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# Determinants of Renewable Electricity Share in a Just Energy Transition: An ARDL Analysis of Economic, Emissions, and Energy Access Factors

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**ABSTRACT**

The urgent need to shift to sustainable energy systems is critical for South Africa, where deep-rooted fossil fuel reliance coincides with significant socio-economic and environmental issues. Although the potential of renewable electricity for promoting decarbonization and inclusive development is acknowledged, the macroeconomic and institutional factors influencing its share in a just energy transition are still inadequately examined. This study examines the changing interactions among economic growth, carbon emissions, and energy access in shaping South Africa's share of renewable electricity. Utilizing the autoregressive distributed lag (ARDL) bounds testing method, the analysis reflects both short-term dynamics and long-term equilibrium relations among the chosen variables. The findings indicate a statistically significant positive relationship between carbon dioxide emissions and the proportion of renewable electricity, implying that environmental decline could stimulate investments in renewables through regulatory or financial motivators. On the contrary, both GDP per capita and access to electricity show negative relationships with the share of renewable electricity, emphasizing the ongoing reliance on fossil-fuel-driven growth and centralized energy access approaches. These results reveal systemic compromises among economic growth, increased energy accessibility, and environmental sustainability. Policy suggestions highlight the incorporation of decentralized renewables into electrification initiatives, alignment of industrial strategies with green growth objectives, and enhanced institutional collaboration to promote South Africa's equitable transition agenda. Future studies ought to broaden to comparative panel analyses throughout the Southern African area and include distributive justice metrics to guide fair energy policy development.

**Keywords:** Renewable Energy, Energy Access, Carbon Emissions, Just Energy Transition, South Africa
**JEL Classifications:** Q41, Q42, Q54, Q56, O13, O55, C32

## 1. INTRODUCTION

The need to accelerate global energy transitions has grown stronger in the last 10 years, driven by the combined demands of addressing anthropogenic climate change and promoting sustainable economic development. Global frameworks, such as the Paris Agreement (2015) and the United Nations Sustainable Development Goals (SDGs) particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action) have catalyzed worldwide policy initiatives aimed at decarbonizing national energy systems (Citaristi, 2022; Sovacool, 2016). In this context, renewable electricity sourced from solar, wind, hydropower, and bioenergy plays a crucial role in harmonizing environmental sustainability with inclusive development needs (Baker et al., 2014; Aklin et al., 2017).

The shift to renewable energy is crucial not only for ecological sustainability but also for wider socioeconomic development goals, especially in developing nations marked by ongoing energy poverty and deep-rooted structural inequalities (Apergis and Payne, 2010; Bhattacharyya, 2012). A significant amount of empirical research shows that a greater proportion of renewable electricity can aid in poverty reduction by enhancing energy access, fostering green jobs, and providing long-term decreases in household energy costs (Sarkodie and Strezov, 2019; Gyamfi et al., 2018). To achieve these advantages fairly, energy transitions need to be equitable, addressing social and regional inequalities linked to energy reforms, and protecting the livelihoods of workers and communities that have traditionally depended on carbon-heavy industries (Swilling et al., 2016; Newell and Mulvaney, 2013).

In South Africa, the need for a fair energy transition is particularly evident due to the nation's heavy reliance on coal for electricity and its complex socio-economic issues, such as high unemployment rates, regional disparities, and energy instability (Baker, 2015; Marquard, 2019). National policy frameworks like the Integrated Resource Plan (IRP) and the Just Energy Transition Investment Plan (JET-IP) clearly highlight the need of incorporating social justice aspects into South Africa's comprehensive decarbonization approach (Ting and Byrne, 2020; Tyler and Steyn, 2021). However, there is still a gap in thorough empirical studies examining the macroeconomic, environmental, and institutional factors affecting the share of renewable electricity in South Africa's energy mix.

This study seeks to address this gap by systematically examining the economic, environmental, and energy access-related determinants of renewable electricity share in South Africa. Utilizing the autoregressive distributed lag (ARDL) bounds testing framework, the study empirically explores the dynamic interrelationships between economic growth, carbon emissions, and energy access. In doing so, it contributes to the growing body of scholarly literature interrogating sustainable energy transitions and their developmental implications in emerging economies (Omri and Nguyen, 2014; Sebri and Ben-Salha, 2014).

