms, impulses, or shocks. The study also relies on the Autoregressive Distributed Lags (ARDL) model proposed by Pesaran et al. (2001) for robustness checks. The ARDL model has several advantages over other estimators, such as the VECM model, in that it is flexible in handling variables with different orders of integration, it can estimate both short-and run relationships, allows for dynamic modelling, can handle data with a small sample size, uses the bounds test to handle cointegration, and uses a combination of endogenous and exogenous variables. The generalised ARDL (*p, q*) model used in this study can be specified as given below.

$$Y_t = \gamma_{0i} + \sum_{i=1}^{p} \delta_i Y_{t-i} + \sum_{i=0}^{q} \beta_i^{'} X_{t-i} + \varepsilon_{it} \qquad (10)$$

Where $Y_t$ is a vector, and the variables in $X_t$ are allowed to be purely I(0) or I(1) or cointegrated. $\beta_i^{'}$ and $\delta_i$ are coefficients, $\gamma_{0i}$ is the constant, $I = 1,\ldots,k,p,q$ are optimal lag orders; $\varepsilon_{it}$ is a vector of the error terms representing an unobservable zero-mean white noise vector process that is serially uncorrelated or independent. *p* lags are used for the dependent variable, while *q* lags are used for exogenous variables.

*3.2.5. Residual diagnostics test*

The study will perform the Jarque-Bera test to check for normality of residuals, Breusch-Godfrey for serial correlations, Breusch-Pagan-Godfrey for heteroskedasticity tests, Ramsey RESET test for model specifications for the ARDL model residual diagnostics. Furthermore, the study will perform the Portmanteau test for autocorrelations, residual serial correlations, and the Jarque-Bera joint residual normality test. The study continues to present the results of the role of energy sources and macroeconomic factors in environmental sustainability in South Africa, as given in Section 4 below.

## 4. RESULTS AND DISCUSSIONS

The study has conducted descriptive and statistical analyses as presented in Table 2. Based on the data presented, $CO_2$ emissions, greenhouse gas emissions, electricity consumption, economic growth, non-renewable electricity generation, and nuclear power are negatively skewed. In contrast, inflation, electricity prices, population growth, and renewable electricity generation are positively skewed. Considering the kurtosis values, $CO_2$ emission, greenhouse gas emissions, inflation, electric consumption, and nuclear power have a value of <3, meaning they are platykurtic. In contrast, electric prices, economic growth, non-renewable electric power, population growth, and renewable electric generation have values above 3, implying that they are leptokurtic. Nonetheless, when focusing on the probability values of the Jarque-Bera test, $CO_2$ emissions, greenhouse gas emissions, inflation, electric power consumption, economic growth, and nuclear power are normally distributed, while electricity prices, non-renewable power generation, population growth, and renewable power generation shows characteristics of non-normal but this does not affect the study since we assume normality from estimated residuals of the model. The study continues to estimate correlation analysis as shown in Table 3 below.

The study performed the variables correlation analysis as presented in Table 3 and the data shows that inflation, population growth, and renewable energy generation are negatively correlated with $CO_2$ emissions, whilst electric power consumption, electricity prices, economic growth, non-renewable energy generation, and nuclear energy are positively correlated with $CO_2$ emissions for model 1. On the other hand, considering model 2, inflation, population growth, and renewable energy generation are negatively correlated with greenhouse gas emissions, whilst electric power consumption, electricity prices, economic growth, non-renewable energy generation, and nuclear energy are positively correlated with greenhouse gas emissions in South Africa. The study continues to perform a unit root test for the variables as presented in Table 4 below.

To avoid spurious regressions, the study performed Augmented Dickey-Fuller and Phillips-Perron unit root tests as presented in Table 4. Based on the presented results, electricity prices, economic growth, and nuclear energy are stationary at the level form, implying that they are integrated of I(0). On the other hand, the results indicate that $CO_2$ emissions, greenhouse gas emissions, inflation, electric power consumption, non-renewable energy

**Table 2: Descriptive and statistical analysis**

| Variables | $LCO_2$ | LGHG | LINF | LEC | LEP | LEG | LNRE | LNUC | LPG | LRE |
|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 7.8597 | 10.072 | 8.7299 | 4055.3 | 8.9410 | 0.3205 | 92.041 | 5.1768 | 1.5895 | 2.3965 |
| Median | 7.8996 | 10.152 | 7.3763 | 3981.5 | 7.5000 | 0.6522 | 93.025 | 5.2290 | 1.3125 | 1.0625 |
| Max | 9.5454 | 11.857 | 17.082 | 4716.4 | 34.200 | 4.5303 | 94.994 | 6.7942 | 3.3348 | 13.190 |
| Min | 6.2863 | 8.0300 | 3.8433 | 3200.0 | −4.2400 | −7.6787 | 83.314 | 3.4966 | 0.6538 | 0.0836 |
| Standard deviation | 0.7761 | 0.8630 | 4.1200 | 369.74 | 8.5499 | 2.6300 | 2.8115 | 0.8388 | 0.7194 | 3.2204 |
| Skewness | −0.0721 | −0.3264 | 0.8307 | −0.2345 | 1.2092 | −0.7440 | −1.6673 | −0.1079 | 1.1956 | 2.1598 |
| Kurtosis | 2.4689 | 2.7902 | 2.2428 | 2.2613 | 4.4918 | 3.6437 | 5.4476 | 2.3680 | 3.3318 | 6.8783 |
| Jarque-Bera | 0.5047 | 0.7839 | 5.5558 | 1.2763 | 13.457 | 4.3806 | 28.518 | 0.7434 | 9.7131 | 56.167 |
| Probability | 0.7770 | 0.6757 | 0.0622 | 0.5283 | 0.0012 | 0.1119 | 0.0000 | 0.6895 | 0.0078 | 0.0000 |
| Observation | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |

Source: Author's computation

**Table 3: Correlation analysis**

| Variables | $LCO_2$ | LGHG | LINF | LEC | LEP | LEG | LNRE | LNUC | LPG | LRE |
|---|---|---|---|---|---|---|---|---|---|---|
| $LCO_2$ | 1.0000 | | | | | | | | | |
| LGHG | 0.9932 | 1.0000 | | | | | | | | |
| LINF | −0.1212 | −0.0325 | 1.0000 | | | | | | | |
| LEC | 0.7276 | 0.7316 | −0.2046 | 1.0000 | | | | | | |
| LEP | 0.2066 | 0.1491 | −0.3679 | 0.1005 | 1.0000 | | | | | |
| LEG | 0.3055 | 0.2861 | −0.3542 | 0.5934 | −0.0321 | 1.0000 | | | | |
| LNRE | 0.6614 | 0.7146 | 0.2824 | 0.6196 | −0.0288 | 0.1927 | 1.0000 | | | |
| LNUC | 0.0658 | 0.1169 | 0.2608 | 0.2369 | −0.2390 | 0.1497 | 0.1694 | 1.0000 | | |
| LPG | −0.0983 | −0.0400 | 0.7390 | −0.4321 | −0.3095 | −0.5533 | 0.0254 | −0.0167 | 1.0000 | |
| LRE | −0.5535 | −0.6288 | −0.4297 | −0.5799 | 0.1571 | −0.1527 | −0.9407 | −0.4568 | −0.1156 | 1.0000 |