This study aims to fill this gap by methodically investigating the economic, environmental, and energy access factors influencing the proportion of renewable electricity in South Africa. Employing the autoregressive distributed lag (ARDL) bounds testing approach, the study investigates the dynamic relationships between economic growth, carbon emissions, and access to energy. By doing so, it adds to the expanding collection of academic research examining sustainable energy transitions and their developmental impacts in developing countries (Omri and Nguyen, 2014; Sebri and Ben-Salha, 2014).

### 1.1. Research Objectives

Accordingly, the study is guided by the following research objectives:

- To assess the long-run relationship between economic growth and the share of renewable electricity in South Africa
- To examine the impact of carbon emissions intensity on renewable electricity share
- To evaluate the role of energy access in shaping renewable electricity dynamics
- To determine the short-run adjustments in renewable electricity share in response to differences in economic, environmental, and access-related factors.

### 1.2. Structure of the Paper

The structure of the paper is as follows: Section 2 offers a critical review of the literature relevant to renewable electricity transitions and just transition models. Section 3 details the methodological framework, covering model specification, data sources, and econometric techniques. Section 4 provides the empirical results and discusses these findings in the context of current policy debates and empirical literature. In conclusion, Section 5 presents important policy suggestions and highlights potential directions for future studies.

## 2. LITERATURE REVIEW

### 2.1. Global Trends in Renewable Electricity Integration

Global energy systems are experiencing a significant shift, with renewable energy being essential to decarbonization initiatives. Improvements in technology and decreasing generation expenses have sped up the adoption of renewable energy, especially solar and wind (Клавдиенко, 2020; Al-Shetwi, 2022). Technologies like smart grids, energy storage solutions, and demand-side management approaches are being more frequently utilized to tackle integration issues related to intermittency and grid stability (Ogunyemi et al., 2024; Hussain et al., 2017). Despite of advancements, structural barriers like fossil fuel subsidies, established pathways, and investment risks in developing markets still obstruct comprehensive integration (Thompson, 2023). Research forecasts indicate that by 2050, renewable energy may account for as much as two-thirds of the worldwide primary energy supply, with Europe at the forefront, Asia moving quickly, and different patterns in the Americas (Hassan et al., 2024). However, different national circumstances require distinct policy strategies, especially in developing countries where structural issues are more pronounced (Yılmaz, 2022; Hunt et al., 2024).

### 2.2. Economic and Policy Determinants of Renewable Energy Share

The factors influencing the adoption of renewable electricity are multi-faceted, showcasing the intricate interaction of economic, political, and institutional elements. Global research consistently emphasizes GDP expansion, fossil energy costs, and environmental policies as key factors promoting the growth of renewable energy (Przychodzeń and Przychodzen, 2020; Hunt et al., 2024). In addition, the rate and extent of renewable electricity implementation are significantly influenced by political stability, regulatory standards, and institutional structures (Tu et al., 2022; Bourcet, 2020). In emerging economies, the development of human capital, the complexity of the financial sector, and availability of international financing also affect the adoption of renewables (Wiredu et al., 2023; Lawal, 2023). Nevertheless, the empirical research is still unclear about the relative importance of these factors, attributed to methodological variations, different national environments, and differing definitions of renewable energy (Bourcet, 2020; Hunt et al., 2024). Particularly in Africa, research indicates that urbanization, ecological impact, and carbon emissions serve as both facilitators and obstacles to the growth of renewable energy (Lawal, 2023). The quality of institutions, especially a reduced perception of corruption, is recognized as a crucial facilitator in South Africa's shift to renewable energy (Inglesi-Lotz, 2023), although socio-political elements frequently impose limitations (Mirzania et al., 2023).

### 2.3. Role of Energy Access and Equity in Just Transitions

The idea of a just transition highlights the importance of including equity and distributive justice in the overall decarbonization process, ensuring that the move toward renewable energy does not worsen existing social or regional inequalities (Newell and Mulvaney, 2013). In sub-Saharan Africa, especially in South Africa, attaining universal energy access continues to be a key component of energy justice (Tomei, 2021; McCauley et al., 2022). Inequities in electricity access sustain socio-economic marginalization, thus prioritizing the fair allocation of renewable energy investments as a key policy goal. Kime et al. (2023) present an analytical framework that classifies equity dimensions into health, access, and livelihoods, thus providing a systematic method for assessing the distributive effects of low-carbon transitions. The equilibrium among energy safety, economic development, and fair access determines the viability of equitable transitions in African settings (Nsafon et al., 2023). South Africa's distinct structural issues such as elevated unemployment in coal-reliant areas like Mpumalanga highlight the need for creating focused policies that tackle techno-economic, socio-political, and socio-technical limitations alongside (Bohlmann et al., 2023; Mirzania et al., 2023).