Source: Author's computation

**Table 4: unit root test**

| Variables | Augmented Dickey-Fuller test | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Without trend | | Trend and intercept | | Without trend | | Trend and intercept | |
| | Level | Δ | Level | Δ | Level | Δ | Level | Δ |
| $LCO_2$ | −0.6085 | −5.7944*** | −0.5292 | −5.9787*** | −0.9261 | −5.8200*** | −0.6973 | −5.9794*** |
| LGHG | −0.2647 | −5.5243*** | −0.2904 | −5.7531*** | −0.5634 | −5.5244*** | −0.5128 | −5.7531*** |
| LINF | −1.7007 | −9.2157*** | −3.0221 | −9.2039*** | −0.5331 | −10.765*** | −3.0221 | −14.352*** |
| LEC | −1.5922 | −4.6097*** | −1.6468 | −4.4564** | −1.6675 | −4.6219*** | −1.6823 | −4.4564** |
| LEP | −3.0626** | −7.2445*** | −3.2643* | −7.1485*** | −3.0588** | −7.3649*** | −3.2887* | −7.2634*** |
| LEG | −4.0252*** | −8.3192*** | −3.9125** | −8.2905*** | −4.0252*** | −14.515*** | −3.9125** | −24.188*** |
| LNRE | 0.3727 | −7.2950*** | −0.3441 | −8.2786*** | 0.4860 | −7.1562*** | −0.1797 | −8.2786*** |
| LNUC | −4.1428*** | −10.493*** | −5.2103*** | −10.459*** | −4.4427*** | −12.077*** | −5.2368*** | −12.290*** |
| LPG | −2.5589 | −5.7427*** | −2.0931 | −6.3340*** | −2.6828 | −6.1281*** | −1.9641 | −6.7591*** |
| LRE | 3.9685 | −3.7911** | 2.0432 | −4.9729*** | 5.5118 | −3.8424** | 3.6677 | −4.9682*** |

Source: Author's computation (***), (**), (*) indicates significance at 1%, 5% and 10% level

generation, population growth, and renewable energy generation are stationary at first difference, implying that they are integrated of I(1). These results imply that the study can be able to employ both the VECM and ARDL models to estimate the relationship between energy sources and macroeconomic factors in environmental sustainability in South Africa, since these models are able to handle the data that is a mixture of I(0) and I(1). The study continues to estimate the optimal lag length to be used in both models 1 and 2 and presents it in Table 5 below.

The study employed the VAR lag order selection criteria as presented in Table 5 for both models 1 and 2. The LR, FPE, AIC, and HQ criteria show that 1 lag may be used in both models; however, the SC shows that zero lags are recommended for both models 1 and 2. Based on these results, the study will utilize 1 lag for both models 1 and 2 in the VECM and ARDL estimation techniques to estimate the relationship between energy sources and macroeconomic factors in environmental sustainability in South Africa, as selected by the majority of the criteria in Table 5

**Table 5: Optimal lag length criterion**

| VAR Lag order selection criteria Sample: 1985-2024 | | | | | | |
|---|---|---|---|---|---|---|
| Lag | LogL | LR | FPE | AIC | SC | HQ |
| Model 1 | | | | | | |
| 0 | −650.23 | NA | 24174 | 35.634 | 36.026* | 35.772 |
| 1 | −545.18 | 153.31* | 7458.5* | 34.334* | 38.253 | 35.716* |
| 2 | −465.03 | 77.985 | 18226 | 34.380 | 41.825 | 37.005 |
| Model 2 | | | | | | |
| 0 | −652.80 | NA | 27779 | 35.773 | 36.165* | 35.911 |
| 1 | −547.17 | 154.16* | 8305.5* | 34.442* | 38.360 | 35.823* |
| 2 | −466.50 | 78.487 | 19738 | 34.460 | 41.905 | 37.084 |

Source: Author's computation (*) indicates lag order selected by the criterion above. The study continues to check for cointegration relationships between energy and macroeconomic factors in environmental sustainability in South Africa by employing the ARDL F-Bounds test, as shown in Table 6 below.

The study employed the ARDL F-Bounds test to check for long-run relationships between the variables in both models 1 and 2, as presented in Table 6. The F-statistic for both models 1 and 2 shown in Table 6 above is greater than the critical values at 1%, 5%, and 10% at both I(0) and I(1), indicating that we fail to accept the null hypothesis of no level relationships. Based on these results, we conclude that there are long-run relationships between energy sources and macroeconomic factors in environmental sustainability in South Africa, and as a result, the study will estimate a long-run relationship for both models 1 and 2 using the employed VECM and ARDL estimation techniques. The study continues to estimate short-run relationships as presented in Table 7 below using the VECM model.

The study employed the VECM technique to estimate the relationship between energy and macroeconomic factors in environmental sustainability in the short run, as shown in Table 7 for both models 1 and 2. The error correction terms for model 1 (−0.2874) and model 1 (−0.4168) are both negative and statistically significant, implying that if there are errors in environmental sustainability in models 1 and 2, 28.74% and 41.68% of the errors are adjusted annually towards the long-run equilibrium. Furthermore, the results from both models 1 and 2 indicate that there is a negative relationship between electricity prices on $CO_2$ emissions and greenhouse gas emissions in South Africa. A 1% increase in electricity prices results in $CO_2$ emissions and greenhouse gas emissions declining by 0.02% and 0.02% respectively, at 5% significance level, ceteris paribus. These results imply that an increase in electricity prices is good for environmental sustainability since they result in a fall in $CO_2$ and greenhouse gas emissions. These results are consistent with the studies of Li et al. (2020), Ghazouani (2021), Pang et al. (2023), and Balsalobre-Lorente et al. (2018), who found that found increase in electricity prices, reducing $CO_2$ emissions, implying that they promote environmental sustainability.

Moreover, the results show that there is a negative relationship between inflation on $CO_2$ emissions and greenhouse gas emissions in South Africa. A 1% increase in inflation results in $CO_2$ emissions and greenhouse gas emissions declining by 0.05% and 0.05% at 10% and 5% significance levels, respectively, ceteris paribus. These results imply that an increase in inflation is good for environmental sustainability in South Africa since it results in $CO_2$ and greenhouse gas emissions. These results are consistent with the studies of Musarat et al. (2021), Grolleau and Weber (2024), and AlShafeey and Saleh-Saleh (2024), who found that an increase in inflation reduces greenhouse gas and $CO_2$ emissions. Nonetheless, the results in both models 1 and 2 indicate that electricity consumption, nuclear power generation, non-renewable energy generation, renewable energy generation, economic growth, and population growth have an insignificant influence on environmental sustainability in South Africa. These results suggest that electricity consumption, nuclear power generation, non-renewable energy generation, renewable energy generation, economic growth, and population growth do not have strong evidence to support their impact on $CO_2$ and greenhouse gas emissions in the short-term period.

**Table 6: Cointegration test**

| ARDL F-Bounds test<br>Null hypothesis: No level relationship | | | | |
|---|---|---|---|---|
| **Test statistic** | **Value** | **Significance (%)** | **I (0)** | **I (1)** |
| Model 1 | | | | |
| F-statistic | 11.596 | 10 | 1.85 | 2.85 |
| k | 8 | 5 | 2.11 | 3.15 |
| | | 1 | 2.62 | 3.77 |
| Model 2 | | | | |
| F-statistic | 10.692 | 10 | 1.85 | 2.85 |
| k | 8 | 5 | 2.11 | 3.15 |
| | | 1 | 2.62 | 3.77 |

Source: Author's computation

**Table 7: VECM short-run results**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | **Coefficient** | **t-statistic** | **Coefficient** | **t-statistic** |
| CointEq1 | −0.2874 | −2.4988** | −0.4168 | −3.0152*** |
| DLEC(−1) | −0.0002 | −0.3916 | −0.0003 | −0.5204 |
| DLNUC(−1) | 0.1507 | 0.8485 | 0.1984 | 1.1463 |
| DLNRE(−1) | −0.0520 | −0.7581 | −0.0500 | −0.7340 |
| DLRE(−1) | −0.1692 | −1.3226 | −0.1641 | −1.2949 |
| DLEP(−1) | −0.0225 | −2.6072** | −0.0238 | −2.7914*** |
| DLEG(−1) | 0.0197 | 0.5230 | 0.0168 | 0.4600 |
| DLINF(−1) | −0.0485 | −1.7637* | −0.0546 | −2.0676** |
| DLPG(−1) | −0.0644 | −0.4030 | −0.0906 | −0.5672 |
| $R^2$ | 0.6353 | | 0.6004 | |
| Adjusted-$R^2$ | 0.4951 | | 0.4468 | |

Source: Author's computation (***), (**), (*) indicates significance at 1%, 5% and 10% level

**Table 8: VECM long-run results**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | **Coefficient** | **t-Statistic** | **Coefficient** | **t-Statistic** |
| LEC(−1) | −0.0039 | −6.9578*** | −0.0032 | −6.5881*** |
| LNUC(−1) | 0.5383 | 5.8212*** | 0.4399 | 5.5388*** |
| LNRE(−1) | −0.9907 | −4.7838*** | −0.7522 | −4.2400*** |
| LRE(−1) | −0.7432 | −3.2787*** | −0.5201 | −2.6767** |
| LEP(−1) | 0.0112 | 1.6164 | 0.0125 | 2.1136** |
| LEG(−1) | −0.0143 | −0.5466 | −0.0343 | −1.5275 |
| LINF(−1) | −0.2931 | −5.7031*** | −0.2163 | −4.8882*** |
| LPG(−1) | 0.4775 | 2.0425** | 0.3672 | 1.8159* |

Source: Author's computation (***), (**), (*) indicates significance at 1%, 5% and 10% level

The study has conducted long-run relationships between energy sources and macroeconomic factors in environmental sustainability in South Africa as presented in Table 8. The results indicate that there is a negative relationship between electricity consumption and environmental sustainability in both models 1 and 2. A 1% increase in electricity consumption results in $CO_2$ and greenhouse gas emissions decreasing by 0.004% and 0.003% respectively, at 1% significance level, ceteris paribus. These results are inconsistent with the studies of Usman et al. (2020), Akadiri et al. (2019), Chontonawat (2019), and Destek and Sarkodie (2019), who found that electricity consumption increases $CO_2$ and greenhouse gas emissions. Moreover, there is a negative relationship between inflation on $CO_2$ and greenhouse gas emissions in South Africa. A 1% increase in long-run inflation results in $CO_2$ and greenhouse gas emissions decreasing by 0.29% and 0.23% respectively, at 1% significance level, ceteris paribus. These results imply that an increase in electricity consumption and inflation plays a crucial role in encouraging environmental sustainability in South Africa in the long run, since it results in reduced $CO_2$ and greenhouse gas emissions. These results are inconsistent with the studies of Musarat et al. (2021), Grolleau and Weber (2024), and AlShafeey and Saleh-Saleh (2024), who found that an increase in inflation reduces greenhouse gas and $CO_2$ emissions.

Furthermore, the results show a negative relationship between non-renewable energy generation and environmental sustainability in South Africa in both models 1 and 2. A 1% increase in non-renewable energy generation results in $CO_2$ and greenhouse gas emissions decreasing by 0.99% and 0.75% at 1% significance level, respectively, ceteris paribus. These results are inconsistent with the studies of Voumik et al. (2022) and Abbasi et al. (2022), who found that non-renewable energy increases greenhouse gas emissions. Additionally, the results show that there is a negative relationship between renewable energy generation on $CO_2$ and greenhouse gas emissions in the long run in South Africa. A 1% increase in renewable energy generation results in $CO_2$ and greenhouse gas emissions decreasing by 0.74% and 0.52% at 1% and 5% significance level, respectively, ceteris paribus. These results imply that an increase in non-renewable and renewable electricity generation plays a crucial role in encouraging environmental sustainability in South Africa in the long run, since it results in reduced $CO_2$ and greenhouse gas emissions. These results are consistent with the studies of Saidi and Omri (2020), Li et al. (2023), Lee (2019), Abbasi et al. (2022), and Bekhet and Othman (2018), who found that renewable energy reduces $CO_2$ emissions.