### 2.4. Emission Reduction Targets and Environmental Justice

Although commitments to reduce emissions are essential for worldwide climate frameworks, recent research emphasizes the complex relationships between overall climate mitigation goals and specific environmental justice results. Research shows that disadvantaged communities frequently experience an unequal impact of air pollution resulting from fossil fuel energy production (Declet-Barreto and Rosenberg, 2022; Hernández-Cortés and Rosas-López, 2021). While climate mitigation strategies like cap-and-trade programs lower emissions overall, their effects on environmental at the local level differ (Anderson et al., 2018). California's cap-and-trade initiative, for instance, has shown minimal enhancements in air quality in underserved communities, highlighting the need to incorporate environmental justice factors into mitigation planning (Declet-Barreto and Rosenberg, 2022). To achieve equitable environmental results, more efficient approaches, including focused local pollution regulations and aligned mitigation co-benefits, might be necessary (Marshall et al., 2014). These results are vital for South Africa, where reliance on fossil fuels has traditionally placed pollution pressures on at-risk communities, prompting concerns regarding the equitable effects of decarbonisation methods.

### 2.5. Summary of Research Gaps

Although the body of research on renewable energy transitions has grown significantly, numerous gaps still exist. Firstly, there is limited empirical research that systematically combines the roles of economic growth, carbon emissions, and energy access in clarifying the renewable electricity proportion particularly within the framework of a just transition in South Africa. Global studies offer insights into overarching factors, yet localized analyses are crucial to understand country-specific dynamics, institutional frameworks, and equity issues (Bourcet, 2020; Omri and Nguyen, 2014). Secondly, few studies thoroughly evaluates how the trade-offs among emission reduction, economic growth, and distributive justice appear in the South African context, especially utilizing time-series econometric approaches such as ARDL frameworks. Finally, there exists a lack of analytical studies that apply equity variables to assess the results of renewable energy policies, especially in situations where energy poverty is widespread. Filling these gaps will help in creating more efficient, inclusive, and sensitive renewable energy policies for South Africa's equitable transition.

## 3. METHODOLOGY

### 3.1. ARDL Approach and Justification

This study utilizes the autoregressive distributed lag (ARDL) bounds testing method to analyze the long-term and short-term factors influencing the share of renewable electricity in South Africa. The ARDL model, developed by Pesaran, Shin, and Smith (2001), is effective for examining time-series data that includes both stationary (I [0]) and non-stationary (I [1]) variables, as long as none are integrated of order two or more (I [2]). Its adaptability in managing various orders of integration makes it more desirable than traditional cointegration methods, like Johansen's approach, which require that all variables be integrated at the same order (Nkoro and Uko, 2016).

Moreover, the ARDL framework facilitates the estimation of short-run dynamics and long-run equilibrium relationships within a single reduced-form model, rendering it especially appropriate for small-sample research such as this (Narayan, 2005). This methodological decision is consistent with recent empirical research examining the relationship among renewable energy, emissions, and macroeconomic factors in developing nations (Sebri and Ben-Salha, 2014; Omri and Nguyen, 2014).

### 3.2. Data Sources and Period Covered

The empirical analysis employs yearly time-series data for South Africa spanning from 1996 to 2022. The selected period is determined by the availability of data for essential variables and its significance to South Africa's energy policy reforms and climate obligations after apartheid.

Information is obtained from trusted global databases, providing methodological accuracy:

Macrotrends Database- for renewable electricity share, $CO_2$ emissions, GDP per capita, energy use, and access to electricity;

International Monetary Fund (IMF) - for Debt-for-Nature Swaps (DNS);

Mosomi and Cunningham (2024, World Bank Policy Research Working Paper 10779) - for Green Job Share (GJS), offering recent and country-specific estimates of green employment dynamics in South Africa.

### 3.3. Description of Variables

#### *3.3.1. Dependent variable*

Renewable electricity share (REI): Refers to the percentage of electricity produced by renewable energy sources in relation to the total electricity generated from all sources (%). It indicates South Africa's advancement in incorporating renewables into the national electricity portfolio.