On the contrary, there is a positive relationship between nuclear power generation on $CO_2$ and greenhouse gas emissions in the long run in South Africa, as shown in both models 1 and 2. A 1% increase in nuclear power generation results in $CO_2$ and greenhouse gas emissions increasing by 0.54% and 0.45% respectively, at 1% significance level, ceteris paribus. These findings are inconsistent with the study of Petruška et al. (2022), Naimoğlu (2022), and Murshed et al. (2022), who found that nuclear power reduces $CO_2$ emissions. Additionally, a 1% increase in electricity prices results in greenhouse gas emissions increasing by 0.01% at 5% significance level, ceteris paribus. These results are inconsistent with the studies of Li et al. (2020), Ghazouani (2021), Pang et al. (2023), and Balsalobre-Lorente et al. (2018), who found that found increase in electricity prices, reducing $CO_2$ emissions, implying that they promote environmental sustainability. Nonetheless, a 1% increase in population growth results in $CO_2$ and greenhouse gas emissions increasing by 0.48% and 0.37% respectively, at 5% and 10% significance levels, ceteris paribus. These results are inconsistent with the study of Shaari et al. (2021), who found an insignificant impact, while being consistent with the study of Namahoro et al. (2021), who found a positive impact of population growth on $CO_2$ emissions. These results imply that an increase in nuclear power generation, electricity prices, and population growth plays a crucial negative role in encouraging environmental sustainability in South Africa in the long run, since it results in increased $CO_2$ and greenhouse gas emissions. Conversely, economic growth has an insignificant impact on $CO_2$ emissions and greenhouse gas emissions, while electricity prices have an insignificant impact on $CO_2$ emissions only.

The study has performed the variance decomposition for $CO_2$ emissions as shown in Table 9 for 10 periods. The results reveal that in the $10^{th}$ year, one standard deviation shock from electricity consumption, nuclear power generation, non-renewable energy generation, renewable energy generation, electricity prices, economic growth, inflation, and population growth, will result in 9.44%, 5.34%, 1.31%, 2.37%, 5.12%, 0.25%, 1.10%, and 0.84% forecast error variance respectively. After 10 periods, a greater percentage of 74.23% becomes self-explanatory. These results show that renewable energy plays a huge positive role in promoting environmental sustainability than non-renewable energy in South Africa. The study continues to perform variance decomposition for greenhouse gas emissions as presented in Table 10.

The study has performed the variance decomposition for greenhouse gas emissions as shown in Table 10 for 10 periods. The results reveal that in the $10^{th}$ year, one standard deviation shock from electricity consumption, nuclear power generation, non-renewable energy generation, renewable energy generation, electricity prices, economic growth, inflation, and population growth, will result in 13.55%, 5.84%, 1.56%, 2.79%, 5.91%, 0.37%, 1.33%, and 1.24% forecast error variance respectively. Notably, after 10 periods, a greater percentage of 67.42% becomes self-explanatory. These results show that as time increases, renewable energy has more positive effect than non-renewable energy in environmental sustainability in South Africa. The study continues to perform VECM residual diagnostics tests for both models 1 and 2 as presented in Table 11.

The study has performed the residual diagnostics test for the VECM estimator as presented in Table 11 for both models 1 and 2. The results of the VEC residual Portmanteau test for autocorrelations indicate that there is no residual autocorrelation up to lag h for both models 1 and 2, since their probabilities are >0.05. Furthermore, the results of the VEC residual serial correlations LM test show that there is no serial correlation at lag h, since the probability values for both models 1 and 2 are >0.05, the significance. Additionally, the results of the VEC Jarque-Bera joint residual normality test show that the residuals are multivariate normal for both models 1 and 2, since the probability values are >0.05, the significance level. Overall, we conclude that models 1 and 2 do not suffer from any issues of autocorrelation, serial correlation, or non-normality, and that the results are reliable for policy formulation and recommendations. The study continues to employ the ARDL model as given in Tables 12-14 for robustness checks against the results from the VECM model presented in the preceding tables above.

The study employed the ARDL technique to estimate the

**Table 9: Variance decomposition model 1**

| Variance decomposition of D ($CO_2$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Period | Standard error | D ($CO_2$) | D (LEC) | LNUC | D (LNRE) | D (LRE) | LEP | LEG | D (INF) | D (LPG) |
| 1 | 0.3465 | 100.00 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 2 | 0.5098 | 66.499 | 16.365 | 3.5668 | 2.0549 | 1.2868 | 7.4888 | 0.0745 | 1.9017 | 0.7616 |
| 3 | 0.5806 | 69.044 | 13.067 | 4.6976 | 2.6968 | 1.8164 | 5.9512 | 0.2017 | 1.5686 | 0.9572 |
| 4 | 0.6549 | 69.235 | 11.347 | 5.5959 | 2.6674 | 1.9878 | 6.9207 | 0.1774 | 1.2708 | 0.7980 |
| 5 | 0.7165 | 71.797 | 11.091 | 4.6966 | 2.2506 | 1.8041 | 5.9404 | 0.1515 | 1.4700 | 0.7982 |
| 6 | 0.7721 | 71.320 | 10.386 | 5.5466 | 1.9884 | 2.3130 | 6.0293 | 0.2884 | 1.2661 | 0.8628 |
| 7 | 0.8245 | 72.549 | 10.2422 | 5.4548 | 1.7444 | 2.1258 | 5.5024 | 0.2536 | 1.3246 | 0.8038 |
| 8 | 0.8723 | 73.152 | 9.8138 | 5.3293 | 1.5677 | 2.3621 | 5.4597 | 0.2685 | 1.1834 | 0.8635 |
| 9 | 0.9175 | 73.725 | 9.7425 | 5.3452 | 1.4269 | 2.2985 | 5.1870 | 0.2496 | 1.1941 | 0.8316 |
| 10 | 0.9601 | 74.227 | 9.4436 | 5.3402 | 1.3066 | 2.3672 | 5.1243 | 0.2482 | 1.0987 | 0.8445 |

Source: Author's computations

**Table 10: Variance decomposition model 2**

| Variance decomposition of D (GHG) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Period | Standard error | D (GHG) | D (LEC) | LNUC | D (LNRE) | D (LRE) | LEP | LEG | D (INF) | D (LPG) |
| 1 | 0.3450 | 100.00 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 2 | 0.5334 | 58.620 | 22.522 | 3.0880 | 2.4703 | 1.3915 | 8.8065 | 0.1278 | 1.9170 | 1.0575 |
| 3 | 0.6046 | 61.215 | 18.327 | 4.9189 | 3.0936 | 2.0222 | 7.0448 | 0.3273 | 1.7184 | 1.3327 |
| 4 | 0.6781 | 62.063 | 15.875 | 5.9275 | 3.0738 | 2.2838 | 7.9337 | 0.2851 | 1.4209 | 1.1377 |
| 5 | 0.7408 | 64.795 | 15.657 | 4.9769 | 2.5936 | 2.0554 | 6.8277 | 0.2399 | 1.7088 | 1.1458 |
| 6 | 0.7979 | 64.156 | 14.780 | 5.9621 | 2.3211 | 2.6977 | 6.9404 | 0.4254 | 1.4733 | 1.2448 |
| 7 | 0.8498 | 65.540 | 14.564 | 5.9279 | 2.0462 | 2.4779 | 6.3343 | 0.3750 | 1.5653 | 1.1693 |
| 8 | 0.8987 | 66.244 | 14.005 | 5.7796 | 1.8531 | 2.7685 | 6.2985 | 0.3945 | 1.4004 | 1.2559 |
| 9 | 0.9440 | 66.840 | 13.968 | 5.8023 | 1.6911 | 2.6920 | 5.9768 | 0.3708 | 1.4391 | 1.2196 |
| 10 | 0.9869 | 67.420 | 13.551 | 5.8359 | 1.5555 | 2.7869 | 5.9104 | 0.3733 | 1.3275 | 1.2396 |

Source: Author's computation

**Table 11: VECM residual diagnostic test**

| Test | Statistic | Probability | Conclusion |
|---|---|---|---|
| Model 1 | | | |
| VEC residual portmanteau tests for autocorrelations | 96.203 | 0.9999 | No residual autocorrelations up to lag h |
| VEC residual serial correlations LM Test | 64.995 | 0.9029 | No serial correlations at lag h |
| VEC residual normality test joint Jarque-Bera | 716.34 | 0.0634 | Residuals are multivariate normal |
| Model 2 | | | |
| VEC residual portmanteau tests for autocorrelations | 98.006 | 0.9998 | No residual autocorrelations up to lag h |
| VEC residual serial correlations LM Test | 64.213 | 0.9146 | No serial correlations at lag h |
| VEC residual normality test joint Jarque-Bera | 692.26 | 0.1861 | Residuals are multivariate normal |

Source: Author's computation

**Table 12: ARDL short-run results**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Coefficient | Probability | Coefficient | Probability |
| CointEq1 | −1.0739 | 0.0000*** | −1.1309 | 0.0000*** |
| DLEC(−1) | 8.2400 | 0.7348 | −4.7200 | 0.7615 |
| DLNUC(−1) | −0.0700 | 0.3200 | −0.0611 | 0.4149 |
| DLNRE(−1) | −0.0686 | 0.2690 | −0.0664 | 0.3131 |
| DLRE(−1) | −0.2199 | 0.0209** | −0.2212 | 0.0287** |
| DLEP(−1) | −7.2500 | 0.9877 | −0.0057 | 0.3341 |
| DLEG(−1) | 0.0818 | 0.0001*** | 0.0885 | 0.0001*** |
| DLINF(−1) | −0.0282 | 0.2068 | −0.0178 | 0.4791 |
| DLPG(−1) | −0.1076 | 0.4782 | −0.0731 | 0.6576 |
| $R^2$ | 0.8149 | | 0.8060 | |
| Adjusted-$R^2$ | 0.8097 | | 0.8007 | |

Source: Author's computation (***), (**), (*) indicates significance at 1%, 5% and 10% level

**Table 13: ARDL long-run results**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Coefficient | Probability | Coefficient | Probability |
| LEC(−1) | 7.6700 | 0.7360 | 0.0004 | 0.2509 |
| LNUC(−1) | −0.0652 | 0.3260 | −0.0541 | 0.4194 |
| LNRE(−1) | −0.0638 | 0.2655 | −0.0587 | 0.3087 |
| LRE(−1) | −0.2047 | 0.0219** | −0.1956 | 0.0310** |
| LEP(−1) | −0.0090 | 0.1058 | −0.0051 | 0.3297 |
| LEG(−1) | 0.0762 | 0.0004*** | 0.0782 | 0.0007*** |
| LINF(−1) | −0.0262 | 0.2081 | −0.0157 | 0.4842 |
| LPG(−1) | −0.1002 | 0.4913 | −0.0646 | 0.6646 |

Source: Author's computation (***), (**), (*) indicates significance at 1%, 5% and 10% level

relationship between energy sources and macroeconomic factors in environmental sustainability in the short run, as shown in Table 12 for both models 1 and 2. The error correction terms for model 1 (−1.0739) and model 1 (−1.1309) are both negative and statistically significant, implying that if there are errors in environmental sustainability in models 1 and 2, 107.39% and 113.09% of the errors are adjusted annually towards long-run equilibrium. Additionally, the results show that there is a negative relationship between renewable energy generation on $CO_2$ and greenhouse gas emissions. A 1% increase in renewable energy

**Table 14: ARDL residual diagnostic test**

| Test | Statistic | Probability | Conclusion |
|---|---|---|---|
| Model 1 | | | |
| Ramsey RESET Test | 3.5588 | 0.0704 | The model is correctly specified |
| Breusch-godfrey serial correlation LM Test | 0.6184 | 0.4317 | The model does not suffer from serial correlation |
| Breusch-Pagan-Godfrey Heteroskedasticity Test | 5.6203 | 0.8461 | Residuals are homoscedastic |
| Jarque-Bera residual normality Test | 1.5018 | 0.4719 | Residuals are normally distributed |
| Model 2 | | | |
| Ramsey RESET test | 1.5570 | 0.2232 | The model is correctly specified |
| Breusch-Godfrey serial correlation LM test | 1.5074 | 0.2195 | The model does not suffer from serial correlation |
| Breusch-Pagan-Godfrey Heteroskedasticity test | 8.7724 | 0.5538 | Residuals are homoscedastic |
| Jarque-Bera residual normality test | 0.4010 | 0.8183 | Residuals are normally distributed |

Source: Author's computation

generation results in $CO_2$ and greenhouse gas emissions decreasing by 0.22% and 0.22% respectively, at a 5% significance level, ceteris paribus. Contrary to the VECM short-run results, these results indicate that an increase in renewable energy generation is good for environmental sustainability since it results in reduced $CO_2$ and greenhouse gas emissions in South Africa. These results are consistent with the studies of Saidi and Omri (2020), Li et al. (2023), Lee (2019), Abbasi et al. (2022), and Bekhet and Othman (2018), who found that renewable energy reduces $CO_2$ emissions.