#### *3.3.2. Independent variables*

- GDP per capita (GDP): Expressed in constant US dollars, this metric reflects economic expansion and its possible influence on the adoption of renewable electricity.
- Carbon dioxide emissions (CCE): Expressed in metric tons per person, $CO_2$ emissions act as an indicator of ecological harm and highlight the necessity for a shift to renewable energy sources.
- Access to electricity (AMES): Denoted as the proportion of the population that has access to electricity, reflecting the energy equity aspect of the fair transition.
- Energy use (EU): Total primary energy consumption per person (kg of oil equivalent), indicating the overall energy demand influences on the electricity sector.

#### *3.3.3. Control variables*

- Population (POP): Included to account for demographic factors affecting overall electricity demand. Debt-for-Nature Swaps (DNS) considered a financial tool that could be associated with investments that promote environmental benefits.
- Green job share (GJS): Indicates the percentage of green jobs in the workforce, important for understanding the socio-economic advantages of growing renewable electricity.

### 3.4. Stationarity and Cointegration Testing

Before estimating the ARDL model, the stationarity characteristics of each variable will be assessed using the Augmented Dickey-Fuller (ADF) test and Phillips-Perron (PP) test to ensure that the variables are integrated of order I(0) or I(1) (Dickey and Fuller, 1979; Phillips and Perron, 1988). The ARDL bounds testing method will subsequently be utilized to determine the presence of a long-term cointegrating relationship among the variables (Pesaran et al., 2001). Post-estimation diagnostics will verify model adequacy, featuring tests for serial correlation (Breusch-Godfrey LM), heteroskedasticity (ARCH test), and assessing model stability (CUSUM and CUSUMSQ tests).

### 3.5. Model Specification

The empirical model employed in this study is specified within the ARDL bounds testing framework as follows:

$$\Delta REI_t = \alpha_0 + \sum_{i=1}^{p} \beta \Delta REI_{t-i} + \sum_{i=0}^{q} \gamma_i \Delta GDP_{t-i} + \sum_{i=0}^{r} \delta_i \Delta CCE_{t-i} + \sum_{i=0}^{s} \theta_i \Delta AMES_{t-i} + \sum_{i=0}^{u} \phi_i \Delta EU_{t-i} + \sum_{i=0}^{v} \psi_i \Delta Z_{t-i} + \lambda_1 REI_{t-1} + \lambda_2 GDP_{t-1} + \lambda_3 CCE_{t-1} + \lambda_4 AMES_{t-1} + \lambda_5 EU_{t-1} + \lambda_6 Z_{t-1} + \varepsilon_t$$

Where:

$REI_t$ = Renewable Electricity Share
$GDP_t$ = GDP per capita (US$)
$CCE_t$ = Carbon dioxide emissions (metric tons per capita)
$AMES_t$ = Access to electricity (% of population)
$EU_t$ = Energy use (kg of oil equivalent per capita)
$Z_t$ = Vector of control variables, including population (POP), Debt-for-Nature Swaps (DNS), and Green Job Share (GJS)
$\Delta$ = First-difference operator
$\alpha_0$ = Constant term
$\varepsilon_t$ = White noise error term
$p, q, r, s, u, v$ = Optimal lag orders determined by Akaike Information Criterion (AIC) or Schwarz Bayesian Criterion (SBC)
$\lambda_1$ to $\lambda_6$ = Long-run coefficients to be estimated.

The short-run dynamics are captured by the lagged first differences of the explanatory variables, while the presence of a long-run relationship is established through the joint significance of the lagged level variables via the F-bound statistic.

If cointegration is confirmed, the corresponding error correction model (ECM) form will be estimated to capture the speed of adjustment ($\phi$) towards long-run equilibrium:

$$\Delta REI_t = \alpha + \sum_{i=1}^{P} \beta_i \Delta REI_{t-1} + \sum_{i=1}^{q} \gamma_i \Delta X_{t-1} + \phi ECM_{t-1} + \varepsilon_t$$

Where $ECM_{t-1}$ represents the lagged residuals from the long-run equation.

### 3.6. Diagnostic Testing Procedures

To guarantee the dependability and strength of the estimated ARDL model, the subsequent diagnostic tests will be utilized:

1. Serial correlation: The Breusch-Godfrey LM Test is employed to identify autocorrelation in the residuals. For an appropriately specified model, the null hypothesis of no autocorrelation ought to remain accepted.
2. Heteroskedasticity: The ARCH (autoregressive conditional heteroskedasticity) Test will be utilized to evaluate the existence of heteroskedasticity in the residuals. Homoskedastic residuals suggest consistent variance throughout time.
3. Normality: The Jarque-Bera Test will evaluate the normality of the residuals. The normal distribution of residuals validates the use of t-tests and F-tests on parameter estimates.
4. Model stability: CUSUM (cumulative sum of recursive residuals) and CUSUMSQ (cumulative sum of squares) tests will be performed to assess the structural stability of the model. Should the plots stay within essential limits, the model is regarded as stable.
5. Functional form: The Ramsey RESET Test will be used to determine if the model's functional form is appropriately specified.
6. Multicollinearity: Variance inflation factors (VIFs) will be computed to evaluate multicollinearity between the regressors. Values under 10 suggest acceptable levels of collinearity.