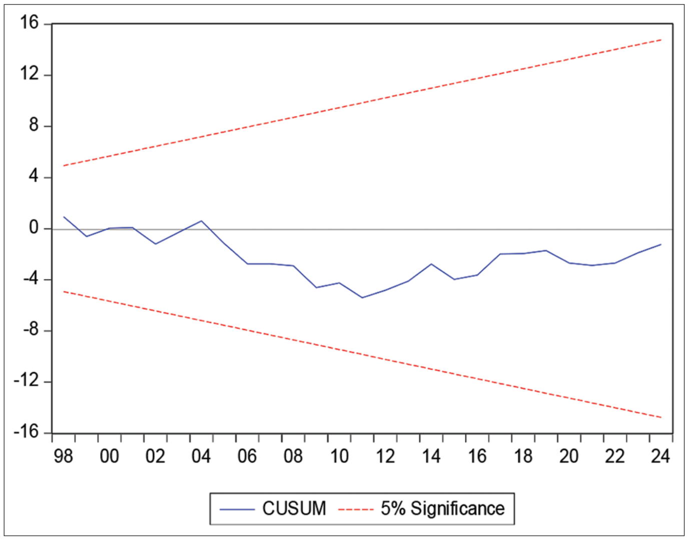
On the other hand, the results show that there is a positive relationship between economic growth on $CO_2$ and greenhouse gas emissions at 1% significance level. A 1% increase in economic growth results in $CO_2$ and greenhouse gas emissions increasing by 0.08% and 0.09% respectively, ceteris paribus. These results, unlike the VECM results, imply that an increase in economic growth is not good for environmental sustainability in South Africa in the short run, since it results in increased $CO_2$ and greenhouse gas emissions. The findings are consistent with the studies of Bekhet and Othman (2018), Bekun and Sarkodie (2019), Osobajo et al. (2020), Destek and Sarkodie (2019), and Kirikkaleli et al. (2022), who found that economic growth results in increased $CO_2$ emissions. Contrary to the VECM model, electricity consumption, nuclear power generation, non-renewable energy generation, electricity prices, inflation, and population growth insignificantly affect $CO_2$ and greenhouse gas emissions in the short-run period in South Africa. The study continues to estimate the long-run relationships between energy sources and macroeconomic factors in environmental sustainability, as presented in Table 13.

The results of the long-run relationship between energy sources and macroeconomic factors in environmental sustainability are presented in Table 13 from the ARDL model. The results show that there is a negative relationship between renewable energy generation on $CO_2$ and greenhouse gas emissions in South Africa at 5% significance level. A 1% increase in renewable energy generation results in $CO_2$ and greenhouse gas emissions decreasing by 0.20% and 0.20% respectively, ceteris paribus. These results imply that an increase in renewable power generation is good for environmental sustainability in South Africa, since it results in reduced $CO_2$ and greenhouse gas emissions. These results are consistent with the studies of Saidi and Omri (2020), Li et al. (2023), Lee (2019), Abbasi et al. (2022), and Bekhet and Othman (2018), who found that renewable energy reduces $CO_2$ emissions. On the other hand, there is a positive relationship between economic growth on $CO_2$ and greenhouse gas emissions in South Africa at 1% significance level. A 1% increase in economic growth results in $CO_2$ and greenhouse gas emissions increasing by 0.08% and 0.08% respectively, ceteris paribus. The findings are consistent with the studies of Bekhet and Othman (2018), Bekun and Sarkodie (2019), Osobajo et al. (2020), Destek and Sarkodie (2019), and Kirikkaleli et al. (2022), who found that economic growth results in increased $CO_2$ emissions. Nonetheless, electricity consumption, nuclear power generation, non-renewable energy generation, electricity prices, inflation, and population growth are found to have an insignificant impact on $CO_2$ and greenhouse gas emissions, implying that they are not determinants of environmental sustainability in the long run.

The study has performed the residual diagnostics test for both models 1 and 2 from the ARDL model to check for the reliability of the results as presented in Table 14. The results of the Ramsey RESET test show that models 1 and 2 are correctly specified, since their probability values are >0.05, the significance level. Furthermore, the results of the Breusch-Godfrey serial correlation test show that the model does not suffer from serial correlation for both models 1 and 2, since the probability values are >0.05, the significance level. Additionally, the results of the Breusch-Pagan-Godfrey heteroskedasticity test show that the residuals are homoscedastic for both models 1 and 2, since their probability values are >0.05, the significance level. Finally, the results of the Jarque-Bera normality test show that residuals are normally distributed for both models 1 and 2, since their probability values are >0.05, the significance level. Overall, these results indicate that the results from the study do not suffer from misspecification, serial correlation, heteroskedasticity, or normality problems, and they are reliable for policy formulation and recommendation.

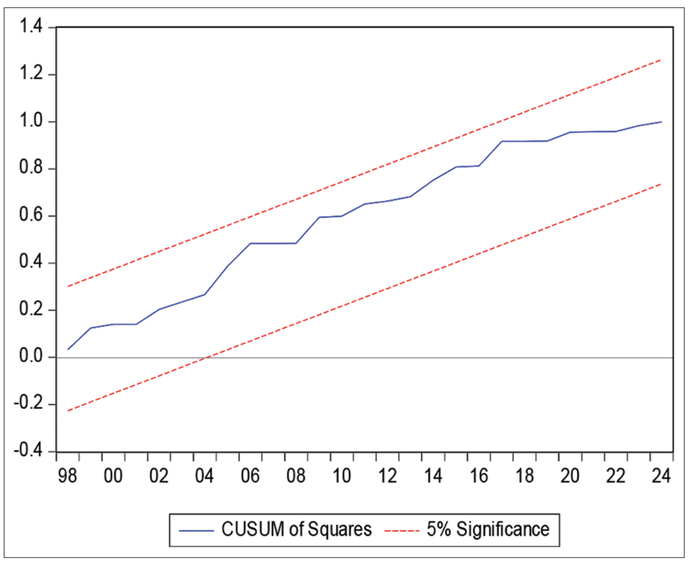
The study has performed the CUSUM and CUSUM of Squares as demonstrated in Figures 2-5 for both models 1 and 2. The results of the CUSUM test in Figures 2 and 4 show that the blue line drifts within the 5% critical bounds, indicating that the null hypothesis of parameter stability is accepted. Likewise, the results of the CUSUM of Squares test in Figures 3 and 5 fluctuate randomly around the 5% critical bounds, indicating that the null hypothesis of constant variance is accepted. Overall, these results indicate that the model is stable, and the results are reliable for policy formulation and recommendations. Therefore, the study will continue to offer conclusions and policy recommendations

**Figure 2:** CUSUM test model 1




Source: Author's computation

**Figure 3:** CUSUM of squares test model 1




Source: Author's computation

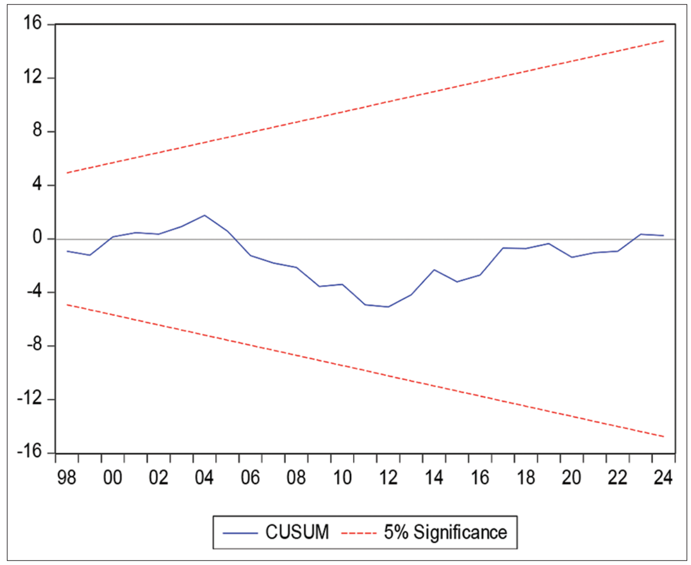
as presented in Section 5 below.