## 4. FINDINGS

### 4.1. Augmented Dickey-Fuller (ADF) Unit Root Test

To evaluate the stationarity characteristics of the time series variables, the Augmented Dickey-Fuller (ADF) test was performed

**Table 1: Augmented dickey fuller unit root tests**

| Variable | P-values | | t-statistic | | t-statistic and critical values | | | Order of integration |
|---|---|---|---|---|---|---|---|---|
| | Levels | First difference | Levels | First difference | 1% | 5% | 10% | |
| REI | 0.0230 | | −3.9855 | | −4.3743 | −3.6032 | −3.2380 | I (0) |
| GDP | 0.0431 | | −3.6607 | | −4.3393 | −3.5875 | −3.2292 | I (0) |
| CPI | 0.0785 | 0.0002 | −3.3579 | −6.1798 | −4.3560 | −3.5950 | −3.2335 | I (1) |
| CCE | 0.3372 | 0.0028 | −2.4729 | −4.9747 | −4.3943 | −3.6122 | −3.2431 | I (1) |
| TCHG | 0.0170 | | −4.1131 | | −4.3561 | −3.5950 | −3.2334 | I (0) |
| AMES | 0.0298 | | −3.8996 | | −4.4679 | −3.6449 | −3.2615 | I (0) |

Source: Author (s) computation using EViews 12

with the null hypothesis of a unit root and the alternative hypothesis of stationarity. The findings shown in Table 1 reveal the integration order for each variable.

#### *4.1.1. Interpretation*

The unit root test of Augmented Dickey-Fuller (ADF) was used to evaluate the stationarity characteristics of each time series variable based on the null hypothesis of a unit root. The findings show a combination of stationary and non-stationary variables at level, aligning with the criteria for autoregressive distributed lag (ARDL) modelling.

- REI (renewable electricity share), the dependent variable, is found to be stationary at level (I [0]), as its t-statistic (−3.9855) exceeds the 5% critical value (−3.6032), with a corresponding P = 0.0230.
- GDP per capita is also stationary at level (I [0]), with a t-statistic (−3.5875) slightly beyond the 5% critical value and P = 0.0431.
- CPI (inflation) is non-stationary at level (P = 0.0785) but becomes stationary after first differencing (P = 0.0002), indicating it is integrated of order one, i.e., I (1).
- CCE (carbon emissions) similarly exhibits a unit root at level (P = 0.3372) but is stationary at first difference (P = 0.0028), hence it is also I (1).
- TGHG (total GHG emissions) is stationary at level (t-statistic = −4.1131), exceeding the 5% and 10% critical values, thus identified as I (0).
- AMES (access to electricity) is likewise stationary at level, with a t-statistic of −3.8996 and P = 0.0298, making it I (0).

In conclusion, the stationarity test results confirm that the dataset is appropriate for ARDL modelling, given the mixed orders of I (0) and I (1) variables and the absence of any I (2) series. This allows strong estimation of both short- and long-run equilibrium relationships among the variables under study.

### 4.2. ARDL Cointegration Bounds Test

Given the mixed order of integration among the variables (I [0] and I [1]), the autoregressive distributed lag (ARDL) bounds testing procedure was employed to determine the existence of a long-run equilibrium relationship.

#### *4.2.1. Bounds test*

Table 2.

**Table 2: ARDL cointegration bounds test**

| Test statistic | Value | Significance (%) | I (0) | I (1) |
|---|---|---|---|---|
| F-statistic | 9.5494 | 10 | 2.08 | 3 |
| K | 5 | 5 | 2.39 | 3.38 |
| | | 2.5 | 2.7 | 3.73 |
| | | 1 | 3.06 | 4.15 |

Source: Author's computation using EViews 12

#### *4.2.2. Interpretation*

The calculated F-statistic of 9.5494 surpasses the upper critical values at the 1%, 5%, and 10% significance levels as indicated by the Pesaran et al. (2001) bounds testing method (Table 2). This empirical finding results in the rejection of the null hypothesis indicating no cointegration between the variables.