## 5. DISCUSSION

### 5.1. Interpretation of Findings Considering the Literature Review

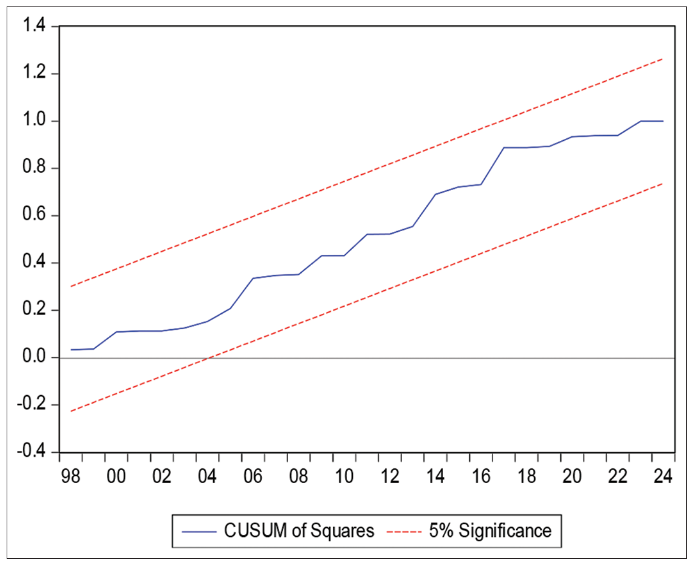
The study's main objectives were to examine the role of energy sources and macroeconomic factors in environmental sustainability in South Africa, utilising greenhouse gas emissions and $CO_2$ emissions as dependent variables. The results of the VECM short-run relationships revealed that there is a negative statistically significant relationship between electricity prices on $CO_2$ and greenhouse gas emissions in South Africa. These results imply that the increase in electricity prices plays a significant role in reducing emissions and promoting environmental sustainability. These results are consistent with the studies of Li et al. (2020),

**Figure 4:** CUSUM test model 2




Source: Author's computation

**Figure 5:** CUSUM of squares test model 2




Source: Author's computation

Ghazouani (2021), Pang et al. (2023), and Balsalobre-Lorente et al. (2018), who found that found increase in electricity prices, reducing $CO_2$ emissions, implying that they promote environmental sustainability. Nonetheless, the VECM long-run results indicate that electricity prices increase greenhouse gas emissions, but the ARDL model shows an insignificant impact. Furthermore, the results indicate that inflation has a significant negative impact on $CO_2$ and greenhouse gas emissions in South Africa. These results are consistent with the studies of Musarat et al. (2021), Grolleau and Weber (2024), and AlShafeey and Saleh-Saleh (2024), who found that an increase in inflation reduces greenhouse gas and $CO_2$ emissions. These results imply that inflation plays a crucial role in promoting environmental sustainability in South Africa.

Nonetheless, considering the long-run relationship, the results show that there is a negative relationship between electricity consumption on $CO_2$ and greenhouse gas emissions in South Africa. These results are inconsistent with the studies of Usman et al. (2020), Akadiri et al. (2019), Chontonawat (2019), and Destek and Sarkodie (2019), who found that electricity consumption increases $CO_2$ and greenhouse gas emissions. Furthermore, the results indicate that nuclear power has a positive impact on $CO_2$ and greenhouse gas emissions in South Africa. Renewable energy has a significant negative impact on $CO_2$ and greenhouse gas emissions in South Africa. These results are consistent with the studies of Saidi and Omri (2020), Li et al. (2023), Lee (2019), Abbasi et al. (2022), and Bekhet and Othman (2018), who found that renewable energy reduces $CO_2$ emissions.

Moreover, the VECM results indicate that economic growth plays an insignificant role in $CO_2$ and greenhouse gas emissions in both the short and long run periods. On the other hand, the ARDL robust results reveal that economic growth increases $CO_2$ and greenhouse gas emissions in both the short and long run periods. These results support the Environmental Kuznets Curve, which explains the positive effect of economic growth on increasing environmental degradation. The findings are consistent with the studies of Bekhet and Othman (2018), Bekun and Sarkodie (2019), Osobajo et al. (2020), Destek and Sarkodie (2019), and Kirikkaleli et al. (2022), who found that economic growth results in increased $CO_2$ emissions. These results imply that economic growth has not been playing a good role in promoting environmental sustainability since it results in increased $CO_2$ emissions. When considering population growth, the VECM results reveal that it increases $CO_2$ and greenhouse gas emissions in the long run, while being insignificant in the short run and in the robust ARDL results. These results are inconsistent with the study of Shaari et al. (2021), who found an insignificant impact, while being consistent with the study of Namahoro et al. (2021), who found a positive impact of population growth on $CO_2$ emissions.

## 5.2. Discussion of Unexpected Results

Surprisingly, the study shows that non-renewable energy negates $CO_2$ and greenhouse gas emissions in South Africa. These results imply that non-renewable energy has not been contributing to increased $CO_2$ and greenhouse gas emissions in South Africa. These results are inconsistent with the studies of Voumik et al. (2022) and Abbasi et al. (2022), who found that non-renewable energy increases greenhouse gas emissions. When considering nuclear energy, the findings of the VECM reveal that it results in increased $CO_2$ in the long run, while being insignificant in the short run in $CO_2$ and greenhouse gas emissions. These findings are inconsistent with the study of Petruška et al. (2022), Naimoğlu (2022), and Murshed et al. (2022), who found that nuclear power reduces $CO_2$ emissions. The findings of the ARDL model also reveal that population growth, inflation, electricity prices, non-renewable energy, and nuclear power play an insignificant role in $CO_2$ and greenhouse gas emissions in the short and long run. Nonetheless, these results do not have much impact on the study's objective since the main VECM model revealed their impact.

## 5.3. Theoretical and Practical Implications

The study's findings have significant theoretical and practical implications for environmental sustainability in South Africa.

### *5.3.1. Theoretical and methodological implications*

The negative inverse relationship between electricity prices and carbon dioxide emissions supports the theory that price mechanisms can influence consumer behaviour and reduce emissions. The Environmental Kuznets Curve hypothesis is validated, suggesting that economic growth initially leads to increased environmental degradation but may eventually reduce emissions as the economy transitions to cleaner energy sources. Nonetheless, the study's findings on renewable energy and carbon emissions reinforce the theoretical framework of sustainable development, emphasizing the role of renewable energy in reducing emissions. The study demonstrates the effectiveness of using vector error correction model (VECM) and autoregressive distributed lag (ARDL) models to analyse the relationships between energy sources and macroeconomic factors in environmental sustainability. The findings highlight the importance of considering both short- and long-run relationships between variables when analysing energy sources and macroeconomic factors in environmental sustainability.