### 4.3. ARDL Long-Run and Short-Run Estimates

To empirically evaluate the factors influencing the share of renewable electricity (RE) within the framework of a fair energy transition, an autoregressive distributed lag (ARDL) model was utilized. This specification includes both long-term equilibrium relations and short-term dynamics between RE and a set of macroeconomic and energy-related explanatory variables specifically GDP per capita (GDP), consumer price inflation (CPI), carbon dioxide emissions (CCE), total household consumption (TCHC), and access to modern energy services (AMES). Table 3 presents the estimated coefficients.

#### *4.3.1. Long-run estimates and economic interpretation*

In In the long run, carbon dioxide emissions (CCE) show a statistically significant and positive relationship with the share of renewable electricity (coefficient = 2.5706, P = 0.0439). This indicates that increasing carbon emissions serve as a catalyst for the growth of renewable electricity adoption, likely influenced by regulatory demands or climate action pledges under agreements like the Paris Accord. A one-unit rise in CCE corresponds to a 2.57 unit increase in REI, highlighting the sensitivity of renewable energy systems to environmental factors.

On the other hand, access to modern energy services (AMES) shows a statistically significant negative relationship with REI over the long term (coefficient = −0.3350, P = 0.0122). This surprising outcome might indicate structural imbalances in energy access initiatives, where growth in access mainly depends on fossil-fuel-based grid expansion in less developed regions. Alternatively, it could suggest that the rise in electrification has not yet sufficiently in line with renewable sources because of delays in infrastructure, financing, or policies.

**Table 3: Estimated long-run and short-run coefficients**

| Dependent variable: D (REI) | | | | |
|---|---|---|---|---|
| Included observations: 20 | | | | |
| **Variable** | **Coefficient** | **Standard error (SE)** | **t-statistic** | **Probability** |
| GDP_ | −0.1414 | 0.0737 | −1.9163 | 0.0746 |
| CPI_ | 0.0021 | 0.0780 | 0.0259 | 0.9796 |
| CCE | 2.5706 | 1.1706 | 2.1998 | 0.0439 |
| TCHC | −0.0575 | 0.0632 | −0.9094 | 0.3775 |
| AMES | −0.3350 | 0.1175 | −2.8495 | 0.0122 |
| C | −0.1510 | 0.9478 | −0.1593 | 0.8755 |
| Short-run estimates: ECM short run dynamic ARDL estimation | | | | |
| D (GDP_) | −0.0608 | 0.0532 | −1.1426 | 0.0003 |
| D (AMES) | −0.1531 | 0.0545 | −2.8074 | 0.0133 |
| CointEQ (−1)* | −1.4501 | 0.1499 | −9.6739 | 0.0000 |
| ECM model performance | | | | |
| R-squared | 0.8384 | Mean dependent var | | 0.0125 |
| Adjusted R-squared | 0.8230 | S.D dependent var | | 1.2852 |
| S.E. of regression | 0.5407 | Akaike info criterion | | 1.7246 |
| Sum of squared resid | 6.1396 | Schwarz criterion | | 1.8718 |
| Log likelihood | −17.695 | Hannan-Quinn criter | | 1.7637 |
| Durbin-Watson stat | 2.2352 | | | |

Source: Author's computation using EViews 12

In the long term, GDP per capita shows a negative relationship with the REI share (coefficient = −0.1414), although the significance of this relationship is only marginal (P = 0.0746). This could indicate an energy transition dilemma, as initial phases of economic growth remain largely dependent on traditional energy sources, especially in industrial areas, thus side lining renewables unless supported by intentional policy measures.

Additional factors like CPI and TCHC are statistically insignificant, indicating that these macroeconomic aggregates have limited explanatory power for REI over the long term within this particular estimation timeframe.

### *4.3.2. Short-run dynamics and speed of adjustment*

In the short term, both GDP and AMES exhibit negative and significant coefficients. The short-run elasticity of GDP (−0.0608, P = 0.0003) supports the idea that energy demand driven by growth may predominantly favor affordable non-renewable sources initially, unless subsidized actions alter the marginal cost benefit in favor of renewables.

The negative short-run coefficient for AMES (−0.1531, P = 0.0133) aligns with the long-run estimate, indicating a persistent misalignment between the expansion of energy access and the growth of renewable energy. These results indicate the necessity for cohesive energy planning that directly connects universal access objectives with sustainable supply sources.

The error correction term (CointEQ [−1]) is markedly negative and statistically significant (coefficient = −1.4501, P < 0.001), confirming the presence of a stable long-term equilibrium. The size indicates that around 145% of the imbalance is rectified in every period—implying a swift alignment to long-term equilibrium, possibly due to effective policy reactions or external adjustment forces in the energy industry.

**Table 4: Diagnostic tests**

| Diagnosis and null hypothesis | Test | P-value | Conclusion |
|---|---|---|---|
| 1. Normality<br>$H_0$: Residuals are normally distributed | Jarque-Bera | 0.6883 | Accept the null hypothesis |
| 2. Heteroskedasticity<br>$H_0$: No heteroskedasticity | Breusch-pagan godfrey | 0.5920 | Accept the null hypothesis |
| 3. Serial correlation<br>$H_0$: No serial correlation | Breusch godfrey | 0.1431 | Accept the null hypothesis |
| 1. Multicollinearity<br>$H_0$: No multicollinearity | Variance inflation factor | VIF <5 | Accept the null hypothesis |
| 2. Stability<br>$H_0$: No omitted variables | Cusum squares | 0.05 | Accept the null hypothesis |

Source: Author (s) Computation using EViews 12

### *4.3.3. Model diagnostics and specification adequacy*

The model exhibits strong explanatory power, with an R-squared of 0.8384 and adjusted R-squared of 0.8230, indicating that over 82% of the variation in REI is accounted for by the included variables. The Durbin-Watson statistic (2.2352) supports the absence of serial correlation, and the relatively low Akaike Information Criterion (AIC = 1.7246) reflects a well-specified model. These diagnostics suggest the estimated ARDL-ECM is robust and suitable for drawing policy inferences.

## 4.4. Diagnostic Tests

The diagnostic tests of the ARDL-ECM model estimation verifies the econometric strength of the model and the accuracy of classical linear regression assumptions. Firstly, the normality of residuals was evaluated with the Jarque-Bera test, resulting in a P = 0.6883 (Table 4).

Secondly, the Breusch-Pagan-Godfrey test was utilized to investigate the existence of heteroskedasticity. The associated P = 0.5920 suggests that the null hypothesis of homoscedastic residuals remains unchallenged, affirming the stability of error variance throughout the observations.

Thirdly, the Breusch-Godfrey LM test was used to identify serial correlation. A $P = 0.1431$ led to the acceptance of the null hypothesis indicating no autocorrelation. This suggests that the residuals show no consistent patterns over time, validating the model's dynamic structure and guaranteeing unbiased estimation of the lagged parameters.

The problem of multicollinearity was assessed with the variance inflation factor (VIF). All VIF values were indicated to be under 5, which is significantly lower than the standard threshold that raises concern. This indicates that the explanatory variables in the model are not overly correlated with each other, maintaining the clarity of individual coefficients and the accuracy of parameter estimates.

Finally, the stability and specification of the model were evaluated using the cumulative sum of squares (CUSUMSQ) method. The analysis revealed that the model stayed within the 5% significance limits during the estimation period, thereby validating the lack of structural breaks or omitted variable bias.

In conclusion, the diagnostic tests together indicate that the ARDL model estimation for renewable energy (REI) dynamics in Southern Africa is economically robust. The lack of violations of normality, heteroskedasticity, serial correlation, multicollinearity, and structural instability boosts confidence in the dependability of both short-run and long-run conclusions derived from the model, especially concerning the policy-relevant factors influencing REI expansion.

## 5. DISCUSSION

### 5.1. How Economic and Environmental Indicators Affect Renewable Energy Share

The ARDL analysis offers important perspectives on the relationship among macroeconomic variables, environmental elements, and renewable energy's contribution in Southern Africa. The favourable long-term connection between carbon dioxide emissions (CCE) and renewable electricity share indicates that heightened environmental damage has driven changes in policy or market trends toward cleaner energy sources. This discovery corresponds with worldwide evidence indicating that carbon emissions frequently serve as catalysts for renewable investments via mechanisms like regulatory frameworks, carbon pricing, and international environmental accords (Shahbaz et al., 2013; Destek and Sinha, 2020).

In contrast, the negative relationship between electricity access (AMES) and the share of renewable energy illustrates that the expansion of energy access in the area has mainly depended on traditional fossil-fuel grids instead of decentralized renewable systems (Citaristi, 2022). This result aligns with criticisms of centralized electrification approaches relying on fossil fuels throughout sub-Saharan Africa (Trotter, 2016).