### *5.3.2. Practical implications*

Energy pricing: Policymakers can use electricity prices as a tool to reduce emissions and promote environmental sustainability in South Africa. Implementing time-of-use pricing or increasing prices for high consumption households could encourage energy conservation.

Renewable energy: Investing in renewable energy sources, such as solar and wind power, can significantly reduce carbon emissions and promote sustainable development. Policymakers should incentivize private investment in renewable energy and develop infrastructure to support its integration into the grid.

Economic growth: The study's findings suggest that economic growth in South Africa has not been environmentally sustainable. Policymakers should prioritize sustainable development strategies that balance economic growth with environmental protection, such as promoting green technologies and implementing carbon pricing mechanisms.

Population growth: The positive relationship between population growth and carbon emissions highlights the need for policymakers to address population growth and urbanization through sustainable planning and green infrastructure development.

Nuclear energy: The study's findings on nuclear energy are unexpected and warrant further investigation. Policymakers should carefully consider the role of nuclear energy in South Africa's energy mix, weighing the benefits of low-carbon energy against the potential risks and challenges.

# 6. CONCLUSION AND RECOMMENDATIONS

## 6.1. Main Findings from the Study

The study's objective was to examine the role of energy sources and macroeconomic factors in environmental sustainability in South Africa using time series data spanning from 1985 to 2024. To achieve this objective, the study formulated secondary objectives as follows: Firstly, it investigated the impact of different energy sources, such as nuclear, renewables, and non-renewable energy, on $CO_2$ emissions and greenhouse gas emissions in South Africa. Secondly, the study examined the short-run and long-run relationships between energy consumption, energy generation, economic growth, and environmental sustainability in South Africa. To achieve these objectives, the study answered the following research questions: Firstly, what is the impact of different energy sources, such as nuclear, renewable, and non-renewable, on $CO_2$ emissions in South Africa? Secondly, what is the impact of different energy sources, such as nuclear, renewable, and non-renewable, on greenhouse gas emissions in South Africa? Thirdly, what is the impact of electricity prices, economic growth, population growth, and inflation on both $CO_2$ emissions and greenhouse gas emissions in South Africa? Lastly, what is the short-run and long-run relationship between energy consumption, economic growth, and environmental sustainability in South Africa? Based on these research objectives and questions, the study employed the VECM and ARDL models, and the key findings are given below.

Firstly, a negative statistically significant relationship exists between electricity prices and $CO_2$ emissions, indicating that increasing electricity prices can reduce emissions and promote environmental sustainability in the short run. However, in the long run, electricity prices increase greenhouse gas emissions. Secondly, renewable energy has a significant negative impact on $CO_2$ and greenhouse gas emissions, supporting the idea that it can promote environmental sustainability. Thirdly, economic growth has an insignificant role in $CO_2$ and greenhouse gas emissions in the short and long run, according to VECM results. However, ARDL robust results reveal that economic growth increases $CO_2$ and greenhouse gas emissions, supporting the Environmental Kuznets Curve hypothesis. Fourthly, population growth increases $CO_2$ and greenhouse gas emissions in the long run. Fifthly, nuclear power has a positive impact on $CO_2$ and greenhouse gas emissions, contradicting some previous studies. Lastly, non-renewable energy negates $CO_2$ and greenhouse gas emissions, which is unexpected and inconsistent with some previous studies.

## 6.2. Policy Recommendations

### *6.2.1. Electricity pricing policy*

Implement pricing mechanisms that encourage energy conservation and reduce emissions. Increasing electricity prices can be an effective tool in the short run, but policymakers should consider the long-term implications and potential unintended consequences.

### *6.2.2. Renewable energy investment*

Invest in renewable energy sources like solar and wind power to reduce dependence on non-renewable energy and decrease $CO_2$ emissions. Incentivize private investment in renewable energy and develop infrastructure to support its integration into the grid.

### *6.2.3. Sustainable economic growth*

Promote sustainable economic growth by investing in green technologies and implementing policies that balance economic development with environmental protection. This can be achieved through the implementation of the National Environmental Management Act and the Climate Change Bill.

### *6.2.4. Population growth management*

Develop strategies to manage population growth and its impact on the environment. This can include investing in education, family planning, and sustainable urban planning.

### *6.2.5. Climate change mitigation*

Develop and implement policies to mitigate the impacts of climate change, such as the Climate Change Adaptation Response Plan and the Low Emissions Development Strategy.

### *6.2.6. Green economy*

Promote a green economy by investing in green infrastructure, green buildings, and sustainable agriculture practices. This can create jobs and stimulate economic growth while reducing environmental degradation.

### *6.2.7. Environmental education and awareness*

Educate the public about the importance of environmental conservation and the impacts of human activities on the environment. This can be achieved through awareness campaigns and environmental education programs.

### *6.2.8. Collaboration and coordination*

Encourage collaboration and coordination between government departments, the private sector, and civil society to promote environmental sustainability and address the challenges of climate change.

## 6.3. Limitations of the Study

The study acknowledges the following limitations that should be considered when interpreting the findings. The study's findings are based on a specific period from 1985 to 2024 and may not reflect current trends or circumstances. The vector error correction model (VECM) and autoregressive distributed lag (ARDL) models used in the study have their own limitations, such as assuming linearity and stationarity in the relationships between variables. The study focuses on South Africa and may not capture the nuances of other countries or regions. Lastly, methodological limitations since the study's reliance on econometric techniques may not capture non-quantifiable factors or unforeseen events that can impact environmental sustainability.

## 6.4. Suggestions for Future Research

The studies in the future can consider exploring the following areas: Firstly, investigate the long-term effects of electricity prices on greenhouse gas emissions and environmental sustainability, as the study's findings showed inconsistent results between short-run and long-run relationships. Secondly, investigate the relationship between nuclear energy and $CO_2$ emissions, as the study's findings were inconsistent with previous research. Thirdly, explore the unexpected finding that non-renewable energy negates $CO_2$ and greenhouse gas emissions in South Africa using different models, including potential explanations and implications. Lastly, research how energy sources and macroeconomic factors can contribute to achieving sustainable development goals in South Africa, including affordable and clean energy.

### 6.5. Concluding Remarks

This study examined the role of energy sources and macroeconomic factors in environmental sustainability in South Africa, focusing on the impact of different energy sources, electricity prices, economic growth, population growth, and inflation on $CO_2$ emissions and greenhouse gas emissions. The findings highlighted the significance of renewable energy in promoting environmental sustainability, while also revealing complex relationships between energy sources and macroeconomic factors in environmental sustainability.

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