The negative and somewhat significant link between GDP per capita and the share of renewable energy highlights the continued presence of carbon-heavy industrial frameworks in the area, notably in industries like mining, manufacturing, and heavy industry (Bekun et al., 2019; Inglesi-Lotz, 2023). This result supports earlier research in comparable resource-dependent developing nations, where economic growth continues to be linked to fossil fuel consumption (Omri and Nguyen, 2014).

### 5.2. Evidence of Trade-offs or Synergies in Energy Justice

These findings highlight distinct trade-offs in South Africa's quest for energy justice. Increasing electricity access crucial for socio-economic progress has primarily been accomplished via traditional, high-emission methods, compromising environmental sustainability goals. Likewise, the path of GDP growth continues to clash with the growth of renewable energy, highlighting a separation between economic progress and decarbonization initiatives. The notably significant error correction term (ECT) indicates that synergies may be leveraged if intentional policies address these discrepancies. Dynamic policy measures aimed at cutting emissions and expanding renewable energy could take advantage of the system's natural ability for swift adaptation.

### 5.3. Comparison with Prior Studies

The results align with both global and regional empirical research. Research by Shahbaz et al. (2013) and Omri and Nguyen (2014) also showed positive links between environmental degradation and investments in renewable energy, highlighting environmental externalities as drivers for the shift to clean energy. Trotter (2016) and the Citaristi (2022) indicated that electrification initiatives in Africa frequently lack alignment with renewable energy objectives, supporting the negative correlation between AMES and renewable share noted here. Finally, the tenuous connection between GDP growth and renewables reflects conclusions drawn by Bekun et al. (2019) and reinforces Inglesi-Lotz (2023) observations about South Africa's reliance on fossil fuels in industry.

### 5.4. Policy Relevance for South Africa and Similar Economies

For South Africa and economies with comparable reliance on fossil fuels, these results highlight the necessity for cohesive, equitable, and emission-aligned energy strategies. Increasing access to renewable electricity and separating economic development from fossil fuel use will necessitate intentional adjustments in institutional, financial, and infrastructural approaches, guaranteeing a truly equitable transition.

## 6. CONCLUSION AND POLICY RECOMMENDATIONS

### 6.1. Summary of Main Findings

The empirical analysis shows that environmental deterioration has positively influenced the share of renewable electricity, probably due to environmental regulations and international funding systems. Nonetheless, the growth of the economy and the expansion of energy access have been structurally mismatched with the implementation of renewable energy, indicating a regional dependence on traditional energy technologies. The model's quick adjustment dynamics present a chance for faster renewable integration if policy measures are successfully enacted.

### 6.2. Implications for Just Energy Transition Policy and Planning

A successful energy transition in South Africa must tackle not only technical decarbonization but also social equity, economic restructuring, and environmental justice. Policy frameworks must clearly combine the growth of energy access with the implementation of decentralized renewables to prevent ongoing reliance on fossil fuels.

### 6.3. Recommendations for Scaling Renewables While Addressing Equity

#### *6.3.1. Renewable integration in electrification strategies*

Integrate renewable sources into grid-connected and off-grid electrification initiatives, bolstered by institutional directives for decentralized, community-managed renewable systems.

#### *6.3.2. Decoupling economic growth from emissions*

Encourage sustainable industrial development by providing incentives for low-emission production in major industries and improving access to preferential green financing options like green bonds and guarantees.

#### *6.3.3. Strengthening emissions-based incentives*

Broaden carbon pricing systems, incorporate emissions objectives into national development strategies, and establish financial rewards supporting renewable energy implementation.

#### *6.3.4. Cross-sectoral institutional coordination*

Enhance horizontal collaboration among energy, environmental, and financial sectors to integrate renewable targets into nationally determined contributions (NDCs) and other macroeconomic planning frameworks.

#### *6.3.5. Social safeguards and participation*

Create policy sets that include focused job programs, social protection systems, and participatory governance structures, especially in coal-reliant areas like Mpumalanga.

### 6.4. Suggestions for Future Research

Future studies should investigate panel data analyses across various African nations to assess generalizability, employ structural equation modelling (SEM) to analyse causal pathways, and create quantitative equity metrics to evaluate distributive justice results in renewable energy transitions. A heightened emphasis on the convergence of gender equity, green jobs, and the expansion of renewable energy would enhance the policy significance of upcoming research.

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